ABSTRACT BOOK

SETAC EUROPE 27TH LCA CASE STUDY SYMPOSIUM

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DESIGNING TOMORROW: ADVANCING LIFE CYCLE APPROACHES FOR EUROPEAN SUSTAINABILITY INITIATIVES.



Abstract Book

SETAC Europe 27th LCA Symposium

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This book compiles the abstracts from the 27th LCA Symposium of the Society of Environmental Toxicology and Chemistry – Europe (SETAC Europe), conducted from 19–21 October 2026 in Bruges, Belgium.

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About SETAC

In the 1970s, no forum existed for interdisciplinary communication among environmental scientists, biologists, chemists, toxicologists, managers, engineers or others interested in environmental issues. The Society of Environmental Toxicology and Chemistry (SETAC) was founded in North America in 1979 to fill the void and quickly saw dynamic growth in the Society's membership, meeting attendance and publications.

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Track 1: Methodological advancements in prospective and consequential LCA

1.01 - Advancing Life Cycle Assessment for Carbon Dioxide Removal (CDR)

1.01.T01 Time-Explicit Life Cycle Assessment Linked to Prospective Background Scenarios and Climate Emulator

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Robust environmental assessments of carbon dioxide removal (CDR) technologies require more than static carbon accounting. The environmental performance and climate effectiveness of CDR technologies depend on when infrastructure is built, when energy and material inputs occur, when carbon is removed, and how background systems evolve during deployment. These temporal dynamics are especially important for emerging CDR options assessed under future large-scale deployment conditions. Yet, they remain only partially captured in conventional life cycle assessment (LCA).

Here, we present TRAILS, a time-explicit open-source LCA tool developed to assess product systems whose impacts unfold over time and under changing prospective background economies TRAILS distributes life-cycle systems over time, not only in the foreground but also throughout the supply chain. As such, it links temporally differentiated demands to background scenarios. From a methodological point of view, it combines temporal routing of exchanges with sequential, year-wise (prospective) life-cycle inventory calculations, allowing scenario-consistent quantification of inventories and impacts over time while preserving computational feasibility. In addition, TRAILS is coupled to a climate emulator, enabling the translation of temporally distributed greenhouse gas emissions and removals across different potential trajectories of future atmospheric and oceanic greenhouse gas concentrations, yielding climate-relevant outcomes (i.e., radiative forcing and temperature anomaly).

Our novel open-source framework is particularly relevant to CDR technologies, where the life-cycle climate effectiveness largely depends on the timing of construction, operation, energy provision, carbon uptake, and background decarbonization. In this contribution, we will present a series of applications that cover different CDR options and show how temporalization can alter the assessed climate performance relative to static LCA approaches. The results highlight that both the timing of life-cycle interventions and the evolution of future background systems can significantly affect conclusions about the climate effectiveness of CDR technologies.

By combining dynamic system representation, prospective background integration, and climate response modelling, TRAILS advances LCA for CDR beyond static LCA comparisons.

1.01.T02 Biogenic Carbon Modelling in LCA: A Temporal Perspective

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Biogenic carbon modelling has long been debated in LCA, shaped by competing stakeholder interests, differing interpretations of natural science, concerns about greenwashing, and the methodological limits of LCA in representing carbon uptake, release, and storage over time. The core issue is temporal: biogenic carbon is not inherently climate-neutral but depends on timing. Its impact is determined by the relationship between uptake and release within a defined time horizon, as well as by biomass rotation periods and product service life. Current static accounting methods, particularly the −1/+1 approach in EN 15804+A2 and the alternative 0/0 approach, remove this temporal dimension. While acceptable for fast-cycling, sustainably managed systems, they can misrepresent long-lived products, slow-rotation biomass, or delayed re-uptake, cases increasingly relevant in construction and bio-based materials.
This work examines temporal biogenic carbon in LCA using system dynamics modelling. In openLCA, both −1/+1 and 0/0 approaches are implemented as stock-and-flow models, enabling explicit tracking of carbon uptake, in-use storage, and end-of-life emissions over time rather than compressing them into static inventory values. This also enables the

application of temporal characterization factors. Comparison with current product category rules and standards highlights a significant gap: existing guidance does not provide sufficient technical detail to ensure consistent or physically meaningful modelling. Critical parameters, such as product lifespan, end-of-life scenarios, and characterization time horizons, are often missing, unclear, or inconsistently defined across PCRs and standards.
This work proposes clearer guidance for biogenic carbon modelling through a structured set of parameters to support transparent and consistent accounting. It argues for separating modelling objectives, such as avoiding greenwashing, recognizing carbon storage, or reflecting radiative forcing, from the technical methods used to achieve them. This distinction supports clearer interpretation of existing rules, facilitates consensus, and enables LCA practice that aligns with study goals and complies with applicable PCRs and standards

1.01.T03 Life Cycle Assessment of Enhanced Weathering in the UK Coupled with Site-Specific Ecohydrological Modelling

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Enhanced Weathering (EW) has emerged as a promising Carbon Dioxide Removal (CDR) technology in the global effort to reach net-zero emissions. Through the application of crushed silicate rock to agricultural soils, the UK alone has the theoretical capacity to capture 6-30 Mt of CO2 per year by 2050. To facilitate the sustainable scale-up of EW, it is critical that comprehensive life cycle assessments (LCAs) are carried out using detailed life cycle inventories (LCIs). Existing LCA studies of EW use static CDR yield potential factors for a given feedstock and have LCIs that fail to capture the complex interactions between hydrology, soil chemistry and weathering processes. This underrepresents the environmental inventory of an EW project, as environmental flows such as nutrient leaching and carbonate precipitation after initial application are omitted. This risks both the misrepresentation of the CDR potential of an EW project and failing to highlight potential environmental hotspots in categories such as freshwater eutrophication and ecotoxicity.
This study presents an LCA for an EW project using basalt on a single agricultural field site in the UK, using the T&C-SMEW ecohydrological model to address the gaps in existing LCIs. Coupled with climatic data from the UKCP18 climate projections and site-specific soil properties, T&C-SMEW resolves carbon, water and nutrient budgets at an hourly timestep, developing a dynamic accounting of the CDR during the EW project.
The LCI developed from the model outputs includes dynamic CO2 removal, nutrient leaching (Na, Ca, Mg, Si, Al, P, N, K) fluxes driving other environmental burdens, as well as environmental co-benefits such as change in net primary productivity. The background processes of mining, grinding, transportation and field application are also included within the system boundaries.
The inclusion of these environmental flows after application is critical to ensure that the environmental trade-offs of EW can be assessed, particularly in the UK, where high rainfall can intensify nutrient leaching. Climate uncertainty was also considered through the use of different RCP scenarios for climatic data.
This study advances EW LCA methodologies by demonstrating how site-specific modelling can close inventory gaps to comprehensively assess a full range of environmental impacts, using a framework that can be applied to support more robust future MRV methodologies.

1.01.T04 Advancing LCA method for CDR: Integrating soil feedbacks into the LCA assessment of Biochar application to agricultural soils.

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Biochar is increasingly recognized as one of the preferred carbon dioxide removal pathways because it not only

sequesters biogenic carbon in soils but also influences soil processes, crop performance, and greenhouse gas emissions in a positive way. In LCA, biochar systems are often represented mainly through production emissions and carbon storage assumptions, while soil feedbacks are treated inconsistently or omitted. This limits LCA models' ability to capture co-benefits, side effects, and trade-offs associated with biochar application in agricultural soils.

This study presents a methodological framework for translating field trial data following biochar application to agricultural soil into indicators for LCA modeling. The framework focuses on converting measured soil and crop responses into transparent foreground inventory elements, including changes in soil carbon stocks, nitrogen-related soil responses, crop productivity, direct field greenhouse gas emissions, and net climate-related outcomes. The aim is to improve how experimental biochar evidence is represented in LCA without relying on unsupported assumptions about avoided inputs or indirect benefits.

A key issue is the difference between an observed soil response and a defensible substitution claim. For example, an increase in soil nitrogen retention does not automatically mean that mineral fertilizer has been avoided. Similarly, a change in pH should not be converted into a yield benefit unless the supporting evidence is strong enough. The proposed approach keeps measured field effects separate from optional avoided-input effects, so that co-benefits are only included when they are supported by appropriate data.

Applying the approach to available biochar field-trial data shows that many studies provide enough information to estimate soil carbon changes, yield responses, and direct greenhouse gas effects. However, fewer studies report the full set of soil, crop, and management variables needed to support stronger claims about avoided fertilizer or other substitutions. This points to an important data gap for biochar carbon removal assessment: field trials often measure useful soil responses, but not always in a way that can be directly used in LCA.

Overall, this work supports more complete and reliable LCA modelling of biochar CDR where soil-mediated effects influence environmental performance.

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1.01.T05 JuDCB-DAC: An Open-Source Framework for Systems Optimization and Prospective Life Cycle Assessment of Adsorption-based Direct Air Capture

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Upscaling carbon dioxide removal (CDR) to gigaton-per-year levels introduces system-wide impacts that cannot be captured by conventional life cycle assessment (LCA). For direct air capture (DAC), environmental performance depends strongly on system design, regional conditions, and deployment strategies, yet most existing studies rely on simplified or static representations. This limits the ability of LCA to assess large-scale deployment.

This work presents JuDCB-DAC, an open-source modelling framework in Julia that integrates process-based system optimization with prospective LCA (pLCA) for adsorption-based DAC technologies. The framework bridges engineering-level systems modelling and pLCA to enable consistent and reproductive evaluation of emerging systems.

The approach combines modular representations of adsorption processes with multi-scale system modeling. It links material properties (isotherms and kinetics), dynamic column behavior (breakthrough modelling), and process-level

energy and mass balances to plant-level design and optimization. A dedicated pLCA module is developed and interfaced with the Brightway ecosystem to incorporate life cycle inventories and baseline LCA results. This integration allows systematic propagation of process-level parameters into environmental impact assessment. Location-specific and time-dependent factors, including electricity supply, climate conditions, water availability, and CO_2 transport and storage, are explicitly considered. Scenario-based optimization is applied to explore trade-offs among energy demand, water use, costs, and life cycle carbon removal efficiency across operating strategies, geographic contexts, and deployment scales. Case study is given to hybrid configurations coupling DAC with atmospheric water extraction, where water–energy interactions introduce additional environmental trade-offs.

Preliminary results indicate that system-level design choices, process configurations, and regional conditions can lead to substantial variation in environmental performance across impact categories. These results demonstrate that simplified representations may overlook critical interactions between process design and environmental outcome.

By providing a transparent and extensible open-source framework, this work highlights the importance of coupling systems optimization with prospective LCA for DAC scale-up assessment, contributing to more robust assessment and design of carbon removal strategies.

1.01.P - Advancing Life Cycle Assessment for Carbon Dioxide Removal (CDR)

1.01.P-Mo001 Scenario-Aware Uncertainty Assessment for Carbon Dioxide Removal Through the Built Environment

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Life-cycle assessment (LCA) is essential for evaluating the carbon dioxide removal (CDR) potential of processes and materials, yet many studies report point estimates that obscure whether a system is robustly net-removing under plausible process, scenario, and modeling choices. This is especially critical for carbon-storing materials in the built environment, where net removal and storage outcomes depend on feedstock sourcing, processing energy, co-product fates, storage duration, displacement assumptions, and end-of-life pathways. This presentation synthesizes lessons from a scenario-aware uncertainty framework, first demonstrated for building-material emissions and then extended to carbon-storing materials, including biochar and mass timber. These case studies are used to propose a more transparent accounting structure for CDR assessment. The approach separates parameter, scenario, and model uncertainty, then propagates each through stage-resolved life-cycle inventories. It reports both median impacts and the likelihood of net removal or durable storage under different operating pathways. It also separates durable carbon storage from displacement benefits, preventing avoided emissions, such as material substitution or energy credits, from being interpreted as equivalent to atmospheric carbon removal. In the biochar case, uncertainty analysis distinguishes scenarios that are highly likely to deliver net removal from pathways where the sign of the result becomes uncertain, with energy inputs and co-product treatment driving most of the difference. In the mass-timber case, the framework is extended to include dynamic biogenic carbon accounting and time-adjusted warming potential to evaluate release timing, permanence, and storage losses across harvest slash, mill residue, product use, and end-of-life. Ultimately, this synthesis shows that robust CDR assessment requires scenario-aware framing, explicit treatment of temporal carbon fluxes, and uncertainty attribution that prioritizes data collection for high-uncertainty, high-impact processes. Together, these lessons define pathways forward for robust CDR assessment including scenario-based reporting, transparent boundary and time-horizon choices, and explicit separation of removal/storage from displacement claims in emerging carbon-storing materials.

1.01.P-Mo002 Integrated Dynamic Life Cycle Assessment as a Tool to Assess the Technological Efficacy of

Mineral Carbonation of Steel Slags as a Carbon Capture, Utilization and Storage Technology

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Mineral carbonation of steel slags is increasingly recognized as a promising carbon capture, utilization, and storage (CCUS) pathway, enabling both the valorization of steelmaking by-products and the mitigation of CO_2 emissions. In addition to permanent CO_2 sequestration during the carbonation process, carbonated steel slags can be applied in agriculture as substitutes for liming agents or basalt rock powder, where further CO_2 uptake may occur during the use phase. Robust evaluation of such systems therefore requires a life-cycle-based approach that accounts for the temporal dynamics of emissions and sequestration, which are not captured by conventional static life cycle assessment (LCA). This study proposes an integrated environmental assessment framework combining conventional LCA with dynamic life cycle assessment (DLCA) to quantify time-dependent CO_2 emissions, sequestration, and associated radiative forcing. The framework enables a comparative evaluation of carbonated and non-carbonated steel slags by tracking CO_2 uptake during both the production (carbonation) phase and the agricultural use phase, thereby assessing the necessity and added value of mineral carbonation. The approach is demonstrated using empirical carbonation and emission data collected over 435 days from the FWO-funded AgriCarb project. Results show that carbonated slags achieve substantially higher cumulative CO_2 sequestration over the observation period than non-carbonated slags, due to the combined effects of accelerated carbonation and continued CO_2 uptake during agricultural application.

1.01.P-Mo003 Challenges and Prospects of Direct Ocean Carbon Capture and Storage (DOCCS) as a Carbon Dioxide Removal Technology: Findings From an Ex-Ante LCA

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Direct Ocean Carbon Capture and Storage (DOCCS) is a relatively new concept among carbon dioxide removal (CDR) technologies. Currently, specific guidelines and methodologies for monitoring, reporting, and verification (MRV) of DOCCS remain limited, while R&D, pilot, and demonstration activities are advancing rapidly toward scale-up and commercial deployment.

Further research is required to better understand both the technical performance and environmental implications of DOCCS systems. Environmental sustainability must be considered alongside carbon removal efficiency. Potential impacts on seawater chemistry, marine ecosystems, and biodiversity require careful assessment, and robust monitoring and modeling frameworks will be essential to ensure environmentally responsible development.

This presentation outlines findings from a preliminary sustainability assessment of a projected DOC plant, based on the system boundary defined in the MRV framework by Isometric, currently the only DOCCS-specific MRV guideline available. The analysis highlights challenges related to data collection for equipment and infrastructure, identifies environmental hotspots associated with DOCCS operation using ex-ante LCA, and discusses environmental aspects that are not fully captured by conventional LCA approaches.

The work also considers the role of potential co-products from DOCCS operations and points to unresolved questions related to allocation rules and financial additionality. Allowing the responsible use or sale of co-products under clearly defined rules could improve project economics and support early deployment.

Overall, our results underscore the need for clear regulatory guidance to steer responsible innovation, support real-world pilot and demonstration efforts, and ensure that marine-based CDR technologies are developed in a scientifically robust and environmentally responsible manner.

1.01.P-Mo004 An Uncertainty-Informed Comparative Life Cycle Assessment: Zeolite 13X and Aluminium-

Based MOFs versus MEA for CO_2 Capture

Yipeng YAO[1], Arnaud Henrotin[2], Marie-Eve Duprez[1] and Guy De Weireld[1] (1)University of Mons, (2)Unversity of Mons

Solid adsorbent-based CO_2 capture is increasingly considered a promising alternative to conventional monoethanolamine (MEA) absorption due to its potential for lower regeneration energy and improved environmental performance. However, the life-cycle impacts of emerging adsorbents remain insufficiently characterised, and comparative studies often lack robustness because uncertainty in key inventory parameters is rarely addressed.

This study presents a cradle-to-grave, uncertainty-informed life cycle assessment comparing MEA with three representative solid adsorbents: Zeolite 13X, MIL-120(Al), and MIL-160(Al). The assessment was conducted using the Environmental Footprint (EF) 3.1 methodology, integrating sensitivity and uncertainty analyses to evaluate both environmental performance and the robustness of material comparisons.

Results indicate that CO_2 recovery rate and regeneration energy demand are the primary contributors to environmental variability across all scenarios. Under uncertainty conditions, MIL-160(Al) exhibits the most favourable environmental performance. Based on the EF 3.1 single score, the probabilities that MIL-160(Al) outperforms MEA, Zeolite 13X, and MIL-120(Al) are 68%, 83%, and 69%, respectively. When global warming potential is used as the sole indicator, these probabilities increase to 100%, 100%, and 91%, respectively.

By explicitly accounting for uncertainty in key inventory parameters, this work strengthens the environmental screening of next-generation CO2 adsorbents and supports more credible, and decision-relevant material selection for industrial CO_2 capture applications.

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1.01.P-Mo005 Life Cycle Assessment of Methane Production via CO2 Hydrogenation: A comparative Analysis and Impact Characterization Model

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Methane synthesis via CO2 hydrogenation represents a promising route for carbon recycling and renewable energy storage. Using renewable energy to produce H2 and convert CO2 into CH2 production via power-to-methane helps reduce global warming potential (GWP) and primary energy demand. Ni/Al2O3 catalysts are widely studied for their efficiency and cost-effectiveness in methanation reactions, as they increase activity at lower temperatures and provide high selectivity and stability for CH4. Consequently, the transition to sustainable methane requires evaluating environmental performance at early innovation stage. Life Cycle Assessment (LCA) provides a systematic method to quantify environmental burdens; however, in practice, data scarcity often limits early-stage evaluation. This study presents the development of a prospective scenario-driven LCA framework integrating LCA using SimaPro software with MATLAB multivariate analysis to create the impact characterization model for methane production over Ni/Al2O3 -catalyzed CO2 hydrogenation. Key operating variables were identify to generate 27 scenarios, each based on the production of 1 kg of CH4 as a functional unit, with CO2 from biogas production and H2 from wind-based electrolysis.

The LCA results of CO2 methanation over Ni/Al2O3 catalyst showed that the process is carbon-negative across most evaluated range. GWP is within the range of -0.26 – -0.29 kg CO2-eq for the most efficient scenarios. H2 production is the highest contributor, which generates a large positive share of the GWP (0.61 kg CO2-eq, representing over 93% of the total process burdens). The impact characterization model (R2=0.91) reveals that the net GWP is primarily driven

by H2/CO2 mass ratio. The optimal efficiency zone identifies scenarios where H2/CO2 mass ratio is between 0.15 and 0.16, and the CH4 yield is within the range 85% – 95%. Later, when experimental data become available, new points can be plotted within the same model, allowing the framework to interpret and compare the environmental performance. Future work may apply the framework to C1-based chemical production case studies for assessing future scenarios.

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1.01.P-Mo006 Addressing Carbon Dioxide Removal's Unique Life Cycle Assessment Challenges

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Billions of tonnes of CO2 must be removed every year globally through Carbon Dioxide Removal (CDR) by 2050 due to increasing global ambient CO2 concentrations. While many industries strive to decarbonize, we still require CDR to ensure we control global temperature increases through net negativity and avoid overshooting our emission targets. This scope includes both durable and non-durable CDR e.g. forestry. Major challenges of CDR include ambiguity and engineering complexity depending upon the technology, with high degrees of uncertainty. Since the value of CDR is its environmental benefits, life cycle assessment (LCA) is a foundational tool to evaluate the 'GHG efficiency' of a CDR pathway relative to a reference business-as-usual scenario. However, many methodological questions remain for conducting LCAs on CDR pathways. Therefore, the goal of this work is to align the processes of carbon removal with the analytical nature of the LCA method. We address these challenges through a working group focused on areas such as the definition of functional units and system boundaries for CDR, determining which CDR inputs can be burden free, co-product modelling, the effect of variable CO2 uptake timing and storage durations, and the use of attributional versus consequential LCA. Our approach involves a systematic and rigorous review of the CDR literature concerning LCA, as well as potential investigative case studies towards selected technologies within the current portfolio. Following this exploratory analysis, we aim to provide detailed guidance to all stakeholders involved with CDR LCA. This working group aims to establish clarity on whether CDR can be a product within LCA studies as well as the potential repercussions of this understanding, such as providing ISO-compliant LCAs on CDR processes and defining how CDR can contribute to the functional unit of the products system. The working group's analysis has already indicated that the final CDR product may be a reference flow, meaning that both intermediate and final CDR flows must carry environmental burdens while offering environmental benefits. Ultimately, the goal of this research is to ensure that all CDR technologies are assessed in a transparent, consistent, and rigorous approach through providing appropriate and effective guidance on how LCA treats CDR. The results of this work may generate insights or implications for broader CDR carbon credit standards, policy approaches, and technology benchmarking.

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1.01.P-Mo007 When does a tree grow? The influence of temporal assumptions of the perceived carbon payback period of forestry-based bioenergy and CCS systems.

Devika Varma[1] and Samantha Eleanor Tanzer[1] (1)Delft University of Technology

Bioenergy with carbon capture and storage (BECCS) is the dominant large-scale carbon removal pathway included in integrated assessment modelling exercises, and came to prominence in its visibility in the IPCC Special Report on Global Warming of 1.5°C. Since then, the possible scalability and efficacy of BECCS has been hotly debated both in academia and civil society, focusing not only on the availability of biomass resources, but also questions of "net removal efficiency" and the timing of when the removal benefits of a BECCS system would even occur.

Regarding the question of this “carbon payback period”, diverging modelling assumptions have led to claims that BECCS plants achieve net removal within a couple of years to not achieving it for over a century. While the net removals of modelled BECCS systems are clearly dependent on specific system configurations, such as biomass sourcing, boundary selection, losses from transport and capture, and background system assumptions—and are commonly considered in sensitivity analyses—assumptions of temporal boundaries and benchmarking, and particularly timing of CO_2 uptake by biomass, also play a critical role, particularly for BECCS system involving long-rotation biomass.

This work elicits the influence of these temporal assumptions by focusing on their impacts on the perceived carbon payback period of a forestry-based BECCS system. Assumptions considered include: the scale of CO_2 uptake considered (e.g., individual tree, plot, or forest), the timing of uptake (e.g., initial biomass growth or replanted growth), and the “t=0” point (e.g., planting, harvest, or capture). Further exploration will consider assumptions of land use change timing, the use of waste biomass or biogenic CO_2 from existing applications, and characterisation factors for global warming potential.

The resulting single-point metrics of net removal, efficiency, and carbon payback period will be compared to the time-explicit warming impacts of the BECCS system to assess how different assumptions reflect or distort the highly intertemporal process of coupling long-rotation biomass with long-lifetime infrastructure projects and long-duration storage. The goal is to provide both recommendations for transparent and representative modelling of BECCS as well as for interpretation of study results both for modellers and for decision-makers seeking to understand whether and to what extent BECCS investment can provide climate change mitigation benefits.

1.01.P-Mo008 Screening Prospective Life Cycle Assessment of Biogenic Carbon Capture and Utilization in Chemical Production

Hanna Steinum[1], Anna Furberg[1] and Anna Björklund[1] (1)Royal Institute of Technology - KTH

Hard-to-abate industries such as chemical manufacturing, which rely heavily on fossil-based feedstocks, will need to transition toward more sustainable alternatives. Our research focuses on innovative bio-carbon capture (bio-CCU) with a novel scrubbing chemistry, low-temperature separation, and cost-effective and scalable catalytic processes to efficiently activate and convert CO2 to value-added chemicals.

Research indicates that using carbon via conventional bio-CCU for chemical production might result in higher environmental impacts than the use of fossil-based feedstocks. By using dense aminated colloids as scrubbing fluids the energy penalty associated with bio-CCU may be reduced, while a high capture capacity is anticipated. This, together with low to no harmful emissions typically associated with more common amine scrubbers makes the innovation interesting from an environmental sustainability perspective.

The aim with this study is to evaluate whether bio-CCU technology has the potential to decrease the environmental footprint compared to conventional carbon capturing. This includes to create value added to society by informing and guiding safety and sustainability by design by taking an interdisciplinary route by incorporating Swedish industry partners and several universities to evaluate the emerging technology.

In this project, we apply prospective LCA approaches alongside laboratory- and pilot-scale processes to guide technology development and, ultimately, to assess overall impacts of emerging value chains. Due to the low technology readiness level (TRL) of bio-CCU technology, primary laboratory-scale data generated within a currently ongoing interdisciplinary research project will be applied to conduct a screening life cycle assessment (LCA). This will be done to identify red-flags early on in the development phase of the technology. Laboratory-scale data, complemented by targeted literature search when needed, will be scaled up to a higher TRL using up-scaling techniques to help identify the most important aspects to consider in future work.

The results will showcase environmental hotspots of the technology, providing input to research and development. We also expect to provide meaningful identification of environmental burdens early on that can offer guidance when precise data are still unavailable. In this way efforts can be made at leverage points that will alleviate environmental pressures in the future.

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1.01.P-Mo009 Does Captured Carbon Count? A Prospective LCA of Methanol from Waste Gasification

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The chemical industry is among the hardest-to-decarbonise sectors due to its reliance on fossil feedstocks. Methanol, a versatile C1 platform chemical, is traditionally produced from natural gas but can alternatively be synthesised from non-recyclable refuse-derived fuel (RDF) via plasma-assisted gasification, a route that combines waste treatment with CO_2 capture from waste-to-energy flue gases and promotes circularity.
Despite growing interest in waste-to-methanol systems, comprehensive environmental assessments remain scarce, leaving key methodological questions, such as including the treatment of carbon capture credits and system boundary definition, largely unresolved.
This study applies a prospective LCA framework to evaluate three plasma-assisted RDF gasification scenarios for methanol production, benchmarked against natural gas reforming and biomass gasification reference pathways. The Environmental Footprint 3.1 method (16 impact categories) was applied. Background inventory data were transformed using the Premise tool linked to the REMIND integrated assessment model across five different future energy system evolution pathways from 2025 to 2050. Multifunctionality was addressed by system expansion; RDF was treated under a cut-off approach; and system boundaries were defined as cradle-to-gate plus downstream carbon release, including end-of-life emissions of carbon embedded in methanol.
Under the current energy mix, RDF gasification scenarios show lower net climate change impacts than natural gas reforming but higher impacts than biomass gasification. Electricity, hydrogen supply, and end-of-life carbon release are the dominant contributors. Carbon capture benefits progressively offset energy-related burdens from around 2030 onwards. The default scenarios exhibit a broader future uncertainty range than the reference pathways, reflecting strong dependence on energy policy trajectories.
Overall, RDF gasification methanol performs best when substituting fossil-based production and should be viewed as a complement to existing waste-to-energy infrastructure. The study further demonstrates how methodological choices, particularly around carbon capture crediting and system boundary definition, substantially shape results, reinforcing the need for transparency and consistency in LCA studies of carbon-capturing waste-to-material systems.

1.01.P-Mo010 How Prospective LCA Can Guide Technology Developers to Design Better and More Sustainable Technologies. A Case Study for CCU Technologies

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Carbon capture and utilization (CCU) technologies are being developed to reduce greenhouse gas emissions and enable circular carbon systems. However, as many of these technologies are still at an early stage, design choices made today will strongly influence their future environmental performance.
This study explores how prospective life cycle assessment (LCA) can support the design of more sustainable CCU systems. The work focuses on plasma-based conversion, electrocatalytic processes, and solar fuel production, using prospective LCA to assess potential impacts under future deployment conditions.
Prospective LCA is applied as a forward-looking tool to evaluate potential environmental impacts under future

deployment conditions, incorporating technological learning, process improvements, and evolving energy systems. Parameterised models are constructed allowing key performance variables to be systematically varied. Model inputs are iteratively updated using experimental data as technologies evolve, while additional scenarios are explored through extrapolation based on theoretical performance limits. This approach creates a feedback loop between LCA outcomes and technology design, enabling early identification of environmental hotspots and trade-offs, including energy demand, material use, and carbon conversion efficiency.
Results indicate that energy source and conversion efficiency are dominant factors across all three CCU pathways. For plasma-based systems in particular, a clear trade-off is observed between conversion efficiency and applied power: higher power increases conversion but leads to greater electricity consumption and environmental impact, while lower power reduces energy use but results in insufficient conversion, thereby increasing impacts per functional unit. The results highlight that early-stage design decisions, such as reactor configuration, catalyst selection, and operating conditions, can substantially influence long-term sustainability outcomes.
This work demonstrates that prospective LCA can move beyond evaluation to actively guide innovation, supporting the development of CCU technologies that are not only technically viable but also environmentally robust. The proposed approach provides actionable insights for researchers and developers, contributing to more informed decision-making and accelerating the transition towards sustainable carbon utilisation systems.

1.01.P-Mo011 Clarifying System Boundaries in LCAs of Carbon Capture and Utilization: An Industrial System Mapping Tool for Scope Definition

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Carbon management technologies, such as carbon dioxide removal (CDR) and carbon capture, utilization, and storage (CCUS) need robust evaluation of the environmental impacts to ensure that they lead to carbon reduction or climate benefits. A review of life cycle assessment (LCA) studies of CCU showed that there is heterogeneity in types of technologies and systems assessed, system boundaries and methodological choices. As a matter of concern, it was found that the goal and scope definition was in many cases insufficiently reported, prohibiting understanding of how method choices relate to the goal of the study. There was also a discrepancy between system boundaries, source of carbon, handling of time and reporting of negative emissions. In reporting the system boundaries of the modelled system, what parts of the industrial system were included under the same “cradle-to-X” terminology varied. Also, it was found that the same scope could be connected to several different goals in different studies. However, these goals were in many cases vague and lacking a clear articulation of the intended use of the assessment, only reporting what was done but not why. In response to these methodological needs, we developed a system map of the industrial CCU system, which can serve as a scoping diagram to choose which parts of the system are modelled. This tool could be used to communicate which parts of a bigger industrial system are modelled in a particular LCA study, and how the scoping is made consistent with the goal of the study. A clearer goal with the assessment, i.e., a stronger focus on the intended use of the results, would help the LCA practitioner make the most suited method choices in line with the goal of the study. An articulated purpose for the LCA study allows for coherent and goal-consistent scope definitions and thus conducting more meaningful LCA studies. This makes the LCA studies relevant for their specific purposes, enabling them to inform the decision-makers they intend to and support the development of these technologies. Effective definition of such goals and scopes calls for further strategies to contextualize and understand the situation of the assessment. Further research on this includes incorporating strategies from utilization-focused evaluation to tailor LCA studies for specific purposes.

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1.01.P-Mo012 Modeling Negative Emissions Technologies in LCA of Construction Materials: Challenges and

Uncertainties

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The construction sector and particularly cement and steel production belong to the "hard-to-abate" industries, meaning that a series of transformations (e.g. improving material and energy efficiency, developing alternative binders) are necessary in order to reduce their environmental impacts in the short to medium term. The long-term carbon neutrality, on the other hand, can only be achieved through incorporation of functional negative emissions technologies (NETs), allowing storing CO2 of atmospheric or biogenic origin on a permanent basis. In Switzerland, some of these technologies have already reached pilot or even operational phases (e.g. CO2 mineralization in recycled concrete), while others are being actively researched. However, both conventional (i.e. timber) as well as novel NETs are associated with a high level of uncertainty stemming e.g. from biomass sourcing, biogenic carbon and upscaling modeling or from indirect environmental implications, such as reduced service life or decreased recyclability. The propagation of such epistemic uncertainty onto the carbon storage in NETs and the associated climate benefits in the long-term perspective are thus unclear. In addition, considering the underlying intent to using NETs, we assume that dynamic modeling may provide more insights about the changes in the cumulative radiative forcing assured by long-term carbon sinks. Although uncertainty analysis is being more commonly addressed in static LCA studies, it is rarely applied in dynamic models.

Therefore, the goal of our study is to investigate the differences in modeling choices and climate impacts between common construction materials and NETs, both conventional and novel ones. We endeavor to i) investigate and harmonize modeling choices (e.g. system boundary), ii) select an appropriate modeling method (e.g. static or dynamic), and iii) integrate probabilistic modeling to address the uncertainty. Furthermore, we aim to compare the performance of NETs with material efficiency measures, primarily focusing on reducing clinker content in cement and cement content in concrete, following the equivalent performance concrete specifications. With this, our study will shed light on (time-dependent) climate impacts and benefits of various construction materials and may contribute to the assessment of long-term environmental trade-offs of these decarbonization strategies.

1.02 - Advancing Safe and Sustainable by Design Through Prospective and Life Cycle Sustainability Assessment

1.02.T01 A Predictive LCSA Framework for Lubricants within SSbD: Linking Environmental (LCA) and Socioeconomic (LCC, S-LCA, CRM, SVHC) Dimensions across Four Use Cases

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Lubricants are an essential material class, yet their reliance on problematic substances such as per- and polyfluoroalkyl substances (PFAS) and their potential release into the environment highlight the need for more sustainable solutions. The Safe and Sustainable by Design (SSbD) framework offers a promising pathway, but its implementation at early design stages remains limited and lacks practical case studies. This work presents a Life Cycle Sustainability Assessment (LCSA) approach developed in the SiToLub project to advance SSbD for lubricants. It addresses the need for early-stage methods and metrics by capturing life cycle impacts at the formulation and application levels, which influence functional performance, use-phase behaviour, and end-of-life effects. Furthermore, we present novel methods for assessing critical raw material (CRM) and substances of very high concern (SVHC) use across four representative use cases.

The proposed framework integrates environmental, economic, and social assessments based on established LCSA methodologies and industrial guidance. To address data gaps, multiple modelling strategies are applied, including stoichiometric and literature-based approaches for substances and formulations not represented in existing databases. A central feature of the model is the mapping of predefined life cycle scenarios, as defined by the application via the Ecolabel, enabling predictive assessment based on the lubricant’s elemental composition. Product costs for formulations were estimated, and social impacts were linked to model inputs alongside costs. The methodology was

validated across LCA, LCC, and social LCA dimensions and applied to four use cases. Results show that sustainability performance is shaped not only by upstream production but also by use-phase losses and end-of-life effects, depending on application and formulation. Across the assessed cases, fluorinated systems emerged as key hotspots, with high CRM demand, fugitive hydrofluorocarbon (HFC) emissions during production, high societal costs, and a very high risk of workplace accidents in the supply chain.

Finally, this work explores how sustainability results can be translated into scoring approaches at the indicator or aggregated level to support decision-making within SSbD. Overall, the framework enables early-stage screening, hotspot and trade-off identification, and more holistic decision-making in lubricant development.

1.02.T02 "Safe and Sustainable by Design" (SSbD) strategy for the development of PFAS-Free coatings for the textile industry

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The textile sector is facing increasing pressure to reduce its environmental footprint, improve social responsibility, and ensure chemical safety throughout increasingly complex global value chains. Within the European context, Safe and Sustainable by Design (SSbD) is emerging as a key framework to guide innovation toward safer materials, production processes, and products while supporting long-term sustainability goals. This approach is particularly relevant for textiles, where challenges related to hazardous chemicals, resource-intensive production, waste generation, and social risks remain significant.

The BIO-SUSHY project (Horizon Europe, GA 101091464) aims to develop PFAS-free coatings using innovative coating solutions developed within the "Safe and Sustainable by Design" (SSbD) framework. BIO-SUSHY focuses on three target markets: textiles, food packaging, and glass coatings for cosmetic applications, with the goal of reducing environmental impact by 25%. The project also examines trade-offs between environmental performance, economic feasibility, social impacts, and chemical safety.

As the project nears completion, the purpose of this presentation is to explain how LCA was used as an eco-design tool to develop a coating with hydrophobic and oleophobic properties, aimed at creating a final product with a lower environmental impact. Furthermore, the presentation investigates how SSbD assessment outcomes can support decision-making across textile innovation stages, from material selection to industrial scaling. By identifying methodological gaps and implementation barriers, this work contributes to improving the practical integration of sustainability and safety considerations in textile innovation and supports the transition toward a more circular, resilient, ecological and socially responsible textile industry.

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1.02.T03 From multicriteria to multi-objective: proposal of an integrative LCSA based multi-objective model to optimize Safe and Sustainable by Design scenarios identification in prospective studies

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Safe and Sustainable by Design (SSbD) is argued to be one of the main approaches to promote the so-called transition. LCA methods, more precisely Life Cycle Sustainability Assessment (LCSA), have proven to be an interesting approach to support SSbD process in any sector, by offering a standardized and quantitative approach that combines environmental, social and economic aspects through Life Cycle Assessment (e-LCA), social LCA (s-LCA), and Life Cycle Costing (LCC), respectively.

However, using LCSA in SSbD can also be challenging, because comparing different scenarios in prospective LCSA normally leads to conflicting results among impact categories in LCA, s-LCA and LCC. In this context multicriteria decision methods (MCDM) can be an interesting way to support the decision-making process. However, in complex systems, there are numerous possibilities that make it hard to define on beforehand the potential candidate scenarios to be tested in a conventional MCDM. In this context multi-objective optimization arises as an alternative as it enables to consider an infinitude of scenarios that are not necessarily obvious, while respecting the system constraints and keeping a balance among sustainability aspects. So, the goal of this study is to propose a SSbD LCSA-based multi-objective framework to support the identification of optimized scenarios in prospective studies.
The multi-objective model framework was developed using the following steps. Selection of objective functions: it was chosen 4 objective functions, one for each sustainability aspect (economy, environment and society) and an extra one addressing safety. Them criteria for each objective function was defined based on impact categories for LCA, S-LCA and LCC. The multi-objective mathematical formulation compared 3 approaches: Epsilon restraint, Goal programming, weighted sum. The preference level (stakeholder weights vs data-informed weights) was also explored. Finally, a final MCDA methods were compared in order to assess the final set of optimized scenarios defined by the SSbD multi-objective optimization.
Model framework was first verified in terms of mathematical coherence using simplified case tests and will now be validated using case studies from different sectors. It is expected that it will serve as a comprehensive and holistic approach that can facilitate a broader analysis in prospective stages, aiming at facilitating implementation of SSbD pathways identification in complex systems.

1.02.T04 Prospective LCA and Planetary Boundaries: Designing Societies for Absolute Sustainability

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Absolute Environmental Sustainability Assessment (AESA), grounded in the Planetary Boundaries (PB) framework, is increasingly recognized as a promising approach to evaluate whether systems operate within the Earth system's limits. While Life Cycle Assessment (LCA) has been identified as a key methodology to operationalize AESA through the allocation of a Safe Operating Space (SOS), current applications remain largely focused on environmental limits, often overlooking the role of socio-economic dynamics in shaping future impacts. This study addresses the challenge of integrating societal development into AESA by linking prospective LCA (pLCA) with extended Shared Socio-economic Pathways (SSPs). We propose a methodological framework that combines scenario-based modelling with PB-based LCA assessment to explore how alternative socio-economic futures influence the ability of emerging technologies to operate within absolute sustainability limits. The approach is developed for the Safe and Sustainable by Design (SSbD) context and targets early-stage innovation in the textile sector. It is applied to a bio-based and removable ink for textile printing, designed to substitute PVC-based plastisol inks and enable recycling. It includes the construction of textile-specific extended SSP narratives, the upscaling of the low-TRL technology to industrial conditions, and a PB-based LCA applying different sharing principles to assess SOS allocation. This combination enables both the incorporation of socio-economic assumptions into life cycle modelling and a sensitivity analysis of distributive justice perspectives within AESA. The aim is to discuss how the sustainability performance of technology is dependent on the underlying socio-economic pathway, and how variations in PB exceedance might be driven by changes in energy systems, consumption patterns, and waste management practices. Differences between sharing principles will further highlight the importance of fairness considerations in interpreting AESA outcomes. This work contributes to methodological advancements in AESA by explicitly integrating socio-economic scenarios into PB-based pLCA. It demonstrates how pLCA can support decision-making at early innovation stages and provides a pathway to use AESA not only as an assessment tool, but also as a framework to inform the design of sustainable future societies.

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1.02.T05 Combining risk assessment with LCA to make sofas safe and sustainable

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Evaluations of safety and sustainability are considered consecutively in the well-known framework for Safe and Sustainable by Design by Caldeira et al. (2022) and there are good reasons for this. But is it possible to integrate the two in a single step? In this study, we describe recent work in which we considered the case for using a flame retardant in sofas. Flame retardants are often chemicals of concern on account of their persistence, mobility and toxicity. Chemicals classed as persistent and mobile are extremely challenging to remove from drinking water supplies and the environment in general. In the Swedish context, sofas are generally not treated with flame retardants, though this practice is more common elsewhere. The question is whether adding a flame retardant would save more lives from fires than it damages via the life-cycle impacts from toxic emissions throughout the product life cycle, including chemical production, introduction into manufactured goods, potential leakage during their use, and ultimately waste treatment. To enable this comparison, the disability-adjusted life years (DALY) indicator is applied.

Estimation of the life-cycle impacts of flame retardants is a natural task for product life cycle assessment. For this study, a new characterisation factor for flame retardant melamine had to be calculated. As for the estimation of lives saved by avoiding fire fatalities, this is normally a question answered by actuarial studies or probabilistic human health risk assessment. In the Swedish context, we were able to find publicly available statistics on the loss of life due to fires started on sofas. By converting all this information to DALYs lost and saved on a common functional unit basis (the provision of a three-seater sofa seating for one household over 10 years), we are able to integrate the question of sofa safety with sofa sustainability. We present results showing that the flame retardants provide a net benefit in terms of human health impacts. This is predicated on the use of melamine, which we have shown in previous work to be relatively innocuous compared with other flame retardants. However, the same approach can be used to evaluate other flame retardants, and also other chemical substances with the direct function of reducing injuries or improving health, such as pharmaceuticals.

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1.02.P - Advancing Safe and Sustainable by Design Through Prospective and Life Cycle Sustainability Assessment

1.02.P-We001 A Multi-Criteria Decision Analysis Framework for Safe-and-Sustainable-by-Design: Steel Slag Mineral Carbonation for CCUS

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In 2026, the European Commission's Joint Research Centre published a revised methodological guidance for implementing the Safe and Sustainable-by-Design (SSbD) framework, which seeks to integrate safety, environmental, economic, and societal dimensions into the early design of chemicals, materials, and industrial processes. Despite the comprehensive conceptual basis provided by the framework, its practical implementation remains challenging due to the limited availability of structured workflows, clearly defined data requirements, and real-world case studies demonstrating how the SSbD principles can be operationalized in practice. To address this gap, this study proposes a systematic methodological workflow for operationalizing the SSbD framework through the integrated application of safety risk assessment, environmental life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA). The study identifies the key data requirements and analytical steps associated with each

assessment pillar and introduces a process-flow model that illustrates how safety, environmental, economic, and social performance indicators can be generated and seamlessly integrated within a unified SSbD-aligned assessment framework. The proposed workflow is demonstrated through a case study on the mineral carbonation of steel slags, a carbon capture, utilization, and storage (CCUS) technology that enables the valorization of industrial residues while contributing to climate-change mitigation. The case study illustrates how multiple design and operational scenarios can be evaluated consistently across all SSbD dimensions. To support transparent comparison and trade-off analysis among competing options, the Analytical Hierarchy Process (AHP) is incorporated as a multi-criteria decision analysis tool within the workflow. Overall, the proposed methodology provides a practical and replicable approach for translating the SSbD framework into actionable decision-support tools. By enabling systematic data generation, integration, and multi-criteria evaluation, this work supports real-world SSbD implementation and continuous improvement toward safer and more sustainable manufacturing value chains.

1.02.P-We002 Operationalising Safe and Sustainable by Design Through Prospective Life Cycle Sustainability Assessment of Lignin-Based Epoxy Resins

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Safe and Sustainable by Design (SSbD) is increasingly positioned as a cornerstone of European innovation policy. Integrating SSbD into innovation processes can guide decision-making and reduce the risk of harmful substitutions. However, its practical application remains challenging, mainly due to uncertainties related to process upscaling and limited data availability.

This contribution presents the application of a Life Cycle Sustainability Assessment (LCSA) within an SSbD context of a lignin based epoxy resin developed as a bio based alternative to a bisphenol A (BPA) epoxy flooring within the BBBC LEGACY project. The study uses a prospective life cycle approach, focusing on upscaling, refining of foreground inventories and process optimisation decisions. Pimary data was generated within the LEGACY project itself. These include results from laboratory experiments, pilot-scale trials, and internal process simulations. Finally, the work includes an integated assessment of safety and environmental performance following a case study example by JRC.

Results of the prospective life cycle assessment (LCA) show that environmental hotspots evolve along the innovation pathway: while early development stages are dominated by energy demand, process optimisation reduces these impacts and increases the relative importance of the formulation. Furthermore, results indicate that impacts at the functional level are comparable to, and in some scenarios slightly lower than, the BPA based benchmark. Economic performance depends on price of materials, energy consumption, process yields and the scale at which the process is operated. The reference scale social LCA remains inconclusive due to minor overall differences per social impact category or trade-offs among alternatives. The results of the social LCA are significantly affected by data limitations and aggregation uncertainties. Finally, the integrated SSbD assessment shows that lignin-based epoxy offers better intrinsic safety than the BPA benchmark and has a comparable overall environmental impact.

The study also reflects on the SSbD framework, particularly on inventory scaling, data availability and the interpretation of integrated SSbD scoring results. The findings illustrate how LCSA can function as a decision support tool within SSbD, using comparative evaluations per sustainability domain, while emphasising the need for cautious interpretation of integrated scores when assessing emerging bio based systems.

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1.02.P-We003 Integrating Life Cycle Sustainability Assessment and Planetary Boundaries for Early-Stage Design of Wearable Electronic Textiles

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Wearable electronic textiles (e-textiles) constitute an emerging class of smart products that integrate electronic functionalities—such as sensing, energy supply, and data processing—into textile systems for applications in healthcare, sports, and occupational safety. At the same time, the textile sector poses significant sustainability challenges, producing approximately 92 million tonnes of waste annually, with the majority of textiles ultimately landfilled. In response, new e-textile developments increasingly adopt eco-design strategies, sustainable material sourcing, improved manufacturing efficiency, and targeted end-of-life solutions to enhance circularity. However, the extent to which these strategies contribute to climate mitigation and broader sustainability objectives must be assessed against biophysical limits rather than relative improvements alone. This study proposes an integrated Life Cycle Sustainability Assessment (LCSA) framework to evaluate e-textiles across environmental, economic, and social dimensions from a whole-life-cycle perspective. The framework combines environmental life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) to quantify trade-offs across alternative value-chain configurations. Particular emphasis is placed on the challenges of applying LCSA at early stages of product design, including limited data availability, high uncertainty in material and process choices, evolving supply chains, and the absence of well-defined end-of-life pathways for complex hybrid products such as e-textiles. To address the particular limitation of lacking meaningful comparative benchmarks at early design stages, this study integrates absolute sustainability concepts grounded in planetary boundaries into the LCSA framework. By relating life-cycle impacts to science-based environmental thresholds and carrying-capacity limits, the approach enables an assessment of whether e-textile systems operate within a safe operating space for humanity, rather than merely outperforming alternative designs. The framework is applied within the UPWEARS project to evaluate e-textile value-chain scenarios and support iterative design improvement. Overall, the proposed approach strengthens early-stage decision-making and contributes to the development of circular e-textile systems aligned with absolute sustainability boundaries.

1.02.P-We004 Toward Safe and Sustainable Pharmaceutical Synthesis: Laboratory-Scale and Prospective Life Cycle Assessment of Palladium-Based Heterogeneous Catalyst for Suzuki-Miyaura Coupling

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Over the past few years, European Commission has strongly been promoting a transition into a more sustainable and non-toxic chemical industry by publishing a set of policy frameworks; predominantly, EU Chemical Strategy for Sustainability (CSS) and Safe and Sustainable by Design (SSbD), respectively. These frameworks aim to provide tools – to be used from the early development stages onward – for the designing of more environmentally-friendly and safer chemical compounds.

Metal-Organic Frameworks (MOFs), a type of porous crystalline materials, have garnered increased attention in the scientific community due to their tunable composition as well as excellent thermal and chemical stability, making them potential materials for several applications, for example as homogeneous or heterogeneous catalysts in pharmaceutical synthesis. However, traditional homogeneous catalysts cannot be recycled, which is problematic considering the unevenly distributed critical minerals – the common constituents of MOFs. Moreover, MOFs are typically synthesized using elevated temperatures, long reaction times, and excess amounts of toxic solvents, creating substantial environmental and safety concerns that simultaneously hinder their efficient large-scale production. Although pharmaceutical industry would benefit from the safer and more environmentally benign operations in compliance with EU legislation, the sustainability aspects of MOFs and their feasible scale-up remain largely unexploited.

Accordingly, in this study, the environmental impacts of a recyclable heterogeneous catalyst – a MOF, immobilized by palladium nanoparticles (in short, Pd@MOF) – for Suzuki-Miyaura coupling was examined by employing Life Cycle Assessment (LCA) methodology. Firstly, a laboratory-scale LCA was performed to iteratively support the optimization of the early-stage synthesis processes, followed by scaling up the laboratory-scale setup with the aid of available frameworks. Subsequently, a prospective LCA (pLCA) with future background and foreground scenarios was

performed, using the estimated future technologies and energy mixes, to examine the potential environmental impacts of industrial-scale Pd@MOF production. The results of the conducted study can be used as a foundation for further research and as a decision-making aid both in academia and industry. Ultimately, the study helps to steer the way for more sustainable, non-toxic, and scalable production of MOFs for heterogeneous catalysis.

1.02.P-We005 Sustainability-by-Design: A Modular Parametric Life Cycle Assessment in Configurable Products

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Sustainable product design requires integrating life cycle thinking early in the planning phase. Nevertheless, traditional life cycle assessment (LCA) remains resource-intensive and disconnected from the decision-making process. It is particularly prominent for companies manufacturing modular and configurable products such as metalworking machinery. Customers can order many different configurations, making individual LCA calculations impractical and not design-informing. The study proposes a modular parametric LCA (MP-LCA) that integrates life cycle thinking into the design phase rather than post-hoc reporting. By conducting LCA at the module level, a database of reusable module impacts can be constructed. This framework enables rapid impact calculation for configuration-specific products based on module combinations. Parameterisation extends this further for scalable modules, where mathematical relationships translate different parameters into environmental impacts, fast-tracking the process by removing the need to repeat or rebuild the model from scratch. The proposed solution is tested through application to a Finnish company that provides metalworking machinery, where the product consists of a module combination tailored to customer specifications. The case will demonstrate how MP-LCA can support decision-making during the design phase, enabling the company to generate rapid impact calculations without costing significant time or resources. It shifts the role of LCA from a compliance tool to a decision-support tool in design for sustainability. The study will contribute to methodology and application of modular parametric LCA in configurable product design, providing a conceptual structure for manufacturing facing similar challenges.

1.02.P-We006 A Safe and Sustainable Hybrid Solid Electrolyte for Batteries

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Emerging battery technologies increasingly rely on solid or hybrid solid electrolytes to improve thermal stability, reduce flammability, and enhance mechanical robustness. At early innovation stages, however, these performance expectations must be examined within a structured Safe and Sustainable by Design framework. The challenge lies in assessing multiple safety and sustainability criteria while the technology remains at low technology readiness level. This study applies a life cycle based approach to a hybrid solid electrolyte under development, addressing processability, ionic conductivity, intrinsic material hazards, and environmental and social implications. More than 40 electrolyte variants were initially screened for processability and electrochemical performance, leading to 7 candidates selected for further assessment. Primary data were collected for monomer batches of 1.45 kg, polymer batches of approximately 200 g, and hybrid electrolyte batches of around 10 g. Several scenarios are addressed for upscaling. Safety screening focused on intrinsic hazards of constituent materials. One variant contained a plasticizer associated with reproductive toxicity and long lasting aquatic impacts, highlighting the need for early hazard identification, in conjunction with exposure assessment. Later in the project, the results of safety tests at pouch cell level will be included as the project aims for EUCAR safety level 4 for automotive applications and level 2 for aviation. Environmental impacts were evaluated using the Environmental Footprint 3.1 method across all midpoint categories, with ionic conductivity as the functional unit. To support interpretation under uncertainty, several normalization and weighting approaches were applied, including Environmental Footprint factors and planetary boundary based options. Social aspects will be later explored through a screening of countries of origin for externally sourced materials. Preliminary results show clear trade offs between electrochemical performance, hazard profiles, and environmental impacts, demonstrating the importance of integrating safety and sustainability considerations before scale up. However,

the different weighting and normalization factors show similar tendencies in terms of preferred options. This work illustrates how safety and sustainability assessment can guide design choices, support early stage decisions, and align it with sustainability objectives.

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1.02.P-We007 Supporting Design Decisions for PEM Electrolysers Using Uncertainty Aware Prospective LCA

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Green hydrogen is expected to play an important role in the energy transition, and substantial effort is currently focused on developing proton exchange membrane (PEM) electrolysers that are both more efficient and lower cost. As new electrolyser designs are proposed, comparisons are typically based on techno-economic criteria, yet design choices can also lead to meaningful differences in life-cycle environmental impacts. These differences often involve trade offs between manufacturing requirements and use phase performance, making environmental assessment an important complement to cost optimisation.
A key challenge in assessing emerging electrolyser designs is that the use phase performance and durability are uncertain due to the nascent nature of the technology and variability in operational conditions. Deterministic life cycle assessment (LCA) approaches based on single-point assumptions risk obscuring these uncertainties. To support evidence based design choices, it is therefore necessary to evaluate environmental performance in a way that explicitly accounts for uncertainty and the context of use.
This work applies a prospective LCA framework to compare two PEM electrolyser system designs differentiated by membrane thickness (80 μm and 50 μm). The assessment evaluates environmental impacts across multiple scenarios while explicitly representing uncertainty in key foreground parameters that drive trade-offs and hotspots.
The model uses probability distributions to reflect plausible ranges for the foreground parameters consistent with current knowledge of emerging PEM electrolyser technologies. This enables the propagation of uncertainty through the LCA results and allows comparison of impact distributions rather than single values. For a given scenario, the approach facilitates estimation of confidence intervals for whether one design option has lower environmental impacts than the other. In some cases, differences between design options that appear decisive under deterministic assumptions become less clear once uncertainty is considered. By combining scenario analysis with explicit representation of foreground uncertainty, the approach supports probabilistic, context specific comparisons.
The method demonstrated here is transferable to other electrolyser configurations and emerging energy technologies and can better inform technology design choices, balancing both environmental performance and cost considerations under uncertainty.

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1.02.P-We008 A Life-Cycle-Informed Framework for Quantifying Use-Phase Impacts in Fluid Power Components: A Rotary Hydraulic Valve Case Study

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Hydraulic valves are critical fluid power components whose pressure losses, leakage, actuation demand and duty cycle can strongly influence system-level energy consumption and environmental impact. However, life-cycle assessments of hydraulic valves often emphasise material production and manufacturing, while the operational use phase is simplified or insufficiently characterised. This can lead to incomplete conclusions for long-lived components shaped by in-service performance. Here, we propose a life-cycle-informed framework for quantifying use-phase impacts in fluid power components, using a rotary hydraulic valve prototype as a case study. The framework retains the full life-cycle context, including material production, manufacturing, operation and end-of-life, but focuses on how valve behaviour

contributes to environmental burden during operation. First, a screening life-cycle inventory was developed from the valve's main materials and manufacturing route. Second, representative operating scenarios were constructed using pressure drop, flow rate, opening angle, leakage, actuation demand and duty cycle. Third, these variables were linked to use-phase energy demand through a parametric loss model and translated into impacts, using global warming potential as the primary indicator. Preliminary scenario calculations suggest that use-phase contributions vary substantially across operating conditions. Under low-flow and low-pressure-drop operation, pressure-loss-related dissipation is expected to remain relatively small, making embodied manufacturing impacts more visible. In contrast, under higher-flow, higher-pressure-drop or high-duty-cycle operation, cumulative use-phase impacts may become comparable to, or exceed, embodied impacts over a long service life. Leakage and actuation demand are expected to be secondary but may become relevant when small inefficiencies accumulate. The results highlight a key limitation of current LCA practice for fluid power components, as a predominant focus on material production and manufacturing may underrepresent use-phase losses and overlook the balance between embodied and operational burdens. This balance depends strongly on where and how the valve is used, with pressure drop, flow rate, duty cycle and lifetime likely to dominate total life-cycle impact. The proposed framework supports early-stage design, architecture comparison and sustainability-informed decision-making for fluid power components and systems.

1.02.P-We009 Advancing Exergy-Based Indicators in Life Cycle Assessment: Integrating Irreversibilities and Resource Degradation

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Exergy has been increasingly recognised as a rigorous thermodynamic basis for assessing resource use and environmental impacts within Life Cycle Assessment (LCA). By accounting for the quality of resources relative to thermodynamic equilibrium, exergy-based approaches provide a consistent framework to evaluate resource efficiency, compare materials and analyse circularity strategies. However, current applications in LCA remain heterogeneous and do not fully capture the complexity of resource degradation across life cycles.

This study critically examines the limitations of existing exergy-based methodologies in representing the progressive transformation of resources throughout production, use and end-of-life stages. In particular, conventional approaches tend to insufficiently account for the effects of material dispersion, loss of functionality and the accumulation of thermodynamic irreversibilities, which are key to understanding the physical limits of circularity.

Building on developments in thermoeconomics, this work explores the integration of irreversibility-based metrics and concepts such as exergy replacement cost, which quantify the effort required to restore resources to their initial state. This perspective allows for a more comprehensive assessment of resource degradation by linking life cycle processes with the underlying thermodynamic constraints governing resource use and recovery.

The analysis compares alternative exergy-based indicators and discusses their implications for allocation procedures, particularly in systems involving recycling and secondary material flows. Results indicate that incorporating irreversibilities provides a more robust representation of resource consumption and highlights constraints that are not captured by conventional approaches.

This work contributes to advancing and harmonising the application of exergy in LCA by identifying key methodological gaps and proposing directions for integrating thermodynamic principles into life cycle sustainability assessment. The findings support the development of more physically grounded indicators for evaluating circular systems and critical resource management.

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1.02.P-We010 Prospective Life Cycle Assessment of a Bio-Based Printed Circuit Board Substrate: Environmental and Technical Trade-Offs with Use-Case Sensitivity

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Printed circuit boards (PCBs) are ubiquitous in electronic systems. PCB substrates, which mechanically support and electrically connect all components, have already drawn the attention of the scientific community, since they play an essential role in the electronics supply chain, as they directly influence: the types of chemicals used for traces etching, the types of electronic components assembling techniques, the toxic emissions at End-of-Life (i. e. brominated flame retardants and (non-)metallic materials), and the efficiency of recycling valuable components and precious metals (i.e. copper, gold, ...).
This study uses Life Cycle Assessment (LCA) to evaluate a bio-based alternative to conventional fiberglass-reinforced phenolic resin substrates: a flame-retarded polylactic acid (PLA) composite reinforced with flax fibers.
It contributes to LCA practice by systematically varying functional units and system boundaries for the same bio-based material across distinct use cases, including a microcontroller board (consumer electronics), single-use electrochemical electrodes (biomedical sector), and high-frequency antennas (telecommunications). This study varies functional units and system boundaries for the same bio-based material across distinct use cases. By tailoring functional units to reflect sector-specific performance demands, it exposes diverse burden shifting possibilities with application context. Particularly, for cradle-to-gate boundaries, the bio-based substrate reduces most environmental impacts in comparison to the production of conventional substrates but increases land and water use due to agricultural feedstocks. Broader system boundaries introduce new trade-offs, particularly given the thermomechanical properties of the bio-based composite: low-temperature soldering reduces energy demand during assembly steps but relies on alternative alloys, such as bismuth-based solder pastes, raising abiotic depletion potential. Additional results highlight that relative beneficial contribution to the system's overall environmental impacts from the substrate substitution depend heavily on the use case. For example, where integrated circuits dominate environmental burdens in highly populated PCBs or where the use phase prevails in high-intensity telecommunications applications. Thus, assessments must span the entire life cycle, as bio-based substrates also enable alternative End-of-Life pathways, such as bioleaching.

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1.02.P-We011 Integrating life cycle assessment and design for sustainability for continuous improvement inindustrial production systems

Growing regulatory pressure and societal awareness have made sustainability a strategic necessity for industry. However,
despite increasing academic research, significant gaps remain between theoretical approaches and their implementation in
industrial decision making, where sustainability assessment often serves certification purposes rather than offering contin
uous improvement. This study proposes a replicable methodological framework that integrates sustainability into corporate
design and decision-making processes. The framework includes three main phases: (i) assessment of the current system through Life Cycle Assessment (LCA), (ii) LCA identification of environmental hotspots to define improvement priorities,
and (iii) interdisciplinary ideation of circular redesign scenarios using the eco-design approach—a multicriteria, multistage,
andmultistakeholder systematic process that considers environmental design and development aspects while aiming to reduce
adverse environmental impacts throughout a product's lifecycle. The multifunctional team brings diverse expertise, enriches

the holistic framework, and enables innovative and creative design proposals while evaluating competing priorities and facil
itating trade-offs between life cycle phases. A game-changer has been challenging the status quo, from a conventional design
methodology to an environmentally conscious design perspective with emission reduction as the primary core driver. When
applied to an industrial case study at ABB S.p.A. on a medium-voltage circuit breaker, the framework proved effective in
identifying design modifications that lower environmental impacts without compromising economic or technical feasibility.
The results demonstrate the applicability of the Design for Sustainability initiative in promoting continuous product improve
ment. This methodology fosters an organizational culture that embeds sustainability into industrial innovation across internal
ABBbusiness areas and other manufacturing sectors.

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1.03 - Geographic Precision in Life Cycle Assessment: Tools, Data and Methods for EU Sustainability Governance

1.03.T01 Customs Data-Based Methodology for Determining Market Processes in Life Cycle Assessment

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Understanding the geographic origin of materials and products is critical for assessing life-cycle environmental impacts. Regional differences in energy systems, technologies, and supply chains can lead to substantial variation in life cycle assessment (LCA) results. This is particularly relevant for technologies where environmental burdens are concentrated in the upstream raw material extraction and production, such as photovoltaics, wind turbines, and batteries. As materials move through supply chains, the influence of their origin accumulates across stages as additional material inputs are involved.

Capturing these differences in origin requires spatially explicit modelling of supply routes. In LCA, this is typically achieved through market processes that define regional supply mixes. The Ecoinvent database provides widely used market activities incorporating interregional trade. However, these market datasets have limitations, including limited temporal sensitivity, coarse spatial resolution, lack of transparency in construction, and trade modelling based only on imports, which may reduce the accuracy of the dataset.

To address this issue, this study develops a methodology that derives market processes with national-level spatial granularity and annual temporal resolution by integrating production and trade data. The approach draws on the structural logic of input-output (IO) tables by constructing import-export (IE) tables from customs and production data. It focuses on resolving interdependencies in global trade systems, which are highly interconnected and involve multiple layers of re-export and re-import, making it difficult to trace material origins. Compared to conventional IO-based methods in LCA, this approach targets inter-country dependencies rather than inter-sectoral relationships.

The methodology is demonstrated using three key minerals for electrification and energy storage: cobalt, copper, and lithium. Results show that it generates country-specific annual market compositions and reveals changes in historic sourcing patterns. Compared to Ecoinvent, it provides higher spatial and temporal resolution. Its applicability depends on the availability of customs data, and the current implementation does not explicitly distinguish between different production processes.

1.03.T02 Quantifying the Impacts of Ship Noise on Marine Biodiversity in European Seas using LCIA

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This study develops spatially differentiated characterization factors that quantify the impacts of ship noise pollution on marine biodiversity for use in Life Cycle Impact Assessment (LCIA). Shipping is the primary anthropogenic contributor to underwater noise pollution, yet its impacts on marine biodiversity remain unquantified within Life Cycle Assessment (LCA). Many marine species rely on sound for navigation, foraging, communication, and reproduction, making healthy soundscapes fundamental to marine ecosystem functioning. Noise from vessels has been documented to alter the behavior and physiology of marine mammals, posing a threat to marine biodiversity. Incorporating vessel noise into LCIA is therefore essential for holistic environmental impact assessment.
The methodological framework integrates three components: a fate factor (FF) describing how shipping transport work is spatially distributed per importing country group; an effect factor (EF) linking noise levels to biodiversity impacts per unit of transport work; and an allocation factor distributing country group impacts to individual countries. Ship noise data from the NAVISON project, covering all European seas (Baltic Sea, Black Sea, Mediterranean Sea, North Sea, and Northeast Atlantic Ocean) for 2019 were combined with species-specific sensitivity thresholds for nine marine mammal species to calculate the spatially explicit Potentially Affected Fractions (PAF) of species affected by shipping noise. Ship noise impacts within Marine Protected Areas (MPAs) and outside these areas were compared to assess potential differences and thus the effectiveness of MPAs regarding ship noise impacts. Subsequently, a consumption-based attribution approach was applied, allocating impacts to importing countries driving demand for shipped goods.
The resulting country-specific CFs enable the integration of ship noise as a novel impact category in LCIA, advancing the methodological framework. By linking trade-driven shipping activity to spatially resolved biodiversity impacts, this framework supports more comprehensive and regionally differentiated environmental assessments of global supply chains. Our results further enable the integration of ship noise alongside other stressors associated with maritime transport, including greenhouse gas emissions and the introduction of marine invasive species, into a holistic LCIA framework, reducing problem-shifting across impact categories.

1.03.T03 Characterization Factors for Water Consumption: Freshwater Habitat Change Potential Resulting From Streamflow Depletion

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Agriculture, industry and the domestic sector require large amounts of freshwater. When freshwater is withdrawn, consumed or used in-stream, ecosystems and biodiversity are potentially impacted. Life Cycle Assessment employs midpoint and endpoint characterization factors (CFs) to assess and quantify these impacts. The Habitat Change Potential midpoint was previously developed to model the potential of habitat changes for freshwater fish and invertebrate species due to changes in discharge. However, this midpoint relies on the assumption that 1 m3 of water consumed leads to 1 m3 of discharge change. This assumption is not supported by water balance models, as demonstrated by streamflow depletion factors which quantify spatially explicit discharge alteration from surface and groundwater consumption.

We combined these streamflow depletion factors with the Habitat Change Potential model to calculate monthly CFs

estimating habitat change potential (in m2 habitat changed · year per m3 water consumed) for about 15.4 million km of river reaches worldwide. We aggregated these CFs into 213 freshwater basins and 178 countries, and further aggregated them temporally into annual CFs. The order of magnitude of the generated CFs range between 10E-8 and 10E-4 m2.yr/m3, with particularly high values in Northwest and South Africa, Central and West Asia and South Australia.

As proof of the broad applicability and the relevance of monthly CFs, we tested the temporal aggregation over crop-agnostic growing seasons and rice-specific growing seasons. The calculations of temporally and spatially explicit impact of rice production in eight rice producing regions demonstrate impact variation across growing seasons. The comparison with another midpoint (AWARE) demonstrates that compromises are needed when discussing where rice production has the least impact.

This Habitat Change Potential midpoint enables the worldwide assessment of freshwater habitat sensitivity due to surface and groundwater consumption and complements existing CFs by being a midpoint related to freshwater ecosystem impacts.

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1.03.T04 Integrating Machine-Learning-Based Population Models with High-Resolution Atmospheric Fate Modeling for Spatially Refined PM2.5 Exposure in LCIA

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Fine particulate matter (PM2.5) is the leading environmental cause of premature mortality worldwide. Current life cycle impact assessment (LCIA) methods for PM2.5 rely on source-receptor relationships from reduced-complexity atmospheric fate models operating at the scale of large world regions or countries to derive characterization factors (CFs). While computationally efficient, this coarse resolution limits spatial differentiation within regions and does not reflect significant variation in human exposure between urban and rural areas. Recent advances have produced country-level CFs using linearized fate models and spatiotemporally resolved factors using Gaussian dispersion approaches. Spatially explicit CFs from the Intervention Model for Air Pollution (InMAP) have also been developed, but only for the United States using the US-InMAP. No study has yet produced point-source-scale CFs globally by coupling a high-resolution variable-grid chemical transport model with machine-learning-derived population fields, the combination needed to capture intra-region exposure variability, particularly the urban–rural gradient that dominates intake fraction differences.

This study uses perturbations from Global InMAP, a variable-resolution steady-state atmospheric model resolving concentrations from approximately 500 km in remote areas down to 4 km in densely populated zones, as a higher-resolution alternative for deriving CFs for PM2.5 and its precursors sulfur dioxide, nitrogen oxides, volatile organic compounds and ammonia. We compare Global InMAP to an established regional source-receptor model using a 10% all-sector emission perturbation for Austria. Preliminary results show population-weighted concentration changes within a factor of two between models, consistent with known inter-model uncertainties.

We couple Global InMAP concentration fields with 100 m population estimates from Google's AlphaEarth Foundations (AEF), trained on Joint Research Centre (JRC) 2021 Census Population grid data, enabling annually updatable intake fractions. An interim Vienna-trained model predicts the JRC 2021 Census population at $r = 0.87$ on test data and transfers to Bratislava without local calibration at comparable performance ($r = 0.86$). Multi-city training and multi-year embeddings are planned to improve the model. The combined approach will yield spatially differentiated CFs that address a recognized limitation of current LCIA and support PM2.5 emission optimization.

1.03.T05 Assessing Variability of Urban Scale Emissions in Life Cycle Toxicity and Ecotoxicity Characterization

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For many impact categories, Life Cycle Impact Assessment (LCIA) models traditionally rely on site-generic approaches and average assumptions to derive characterization factors (CFs), due to the holistic scope of LCA and the scarcity of spatially resolved inventory data. As regionalization capabilities at the inventory level expand, the need to quantify the differences between spatially resolved and existing LCIA methods becomes relevant. For human toxicity and freshwater ecotoxicity, the UNEP/SETAC reference model USEtox already enables partial spatialization through sub-continental archetypes and an urban air compartment. Recent work proposed the inclusion of a nested, multi-compartment local scale to better address emissions occurring at local conditions. In this study, we apply the modified USEtox model to assess the variability of human toxicity and freshwater ecotoxicity CFs for local urban chemical emissions, aiming to (i) analyze the influence of fate and exposure parameters, as well as population settings, on impact characterization results in multi-compartment environments typical of peri-urban areas near major industrial sites; (ii) compare human inhalation intake and toxicity impacts across chemicals and urban areas using the modified USEtox model and a Gaussian plume approach. We model the emissions of 10 toxic chemicals across multiple European urbanized areas, integrating site-specific meteorological data from the ERA5 reanalysis and exposure conditions derived from the Eurostat Census data. To compare inhalation toxicity impacts with those from a dispersion-based approach, air emission data and industrial facility locations were sourced from the European industrial emission inventories (IED/EPRTR). Results show that, for both human toxicity and freshwater ecotoxicity, CF variability for emissions to local air, freshwater, and soil remains within one order of magnitude. The largest variability is observed for natural and agricultural soils, particularly for substances like benzene and toluene, where the highest local CFs are associated with scenarios characterized by elevated annual rainfall. The results contribute to understanding when and how multi-compartment urban-scale modelling can be integrated into LCIA frameworks for chemical emissions impact characterization, limiting underestimation of impacts in specific contexts while balancing model complexity and practical applicability.

1.03.P - Geographic Precision in Life Cycle Assessment: Tools, Data and Methods for EU Sustainability Governance

1.03.P-Tu001 Life Cycle Inventory and Allocation Analysis of Land Use Change in Global Copper Mining

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Land-use change associated with the extraction of metal resources at mining sites is essential information for estimating ecosystem damage and land-use-related greenhouse gas (GHG) emissions; however, knowledge in this area remains limited.
In this study, we focus on copper mining and integrate mine-level data on production volume and ore grade from the S&P Metals & Mining database with geospatial information from a previous study (Maus, V. et al., 2020), which identified global mining areas using geographic data.
By spatially linking these datasets, we estimate land-use change per tonne of copper produced for each mine.
We have mapped mines representing 74.6% of global primary copper production between 1991 and 2017, and we examine the relationships between mine characteristics—such as copper production volume, country of operation, and mining method—and land-use change.
In addition, this study examines allocation methods for land-use change when multiple mineral commodities are produced from a single mine.

Economic allocation based on the market value of co-products is one possible approach in such cases.
However, land-use change is strongly influenced by the amount of ore extracted, which is in turn affected by ore grade; lower ore grades generally require greater material throughput, resulting in larger land disturbance.
Therefore, land-use change attributable to each mineral commodity is expected to depend on its corresponding ore grade within the mine.
Accordingly, we propose a novel allocation method that incorporates ore grade into economic allocation.

1.03.P-Tu002 Variable Rate Fertilization Strategies for Emissions Reduction: Spatially Resolved Life Cycle Assessments of Canadian Cereal Crop Production

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Nitrogen-based fertilizers have been essential for global food production in conventional agriculture. Their widespread use over the past century has supported higher crop yields and contributed significantly to food security. The 4R nutrient management principle (right source, right rate, right time, right place) promotes efficient fertilizer application to both boost yields and reduce negative environmental impacts. Technologies that facilitate the implementation of 4R practices, such as variable-rate (VR) technologies, offer considerable potential to lower greenhouse gas emissions from agriculture by optimizing fertilizer or plant-protection chemical inputs.

Evaluating the full benefits of VR technologies requires integrating highly spatially resolved field operation data with systems-level environmental accounting frameworks, such as life cycle assessment (LCA). This study developed detailed, spatially resolved life cycle inventories for wheat and barley production systems in the Canadian Prairies. ISO 14044-compliant LCAs were conducted to compare the environmental impacts of conventional and VR fertilization. Research sites provided the context for these assessments, with regionally and spatially resolved comparative LCA performed for wheat and barley crops produced using VR and conventional fertilization strategies. Data was obtained from a variety of first-hand sources, including detailed farm management records, soil samples, and operational machinery data from two production seasons.

Preliminary results show that VR fertilization reduced environmental impacts compared with conventional practices across most measured categories. Although implementing VR required more energy for internet and communication technologies (data transfer, software, etc.), this did not significantly affect the overall impacts. Notable improvements included lower GHG emissions, reduced nutrient runoff, and higher scores on climate change and toxicity indicators. These findings highlight VR technology's capacity to optimize input use and its potential for improving agricultural sustainability. Differences were also noted when using a highly spatially resolved inventory compared with default background inventory datasets, particularly in estimates of fuel and chemical inputs, underscoring the value of site-specific data in agricultural LCA.

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1.03.P-Tu003 A GIS–LCA Workflow for Spatially Explicit Quantification of Ecosystem-Quality Impacts from Land-Use Change: Application to the Tours–Bordeaux High-Speed Rail Corridor

Spatial precision in land-use impact assessment remains a key methodological challenge in Life Cycle Assessment (LCA), particularly for linear infrastructure projects where land-cover transitions are heterogeneous and geographically distributed. This study presents a reproducible geographic information system (GIS)–LCA workflow that integrates CORINE Land Cover (CLC) data with Life Cycle Impact Assessment (LCIA) methods to quantify ecosystem-quality impacts along the Tours–Bordeaux high-speed rail corridor (340 km, France).
Land-cover transitions between 2006 and 2018 were characterised across 20 CLC level-3 classes within a 1,000 m

corridor buffer. A systematic four-stage matching procedure was developed to link CLC classes to LCIA elementary flows (occupation and transformation) for two LCIA methods — IMPACT World+ and ReCiPe 2016 — through direct semantic matching, intensity-level rules, and ecological analogy, with documented fallback criteria. The resulting correspondence tables are fully transparent and transferable to other European infrastructure projects using CLC data. Results indicate that land occupation is the dominant driver of ecosystem-quality damage under IMPACT World+, while land transformation yields a net negative impact reflecting partial post-construction ecological recovery. Sensitivity analyses on corridor buffer width and CLC-to-flow mapping confirm the robustness of relative impact rankings, with absolute uncertainties bounded at approximately 15–20%.
By directly mobilising outputs from mandatory post-project environmental observatories, this workflow operationalises the link between EU spatial monitoring frameworks and LCA — supporting evidence-based benchmarking of biodiversity-related impacts across infrastructure projects.

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1.03.P-Tu004 Evolution of Chemicals and Plastics Coverage in ecoinvent (v3.9–3.12): Insights from the Polycarbonate Value Chain

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Robust and credible life cycle assessments (LCAs) rely on comprehensive data describing supply chains, energy systems, material inputs, transport, and end-of-life treatment. Because these elements must be represented consistently across many interconnected processes, background life cycle inventory (LCI) databases are vital in enabling complete and consistent assessments. In this context, the ecoinvent database is widely used by LCA practitioners and sustainability experts globally. The database is continuously maintained and developed to meet demands for transparency, regional specificity, and technological detail. This contribution presents the evolution of chemicals and plastics data within ecoinvent from versions 3.9 (released in 2022) to 3.12 (2025), illustrated by the polycarbonate production system.
Beginning with v3.9, aggregated industry LCIs for polycarbonate production was replaced with a more detailed unit process representation. In v3.10, key precursors relevant to the polycarbonate value chain were also updated. Specifically, chlorine production was revised based on current European industry-average data from EuroChlor, supported by ifeu. Propylene and benzene data was also improved through a broader disaggregation of petrochemical LCIs for steam cracking products, carried out with PlasticsEurope and ifeu, including updates to benzene production from pygas and reformate. Version 3.11 further refined and expanded the value chain with updates to cumene, bisphenol A, phosgene, and synthesis gas and carbon monoxide data. Finally, extensively regionalized polycarbonate production and steam cracking operations data were introduced with v3.12, expanding polycarbonate coverage from two to eleven world regions and propylene from two to twenty-six compared to v3.9. GWP scores across markets for the final product remain within approximately ±10% when comparing v3.9 and 3.12. Shifts in individual precursor scores can be larger, move in different directions, and partly offset each other at the system level, underlining the importance of steadily maintaining, developing and applying background LCA data from a systems perspective. While illustrative, this evolution is representative of wider improvements across the chemicals and plastics data in ecoinvent. Expanded upstream coverage, improved representation, and increased regionalization enhance the database’s ability to support more consistent, transparent, and geographically differentiated LCA modelling.

1.03.P-Tu005 National and Regional Life Cycle Inventory Database for the Italian Bovine Sector: A Cradle-to-Gate Assessment of Environmental Hotspots

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The Italian livestock sector is a vital component of the national agrifood economy but faces significant sustainability challenges. To date, environmental assessments have largely relied on international Life Cycle Inventory (LCI) databases that often fail to capture the specificities of Italian production systems, local breeds, and regional management practices. This study presents the first comprehensive national and regional LCI database for the Italian bovine supply chain, developed within the Growing Resilient, Inclusive and Sustainable (GRINS) project, covering over 280 datasets according to ISO 14040/44 standards.
The system boundaries adopt a cradle-to-gate approach, encompassing agricultural feed production, industrial processing, livestock rearing, and slaughtering. The analysis models diverse farming systems, intensive, semi-intensive, and extensive, for key breeds: Piemontese and Limousine (beef), Frisona (dairy), and Pezzata Rossa (dual-purpose).
Impact assessment using the Environmental Footprint 3.1 method identifies livestock rearing as the primary hotspot. In beef breeds, the Piemontese bull (M>24) shows the highest impact per individual (23.6 kg CO2-eq/kg live weight), while younger calves carry the burden of the suckler cow. For the Limousine breed, imported French calves (3-6 months) exhibit lower impacts than domestic ones due to efficient grazing and lower water stress. In the dairy sector, the Frisona breed's impact is mainly driven by milk production (86% allocation), while the dual-purpose Pezzata Rossa shows higher meat-related impacts for older males. Climate Change, Water Use, and Acidification are the dominant categories across all breeds.
At slaughtering, assessed per kilogram of carcass using economic allocation, the Piemontese bull emerges as the most impactful (6.28 mPt) due to upstream rearing intensity, despite high dressing yields. For dairy chains, culled cows and dual-purpose bulls represent the main contributors.
The study concludes that environmental profiles vary significantly by breed and management system. This database provides a robust, context-specific scientific foundation for stakeholders to identify mitigation strategies, such as optimized feeding, and supports national certification schemes like "Made Green in Italy".

1.03.P-Tu006 A National Dataset of Plant Based Meat Analogues in Turkish Supermarkets: Towards a Spatially Explicit Life Cycle Inventory Linking Nutritional Profile, Ingredient, and Region-Specific Indicators

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Plant-based meat analogues (PMBAs) are lower-carbon alternatives to conventional meat, with a rapidly expanding global market, including retail markets in Türkiye especially in the recent years. This study develops a national dataset of PBMA products which are currently available in Turkish supermarkets by the aim of serving a base for future spatially explicit life cycle inventories for the mentioned products.

At the first stage of the study, data for PBMAs (products which do not substitute meat products are not covered) are collected from the websites of major supermarkets and online shopping websites in Türkiye by the aim of reaching timely and wide product information. Related product categories of websites or main keywords of 'Vegan & Vegetarian' are used for reaching the product data, which is on the main characteristics/definition, ingredients, nutritional profile, producer and origin of the product. In case this information was not available at the visited website, the producer's website is visited to collect the missing information. After constituting the database with the listed information, statistical information related to ingredients and nutritional profiles of the products are produced. At the second stage of the study, a spatially explicit ingredient-level inventory of the products is constituted by connecting the producer companies. In case this is not possible, agricultural products which are main ingredients of the mentioned products (i.e. soy, chickpea, wheat, etc.) are analyzed in terms of the regions they are cultivated to fill the missing data gaps based on secondary data using literature. At the last stage of this still on-going study, after having a spatial mapping of ingredient sourcing, this information will be linked to some region-specific indicators (water scarcity levels and agricultural intensity) using literature-based sources and databases.

This study is the first study aiming to establish a database of PBMAs available in Turkish supermarkets, their

nutritional characteristics, ingredient origins together with region-specific indicators; which will constitute a baseline for a national database of the product category.

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1.03.P-Tu007 EU Country-Level Regionalization Light-Duty Vehicles Environmental Impact: an Extended Well-to-Wheel Environmental Assessment

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Decarbonizing road transport is crucial to the EU's 2050 climate neutrality goal, with CO2 standards requiring a full reduction in new vehicle tailpipe emissions by 2035. National decarbonization trajectories differ markedly across Member States (MS), driven by heterogeneous electricity mixes and vehicle market compositions.
Existing well-to-wheel (WTW) assessments of passenger cars commonly apply EU27-average electricity carbon intensities and fleet-composition weights, masking the geographic variability that determines whether transport and fuels' decarbonisation initiatives deliver at national level, limiting the reliability of metrics used for MS-level sustainability governance.
This study presents a regionalized, extended WTW environmental assessment at the MS level of newly registered EU light-duty vehicles in 2023. It covers different powertrain: internal combustion engine, hybrid, plug-in hybrid, fuel-cells electric, and battery electric vehicles, across body types and size classes. Foreground inventories are constructed at MS level by combining nationally specific vehicle sales shares, real-world consumption data, and electricity carbon intensities. Background inventories are adapted using national electricity mixes for both vehicle manufacturing and operation, constituting a spatially explicit life cycle inventory development at EU sub-national scale.
Vehicle sales shares at MS level are derived from the European Environment Agency 2023 CO2 monitoring dataset. Real-world fuel/energy consumption factors from the EU On-Board Fuel and Energy Consumption Monitoring (OBFCM) dataset are applied to official values to represent tank-to-wheel estimates. Electricity carbon intensities reflect regional variation and scenario assumptions. Vehicle production impacts (cradle-to-gate) use existing background processes, with sensitivity tests for manufacturing-country electricity mixes. The functional unit is one vehicle-km; impact categories align with the Environmental Footprint 3.1. End-of-life follows MS specific waste fates and the EU Circular Footprint Formula.
Results are expected to show how geographic precision improves alignment with EU sustainable objectives and reveals nationally specific decarbonization trade-offs. A key output is a transparent, reproducible implementation framework that integrates publicly available datasets with life cycle inventory databases, designed to be replicable by practitioners and scalable to future reference years.

Disclaimer/Disclosure: The views and analysis presented are purely those of the authors, and do not under any circumstance reflect an official position of the European Commission.

1.03.P-Tu009 A Five-Indicator Comparability Index Framework for Screening and Ranking Life Cycle Assessment Studies

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The growing interest of Life Cycle Assessment for benchmarking technologies, supporting policy and systematic analysis of literature has increased the need for robust cross-study comparison. However, direct comparison of LCA studies remains challenging because results are highly sensitive to differences in functional unit, system boundaries, database choice, geographical context, temporal validity, modeling approach, and allocation procedures. This study

introduces a structured Comparability Indec (CI) framework designed to systematically screen and rank LCA studies against a predefined reference system. The proposed framework builds on established data quality principles and pedigree-based approaches, but reinterprets them as components of comparability rather than as standalone data quality criteria. Five indicators are included – Technological Representativeness, geographical Representativeness, Temporal Representativeness, Completeness of Scope, and Methodological Alignment. These indicators capture the main sources of divergence that influence whether two LCA studies can be meaningfully compared. Technological Representativeness is assessed through technology maturity, geographical dimension through country-level background conditions, and temporal representativeness through the life cycle inventory database and version used. Completeness of scope evaluates the alignment in functional unit and system boundaries, while methodological alignment addresses compatibility in core modelling choices, especially attributional versus consequential modelling and allocation procedures. Two calculation modes are proposed. In Option A, all five indicators are treated as soft filters on a three-level ordinal scale, enabling flexible ranking and exploratory literature screening. In Option B, Completeness of Scope and Methodological Alignment operate as hard filters, while the three representativeness indicators remain graded, ensuring that conceptually non-equivalent studies are excluded before comparison. The framework therefore provides a transparent and reproducible protocol for improving benchmarking robustness, supporting meta-analytical screening, and strengthening evidence synthesis workflows, including AI-assisted literature analysis. To demonstrate its practical applicability, the CI framework will be applied to a biogas upgrading system to biomethane, a key bioeconomy pathway with strong sensitivity to technological configuration and geographical context.

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1.04 - Prospective LCA on Transitional Scenarios

1.04.T01 How Territorial Context Shapes the Environmental Performance of Circular Nutrient Recovery Strategies: A Regionalized LCA Across European Cities.

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European policies increasingly prioritize the recovery and circularity of nutrients to enhance food security and climate change resilience within a circular bioeconomy. Urban and peri-urban agriculture serves as a strategic resource for this transition, leveraging its unique spatial proximity to concentrated municipal resource streams. However, the environmental viability of these recovery pathways is not universal; it is highly sensitive to city-specific factors such as waste composition, local energy mixes, and regional nutrient demand. This study evaluates the environmental trade-offs of circular nutrient recovery strategies (struvite, ammonium salts, and compost) across six diverse European metropolitan regions. Using a harmonized, regionalized Life Cycle Assessment (LCA) framework implemented in a Python-based module, we quantify the impacts of localized nutrient systems under current conditions and future business as usual and decarbonization pathways by applying PREMISE to integrate IMAGE SSP2-M and SSP2-L scenarios. Our framework assesses each city's intrinsic capacity to meet its agricultural nutrient needs through municipal waste valorization, providing footprint-based evidence to guide policymaking toward greater food security and resilience against climate change and market fluctuations. By positioning agricultural soils as the integrating interface between waste treatment and crop cultivation, this research emphasizes that soil health is foundational to nutrient retention and system resilience despite being overlooked in circular economy mandates. A global sensitivity

analysis of pooled parameters isolates the primary drivers of cross-city variability, identifying how territorial factors such as transport logistics and regional data priorities influence environmental outcomes. By interpreting these results alongside regional ecosystem sensitivities, this research provides a robust framework for regionally differentiated policy design. It moves beyond standardized mandates and towards territorially optimized nutrient management that recognizes the soil-waste interface as a cornerstone of territorial resilience.

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1.04.T02 Supporting Urban and Regional Decisions with System Dynamics Sustainability Assessment: A Framework and Toolset

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Life cycle assessments (LCA) are a standardised and broadly accepted methodology for a holistic assessment of sustainability over the life cycle. They have proven useful since about 30 years, also due to their effective simplification of reality. When it comes to regional systems, consideration of developments over time and of links to a regional and broader economy are however often important as well. These are typically ignored in LCA.

System Dynamics Sustainability Assessment (SDSA) is presented as an approach that integrates LCA with system dynamics (SD) modelling to evaluate the long-term environmental, economic, and social impacts of complex systems over time. For the approach, a framework is being developed in the EU-funded research project CIRCULANDIA. The framework involves a close collaboration with stakeholders, mainly municipality representatives, to gain insights into the decision-making process and define requirements for a suitable impact assessment framework for sustainability. The project is also supporting the continuous development of a solution in the open-source software openLCA, allowing SD models and LCA modelled product systems to be linked. In order to demonstrate the framework and tool, the presentation will include an assessment example of regenerative agriculture practices.

For cities and regions, SDSA provides a stronger basis for urban development as it allows policymakers to anticipate short- and long-term sustainability effects of new regulations and urban development projects in the given regional context. It further allows 1) the exploration of how solutions may perform under different scenarios; 2) to identify indirect and unintended consequences such as rebound effects; 3) to consider multiple interest groups and associated trade-offs. Overall, this approach supports regional authorities in administering anticipatory, systems-aware governance, improving the likelihood that sustainability policies deliver their intended outcomes in practice.

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1.04.T03 Prospective LCA of District Heating and Heat Pumps in Austria: Environmental Trade-Offs of Future Heat Supply Systems

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The transformation of heat supply systems is a key component of European decarbonisation strategies. District heating enables the large-scale integration of renewable and low-carbon heat sources, and such shifts in technology portfolios will change environmental impacts across different impact categories.
This study applies a prospective life cycle assessment to future district heating supply mixes in Austria up to 2050 and

compares them with heat supplied by small-scale electricity-based heat pumps. The aim is to analyse how different heat transformation pathways influence environmental indicators and to identify potential trade-offs between greenhouse gas mitigation and other environmental impacts.
The modelling is based on national energy scenarios and is conducted for the time horizons 2030, 2040, and 2050. The district heating mixes reflect nationally-aggregated source mixes. They include biomass-based combined heat and power, large-scale heat pumps, geothermal energy, solar thermal systems, and hydrogen peak load technologies. The modelling of individual heat pump systems is based on scenario-dependent electricity mixes, while other system parameters are kept constant. The prospective representation of the background system is implemented using scenario-based datasets generated with the well-established premise approach. Environmental impacts are assessed across several categories, including climate change, resource use, and toxicity-related indicators.
Initial results indicate a substantial reduction in greenhouse gas emissions of the district heating mix over time, with the magnitude depending strongly on the underlying scenario. At the same time, increasing electrification and the deployment of material-intensive technologies lead to growing impacts in resource use and toxicity-related categories. For the heat pump system, environmental impacts are expected to depend strongly on the future development of their efficiency and of the electricity mix.
The scenario comparison shows that the decarbonisation of heat supply does not lead to a uniform improvement across all environmental impacts. Rather, it results in trade-offs between different impact categories, highlighting the importance of multi-dimensional environmental assessment of future heat supply systems. This applies to both district heating and electricity-based heat pumps, whose environmental impacts are strongly influenced by the composition of the underlying electricity mix.

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1.04.T04 Exploring Futures of Radio Access Networks in France: a Prospective Life Cycle Assessment Study

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1. Background & purpose
Information and Communication Technologies (ICT) raise growing concerns about their present (~4% of global green house gas [GHG] emissions) and future (~35% of global GHG emissions by 2050) environmental impacts. Among the three ICT pillars, networks are the least studied. In France, they represent between 2% and 14% of ICT environmental impacts. Mobile networks are rapidly growing, their carbon footprint has increased by 13% per year between 2015 and 2024 in France. Several studies have explored mobile networks future impacts. However, few quantify more than energy consumption and carbon footprint while none implement a prospective Life Cycle Assessment (pLCA) framework. Additionally, sufficiency measures such as 5G antenna sleep modes are often ignored or simplified.

2. Methods
This study proposes a multi-criteria pLCA framework to evaluate environmental impacts of 4G and 5G Radio Access Network (RAN) deployment in France between 2020 and 2040. Foreground scenarios are developed using a bottom-up approach based on open access data provided by the National Frequencies Agency (ANFR), geo-localising all operational sites and associated characteristics. Data is processed to identify deployment trends which are then extrapolated using logistic curves fitted to historical data to achieve deployment targets by 2040. RAN geolocation data are crossed with population density data from the National Institute of Statistics and Economic Studies (INSEE) to estimate RAN power consumption and identify antennas for which sleep modes are relevant. The background modelling is carried out using Premise, coupled with ecoinvent 3.12 and several IAM, SSP and RCP sets used to

perform sensitivity analyses. Impacts are assessed using Impact World+ v2.2.1 (endpoint).

3. Results & Conclusion
Overall, RAN total impacts are expected to increase across all studied scenarios. Sleep modes are expected to be an efficient sufficiency measure as scenarios implementing them result in potential lower impacts. However, energy efficiency measures and changes in background electricity mix are not enough to balance increase in traffic and equipment deployment, illustrating a rebound effect. Burden shifting is observed between GHG emissions and several categories depending on background scenarios. While sleep modes prove to be a relevant mitigation strategy, results suggest deeper changes in network deployment strategies and in ICTs are needed to reach reduction targets.

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1.04.T05 A life cycle perspective on hybrid-electric aviation for short Nordic routes

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Aviation contributes approximately 2-3% of global greenhouse gas emissions, and its share is expected to increase as air traffic continues to grow toward 2050. Alternative aviation fuels are considered one direct near-term pathways for reducing aviation emissions, as they can be deployed within existing aircraft and fuel infrastructure. At the same time, hybrid-electric aircraft are being explored as a promising longer-term option, especially on short regional routes, where they are technically more feasible than on longer flights. Existing studies have mainly assessed the environmental impacts of individual aircraft technologies, while less attention has been given to how these technologies perform when implemented across real flight routes. The Nordic region provides a relevant case for such an assessment because of its ambitious climate targets, relatively low-carbon electricity supply, and active promotion of electric aviation. This study therefore assesses the environmental and resource impacts of deploying regional hybrid-electric aircraft in the Nordic market, focusing on routes shorter than 300 km, which are considered especially relevant for early hybrid-electric aviation deployment.
A prospective life cycle assessment is applied to quantify cradle-to-grave environmental and resource impacts under future scenarios. Future scenarios are developed based on established international scenario frameworks, including the Shared Socioeconomic Pathways and Nationally Determined Contributions, combined with Nordic-specific scenarios informed by previous studies conducted within Nordregio projects. The impacts of hybrid-electric aircraft are compared with that of conventional regional aircraft powered by alternative aviation fuel. The results provide insight into the potential benefits and trade-offs of hybrid-electric aircraft deployment in the Nordic region, including its implications for climate mitigation, resource demand, and technology prioritization. By evaluating these impacts at the route and market level, the study can support policy development and investment decisions for aviation decarbonization in the Nordics and provide a knowledge base for other regions considering similar technologies.

1.04.P - Prospective LCA on Transitional Scenarios

1.04.P-Mo013 All Aboard! A Prospective, Time-Explicit Life Cycle Assessment of Battery-Electric and Diesel City Buses on a British Route under Net-Zero Policies

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The net-zero targets of the United Kingdom are linked to major reductions in the transport sector, which contributed 28% of UK’s total domestic emissions in 2022. Central and local governments are prioritising electrification as a key method to decrease emissions; however, little has been done regarding indirect impacts of implementing wide-scale electric infrastructure and the application of future scenarios for national climate policies. Therefore, prospective life cycle assessment is performed on a case-study route of an electrified fleet of city buses operating on a singular line in

SW England and compared to a similar analysis of a diesel-powered alternative.

Battery-electric and diesel buses were modelled, with Ecoinvent and carculator-bus being used as inventory databases. Processes for road use, wear, and infrastructure were also modelled. Per-passenger impacts, along with upfront construction and period maintenance, were considered year-by-year. For prospective assessments, premise will be employed to compare scenarios, selected based on ambitiousness of aligned policies, and derived from a REMIND-based integrated assessment model to examine scenarios that align with local government targets.

Results show that electrification of a local bus route within the UK can significantly reduce CO2-eq. emissions, with a pay-off time between 3-6 years of operation. Uncertainty in results is higher when examining the route on a per passenger-kilometre basis, with a large source originating from additional infrastructural wear, although the range of uncertainty is reduced with uptake. It is hypothesised that the application of scenarios aligned with environmental targets set by the UK government will further demonstrate the importance of electrification in reducing transport emissions, yet it is unclear how much of an impact this may make when expanded to a broader context.

The work undertaken supports existing evidence in literature that transitioning towards an electrically driven public transport network is a key step within the decarbonisation of the UK. Additionally, it further emphasises the need for electrification to be directly linked with local governmental efforts towards modal shift away from private transportation. Finally, the use of a time-explicit assessment within this context and the ease and simplicity of producing results can provide an optimal method for more granular control of activities over time-explicit stages.

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1.04.P-Mo014 Integrating Systems Perspectives into Prospective Life Cycle Assessment: A Structured Framework for Enhanced Sustainability Decision Making

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It is crucial to understand the environmental effects of emerging technologies from their early development to their widespread deployment to ensure that they contribute to global sustainability goals. Prospective Life Cycle Assessment (pLCA) has emerged as the primary methodology for forecasting these implications. However, current approaches often operate within a narrow, technocentric scope. These approaches often fail to account for systemic impacts, such as technological lock-ins, or to develop scenarios that reflect dynamic socio-technical shifts relevant to future industrial production.
This study proposes a structured methodology that integrates the Multi-Level Perspective (MLP) framework with pLCA to address these limitations. The MLP framework provides a systemic lens to anticipate dynamic changes by analyzing interactions between the niche, regime, and landscape. This integration ensures that pLCA scenarios move beyond simple technical forecasting to include plausible socio-technical futures, including shifts in regulatory frameworks, infrastructure, and consumer behavior.
The utility of this integrated approach is demonstrated through a case study of an insect-inspired soft robot designed for autonomous environmental monitoring. Initial screening LCA results revealed that energy-intensive fabrication processes, particularly 3D printing, are significant environmental concerns in the laboratory stage. Using the MLP informed framework, we developed three upscale scenarios: optimized autonomous production, high-volume industrial molding for remote inspection, and a maximum circularity scenario involving closed-loop material systems.
The results highlight how transition-oriented design recommendations focusing on material dependencies, hardware sufficiency, and circularity can be identified early in the development process. This framework transforms pLCA from a static evaluation into a proactive tool.

1.04.P-Mo015 Capturing the Consequences of Constrained Biomass Availability and Competition in Bio-based

Productions

Fabio Sporchia[1], Kíra Lancz[1] and Massimo Pizzol[1] (1)Aalborg University

Life cycle assessment (LCA) can compare bio-based alternatives to fossil-based products. However, the limited availability of biomass as feedstock for bio-based production is often overlooked in LCA. We developed a model that addresses this gap by considering physical biomass flows across bioeconomy sectors. The model first maps the existing biomass flows across bioeconomy sectors based on an open and constantly updated dataset at the European Union (EU) level. The dataset is converted into a life cycle inventory matrix with bioeconomy sectors as suppliers and users of biomass. Flows are expressed in absolute mass terms capturing bioeconomy's physical constraints. The model identifies where competition for biomass of different types (e.g. primary products and residues) and from different sources (fisheries, forestry, agriculture) occurs across bioeconomy sectors. Sectors compete for the same biomass feedstock and if one scales production up, the others will have to scale it down to ensure feedstock availability, but also creating a deficit of bio-based products from scaled down production. This deficit can only be covered by resorting to fossil-based substitutes. The model identifies and quantifies these deficits, which can be used directly as input to a consequential LCA model to specify which activities are triggered by an increased demand for bio-based products, and thus estimate the substitution effects. The model outputs can be linked to background datasets (e.g. from ecoinvent) and can also be coupled with LCA databases at the foreground level to assess emerging bio-based technologies and products. Thus, the model allows investigating the unintended consequences of bioeconomy expansion. The fundamental novelty of the model consists in allowing LCA studies of bio-based products not only to capture competitions for users of constrained biomass – already addressed by a few models – but also to identify and quantify the consequent deficits across competing bio-based products, which is an aspect commonly overlooked. The potential of the model is demonstrated with the case study of EU bio-based adipic acid production where the use of wood residues as feedstock causes deficits in bioenergy, pulp and paper, and material industry sectors. Accounting for the compensation of such deficits implies a significant reduction of the greenhouse gas emission savings when compared to fossil-based adipic acid, raising questions on the appropriateness of this solution.

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1.04.P-Mo016 Accounting for Future Biomass Constraints in Prospective LCA of EU Bioeconomy Transitions

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The EU has positioned the bioeconomy as a central driver of the European green transition. Technologies based on the utilization and transformation of biomass feedstocks have been increasingly appraised as more sustainable alternatives to fossil counterparts. Prospective life cycle assessment (pLCA) is often used to evaluate emerging bio-based technologies, yet most studies do not account for biomass supply constraints when scaling such technologies. Current prospective background models are limited in their representation of biomass production and use.

This work presents a pLCA framework for considering the impacts of competition for biomass feedstocks between bioeconomy sectors, and the unintended consequences of replacing fossil-based materials with bio-based alternatives. The approach builds on an EU-wide biomass accounting model that links supply and demand across sectors and identifies deficits arising from increased biomass demand. The model implements several future projections of biomass supply and use in the EU, based on different biophysical, policy, and economic assumptions. Data for the future scenarios have been obtained from forecast reports (by the JRC) and global equilibrium models, such as MAGNET.

The framework is applied to four case studies of bio-based production routes for monoethylene glycol, assuming full substitution of fossil-based production. We compare three feedstock alternatives, wood, wheat, and sugar beet from published literature.

Results show that accounting for constraints in feedstock availability critically affects the environmental performance of the compared pathways. While some feedstocks (wood, wheat) can better meet increased demand under certain scenarios, others (sugar beet) exceed available supply even if a partial sector transition is assumed. Competition for biomass induces shifts across sectors, including impacts on food production, bioenergy, and material uses, requiring substitution by alternative products. The additional impacts of this substantially alter life cycle impact profiles, revealing trade-offs not captured in conventional LCA.

The findings highlight that scaling bio-based technologies without accounting for future resource constraints bears the risk of burden shifting and unintended environmental impacts. By integrating prospective scenarios of the EU bioeconomy, the proposed framework advances methodological capabilities for assessing the transition to a bioeconomy.

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1.04.P-Mo017 Towards Absolute Sustainability in Danish Housing: A Prospective Outlook

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Residential buildings account for a third of the carbon emissions of Denmark, bringing an urge to mitigate their impact. This project focuses on the life cycle impacts of the Danish housing realm, its main determinants and position compared to absolute boundaries, as of now and up to 2050.

Energy data were collected for 863 631 Danish dwellings, complemented with environmental and occupancy data and used within an overall equation to determine the environmental impact per capita of any Danish dwelling. This constituted the first step, assessing the current housing stock, both in terms of heating and embodied impact. Historical data as well as future projections were then implemented in a prospective life cycle assessment frame to determine the status of the housing realm until 2050, accounting for yearly renovations, demolitions and new constructions within the building stock.

With an average carbon footprint per capita of 1.8 tCO2e/cap/yr (reference interval: 0.23 to 8.6 tCO2e/cap/yr), only 0.01% of the Danish dwellings can currently be deemed absolute sustainable from a climate-change perspective, when using an allocated share of the safe operating space of 88 kgCO2e/cap/yr with an economic allocation (0.62% with the grandfathering approach). High variations exist depending on the impact category considered, from 0% of individuals living in absolute sustainable dwellings for freshwater ecotoxicity and human toxicity (non-cancer), to more than 95% for land use and terrestrial acidification.

The study examines the trajectory of a business as usual scenario, considering the Danish government’s planned regulatory measures for construction and heating in the coming years, as well as the progressive improvement of the existing building stock through renovation.

The living area per capita, heating type and energy label have been identified as highly influential variables. Based on these driving parameters, future trajectories are built and tested, trying to combine societal realism (keeping realistic living areas) with absolute boundaries. The learning rates needed to reach absolute sustainability are also determined for various scenarios, highlighting the remaining gap and efforts needed in the near future.

In conclusion, despite gradual reduction of environmental impacts in the building and energy industries in Denmark,

important additional efforts are to be made for the Danish housing sector to reach and stay within the Earth carrying capacities.

1.04.P-Mo018 Life Cycle Assessment of Electricity Generation in Kalimantan: A Comparison of Current and Future Grid Scenarios

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Despite vast renewable energy potential, Kalimantan currently relies on coal for approximately 70% of its electricity. Demand is projected to grow as the region develops to accommodate Indonesia's new capital, yet the environmental assessment of Kalimantan's current and future electricity systems remains insufficiently quantified.

Our study provides an environmental assessment of Kalimantan's electricity generation mix by applying life cycle assessment (LCA) to the currently operating power plants. We use primary operating data from eight power plants managed by the electricity state-owned enterprise, consisting of coal, gas, diesel, and hydropower. The operating data includes fuel characteristics, operational parameters, stack emissions, and consumables. The scope is cradle-to-grave, covering fuel extraction, transportation, operation, construction, and decommissioning. We complement our primary data with secondary sources from available databases, papers, and reports.

Using SimaPro 10.2.0.3, we define functional units as 1 kWh at the plant level and the total 2024 generation of 17,822 GWh at the regional level. For the 2060 decarbonisation scenario, the functional unit is 122,464 GWh, built upon Indonesia's national energy policy, which targets at least 70% of electricity generation from renewable energy by 2060.

Initial results, using ReCiPe 2016 midpoint (H) method, show the current Kalimantan electricity mix has a global warming potential (GWP) of 0.906 kgCO2/kWh, around 20% lower than the ecoinvent dataset's estimate for the Indonesian grid (1.13 kgCO2/kWh). This difference highlights the importance of primary operating data, which is often scarce in emerging economies. By 2060, the GWP decreases by almost 75% due to coal phase-out and renewable expansion. The 2060 scenario shows a reduction in 12 out of 18 impact categories compared to the current system, even though mineral resource scarcity and ionising radiation increase by almost threefold.

These findings offer evidence to support policy decisions such as coal fleet phase-out and the prioritisation of renewable technologies that minimise environmental trade-offs. Our study also shows that generic datasets can misrepresent the environmental performance of electricity systems. The approach is broadly applicable to any fossil-fuel-dominated system seeking to quantify environmental trade-offs of transitioning to lower-carbon sources.

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1.04.P-Mo019 Prospective LCA of Green Hydrogen Production for Supporting National-Scale Low-Carbon Energy Transition

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Green hydrogen is recognised as a key option for decarbonising energy systems and hard-to-abate sectors such as heavy industry and aviation. To ensure a long-term energy transition, UK is expanding green hydrogen production and aiming to reach 6 GW green hydrogen production capacity by 2030. Therefore, there is a growing need to understand how national-scale hydrogen integration will influence environmental burdens across multiple impact categories in UK. This study applies prospective life cycle assessment (p-LCA) to evaluate three main electrolyser technologies: alkaline electrolysis (ALK), proton exchange membrane electrolysis (PEM), and solid oxide electrolysis (SOEL),

under current conditions and projected 2030 and 2050 scenarios. To bridge data gaps, machine learning is used for data upscaling of future developments in electrolyser performance and electricity supply. Global warming potential (GWP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), and ozone depletion potential (ODP) are included in this study. The results of the current scenario indicate that PEM shows the lowest GWP, ALK performs best on TAP, and SOEL achieves the lowest FEP and ODP per kg of green hydrogen. Stack energy consumption contributes more than 85% of total impacts across all technologies, highlighting the importance of efficiency improvements. When scaled to UK's existing project portfolio, PEM is the significant contributor to all environmental impacts due to its high production capacity. The p-LCA is anticipated to show an increasing expansion of PEM capacity by 2050 and a shift toward solar and onshore wind power dominance in UK's renewable energy profile. Environmental impacts of green hydrogen electrolysis are expected to decrease over time due to technology upscaling and an increasing share of low-impact renewable energy sources. Trade-offs across impact categories are expected to persist, highlighting the need for system-level planning to avoid burden shifting. This study provides forward-looking insights into national hydrogen transition pathways and demonstrates how p-LCA can support strategic planning, infrastructure development, and policy design while minimising unintended environmental trade-offs.

1.04.P-Mo020 Scenario Based Mass Balancing of Life Cycle Inventory Attributes in Certified Product Carbon Footprints

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Product Carbon Footprints (PCFs) are increasingly used to inform forward looking climate strategies in value chains. However, conventional PCF practice typically represents functionally similar fossil inputs averaging their emission factors, which limits the ability to reflect differentiated upstream sourcing scenarios in co processing systems.
This contribution addresses the methodological gap of attributing differentiated PCFs to products when conventional feedstocks from multiple origins are processed jointly. Mass balance approaches based on chain-of-custody principles are well established to track certified input characteristics of feedstocks (e.g., biogenic origin) throughout value chains. An extension of mass balance approaches to fossil based inputs with various upstream emission factors has not yet been systematically addressed in a prospective or consequential LCA context.
The study presents an approach of a certification framework for PCFs in which an upstream emission factor is treated as an intrinsic input characteristic subject to mass balance approaches. Building on chain of custody principles, the framework explores virtual segregation of conventional inputs with different emission factors in shared processing units. This allows the scenario modelling with a mass-balanced attribution of inputs with low emission factors to product outputs while maintaining consistency of physical constraints through certification.
Methodologically, the approach contains elements of prospective scenario modelling for low emission factor sourcing by explicitly accounting for both mass balanced PCFs and the resulting residual PCFs. The framework thereby creates a link between product level carbon outcomes and future sourcing decisions in a transitional time while capturing their systemwide implications. This promotes the stepwise implementation of product carbon footprints into purchasing decisions. This accounting approach preserve greenhouse gas integrity at the system level, avoids double counting, and ensure verifiability and robustness of certified and non-certified PCFs.
The results demonstrate how mass balancing of emission factors can extend existing PCF methodologies toward more decision oriented, prospective, and consequential applications. The proposed approach supports more granular representation of regional and sourcing specific differences in upstream emissions, while remaining compatible with certification and auditing requirements.

1.04.P-Mo021 Designing Tomorrow's Feed: A Predictive Dynamic LCA Framework for Cost- and Sustainability-Optimized Pig Feeding

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1 Background and Purpose

Feed is one of the primary contributors to the environmental footprint of livestock products, making feed formulation a key leverage point for sustainability improvements. However, accurately quantifying the true footprint of feed remains challenging due to the dynamic nature of animals and livestock farming. Most life cycle assessments (LCA) fail to capture this complexity, as they remain static and retrospective. This limits their usefulness as decision-support tools, since nutritional requirements shift continuously with life stage, and the environmental impact of feed ingredients depends on temporal factors such as seasonality and market dynamics. The goal of this research is therefore to develop a predictive and dynamic LCA framework, integrated with a nutritional digital twin, for the optimization of pig feed across both economic and environmental dimensions.

2 Materials and Methods

A nutritional digital twin of a growing pig will be developed to predict animal performance, based on real-time inputs such as feed composition and supply. Environmental impacts will be assessed through a dynamic LCA framework directly coupled to the digital twin, capturing temporally differentiated inventory flows and impact characterization. Linear programming for feed formulation will be embedded in an iterative optimization loop, identifying the most cost-efficient and environmentally sustainable feed for each upcoming feeding phase.

3 Results and Discussion

This research is currently in its initial phase; this contribution presents the methodological framework and anticipated outcomes. The integrated framework is expected to demonstrate that phase-specific, predictive feed optimization can meaningfully reduce key environmental impact categories compared to conventional least-cost formulation. Dynamic footprinting will further enable real-time sustainability monitoring and identification of hotspots in time, providing actionable insight at the feed phase level rather than as a single life cycle average.

4 Conclusions

This framework reframes LCA from a retrospective accounting exercise into a forward-looking, operational steering tool for sustainable livestock management. By integrating a nutritional digital twin, dynamic LCA, and feed optimization, it offers dual relevance: supporting on-farm decision-making and providing a data-driven foundation for evidence-based policy on sustainable feed and livestock production in Flanders and beyond.

1.04.P-Mo022 Methodological Choices and Assumptions in Prospective LCA of Future Steelmaking: A Systematic Review

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Steel is crucial to modern society and global demand continues to grow. Its production is responsible for over 7% of global greenhouse gas emissions, making the decarbonization of the sector a recognized priority. Quantifying the environmental impacts of alternative primary production routes is therefore necessary to support the steel industry's transition towards a less carbon-intensive future. Prospective Life Cycle Assessment (LCA) is widely applied for assessing the future environmental impact of the steel sector, but a comprehensive overview of the methodological approaches utilized is currently lacking. This systematic literature review evaluates how prospective LCA has been applied to assess the environmental impacts of future steelmaking technologies, and what methodological choices and assumptions dominate the current literature.

An initial search on the Web of Science and Scopus yielded 585 articles. After applying pre-determined inclusion and exclusion criteria, a shortlist of peer-reviewed articles (n = 80) is analyzed in depth in accordance with a set of attributes. The list includes both the studies of novel steel-making technologies (e.g., hydrogen-based direct reduction

of iron, bio-coke, and carbon capture and storage) and those on the impacts of currently prevalent technologies in the future (e.g., blast furnace and basic oxygen furnace).

Our analysis centers around scenario development and assessment as practiced in the reviewed studies. Foreground scenarios are developed to account for the variations and uncertainty in steelmaking itself, such as the upscaling of pilot-scale operation data, carbon capture and storage choices, and capacity utilization rates. Background scenarios, on the other hand, are applied to consider the variability and uncertainty regarding the conditions under which steel-making technologies will be deployed. These include differing electricity mixes, policy constraints, and supply chain instability.

Expected results include substantial variability in methodological choices, particularly in the treatment of scenarios and uncertainty, reflecting the absence of strict standards in prospective LCA. The study aims to identify prevailing practices and recurring issues, and to provide recommendations for strengthening methodological coherence within the field. In addition, the findings will inform the authors' forthcoming prospective LCA of primary steelmaking.

1.05 - S-LCA Theoretical and Methodological Advances: Gaps, Proposals and Pathways for LCSA Integration

1.05.T01 Operationalising Social LCA in data-scarce contexts: combining multi-stakeholder, socioeconomic value chain analysis and S-LCA for agri-food chains in Sub-Saharan Africa

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Assessing the sustainability of agri-food value chains in low-income countries requires methods that can bridge the gap between macro-level socioeconomic dynamics and product-level impact analysis. Chad, a country in sub-Saharan Africa and one of the world's least developed countries, exemplifies this challenge: cereal value chains support the livelihoods of over 80% of the population, yet operate under conditions of chronic malnutrition, institutional fragility, and data scarcity.
This study examines whether integrating Social Life Cycle Assessment (SLCA) with a multi-stakeholder socioeconomic value chain analysis can produce a more comprehensive and policy-relevant sustainability assessment than either approach alone, using the cereal flour value chains in Chad as a case study.
The Value Chain Analysis for Development (VCA4D) framework, developed by the European Commission/INTPA, was used as the analytical backbone, providing economic and social baselines for two cereal-based product systems (daily porridges and cereal flours) across eight agricultural sub-chains. Economic inclusiveness was assessed through value-added distribution and the Gini index, covering all actor categories from smallholder farmers to processors, traders, retailers, and consumers. The social analysis cross-mapped the six VCA4D social domains (working conditions, land and water rights, gender equality, food and nutrition security, social capital, and living conditions) against 25 PSILCA subcategories, combining database-derived background scores with primary field data from structured interviews across multiple actor categories.
Results show that the cereal value chains generate positive but highly unequal value distribution, with processors and traders capturing disproportionate shares relative to smallholder farmers. Working conditions and living conditions show the strongest alignment with PSILCA indicators, while gender equality and land rights, critical dimensions in the Chadian context, are only partially covered by existing subcategories, exposing structural gaps in current S-LCA databases.
This study demonstrates that multi-stakeholder value chain analysis is indispensable for contextualising S-LCA results: economic inclusiveness indicators reveal structural inequalities that social impact scores alone cannot expose. The proposed VCA4D–PSILCA crosswalk offers a replicable methodological bridge for S-LCA applications in complex agri-food systems across sub-Saharan Africa.

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1.05.T02 Mapping the Terrain: Decision pathways in Social Life Cycle Assessment

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Social Life Cycle Assessment (SLCA) aims to assess the social impacts of products and services throughout their life cycle. Despite surpassing two decades since inception, adopting the method still poses challenges. Obtaining reliable and relevant social data can be challenging, especially for global supply chains or product/service systems with low Technology Readiness Levels (TRLs) where actors along the value chain are often unknown. Many methodical approaches in the different SLCA phases have been introduced (i.e., prioritization, inventory decvelopment, assessment) but an overview as well as categorization of these methods is missing so far. The present work aims to 1) provide an overview and categorization of those methods; 2) analyse effects and relations of different methodical decisions given certain contextual conditions (e.g., TRL, level of analysis); and 3) propose a framework for the selection of methods depending on contextual factors surrounding a study. To investigate these objectives a mulit-method approach was adopted: First, a systematic literature review on SCLA case studies was conducted by using the morphological analysis as analysis framwork, i.e. contextual and methodological dimensions with different variants (the state a dimension can take). Second, a pairwise propbalitity matrix supported identifying probabilities of combinations of variants. Third, an adjacency matrix led to a causal map illustrating depencies between contextual factors and a methodical decision. Finally, building on that a bayesian network model was developed were dependencies of multiple factors can be illustrated and the likelihoods of different methodological pathways calculated. The results show that the objective of a study guide the decisions on the specific SLCA method. For instance, if the objective is to identify social hotspots in a specific product system, most study authors decided for a generic SLCA using the SHDB or PSILCA database. To bring SLCA towards a standardized approch, this work summarizes the state-of-research with regards to the methods applied in different SLCA phases. Guidance for researcher and practitioners is offered by providing a framework depicting possible combination of variants in the dimensions identifed to guide SLCA practioneers with methodical decisions.

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1.05.T03 Assessing Social Sustainability of Bio-Based Products Across TRL Levels as Part of an LCSA

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Bioeconomy plays a key role in achieving the European Union’s climate and sustainability goals. However, social impacts of bio-based products are often insufficiently addressed although they are critical in bio-based value chains due to raw material sourcing and globalised agricultural and forestry sectors. Assessing social impacts is especially challenging at low technology readiness levels (TRLs), where value chains are not yet defined and data availability is limited. This creates a need for a life cycle–based social assessment approach that supports companies in early innovation stages while remaining practical and compatible with full life cycle sustainability assessment (LCSA).

This presentation describes the social assessment approach developed in the EU Horizon Europe ESCIB project as part of an LCSA methodology to assess the sustainability and circularity of industrial bio-based products (excluding food, fuel, and feed) across different TRLs. At low TRLs, social considerations are addressed through a qualitative Responsible Research and Innovation (RRI) framework that supports societal readiness and facilitates value chain mapping, stakeholder identification, anticipation of social risks, and reflection on innovation goals. The early assessment emphasises raw material acquisition and manufacturing, where social risks are typically present for bio-

based products. Practical implementation of the method is supported by harmonised templates and checklists. As the TRL increases and more data become available, the approach progresses to social risk screening based on secondary data and, further, to S-LCA. The goal and scope and results interpretation phases are aligned with the broader LCSA to identify trade-offs.

The approach is currently being tested in ongoing industrial case studies covering bio-based products at different TRLs and sectors. The case studies address the methodology applicability and identify challenges such as data gaps and value chain uncertainty at early innovation stages. Potential ways to overcome those challenges are proposed. Final case study results should be available early 2027. The results from the case studies support further development of the social assessment methodology and its integration into LCSA for bio-based products across TRL levels. The approach can be applied in research projects and as part of product development to support industrial decision-making towards more sustainable bio-based solutions.

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1.05.T04 SENSE: An Open-Source Framework for Integrated Environmental and Social Life Cycle Assessment

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Sustainable decision-making requires integrating environmental and social dimensions in life cycle assessment (LCA), yet current practice largely treats them in isolation. A key barrier is the lack of harmonization between process-level environmental databases such as ecoinvent and sector-level social databases such as the Product Social Impact Life Cycle Assessment (PSILCA) database, which differ in spatial resolution, nomenclature, and physical versus monetary data foundations. Bridging this gap currently requires manual, version-specific coupling workflows that are labor-intensive and difficult to reproduce.
We present SENSE (Social and Environmental Nexus for Sustainability Evaluation), an open-source Python framework that automates integrated environmental-social LCA within the Brightway ecosystem. SENSE couples ecoinvent and PSILCA through four automated steps: deterministic mapping of ecoinvent locations to PSILCA countries, semantic text similarity matching of unit processes to economic sectors, conversion of monetary social intensities to physical flows using product prices, and aggregation of social risks across sectors and countries. The framework is database-version-agnostic, natively supports regioinvent for geography-explicit supply chains, and exposes all coupling assumptions as configurable parameters for sensitivity analysis. Beyond standard background databases, SENSE also supports custom foreground databases with recursive price estimation, enabling practitioners to apply integrated assessment to their own life cycle inventory models.
Validation against the commercial soca database demonstrated strong agreement for national locations. Coupling SENSE with regioinvent revealed that background regionalization increased social risk scores in 89% of assessed locations, indicating that non-regionalized supply chains systematically underestimate location-dependent social risks. SENSE provides a transparent, reproducible, and fully open-source workflow for joint environmental-social LCA, enabling practitioners to identify trade-offs between sustainability dimensions that isolated analyses would fail to capture.

1.05.T05 A Stakeholder-Inclusive Framework for Assessing the Social Performance of Underutilised and Reused Wood in Net-Zero Construction: Towards a Just Transition in Ireland

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The transition of Ireland's construction sector to net-zero emissions requires low-carbon materials such as underutilised (hardwoods, low-quality, and post-consumer) and repurposed wood. Despite the growing recognition of environmental benefits, researchers have critically under examined the social dimensions of this shift. This study addresses that gap by developing a stakeholder-inclusive Social Life Cycle Assessment (S-LCA) framework tailored to assess the social

performance of underutilised and reused wood value chains in Ireland. A mixed-methods sequential explanatory design is employed, combining quantitative S-LCA with qualitative stakeholder engagement. The methodology comprises three phases: (1) a systematic materiality assessment to identify relevant stakeholders and social issues; (2) a social life cycle inventory using the PSILCA database, site-specific data from Irish wood recycling and construction facilities, and national social statistics; and (3) a social impact assessment using linear and nonlinear scoring to evaluate performance and locate social hotspots. Grounded in UNEP S-LCA guidelines and ISO 14075, the framework is enhanced by just transition principles and a participatory materiality process. A stakeholder workshop with forestry associations, contractors, social enterprises, and community groups supports co-development, ensuring coverage of worker safety, fair wages, community well-being, and rural employment. Preliminary evidence suggests significant social risks in collection and processing (e.g., informal labour and health and safety concerns) alongside substantial opportunities, including local job creation, skills development, and public health benefits. The study will identify social hotspots where targeted interventions, such as retraining programmes and inclusive policies, can deliver the greatest gains. By linking technical S-LCA with just transition imperatives, this research offers a theoretically grounded and methodologically robust framework. It delivers policy-relevant insights to support Ireland's circular economy and net zero targets, ensuring that the decarbonisation of construction proceeds in a socially equitable and inclusive manner.

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1.05.P - S-LCA Theoretical and Methodological Advances: Gaps, Proposals and Pathways for LCSA Integration

1.05.P-Tu010 Sustainability Pillar Integration in LCSA through System Dynamics Thinking: Mapping & Preliminary Modelling of Interlinked Cause-Effect Chains in a PVC Case Study

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An objective in Life Cycle Sustainability Assessment (LCSA) is to have a coverage of the three pillars of sustainability. However, most of the approaches commonly employed, especially for the impact phase, are a combination of results that were obtained for each pillar independently, whereas one pillar can have an influence on another (e.g. prosperity influences health care). An approach to analyze complex systems of interacting variables is Systems Dynamics. This modelling approach allows the practitioner to have an overview of the system and a non-linear propagation of cause-effect chains including balancing and feedback loops. In this study, we explore Systems Dynamic Modelling as an approach to integrate the sustainability dimensions in LCSA. We apply this approach to a case study on PVC flows and focus on the aspects of job creation and occupational health. The objective of this study is to identify the cause-effect chains among sustainability pillars over the product life cycles within the case study and partially model those relationships. The methodology we employed is as follows. First, we conducted an initial mapping of variables using a causal loop diagram in a small team of 3 researchers. Second, a stakeholder workshop with around 10 participants was organized that included a mapping exercise designed to capture and integrate stakeholders' knowledge on the topic. Subsequently, both mappings were integrated into a single causal loop diagram. The diagram contains variables from the three dimensions of sustainability. Third, to operationalize the model, selected variables were prioritized based on their relevance to the research focus and the feasibility of modelling them. Results presented include the resulting causal loop diagram of the system. Examples of interrelationship of variables belonging to different sustainability pillars are the effect of pollution (environmental) on the health of population and workers (social) and the effect of sick leave (social) on productivity (economic). As a result of mapping, feedback loops were identified, for example: LCI influences environmental and occupational health, which in turn leads to sick leave due to injuries or disease and to a decrease of productivity leading to a potential increase in prices, which can influence the markets of PVC virgin production and/or recycling, eventually affecting the initial LCI. Additionally, a preliminary modelling of these variables over time is presented.

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1.05.P-Tu011 Social Implications of Circularity in Textile Value Chains

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The textile sector is plagued with significant social impacts across global value chains, including poor working conditions, low wages, occupational health risks, and social inequality. These challenges are particularly pronounced in labour-intensive production stages located in low and middle income countries.

In response to recent EU policy initiatives promoting textile circularity, research and development efforts have intensified, resulting in a growing range of circular technologies and pathways whose environmental and social implications increasingly require assessment through life cycle–based methodologies such as social life cycle assessment (S LCA). However, the application of S LCA to circular textile systems, particularly novel recycling and waste management technologies, remains limited and methodologically challenging due to data gaps, high uncertainty in data available for social risks in specific sectors, and supply chains constantly adapting to circularity, which hinder the identification of relevant stakeholder categories and social risk hotspots.

The goal of this research is to identify potential social risk hotspots associated with garment production from recycled textile fibres and to explore the implications of methodological choices when applying S LCA to emerging circular technologies. A selection of circular pathways incorporated into garment manufacturing including mechanical, thermo mechanical, and chemical recycling of cotton and polyester textile waste, are assessed. These garment manufacturing systems are analysed to capture changes in social risks associated with the introduction of innovative circular technologies.

Current S LCA applications in the textile sector predominantly focus on primary fibre production and conventional garment manufacturing, with limited attention given to circular garment production models. This study contributes empirical and methodological insights into the potential social risks of recycling based garment production and highlights key challenges and limitations in current S LCA practice, particularly in relation to technologies at different stages of development.

1.05.P-Tu012 Safe and Sustainability by Design: Stakeholder Engagement in Socio-Economic Assessments

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The increasing emphasis on integrating Safe-and-Sustainable-by-Design (SSbD) principles into early innovation phases has become essential for achieving the goals of the Chemicals Strategy for Sustainability (CSS) under the European Green Deal. While existing frameworks, such as the SSbD framework, provide methodological guidance, challenges persist, particularly regarding data accessibility, methodological complexity, and expertise gaps. This study investigates Step 5 of the SSbD framework, focusing on the socio-economic dimension through the application of social life cycle assessment (SLCA) within the pharmaceutical industry. The study addresses the challenge of operationalizing Step 5 by identifying relevant social topics, assessing their influenceability by design decisions, and enabling their practical integration into early-stage innovation processes. A multi-method approach was applied, including literature review, stakeholder consultations (interviews) and the screening of sustainability reports. These methods were used to identify and prioritize key social topics, define quantifiable indicators, and develop actionable recommendations to support decision-making in SLCA applications. The focus was on assessing the relevance of social topics to technology features, evaluating how design choices influence or are linked to social impacts. The results indicate that only a limited number of studies have implemented Step 5, confirming a significant gap in literature. A small set of social topics were identified and assessed for design relevance, enabling a more targeted and

efficient implementation of SLCA. This sector-specific prioritization reduces complexity for companies while highlighting the importance of measurable indicators to ensure meaningful assessment outcomes. The findings further demonstrate the need for improved access to high-quality, site-specific data, simplified methodological guidance, and sector-specific adaptations. Enhanced stakeholder engagement and the development of streamlined tools are critical to overcoming current barriers. Overall, this study contributes to advancing SSbD implementation by providing a structured, practical approach to integrating SLCA considerations into early product development, particularly in the context of pharmaceutical innovation.

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1.05.P-Tu013 Aggregation and Comparability in Social Life Cycle Assessment Within a Safe and Sustainable by Design Framework: A Four Use-Case Study on Lubricant Additives

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Aggregation remains an unresolved methodological problem in S-LCA, yet defensible aggregation is now a precondition for integrated sustainability assessment. With the revision of the JRC's Safe and Sustainable by Design (SSbD) framework, S-LCA has transitioned from an optional to a mandatory component. Without a structured aggregation approach, S-LCA outputs cannot inform the trade-off analysis or go/no-go decisions that SSbD requires. The JRC envisions two social pillars, Social Fairness and Competitiveness, but the grouping of results has been left open and is examined here.

The work applies a full S-LCA to four lubricant use cases (PTFE, PFPE, chlorinated paraffins, and corrosion inhibitors) to test whether structured aggregation delivers comparable results across chemically distinct systems. The assessment draws on the soca v4 database, applies a functional unit of 1 kg of lubricant additive consumed with cradle-to-grave boundaries, and implements the Reference Scale Assessment in openLCA. Indicators span the worker, local community, and society stakeholder categories, and are aggregated into the two pillars using equal weighting as a baseline rather than an endorsement. The Competitiveness pillar is reported provisionally to expose its structural incompleteness, since current background databases lack key opportunity indicators including patent activity and knowledge-intensive employment.

The central finding concerns what aggregation reveals and what it obscures. Under equal weighting, the composite pillar score reflects risk volume rather than risk severity: moderate-severity indicators such as fair salary accumulate medium-risk hours comparable to stricter indicators such as forced and child labor. For SSbD, a formulation could pass a pillar-level threshold while carrying very-high-risk exposure in forced or child labor that the aggregate fails to surface. The RSA risk distribution layer resolves this, confirming that aggregated scores and indicator-level granularity must be reported in parallel.

The study delivers a replicable three-layer reporting framework, identifies where equal weighting introduces normative distortion, and maps the database gaps preventing complete pillar coverage. As a prospective extension, ongoing work uses expert elicitation to derive indicator weights reflecting socioeconomic severity rather than arithmetic equality, producing robust aggregation outputs for comparative LCSA and supporting future SSbD trade-off analysis.

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1.05.P-Tu014 Advancing Nutritional Functional Units In Life Cycle Sustainability Assessment Of Gluten-Free Food Systems

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Gluten-free (GF) foods are essential for managing coeliac disease, yet their sustainability performance remains difficult to interpret due to methodological inconsistencies in life cycle-based assessments. This study evaluates key methodological limitations constraining Life Cycle Sustainability Assessment (LCSA) of GF food systems, with a particular focus on the integration of nutrition into functional unit definitions.

A protocol-driven systematic literature review identified 14,723 records published between 2009 and March 2025, of which 553 were assessed for eligibility, and six (6) studies met the inclusion criteria. Moving beyond descriptive synthesis, the analysis systematically classifies methodological gaps across four domains: functional unit specification, system boundary definition, integration of sustainability pillars, and transparency in impact assessment and uncertainty reporting.

The results indicate a dominant reliance on mass-based functional units, limiting the ability to assess GF products based on their intended nutritional function. Nutrition-linked approaches are applied inconsistently, restricting cross-study comparability. Most assessments adopt partial system boundaries, while economic and social dimensions remain insufficiently operationalised within LCSA frameworks. Trade-offs across environmental impact categories are occasionally explored through scenario analysis but are rarely evaluated within a harmonised multi-dimensional framework.

Based on these findings, a conceptual integration pathway is proposed for incorporating nutrition-sensitive functional units into LCSA of GF food systems. The framework defines criteria for selecting functional units, strategies for aligning environmental, economic, and social indicators, and minimum reporting requirements to improve transparency and comparability.

The results demonstrate that current sustainability claims for GF food systems rely on a limited and fragmented evidence base. Advancing robust LCSA requires a shift towards functionally meaningful, nutrition-sensitive assessment frameworks to enable more consistent evaluation and support informed decision-making in specialised food systems.

Keywords
Life cycle sustainability assessment; gluten-free foods; nutritional functional unit; systematic literature review; methodological gaps; life cycle assessment; food systems

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1.06 - Towards Accurate Grid Electricity Modelling in LCA

1.06.T01 Integrating Prospective and Regionalized LCA Indicators in Energy System Models

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Accurate environmental assessment of electricity systems requires going beyond static, global-average life-cycle inventory (LCI) data. Energy System Models (ESMs) are inherently prospective and geographically explicit tools, yet their coupling with LCA has rarely leveraged the full potential of prospective and regionalized LCI databases simultaneously. This presentation demonstrates how mescal, an open-source Python package built on Brightway, enables the endogenous integration of prospective and regionalized LCA indicators into optimization-based ESMs. The workflow combines three open-source tools from the Brightway framework: premise to generate prospective

versions of ecoinvent aligned with IAM scenarios, regioinvent to spatialize elementary flows and regionalize the database with trade-based national market data, and mescal to perform double-counting removal, parameter harmonization, and LCIA score computation for direct integration into the ESM. LCIA scores are computed using the regionalized IMPACT World+ method, enabling location-specific characterization of particulate matter formation, water availability, land use, among others.
We apply this framework to the energy system of Québec, Canada. The optimization targets a net-zero and burden-shifting-free economy by 2050: territorial GHG emissions of the energy system are constrained to net-negative levels (compensating for residual emissions from agriculture and landfilling), abroad GHG emissions are capped at current levels to prevent carbon leakage, and remaining damages to human health and ecosystem quality — excluding climate change — are kept within their current bounds to prevent burden shifting to other impact categories.
We systematically assess the influence of five levels of regionalization — from a default non-spatialized database to fully spatialized and regionalized inventories — on both the environmental assessment of the current energy system and on the optimization outcomes for 2050. Results show that regionalization has a negligible effect on the carbon footprint but substantially affects human health damage, primarily through particulate matter formation.
This framework is model-agnostic and extensible. Its connection to planetary boundary-based LCIA methods opens the door to absolute sustainability assessments, where ESM optimization constraints could be directly grounded in Earth system boundaries — an emerging frontier for energy planning under environmental limits.

1.06.T02 FIONA: Hourly-resolved electricity mixes for prospective life cycle inventories

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Increasing reliance on renewable power share in the grid, leads to more variability in final energy consumption mixes. Yet, from a life cycle assessment (LCA) perspective, available data most often only reflects annual averages from previous years.

We developed the software package SHRECC (Simple Hourly Resolution Electricity Consumption Calculation) to couple hourly, near-live, data on electricity generation in European countries with the ecoinvent database.

In its retrospective application, SHRECC uses background data from the energy-charts.info API, itself sourcing live data from the European network of transmission system operators for electricity (ENTSO-E)'s Transparency platform. Some extra information is required as not all countries report to ENTSO-E with the same quality standard (e.g. Netherlands). The SHRECC flow tracing algorithm, conceptually identical to solving the Leontief inverse in conventional LCA, calculates the consumption mixes (including re-exports across nodes) for each ENTSO-E location, either country or bidding zone. The resulting time series can be filtered, resulting in mixes specific to a given consumption profile. Case studies on electric mobility and electrolytic hydrogen production show that specifying the time of use influence strongly the environmental footprint of electricity-using system, at different scales (hourly, daily, monthly, seasonally). With these results we show how the environmental impacts of renewable-rich and import-dependent grids are especially affected by such variability.

In a next step, we have leveraged the core components of SHRECC to produce prospective life cycle inventories. Through FIONA (Future Integration Of National Assumptions), we integrate ENTSO-E's Ten-Year Network Development Plan (TYNDP) into SHRECC for 1 kWh consumption of electricity mix, as well as energy consumption profiles across European countries under three scenarios. Linking these inventories to the same systems shows an even broader variability of environmental impacts.

We conclude that using FIONA to produce hourly mixes in prospective LCA increases the accuracy of life cycle impact assessment results, and that such an approach should be systematized within the LCA field. Our tools have been

developed as open source and user-friendly software packages, using only open datasets, which can unlock the possibility of standardizing hourly-resolved LCA, even in prospective approaches.

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1.06.T03 Influence of Imports, Storage, and Curtailment on Environmental Impacts of Prospective French Electricity Mix with High Renewable Penetration

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A growing number of future low-carbon scenarios rely on electricity mixes with high shares of variable renewables (photovoltaic and wind). Their intermittency implies an increase in transboundary trade, grid-scale storage, and electricity curtailment to ensure supply-demand equilibrium. However, the environmental impacts of such mechanisms are complex to model and yet to be fully characterized. In this work, prospective Life Cycle Assessment (pLCA) is used to evaluate how imports, storage and curtailment influence the environmental impacts of France's 2050 electricity mix under high-renewable penetration conditions.

Prospective Life Cycle Inventories for French low-carbon electricity scenarios were modelled, including electricity generation, imports, grid-scale storage and curtailment. The scenarios, provided by France's Transmission System Operator, cover mainland France in 2050. They are integrated into pLCA ecoinvent database using the Python library Premise. A contribution analysis is conducted to evaluate differential environmental impacts caused by imports, storage, and curtailment with respect to the impacts of the production mix. This analysis covers eight midpoint indicators, including Global Warming Potential (GWP), acidification, and metals & minerals resources use, as provided through the Environmental Footprint v3.1 method.

An increase in the share of renewables leads to higher contributions to impacts from imports, storage, and curtailed production. For the scenario with the highest rates of photovoltaics and wind (88%), grid-scale storage losses and infrastructure contribute to a non-negligible increase in GWP (+10%), acidification (+25%), and metals and materials resources (+5%) impacts. Additional impacts due to curtailment remain below 3%. Depending on the indicator, imports can contribute to increase or decrease impacts with respect to the production mix. These differences are highly variable due to uncertainties in the import mix.

This case study demonstrates the importance of considering imports and storage when modelling the LCA of electricity mixes with a high share of variable renewables. Key modeling choices, including import accounting rules and storage efficiency, were identified as crucial factors influencing LCA results. These findings also provide insights into assessing the impacts of photovoltaics and wind electricity from a consumer perspective.

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1.06.T04 Greenhouse Gas Emissions of Pumped Storage Hydropower Are Misleading Without Temporal Variations: A Comparison of Static and Temporal-Explicit Life Cycle Assessment of the Le Cheylas Plant

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Pumped storage hydropower (PSH) plays an essential role in decarbonizing electricity systems with rapidly increasing shares and high integration of variable renewable energy. However, its operational greenhouse gas (GHG) intensity, a

major environmental hotspot in PSH systems, depends on the electricity supplied for pumping modes and reservoir-related emissions, which both vary over time. Conventional static life cycle assessment (LCA) approaches fail to represent both the magnitude and timing of emissions for long-lived PSH systems. We develop and apply a temporal-explicit LCA approach to quantify the operational GHG emissions of the Le Cheylas PSH plant in France over its 100-year lifetime (1979–2078) under various scenarios. To achieve this, we integrate retrospective and prospective electricity mixes, scenario-based life cycle inventories generated using premise, the REMIND-EU integrated assessment model, and time-dependent reservoir emissions derived from the G-res tool. Our study demonstrates that GHG emissions estimated using the static approach are substantially higher than those estimated using temporal-explicit approaches, by 31% (static scenario 2017), 38% (static scenario 1998), and 84% (static scenario 1979). These discrepancies arise because the temporal-explicit approach can capture a pronounced early-life emission peak driven by fossil-dominated electricity supply and reservoir emissions, followed by a decline as the grid decarbonizes. Sensitivity analysis further shows that under the static approach, a ±20% change in round-trip efficiency factor can lead to ±95% variation in total GHG emissions whereas changes remain within ±7% under the temporal-explicit approach. Overall, the results highlight the importance of accounting for temporal variations in LCAs of PSH systems in providing more accurate and policy-relevant estimates of PSH operational GHG emissions.

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1.06.T05 Temperature-Driven Electricity Dispatch Model Update to Generate Building-Relevant Electricity Mixes for Life Cycle Assessment

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Electricity plays a major role in life cycle assessment (LCA) of the built environment as buildings increasingly produce and consume electricity. In addition, buildings' electricity demand and electricity generation depend on meteorological variables such as temperature, making temporally and climate-sensitive modelling essential to represent electricity supply and its environmental impacts.

However, many LCA studies still rely on static or annual-average electricity mixes that ignore short-term variability in generation. Existing electricity system models are generally not tailored to building applications and rarely account explicitly for temperature-dependent dynamics. Furthermore, rapidly evolving electricity systems require continuous model updates to reflect current operations.

This study presents an update of an economic optimisation-based electricity dispatch model used to simulate hourly electricity generation for the French power system. The model integrates meteorological drivers, including temperature, and represents both dispatchable and non-dispatchable technologies. Key sub-models, including electricity demand, renewable generation and cross-border exchanges, are revised based on statistical analysis, literature review and recent operational data.

Model performance is evaluated against observed electricity generation in 2022, a year characterised by exceptional conditions in which France became a net electricity importer. Cross-border exchanges are identified as the main source of error. The improved model shows a good representation of temporal, climate-driven dynamics and generation patterns

Following validation, the model derives electricity mixes tailored to building LCA, including temporally resolved attributional mixes (hourly, daily, and annual), marginal mixes from merit-order and model-based simulations, and end-use mixes reflecting building demand patterns. Results show substantial variability: hourly attributional mixes range from 18 to 141 gCO_2eq/kWh with an average of 54 gCO_2eq/kWh, while marginal mixes average 248 gCO_2eq/kWh. This variability highlights the importance of capturing temporal and meteorological dependencies, while the higher impact of marginal mixes demonstrates the need for context-specific electricity modelling in building LCA. The updated temperature-driven dispatch model therefore enables electricity mixes consistent with building energy dynamics and supports more robust building LCA and ecodesign studies.

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1.06.P - Towards Accurate Grid Electricity Modelling in LCA

1.06.P-We012 Representing Future Electricity Systems in Life Cycle Assessment: Insights from a High Renewable Case Study

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Electrification plays a key role in reducing greenhouse gas emissions in the energy sector, with large-scale deployment of renewable energy expected to further accelerate decarbonisation. As the global capacity of wind and solar energy expands, there is an increasing need for comprehensive frameworks to evaluate the environmental impacts of entire electricity systems rather than individual technologies.
Existing studies often focus on specific generation technologies or operational emissions, with limited attention to infrastructure-related impacts in future high-renewable electricity scenarios. This study develops an LCA framework that captures emissions from three key components of electricity systems: operational processes, infrastructure-related construction, and transmission and distribution networks.
The framework is applied to six future electricity scenarios, including a fully renewable electricity system, over the next 3 decades. Results indicate that as electricity systems transition towards higher shares of renewable energy, the contribution of infrastructure-related emissions increases substantially, rising from approximately 8% to 44% of total life cycle emissions across scenarios and time periods. These findings highlight the importance of incorporating infrastructure and network components into prospective electricity system assessments, and demonstrate that early phase-out of fossil fuel generation and decarbonisation of material supply chains are critical to avoid long-term carbon lock-in.
This study uses New Zealand as a case study, characterised by a geographically isolated electricity system and a high share of renewable generation exceeding 88%(2023), with a national target of achieving net zero emissions by 2050. This strong renewable foundation reveals the remaining challenges associated with the final stage of transitioning towards a 100% renewable electricity system. As the transition towards high-renewable electricity systems is a global trend, the proposed framework applies to other countries undergoing similar transitions, even with different renewable resource profiles.

1.06.P-We013 GHG Intensity of Electricity Mixes: Incorporating Photovoltaic Generation at Medium Voltage in Germany

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Life Cycle Assessment (LCA) databases such as ecoinvent, the most widely used life cycle inventory database, do not reflect the rapid expansion of renewable electricity generation. Particularly, photovoltaic generation is currently considered only in low-voltage and excluded from medium-voltage consumption electricity mixes in this database, and greenhouse gas (GHG) intensity values can lag current national systems by several years. Both limit the accuracy and relevance of LCA results for industrial processes. This misrepresentation is particularly relevant as solar installations continue to grow rapidly, widening the gap between database records and actual grid conditions.

This study generates updated German GHG intensities of medium-voltage electricity consumption mixes for 2024, explicitly incorporating photovoltaic contributions. Electricity generation data were sourced from the European Network of Transmission System Operators for Electricity retrieved through Energy-Charts. The background system was modeled using the ecoinvent cut-off system model. Brightway 2, Activity Browser and Wurst were used to map generation categories and integrate photovoltaics at medium voltage, following established ecoinvent electricity market modelling conventions.

For Germany, renewable sources exceeded 50% of total electricity supply mix in 2024. Photovoltaic generation exceeded 60 TWh, representing approximately 13% of the consumption mix. The domestic production mix had a GHG intensity of 422 g CO2-eq/kWh, which decreased by 9% to 385 g CO_2-eq/kWh when imports, predominantly from Denmark, France, and Switzerland, were included. GHG intensity reductions were decomposed into two nearly equal contributing factors: temporal updating of baseline data to 2024, and methodological inclusion of photovoltaic generation at medium voltage. These results demonstrate that excluding photovoltaics from medium-voltage mixes and relying on outdated databases overestimates the GHG intensities for industrial electricity consumers.

As national electricity systems continue to decarbonize at varying rates across Europe, annual updates of this kind of data would allow LCA practitioners to capture emissions differences across countries and over time. This approach provides a replicable framework for keeping LCA electricity data current in rapidly evolving electricity systems.

1.06.P-We014 A Case for European Average and Residual Electricity Data

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European governments historically ensured a supply of electricity to their citizens. Hence, electricity was a national matter. Consistently, the use of national average data was a natural choice in the early days of LCA. However, as the European electricity grid, electricity markets, and electricity suppliers grow more international, the practice of using national electricity data becomes anachronistic. The purpose of this presentation is to lay out four interrelated arguments for the use of European data and to invite a debate on the issue.

1. National electricity data exaggerates the importance of national boundaries. When electricity flows freely between two countries, it does not matter much on what side of the border the electricity is used. In this sense, European data is less inaccurate. Even more accurate data would account for transmission losses and bottlenecks in the grid; however, this requires complex modelling. Transmission losses occur not just at national borders but also within countries. Bottlenecks can also occur within countries and furthermore vary from day to day.

2. With location-based electricity modelling, average electricity data for countries such as Norway, Sweden, and France falsely indicates that it is not important for the climate to use electricity efficiently. But it is important when we can export the excess electricity that we produce. European average data, in contrast, assigns reasonable environmental significance to electricity use and electricity efficiency.

3. The use of average data gives an exaggerated incentive to move electricity-consuming processes to Norway, Sweden, or France. This can cause additional environmental impacts from construction processes, the production of machinery, and from transport of goods. The use of European data gives no such incentives.

4. In market-based electricity modelling, national residual data contributes to distancing market-based electricity modelling from the physical reality. Norwegian power producers export Guarantees of Origin (GoOs) for most of the renewable energy that dominates the national production mix. With Norwegian residual data, the fossil-based electricity assigned to Norwegian customers is many times larger than the quantity of fossil-based electricity that exists in Norway. If we expand the system boundary to Europe, this problem will not occur unless significant share of the GoOs are exported outside Europe.

1.06.P-We015 Scaling Prospective Life Cycle Assessment for Global Real Estate Portfolios

Carlos Kelly[1] (1)ASHRAE

Life cycle assessment applied to large real estate portfolios faces a key methodological challenge: representing electricity grid and refrigerant emissions in a way that is geographically specific, temporally relevant, and scalable

across hundreds of assets worldwide. Conventional approaches frequently rely on static, location-averaged grid factors and simplified refrigerant assumptions, limiting the robustness of prospective and consequential assessments used to inform decarbonization decisions.

This study presents a methodological framework for scaling prospective life cycle assessment across a global logistics real estate portfolio of hundreds of assets in the Americas and Europe, with emphasis on electricity grid decarbonization and refrigerant emissions modelling consistent with the principles outlined in proposed ASHRAE/ICC Standard 240P (Quantification of Life Cycle Greenhouse Gas Emissions of Buildings). The framework has been applied across assets spanning multiple regions, regulatory environments, and grid structures.

An internal Life Cycle Assessment–Carbon Accounting platform, the Carbon Lifecycle Emissions Analysis Resource (CLEAR), was developed to integrate asset-level operational energy demand with forward-looking electricity grid representations and detailed refrigerant inventories. Electricity modelling incorporates regionally specific projections that reflect temporal changes in grid carbon intensity and distinguish between average and marginal generation where decision context requires. Refrigerant emissions are quantified using equipment-level data, refrigerant properties, leakage assumptions, and service life considerations, enabling explicit treatment of both operational and fugitive emissions.

Results show that electricity grid representation and refrigerant modelling assumptions materially influence comparative outcomes between decarbonization pathways, particularly for electrification-focused strategies. The proposed framework demonstrates how prospective and consequential life cycle assessment can be operationalized at portfolio scale while preserving methodological transparency and consistency aligned with emerging standards.

Disclaimer/Disclosure: This work was developed in collaboration with a global logistics real estate portfolio. No external research funding was received. The Carbon Lifecycle Emissions Analysis Resource (CLEAR) is an internally developed analytical tool used to support life cycle greenhouse gas assessments in alignment with emerging standards such as proposed ASHRAE/ICC Standard 240P. This work has been partially presented as the Embodied Carbon Benchmark by BranchPattern.

1.07 - Upscaling of Emerging Technologies in Prospective Life Cycle Assessment

1.07.T01 Energy Modelling in Prospective LCA: A Tool for Early-Stage Process Evaluation

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Prospective Life Cycle Assessment (pLCA) is increasingly used to evaluate emerging technologies at early development stages. However, estimating industrial-scale energy and fuel demand from laboratory-scale data remains challenging, especially when process information is limited. Current approaches often rely either on complex spreadsheet-based calculations, which can be difficult to manage, verify, and reproduce, or on advanced process simulation software such as Aspen, which requires detailed process knowledge, extensive input data, and modelling expertise. This creates a methodological gap for early-stage assessments.
This work presents EnerChem Flow Tool, a dedicated tool designed to support energy and fuel estimation for chemical and pharmaceutical processes in pLCA. The tool provides an optimized interface that enables users to calculate the energy demand of key unit operations without relying on extensive Excel tables or full process simulation environments. Positioned between simplified manual calculations and advanced simulators, EnerChem Flow Tool aims to make early-stage energy modelling more accessible, transparent, and reproducible.
EnerChem Flow Tool supports different process operations, including heating, cooling, drying, solvent recovery, and other utility-intensive steps. For these operations, users can compare different technological options, such as electric heating, steam-based heating, thermal oil systems, chilled water, cooling water, refrigeration, and fuel-based utilities.

The tool also allows the selection of different fuels and energy carriers, enabling the estimation of thermal energy, electricity use, and fuel consumption under alternative process configurations and scale-up scenarios.
A key feature is the integration of AI-supported guidance, which assists users in selecting assumptions, checking input consistency, identifying missing data, and interpreting results.
By providing a user-friendly alternative to spreadsheet-heavy workflows and a simpler option than advanced process simulation software, EnerChem Flow Tool supports the construction of more robust industrial-scale life cycle inventories from early-stage data. The tool improves transparency, consistency, and comparability in pLCA studies of emerging chemical and pharmaceutical technologies.

1.07.T02 Evaluating the Effectiveness of Prospective LCAs for Novel Chemical Technologies: Lessons Learned from a Waste-to-Aromatics Case Study

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Prospective Life Cycle Assessment (pLCA) is frequently employed to support green chemistry and guide sustainable upscaling, offering a systematic approach to predicting the environmental performance of emerging chemical technologies across different Technology Readiness Levels (TRLs). However, the effectiveness of these predictive estimations remains insufficiently validated; to date, few studies have retrospectively compared these early-phase results with assessments conducted at higher TRLs as a chemical technology matures. To improve pLCA methodology, a more robust understanding of its predictive effectiveness and reliability is required.

This case study presents a pLCA of Integrated Cascading Catalytic Pyrolysis - a technology currently at TRL 7 in anticipation of commercial deployment. The process converts waste materials such as mixed plastic waste and used cooking oil into Benzene, Toluene, and Xylenes (BTX), a group of high-value aromatic chemicals pivotal to a wide range of end products. This follows a previous study by Zuiderveen et al. (2024, ACS Sustain Chem Eng), which assessed the environmental sustainability of the same technology at TRL 5. The progression from TRL 5 to 7 offers a critical opportunity to understand how design modifications could influence the environmental impacts of the emerging technology during upscaling. Extending the scope beyond a standard LCA case study, we remodelled the TRL 5 system from the previous study to facilitate a rigorous comparison with the current TRL 7 results.

Results demonstrate bidirectional variations in environmental impacts as the technology matures, contrasting with previous retrospective comparisons that suggest a steady decrease in impacts during upscaling. Subsequent analysis of the impact breakdowns highlights a specific development phase characterised by critical design changes and resulting fluctuations in environmental performance. Nevertheless, the findings are believed to complement, rather than contradict, the existing understanding of the role of pLCA across the development trajectory of a novel chemical process.

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1.07.T03 What Happens after Scaling-Up? The Need for the Right Timing in Life Cycle Assessment of Emerging Technologies

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Prospective life cycle assessment (pLCA) has emerged as a key methodology evaluating future environmental performance of emerging technologies. Current pLCAs are often performed from a present or assumed future baseline, without considering the timing of the scaled-up stage (e.g. pilot, demo, first-of-a-kind, or Nth-of-a-kind) as determined by technological readiness level and economic viability. Yet, pLCA should be rooted at the point at which both

conditions are satisfied, ensuring environmental impacts reflect realistic implementation contexts rather than hypothetical scenarios.

Hence, this study proposes a methodological extension to pLCA by integrating with two complementary approaches: dynamic process system engineering to model technology evolution and scale-dependent performance changes and real options analysis to represent investment decisions under realistic market uncertainties and temporal flexibility.

Time as a central dimension of sustainability assessment is introduced. The objective is to move beyond evaluating the performance at the present or random future point in time, by actually assessing when emerging technologies may reach environmental soundness and economically favorable conditions, under realistic development pathways. These elements are linked through a shared temporal representation, enabling the translation of environmental indicators and economic metrics into time-resolved trajectories. The novel time-driven perspective enables the identification of sustainability attainment points, defined as the time at which a technology meets predefined technological, economic, and environmental criteria.

The novel concept contributes to ongoing methodological developments in pLCA by introducing a novel temporal dimension based on the expected scale-up stage, enhances methodological consistency across disciplines, improves the interpretability of results for decision support, and provides a structured basis for evaluating emerging technologies in a way that is consistent with their developmental nature supporting more informed R&D and investment strategies.

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1.07.T04 Generate Specific LCA Data by Generic Simulation Models: Process Heat Supply by Steam

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The supply of process heat by steam is a crucial factor in the process industry. Its generation and provision contribute substantially to the overall environmental impact that are directly attributable to the chemical products. However, in generic life-cycle inventory databases, this heat supply is generally presented in a simplified manner. The ecoinvent datasets for example disregard distribution losses or the multi¬functionality of combined heat and power plants and they are restricted to steam generation by incineration of fossil fuels. This limits the applicability of generic datasets for the assessment of emerging technologies in the chemical industry.
This contribution presents a generic, thermodynamics based model for steam generation and distribution, using the Python packages TESPy and SiModIn. The model overcomes the limitations of static generic datasets by: (1) quantifying potential environmental impacts as a function of site , process , and ambience specific parameters, such as the temperature level of a heat sink; (2) explicitly accounts for distribution losses and the multifunctionality of combined heat and power systems; and (3) incorporates heat pumps as future steam generation technology. The model combines the advantages of generic datasets and process simulation, enabling the provision of site specific or prospective life cycle inventory data with minimal modelling effort. The model supports the determination of energy-optimal design parameters and design configurations for distillation columns - such as the selected internals and the operating pressure - both of which can affect the required heat supply temperature.
The results from current analyses show that neglecting the effects resulting from steam distribution systematically underestimates the environmental impact of steam supply by around 5 to 15%. The results also suggest that, at different temperature levels depending on the associated pressure level, the potential environmental impact is directly influenced by the ratio of the impact of the substituted electricity to the steam generation.
The proposed model enables the quantification of the impact associated with the steam demand of novel processes at a level of detail required to include LCA in the decision-making during conceptual process development of emerging technologies. Its open-source availability enables fast integration into LCA workflows, and reduces the effort for time-consuming data gathering.

1.07.T05 Towards a Harmonised Upscaling Method for Prospective Life Cycle Assessment of Emerging Chemical Production Technologies

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The application of prospective life cycle assessment (pLCA) to emerging chemical production technologies has grown substantially in recent years, driven by the need to optimise performance or compare against mature alternatives prior to commercialisation. Early innovation stages are characterised by a lack of quantitative data to describe production processes within the new product system. Where available, these data do not reflect technological maturity and production at a commercial scale. Hence, translating data from small-scale production to industrially representative conditions through upscaling is a critical step in product pLCA.
Several upscaling frameworks and methods have been proposed, including simplified chemical engineering-based calculations, patent analysis, process simulation, and machine learning-based impact prediction. Simplified calculations are becoming more common in published case studies because of their straightforward nature. However, they are typically restricted to a narrow range of process configurations (e.g. batch operation and limited separation processes) and provide limited capability to systematically address uncertainty.
This work aims to develop a harmonised upscaling method for pLCA of emerging chemical technologies, building on a critical review of existing pLCA modelling approaches and upscaling methods. We utilise engineering principles and recent research to inform the calculation of unit process level energy demand, going beyond the generic energy consumption estimations provided in existing frameworks for some unit operations. The method builds on existing upscaling approaches in pLCA, while extending them by explicitly accounting for process typology, data requirements, and uncertainty in a more structured way. This new approach aims to improve the reliability and consistency of early-stage life cycle inventory estimation for pLCA of novel chemical production technologies when limited data is available at low technology readiness levels. The method will be evaluated through application to one or more case studies.

1.07.P - Upscaling of Emerging Technologies in Prospective Life Cycle Assessment

1.07.P-Mo023 Influence of Upscaling Choices on LCA Outcomes: Insights from Seaweed-based Vegan Foods

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Life Cycle Assessment (LCA) of emerging technologies is often constrained by the lack of industrial-scale data, requiring the use of upscaling approaches to translate pilot-scale inventories to commercial production. The choice of upscaling method can significantly influence environmental impacts, yet systematic comparisons of these approaches remain limited. Seaweed based products remain largely unexplored in this context, which makes it an ideal area for methodological evaluation. This study investigates how different upscaling methods affect LCA outcomes for a vegan tuna made from cultivated seaweed.

Both pilot-scale and upscaled systems were analyzed across three stages: seaweed cultivation, processing, and vegan tuna production. The results were also compared with conventional canned tuna. Upscaling methods were applied selectively, depending on their relevance to each process stage. Methods included expert interview, proxy data from similar commercial technologies, power-law relationships, process simulation, and input–output (IO) analysis. Climate change impacts were assessed and benchmarked against conventional canned tuna.

Preliminary results show that upscaling choice introduces substantial variability, with climate change impacts ranging 5 to 100 times lower compared to pilot. Use of power laws for seaweed cultivation revealed emissions were 100x lower. This reflects efficiency gains at scale, but also remains uncertain due to limited data to generate power curves. Proxy-based results were about 5 times lower than pilot. On the contrary, IO analysis revealed higher emissions than at pilot level as it includes a wider system boundary. Process simulation and expert-based results are pending but are expected to provide more realistic estimates.

Comparison with pilot-scale results reveals that relying solely on them can misrepresent environmental performance. It can either overestimate or underestimate impacts depending on the scaling method and assumptions behind it. While the upscaled systems showed lower climate impacts relative to pilot production, this conclusion is sensitive to the chosen upscaling method.

This study highlights that upscaling is a critical methodological choice in LCA of emerging technologies The findings reveal the need for transparent reporting, use and triangulation of multiple scaling approaches, and presenting results as ranges rather than single values.

1.07.P-Mo024 Assessing the scalability and environmental impacts of photosynthetic and algal bacteria granular sludge systems for decentralized wastewater systems using prospective life cycle assessment

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There is a growing concern about the ecological status and quality of water. Research across the world has identified similar trends and patterns, suggesting a mismanagement of pollutants from agricultural, industrial and domestic wastewater entering the waterways. Rural and peri-urban areas that are not connected to management systems or with rudimentary small-scale or decentralised treatment systems are often overlooked but are a significant source of water pollution. The use of photosynthetic bacteria and algae with aerobic granular sludge in photo-bioreactors is seen as a potential solution for high-pollutant removal in small-scale and decentralized wastewater management systems. However, despite promising lab results, no large-scale engineering solutions currently exist to sustain this microbial community, and there are still unknowns as to how the different design options could perform at a larger scale. More research is needed to better understand the different potential upscaling alternatives and explore what are the overall environmental implications of these alternatives. The field of prospective life cycle assessment has been emerging as a suitable methodology to assess the design options and forecast environmental impacts of infant technologies once scaled up. In this study, we carry out a prospective life cycle assessment of photosynthetic bacteria and algal anaerobic granular sludge in photo bioreactors for decentralized wastewater management. We do this to (i) identify the most suitable design choices for the scale-up and (ii) assess the overall environmental impacts of the full-scale technology.

1.07.P-Mo025 From Sea to Fuel: Prospective LCA and TEA of Green Methanol from an Integrated Floating Offshore System

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Emerging offshore power-to-fuel concepts lack robust environmental and economic assessments under future conditions. This study applies a prospective life cycle assessment (LCA) to evaluate the environmental performance of an integrated floating offshore system for green methanol production for ships. The system combines renewable electricity generation, seawater-based CO_2 extraction, high-pressure electrolysis and methanol synthesis.
The LCA follows ISO 14040/44 and covers the full life cycle, including manufacturing, installation, operation and end-of-life. A reference scenario representing conventional fossil-based methanol production is used for comparative evaluation. Key methodological challenges addressed include data uncertainty, prospective scenario design and assumptions on future energy and material supply chains. In parallel, a techno-economic analysis (TEA) assesses cost structures, economic feasibility and selected risk factors under different technological and regulatory assumptions.
An integrated LCA–TEA framework is applied to explore potential environmental and economic trade-offs of emerging power-to-fuel and floating photovoltaic systems, with a focus on material-related hotspots in marine environments. Qualitative stakeholder perspectives complement the quantitative assessment by supporting interpretation and identifying non-technical factors relevant for future deployment.
The poster presents the prospective assessment framework and first indicative insights, highlighting key assumptions, sensitivities and data gaps, with emphasis on methodological challenges in prospective LCA. This work is in progress – discussion and feedback is highly appreciated.

1.07.P-Mo026 Upscaling Emerging Sodium-Ion Battery Recycling Technologies for Prospective Life Cycle Assessment

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Sodium-ion batteries (SIBs) are increasingly seen as an alternative and complement to the incumbent lithium-ion batteries (LIBs), mainly because of their higher resource availability, increased safety, and use of low-cost raw materials. Worldwide, policies are being implemented to accelerate the development and commercialization of SIBs, both for stationary storage and in electric vehicles. In Europe, increasing production and use of SIBs will, in turn, increase end-of-life flows of SIBs, highlighting the need for development of dedicated end-of-life treatment processes for SIBs. Previous life cycle assessment (LCA) and prospective LCA studies on SIBs have, however, omitted the end-of-life phase or assumed LIB recycling processes as proxies. Conventional LIB recycling is mainly focused on elemental recovery, which will not necessarily be the main driver for SIB recycling. In this study, environmental and resource impacts of recycling SIBs containing two promising cathode materials, one layered oxide (NaNi1/3Fe1/3Mn1/3O2) and one polyanion (Na3V2(PO4)3), are assessed with a grave-to-gate system boundary. Two SIB-specific recycling routes are considered: direct recycling, where the cathode active material is recovered, and hydrometallurgical recycling, where the main valuable elements are recovered (nickel, manganese, and vanadium). Common for both routes is pretreatment, delamination and impurity removal, followed by route-specific recycling steps. The foreground system is modelled based on SIB-specific recycling processes reported in laboratory studies and scaled up using process calculations to represent future large-scale SIB recycling.
Furthermore, the recycling processes are modelled at a future time (~2040) when the recycling processes are assumed to take place at large scale, and background system data is adapted to this time using integrated assessment models. Preliminary results indicate that direct recycling has the potential to reduce environmental and resource impacts compared to hydrometallurgical routes, although pretreatment and delamination processes emerge as hotspots. This study emphasizes that LIB recycling is not directly transferable to SIBs. Overall, this study provides guidance for further research and development efforts into more environmentally sustainable SIB recycling.

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1.07.P-Mo028 Prospective Environmental Assessment of Next-Generation Batteries: A Cradle-to-Gate LCA of Lithium–Sulfur and Lithium–Oxygen Cells

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New battery technologies are being created to enhance the energy density of electric vehicles and lower reliance on conventional lithium-ion battery components. Nevertheless, environmental accounting at early stages of development is often constrained by laboratory-scale data and processes. This research conducts a cradle-to-gate prospective life cycle assessment of three emerging battery cell designs: lithium-sulfur, lithium-oxygen with catalyst and lithium-oxygen with a gel polymer electrolyte.

The study compares laboratory and pessimistic/optimistic industrial scale-up scenarios using two different functional units: 1 kg of battery cell and 1 kWh of rated energy content. Scenario analysis includes variations in electricity required for manufacturing, solvent use, yield, electricity generation, and future specific energy.

Beyond climate change, the assessment focuses on four midpoint categories particularly critical to battery technologies: mineral and metal resource use, human toxicity, eutrophication related indicators and particulate matter formation. These indicators capture potential burden shifting associated with the use of lithium metal, catalyst preparation, electrolyte materials, chemical manufacturing, and industrial scale-up.

Mass-based results indicate that the environmental impacts are mainly dominated by material composition rather than

manufacturing energy. The lithium-sulfur cell shows the highest mineral and metal resource use and freshwater eutrophication among the assessed systems, mainly driven by the lithium metal anode. The catalyst-based lithium-oxygen cell shows the highest impact on human toxicity, particulate matter formation, marine and terrestrial eutrophication, due to catalyst related inputs especially reduced graphene oxide. The gel polymer-based lithium-oxygen cell generally has mid-range impacts and is dominated by the impacts of lithium metal anode, electrolyte related materials such as lithium bis(trifluoromethanesulfonyl)imide lithium salt and dimethyl sulfoxide as solvent.

1.07.P-Mo029 Prospective environmental assessment of aluminium-ion batteries using lab-scale data

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The demand for electrical energy storage is rapidly increasing due to ongoing electrification and the transition to low-carbon energy systems. With rising concerns and requirements regarding the sustainability of battery materials and manufacturing processes, aluminium-ion batteries (AIB) are emerging as a promising alternative to lithium-ion battery (LIB) technologies for applications with highly dynamic load requirements. Their promise is mainly driven by high power density, long cycle life, less critical electrode materials, and broader global sourcing options, although aluminium has a relatively high embodied energy. While AIB may offer lower or comparable environmental impacts than LIB systems, model-based assessments remain scarce and are largely limited to early development stages. To enable a meaningful comparison with LIBs, prospective LCA methods are required to capture both technological and temporal developments, including the scale-up of LCA-relevant data and future background projections. In this study, approximation and extrapolation methods are applied using primary lab-scale data for AIB cell production. Life cycle inventory material and energy flows are scaled up to evaluate current and future environmental impacts and benchmark them against a reference LIB technology for stationary applications (NMC/LTO). To address uncertainty, two future industrial-scale scenarios were evaluated, combining different parameters (e.g., energy consumption, process yield, and carbon intensity of the electricity mix) from pessimistic to optimistic values based on literature data and engineering assumptions. The results highlight the effects of scale-up on the most relevant environmental impact categories, assess the future environmental performance of AIB relative to NMC/LTO cells, and identify environmental hotspots across different scales (e.g., cathode production, energy consumption during cell manufacturing, with relative contribution decreasing from lab to industrial scale). Overall, the findings underline the importance of prospective LCA for integrating sustainability considerations into the design of emerging battery technologies and in guiding engineering strategies to reduce environmental burdens. Finally, the limitations of the applied prospective LCA approach are discussed, and future research needs are identified to improve robustness when benchmarking emerging battery technologies against established ones.

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1.07.P-Mo030 Prospective LCA/LCC Framework of an Upscaled Hydrometallurgical Recycling Process for Automotive Li-Ion Battery Cells

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The rapid deployment of battery electric vehicles is increasing the demand for critical raw materials, making the recycling of end-of-life batteries essential. However, current recovery processes still involve high energy use and substantial chemical consumption. In this context, prospective life-cycle assessment (LCA) and life-cycle costing (LCC) provide valuable tools for evaluating the future environmental and economic implications of emerging recycling technologies, particularly during the early stages of development, by enabling a reasonable estimation of their potential

impacts at industrial scale.
This study proposes a prospective LCA/LCC framework for a pilot-scale hydrometallurgical battery cell recycling process. Its novelty lies in the use of organic acids instead of inorganic reagents to recover valuable metals from spent battery cells. The process includes leaching with ascorbic acid, centrifugation to separate leaching residues, precipitation with oxalic acid, and recovery of Mn, Co, and Ni as oxalate salts through centrifugation and oven drying. The oxalates are then thermally decomposed to metal oxides and dissolved in sulphuric acid to produce sulphates ($NiSO_4$, $MnSO_4$, and $CoSO_4$), which are required for cathode reconstruction as NMC precursors.
The life cycle inventory of the proposed end-of-life process was developed from laboratory data and up-scaled to an industrially relevant configuration using an engineering-based framework. Leaching and precipitation were modeled as heated batch reactors, solid-liquid separations as centrifugation steps, and final product recovery through oven drying. Reagent consumption was scaled according to laboratory ratios, while energy demand was recalculated for the selected industrial scale based on process conditions and separation assumptions, enabling the definition of a prospective industrial inventory for 1 kg of treated black mass. The framework was applied to a case study involving a 42 kWh battery pack used in a battery electric city car operated in Europe.
The results of the LCA and LCC models demonstrate that the proposed recycling process is effective in recovering Mn, Co, and Ni salts using organic acids in the leaching and precipitation stages. Nevertheless, the overall process still has a significant environmental impact in terms of both carbon footprint and cost. These impacts are mainly driven using ascorbic and oxalic acids.

1.07.P-Mo031 A Prospective Life Cycle Assessment of In-Wheel Motors from Small-Scale to Large-Scale Production

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In-wheel motors are a promising technology for electric mobility. They can improve vehicle design flexibility, reduce drivetrain complexity, and support more efficient propulsion systems. However, the environmental performance depends greatly on manufacturing scale, process maturity and material needs. This study presents a cradle-to-grave life cycle assessment (LCA) of an in-wheel motor prototype. It compares an initial small-scale production scenario with a future large-scale production scenario. The goal is to evaluate how scaling up manufacturing may affect the motor's environmental profile and to pinpoint the main factors driving improvement or shifting burdens throughout the life cycle. The assessment analyses the production of the motor in two representative scenarios. The small-scale scenario represents early-stage manufacturing, with lower automation, higher process losses, and less optimized energy and material use. The large-scale scenario represents industrialized production, featuring improved process efficiency, higher equipment use, reduced material waste, and lower manufacturing costs due to learning effects and economies of scale. Primary data from an European manufacturer have been combined with assumptions about process optimization, and projections about energy needs, material yields, and production volumes. The results show how the shift from small-scale to large-scale production can lessen the impacts tied to manufacturing, while also highlighting which components, materials, or processes are still critical from an environmental viewpoint. Moreover, the prospective LCA methodology introduced in this study contributes to the state-of-the-art of sustainability accounting for automotive electric motors. The study offers insights for technology developers, life cycle assessment practitioners, and decision-makers involved in the industrialization of electric vehicle components. By incorporating future scenarios into the assessment, this work aids in making more informed decisions during early technology development and helps identify design and manufacturing strategies to boost the sustainability of in-wheel motor production.

1.07.P-Mo032 Upscaling Emerging Tandem PV Technologies in Prospective Life Cycle Assessment: A Scenario-Based Assessment of Future Environmental Performance

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Solar photovoltaic (PV) technologies are central to the global energy transition, while many next-generation designs remain at low technology readiness levels. Assessing their future performance requires a combination of prospective life cycle assessment (pLCA), energy payback time (EPBT), and energy return on investment (EROI), together with explicit modeling of how these technologies scale from lab to industrial deployment. This study evaluates the upscaling and long-term performance of two emerging tandem PV systems, SITA (Stable Inorganic TAndem), comparing bonding two terminals (B2T) and circuiting two terminals (C2T) configurations across different European climates and future scenarios.

A pLCA was conducted for 2030 and 2050 using scenario data from the REMIND integrated assessment model, implemented through the premise Python library to transform the Ecoinvent 3.9.1 database into a forward-looking background system. To represent the transition from early-stage designs to large-scale production, technology-specific upscaling assumptions were introduced in the foreground system. These include projected improvements in module efficiency, reductions in material intensity, and changes in manufacturing performance, reflecting potential industrial maturation pathways. This approach enables a combined assessment of foreground technology scaling and background system evolution under multiple Shared Socioeconomic Pathway (SSP) scenarios.

The results indicate that SITA C2T has shorter EPBT (0.3–0.6 years vs. 1.7–3.2 years for B2T) and better EROI, especially in regions with high irradiance and long system lifespans. Environmental impacts decrease for both systems by 2050 due to background decarbonization and technological improvements, while C2T maintains lower impacts across categories such as climate change, acidification, and resource depletion. Sensitivity analysis shows that results are influenced by assumptions on efficiency improvements and material use, highlighting the role of upscaling choices in shaping environmental outcomes.

This study demonstrates that integrating explicit upscaling assumptions with scenario-based background transformations improves the representation of emerging technologies in pLCA. It provides insights into how foreground scaling influences environmental results and supports a more robust interpretation of future-oriented assessments.

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1.07.P-Mo033 From Laboratory to Scaled-Up Production: A Life Cycle Assessment of Catalyst Synthesis Under Changing Energy Systems

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Catalytic development is largely confined to the laboratory scale, while the environmental implications accompanying its production and potential process scaling-up remain inadequately addressed. This limitation can lead to incomplete or misleading sustainability assessments when emerging technologies and the transition toward industrial deployment are considered. The objective of this study is to propose a prospective Life Cycle Assessment (LCA) framework to evaluate the environmental implications involved in scaling up catalyst synthesis, using Ni-CeO_2 catalysts as a representative case. Through a cradle-to-gate approach, the production of 1 kg of catalyst was evaluated and compared to a semi-industrial scaled-up scenario. The scale-up model incorporates key process modifications, including improved synthesis yield, solvent recovery, and realistic industrial energy demand, alongside three electricity scenarios reflecting current and future energy systems. Specifically, the electricity mixes encompassed a global average mix, a

business-as-usual pathway, and a fully decarbonized grid according to the International Energy Agency's (IEA) announced policies. According to the results, solvents and electricity dominate the environmental profile. Process optimization during scaling-up appeared to significantly reduce their contribution by up to 70-90% across multiple indicators. Even though decarbonizing the energy mix substantially mitigates the environmental burdens, solvent use remains a persistent hotspot, highlighting the importance of targeted solvent management strategies. Replacing fossil-derived methanol with ethanol and biomethanol was assessed, with ethanol surprisingly leading to deteriorated performance, while biomethanol proved to be the most promising solution for solvent substitution. A sensitivity analysis comparing other regional mixes, namely the European, German, and French mixes, was performed to investigate the influence of carbon intensity in the energy mix on the final environmental profile. Overall, this study emphasizes how process optimization, electricity decarbonization, and solvent management can promote the sustainable scale-up of novel catalytic materials, while also underscoring the critical role of LCA in bridging the gap between innovation and sustainable industrial application.

1.07.P-Mo034 Unlocking the Potential of Chemical Industry Wastewater: Prospective Life Cycle Assessment and Future Opportunities from Anaerobic Digestion

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Sustainable water management of industrial effluents is a fundamental point to reduce environmental stress across productive sectors. Tapping into industrial wastewater's potential through novel approaches could provide solutions for increasing energy efficiency and strengthening circularity initiatives, meanwhile decreasing environmental pressure from industrial activities. In this regard, the integration of anaerobic digestion in industrial wastewater treatment systems poses opportunities for energy recovery, alongside possible valorisation of biomethane as a marketable product or into sustainable chemical transformation pathways. Early-stage testing with prospective Life Cycle Assessment (p-LCA) is a valuable strategy towards overcoming technical challenges, addressing upscaling from preliminary phases and tackling uncertainties related to sustainability performance. The latter not only supports adopting and transitioning towards alternative waste & wastewater treatment technologies but also underscores its future potential within industrial settings.
This research presents a p-LCA case study for an anaerobic digestion approach for chemical industry wastewater, supporting its future deployment. The tailored approach is based on expanded granular sludge bed reactor coupled with different product valorisation pathways. Process engineering equations and tools such as Piccinno and colleagues, supported by SuperPro Designer insights, are used for upscaling laboratory performance data. Environmental modelling is conducted with ecoinvent 3.10 cut-off coupled with Premise in Brightway 2.5, using the EF v3.1 impact assessment method. As a point of comparison, the baseline wastewater treatment is analysed as well, modelled from chemical composition parameters and site-specific conditions using the Doka LCA - LCI calculation tool.
Preliminary results highlight the potential of the anaerobic digestion approach for chemical wastewater effluents, showcasing opportunities for comparable scoring to the baseline model. Advanced improvements at experimental testing and modelling levels could further emphasize the benefits from upscaling these technologies and valorising its key products. In addition, this study underpins the intersection of technology development and sustainability assessment, and its role for supporting decision making in industrial settings and scaling-up processes

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1.07.P-Mo035 Prospective Life Cycle Assessment in Synthetic Active Pharmaceutical Ingredient Production: A Review on Upscaling Frameworks

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Environmental sustainability assessment in early-stage active pharmaceutical ingredient (API) production is important as early identification of potential environmental impacts at larger scale can support better decision making. At early development stage, environmental sustainability assessment typically relies on green chemistry metrics, such as process mass intensity, solvent intensity, water intensity and number of synthetic steps. However, these metrics provide only a limited perspective, focusing primarily on material efficiency while neglecting energy use and environmental impacts occurring at other life cycle stages.

Prospective life cycle assessment (LCA) offers a more holistic approach by estimating environmental impacts of APIs at early development stage across their full life cycle for future larger-scale production. In this approach, the systems are assessed for a more developed stage and at a projected future point in time. As processes are scaled up, material and energy requirements are expected to change. Therefore, assessing reliable methods to estimate material and energy requirements at higher technology readiness level (TRL) is essential.

This work presents a comprehensive review of existing upscaling frameworks focusing on the application in synthetic API production. The study critically examines the upscaling approaches used, unit operations included and assumptions used in the frameworks. The strengths and limitations of existing frameworks are critically assessed in terms of data requirements, transparency, scalability and applicability within pharmaceutical manufacturing context. Key findings from this study will support the development of future prospective LCA studies in pharmaceutical manufacturing and enable more holistic environmental sustainability assessments for early-stage API development.

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1.07.P-Mo036 Prospective Absolute Environmental Sustainability Assessment of Enzymatic Sugar Beet Pulp Treatment

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Modern enzymatic biorefineries present promising potential for global decarbonization, offering value-added products from biological resources. However, their role within a sustainable societal trajectory remains unclear, particularly when evaluated against prospective environmental boundaries. This uncertainty stems from the lack of a robust methodology for allocating future impacts to biorefinery products. To bridge this gap, this study presents an innovative approach to achieve short- and long-term mitigation targets (2030-2050), as specified by a dynamic Safe Operating Space (SOS). Different sharing principles are combined with shared socioeconomic pathways (SSPs) and the learning theory to project the environmental thresholds for pectin and Cellulose Nanofibers (CNFs) produced via enzymatic and chemical routes. The analysis reveals that pectin production via enzymatic treatment exceeds the allocated SOS within the climate change Planetary Boundary by a factor of 238, while the conventional method surpasses it by 423 times. In comparison, CNFs show exceedances of 84 and 103 times for the enzymatic and the conventional routes, respectively. Products' penetration into the market is analyzed within the dynamic framework, capturing their internal progression toward meeting absolute sustainability targets. Pectin produced via enzymatic treatment can meet 2050 targets, with a 15% learning rate and 14.78% market penetration, whereas CNFs require no additional market penetration under the SSP1 and SSP2, remaining below the prospective threshold of 8.3 × 10-5 ppm CO2 per functional unit. In parallel, enzymatic CNFs demonstrate strong scalability and sustainability potential, achieving absolute targets before 2045, even at low learning rates, driven by the rapid market growth and socioeconomic trajectories. For this product, only under the SSP5 trajectory, a penetration rate of 0.5 to 5.9% was achieved for learning rates of 14 to 19%, thereby

meeting the absolute boundary of 2050 for the climate change impact category. Overall, this study introduces an integrated methodology combining process design, prospective LCA, absolute sustainability, and market modeling to guide biorefinery development within the Planetary Boundaries. The proposed framework provides a decision support to sustainability strategists, enabling the integration of innovative processes that promote global decarbonization and prosperity, while respecting the planet's environmental limits.

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1.07.P-Mo037 Upscaling and Learning effects in Prospective LCA of Emerging Lignin-Derived Bisphenols

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Bio-based bisphenols derived from lignocellulosic biomass are emerging as safer and potentially more sustainable alternatives to fossil-based Bisphenol A for flame retardant applications. However, these compounds produced at laboratory scale, which introduces a bias when comparing them against a mature, fossil incumbent produced at full industrial scale. Upscaling lab data to a representative industrial process combined with integration of environmental learning effects is therefore necessary before any robust prospective life cycle assessment (pLCA) can be carried out. This step is not straightforward, since biorefinery processes involve diverse upstream and downstream configurations, and there are still significant data gaps that are not fully addressed by existing scale-up methods for biorefineries.
This study applies the engineering scale-up framework of Piccinno et al., originally developed for a limited set of chemical processes and unit operations, to an emerging biorefinery context, explicitly considering the uncertainty introduced by the underlying assumptions. The work presents an ongoing cradle-to-gate pLCA of bisguaiacol P (BGP), a lignin-derived bisphenol proposed as a substitute for Bisphenol A. The system boundaries include pine wood supply, reductive catalytic fractionation into refined lignin oil, enzymatic and catalytic intermediate synthesis, alkylation, separation, and evaporative crystallization.
A combined explorative and normative framework for development of environmental learning rates is then applied to the foreground system. Historical learning rates from analogous technologies are applied per process step, projecting multiple development trajectories. The normative dimension identifies the technological conditions required for BGP to achieve a sustainable target. Background system evolution is captured separately through prospective inventory databases derived from Integrated Assessment Model scenarios under shared socioeconomic and representative concentration pathways, covering 2026–2050.
This work serves as a case study demonstrating the application of upscaling and learning frameworks to emerging biorefinery processes when assessing the environmental performance of low-TRL systems, and emphasizes the challenges and uncertainties associated with upscaling and pLCA in a biorefinery context

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1.07.P-Mo038 Upscaling Effects In Life Cycle Assessment Studies Of Emerging Technologies For Converting Biowaste Into Platform Chemicals

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The transition towards a circular bioeconomy in urban ecosystems requires converting biowaste, such as the organic fraction of municipal solid waste (OFMSW), food waste, and sewage sludge, into platform chemicals beyond biogas valorization, including volatile fatty acids (VFAs), polyhydroxyalkanoates (PHAs), lactic acid, and succinic acid. However, as these emerging technologies progress from laboratory scale (low Technology Readiness Levels) to industrial scale (mature technology), Life cycle assessment (LCA) reveals critical shifts in their environmental performance across different scales. This study synthesizes findings from 33 LCA case studies to identify the environmental implications of upscaling emerging technologies.

First, upscaling technologies expose a drastic shift in environmental hotspots. While laboratory-scale models primarily target metabolic yields, industrial-scale LCA demonstrates that direct energy and chemical demands overwhelmingly dominate the footprint. Herein, downstream processing for extracting target products becomes the primary driver of environmental burdens. Second, upscaling consistently reveals a sharp trade-off between global and local impacts. Environmental impact categories such as climate change and fossil resource depletion often improve drastically at a commercial scale. This viability heavily relies on multifunctional systems, including system expansion, in which plants achieve net-negative carbon footprints primarily by substituting petrochemical products and diverting waste from conventional disposal methods like landfills. Conversely, the intensive use of chemical reagents (e.g., NaOH, solvents, strong acids) significantly exacerbates local impacts such as terrestrial acidification, eutrophication, and human aquatic toxicity.

The case studies also revealed that most studies do not incorporate the impact of background projections, including energy matrices and the future electricity grid. Since emerging technologies take years to mature, projecting future background systems is essential for aligning with upscaling technology. Thus, optimizing an upscaled facility for a single, high-purity chemical is inefficient. Sustainable upscaling requires a holistic approach that integrates platform chemical recovery with bioenergy to meet internal demands and adapt to future energy matrices.

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1.07.P-Mo039 Which Methodological Choices Matter Most in Prospective Life Cycle Assessment of an Emerging Bio-Based Building Block?

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The transition toward bio-based chemicals is a key pillar of European sustainability policy, yet prospective life cycle assessment (LCA) of early stage bio-based building blocks faces compounding methodological challenges, including uncertain process scale-up, evolving background energy systems, and limited consensus over which modelling choices are truly decision-relevant. At the same time, The European Safe and Sustainable by Design (SSbD) framework further demands robust, early-stage environmental evidence to guide the development of novel chemicals before large-scale deployment, raising the question of what level of analytical rigour is needed and where.

This study asks which methodological choices in prospective life cycle assessment materially affect interpretation of environmental performance for an emerging bio-based building block, and which are often widely discussed but less influential for decision making. Carbohydrate-derived fatty acid building blocks produced from sugar beet-based streams are used as a case study.

To address this, a cradle to gate prospective LCA model is developed across multiple scale-up scenarios spanning pilot to commercial scale by systematically varying foreground parameters including process yield, energy intensity, solvent recovery and other case relevant process assumptions. These are combined with future background scenarios that reflects near to long term deployment conditions. Contribution and sensitivity analysis are used to assess whether these choices change hotspot identification, comparative performance, and the prioritization of improvement options. For each combination, whether qualitative conclusions change relative to the fossil-based counterpart is assessed, distinguishing robust findings from assumption-sensitive ones.

By separating robust from fragile conclusions, this study contributes a practically oriented robustness framework for prospective LCA of emerging bio-based chemicals. Findings are directly relevant to SSbD-oriented development processes, where knowing which environmental claims can be trusted at early technology readiness levels is as important as the claims themselves.

1.07.P-Mo040 Bio-Electrochemical Systems for Ammonium Recovery: Comparative p-LCA of Divergent Designs and Configurations

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Bioelectrochemical Systems (BES) are technologies that exploit the ability of microorganisms to catalyse electrochemical reactions by transferring electrons to or from electrodes as part of their metabolism. One of the most promising applications is nutrient recovery from wastewaters. Two different laboratories (UAB and LEITAT) have compared the use of different BES-based configuration devices. Ammoniacal nitrogen was recovered as ammonium sulphate (AS) from real bio-based industry wastewaters. Both BES aimed at concentrating the inlet N as ammonia in the catholyte chamber (i.e. high concentration at high pH). The main difference between the systems lies in how this ammonia was transferred to the acid recovery solution. The UAB approach was a three-chamber BES transferring ammonia through a hydrophobic membrane, whereas the LEITAT approach was a two-chamber BES, and ammonia was stripped and recovered in a separate membrane unit.

p-LCA was implemented as a useful tool to evaluate the potential environmental performance of the up-scaled version of these technologies under future market conditions. The life cycle inventory (LCI) for the scaled-up scenarios was estimated based on laboratory-scale data, chemical engineering tools and Piccinno equations for those flows affected by the scale-up factor (e.g. pumping). Other metrics, such as process efficiencies, productivities, current density (j) and voltage, were considered decoupled from production capacity and equipment scale. Brightway 2.5 with PREMISE library and Ecoinvent v3.10 was used for modelling and the Environmental Footprint (EF) midpoint impact method v3.1. Both systems showed a very low impact, particularly in the climate change category, ranging from 0.6 to 1.4 kg CO2-eq per Kg N across all BES and operational conditions tested. In comparison, AS from the Haber-Bosch reaction, in prospective 2030-2050 scenarios, has a much higher value of 4.1-4.3 kg CO2-eq per kg of N. Moreover, the contribution of the sulphate as an anion for the formation of the ammonium sulphate was the main contributor to the GWP category, stressing the promising potential in the obtention of a low-carbon N product with BES systems. Other impact categories' results are diverse, and trade-offs appear, highlighting hotspots such as the cathode manufacturing. This study reveals the relevance of prospectivity in the upscaling of novel deep bio-electrochemical technologies, with no evidence from the upscaling.

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1.07.P-Mo041 Reliable Decision Support for the Life Cycle Engineering of Technologies based on the Life Cycle Assessment of Emerging Technologies

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With an increasing focus on sustainability in policy, society and industry, a shift from life cycle assessment as a retrospective tool to life cycle engineering as a part of the development process in industry becomes key. Current technologies are often not sufficient with their efficiency limits to reach absolute targets for sustainability. As a consequence, new technologies need to be developed. To ensure sustainability, the development process of these emerging technologies needs to be driven by life cycle engineering. Hence, the emerging technologies need to be

assessed and compared with the current technologies and with the absolute targets. As emerging technologies are typically still under development and operating at smaller production scales, it becomes challenging to derive robust recommendations from the life cycle engineering. Therefore, various aspects in the life cycle assessment of emerging technologies for the life cycle engineering need special attention. In our work, we propose a framework which guides the LCA practitioner through the four stages of the life cycle assessment with special focus on relevant methodological aspects of emerging technologies to derive robust recommendations for the further development. Starting with the goal and scope definition, the current scale and the expected future scale of the emerging technology need to be identified as well as the reference technology and its scale. In the life cycle inventory, the inventories of the emerging technologies need to be scaled. While scale-up of inventory data is no new topic in life cycle assessment, clear guidance on which scale-up approach is suitable under which circumstances is rare as well as an evaluation of the linked uncertainties. We therefore propose a hierarchy of scaling approaches with a qualitative evaluation of when they are applicable. Based on the chosen scaling approach, we recommend further analysis such as data quality ratings, sensitivity and uncertainty analyses to determine the robustness of the results and derive guidance on how the results can be used.

1.07.P-Mo042 Towards understanding TRL Effect on Environmental Learning: The Role of Background Scenarios

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Environmental learning effect (ELE) describes how the environmental impacts of a product or process change as a technology develops and it is being increasingly adopted in the market. Existing studies analyze this effect by examining the transition from first of a kind (FOAK) to nth of a kind (NOAK) technologies, where impact reductions mainly result from learning by doing. While this approach is valuable, it is most applicable to technologies that have reached high maturity levels (TRL ≥ 9). For emerging technologies at lower TRLs, presenting the current technology state together with a projected FOAK scale supports transparent prospective life cycle assessment. In addition, conducting LCA of multiple TRL stages together with the FOAK stage helps capture environmental learning arising from technology scale up at early stages.
In an earlier work, we analyzed the effect of increasing TRL on environmental impacts by comparing four development stages of the hydrogen plasma smelting reduction (HPSR) process under a single, status quo background scenario. In the present study, we extend this analysis by incorporating future background system scenarios. We connect foreground system models at TRL 5, TRL 6, and TRL 7 to a FOAK stage to describe the full ELE of HPSR. As a result, the learning curve captures contributions from both foreground technological scale up and background system evolution between TRL 5 and TRL 9. Environmental impacts are calculated using the Environmental Footprint (EF) 3.1 impact assessment methodology under different combinations of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The results provide a unified view of environmental learning across technology maturity and future system conditions.

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1.07.P-Mo043 Environmental learning at low TRLs: a typology-based analysis across emerging low-carbon technologies

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Learning effects have been observed for environmental performance, where environmental impacts typically decrease as technologies evolves from first-of-a-kind (FOAK) to nth-of-a-kind (NOAK) deployment. Most of the existing studies evaluates environmental learning curves from the FOAK stage onwards, implicitly assuming that early-stage developments follow similar trajectories.

This leaves a critical gap in prospective life cycle assessment: the evolution of environmental impacts from low technology readiness levels (TRLs) to FOAK remains poorly understood. In particular, early-stage technologies are characterized by rapidly evolving materials and energy requirements, unstable process configurations, and incomplete system integration. As a result, environmental learning at low TRLs is not only uncertain but may fundamentally differ across technologies, suggesting that FOAK-based learning assumptions may not apply to early-stage technologies.

To address this gap, we investigate TRL-driven environmental impact trajectories prior to FOAK, referred to as the TRL effect, and examines how technology-inherent characteristics systematically shape environmental learning behavior during early stage design. We propose a typology-based framework that classifies emerging technologies according to dominant drivers such as energy intensity, material intensity, and system design complexity.

The framework is applied to multiple case studies across emerging low-carbon technologies, chosen to represent different type of technologies. We breakdown the contributions from foreground processes, background energy systems, and material supply chains across increasing TRLs. Beyond climate change impacts we show that environmental learning at low TRLs is multi-dimensional, and may involve burden shifting across impact categories. Different technology types exhibit distinct trade-offs: energy-intensive systems are driven by efficiency improvements, while material- and system-intensive technologies may shift impacts toward resource use, toxicity, or infrastructure-related burdens.

This study provides a new methodological basis for projecting the environmental performance of emerging technologies from their current development stage, advancing prospective LCA beyond FOAK-based approaches and enabling more comprehensive sustainability assessments that account for environment trade-offs.

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1.07.P-Mo044 Critically Comparing Uncertainty Approaches in Life Cycle Assessment of Emerging Technologies

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Prospective Life Cycle Assessment (LCA) evaluates emerging technologies at future points in time, where systems are still under development and subject to substantial change. This introduces significant uncertainty, particularly in the upscaling of laboratory-scale systems to industrial conditions, where both parameter values and technological pathways remain uncertain. While a range of uncertainty and scale-up approaches have been developed, there is no broadly accepted holistic framework.

This study presents a systematic review of 230 peer-reviewed articles examining how uncertainty is addressed in LCA of emerging technologies . The analysis focuses on parameter uncertainty, scenario analysis, sensitivity analysis, and scale-up, which are frequently applied in combination. Scenario analysis and sensitivity analysis are the most commonly used approaches, while parameter uncertainty is addressed less frequently. Scale-up is explicitly considered in 163 studies and is closely linked to both parameter and scenario uncertainty, as it requires assumptions about future performance and alternative technological pathways.

The review compares these approaches with respect to their ability to represent uncertainty and support interpretation of results. Probabilistic methods are widely used but often rely on simplified assumptions and may misrepresent deep uncertainty as quantifiable risk. Scenario analysis enables exploration of alternative futures, including scale-up pathways, but can become unmanageable as the number of scenarios increases and often lacks information on likelihood. Sensitivity analysis, particularly discrete sensitivity analysis, is favoured for its simplicity but may fail to

capture parameter interactions and non-linear effects, which are especially relevant in scaled-up systems. Scale-up approaches vary widely in complexity and are often combined, yet their assumptions are rarely validated and may not reflect real industrial performance.

These findings highlight that scale-up should not be treated as a separate modelling step, but rather as an integral component of uncertainty treatment This calls for approaches that merge parameter uncertainty with scenario and sensitivity analysis, and integrate scale-up for both parameter values and technological pathways.

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1.07.P-Mo045 Climate Change Performance of Biomass-Based Dimethyl Ether and Synthetic Natural Gas Production Using LCA

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The transportation sector accounts for approximately 23–30% of global energy-related CO_2 emissions, producing around 8 billion tons of CO_2 annually. Road transportation is the dominant source, responsible for about 70–75% of total transport emissions. In 2024, nearly 90% of transport energy demand is still met by fossil fuels. Biomass-based fuels are expected to play an important role in future road transportation by supplying renewable liquid fuels compatible with existing internal combustion engine vehicles, reducing dependence on fossil fuels, and lowering CO_2 emissions, particularly in heavy-duty and long-distance transport. Dimethyl ether (DME) and synthetic natural gas (SNG) produced from different biomass feedstocks can be used as substitutes for example for diesel and natural gas respectively. This study aims to evaluate the carbon footprint of combined production of DME and SNG from three different biomass feedstocks, namely olive pomace, wood waste, and refuse-derived fuel (RDF), using a life cycle assessment approach. The production process includes indirect gasification followed by SEDMES and methanation processes. The ratio of the two products can be changed according to the market situation. The system boundary follows a cradle-to-gate approach, where the carbon footprint is calculated up to the production stage of DME and SNG with energy allocation used for calculating carbon footprint and consequential LCA used to assess the system level impacts.

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Track 2: Digitalisation and artificial intelligence in Life Cycle Assessment

2.01 - Accelerating and Safeguarding Automated LCA: Scalability with Transparency, Trust, and Regulatory Alignment

2.01.T01 Automated AI-Assisted LCA Calculation at Scale to Meet Increasing Market Demands

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The increasing demand for Life Cycle Assessments (LCAs) and improved environmental performance of products across the chemical industry, driven by regulatory frameworks such as the EU Corporate Sustainability Reporting Directive and customer requirements, presents a significant challenge for chemical companies like Evonik managing extensive product portfolios. Traditional manual LCA workflows and individual measures to improve product sustainability are resource-intensive and lack scalability, making automation essential for meeting these demands.

We present an automated LCA framework, enabling efficient LCA calculation for thousands of products. This approach stands out because it focuses on full LCAs instead of just calculating carbon footprints as an isolated KPI. It is deeply integrated into core systems of Evonik, and enables environmental impact reductions in the full magnitude of measured environmental impacts.

First, we introduce the framework applied at Evonik. We describe how we solve the challenges of automated LCA calculation such as identifying Life Cycle Inventory (LCI) data for raw materials, consistent mapping of inputs, modeling of interlinked multi-output processes of Evonik, and assigning comprehensive metadata. The framework aligns with established standards such as ISO 14040/44/67, EN 15804 and industry guidelines.

Second, we introduce how AI tools help in processing and analyzing results. We show how the gathered insights can be used to actively steer the CO2 emissions-reduction strategy of a chemical company.

Third, we explain how the framework enables systematic improvement in the environmental performance of individual products and the portfolio based, e.g. on customer requirements in line with the leading industry standards like mass-balance certification schemes. We put special emphasis on what is required to assure an efficient, audit-proof, scalable implementation of dedicated environmental impact reduction measures.

Fourth, we introduce open topics that need to be addressed to accelerate automated high-quality LCAs and industrial decarbonization. This requires progress in the following fields:

- Further harmonization of standards, regulations and interfaces
- Reduced hurdles for small and medium sized enterprises, which have limited expertise and resources in the field of LCA
- Availability of LCI datasets including uncertainties and data quality ratings

2.01.T02 LCA Automation in a Project Orientated Industrial Setting

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Life Cycle Assessment (LCA) is an increasingly important tool for meeting regulatory sustainability requirements and customer expectations. This is particularly true in the chemical industry where reducing environmental impacts, particularly CO_2 emissions, is a competitive advantage.

However, in a project orientated industrial setting, the scalable application of LCA remains challenging. Such organisations typically develop diverse projects in parallel that involve stakeholders from different departments with

distinct perspectives and expertise. This often means that multiple ideas are being explored simultaneously. So, despite the strong demand to conduct LCAs, the traditional LCA approach often struggles to keep up with the pace of ideation and project development.

The typical solutions to this challenge are not ideal. Training large numbers of staff in LCA can be resource intensive and may still fail to provide non experts with sufficient confidence to apply LCA in practice. Alternatively, centralising LCAs in a specialist department can create operational bottlenecks and isolate LCA thinking from everyday project decisions.

We present an alternative approach based on LCA automation through a technology specific model deployed via a tailor made digital application. This Python application uses the openLCA inter process communication to enable users from different departments to explore a complex LCA model, test scenarios, and compare options relevant to their project context without requiring detailed knowledge of LCA theory or software. Methodological choices, datasets, and assumptions remain centrally controlled, ensuring consistency while allowing decentralised use.

The development of this application has been supported by Copilot artificial intelligence, which significantly reduces the technical barrier to LCA automation. This enables an LCA practitioner with limited programming experience to build, adapt, and maintain the application, supporting repeatable and scalable LCA workflows.

LCA automation simplifies staff training by shifting the focus from methodological LCA theory as a specialist topic to more accessible generation, iteration and interpretation of results, integrating LCA in decision making. This approach demonstrates how LCA automation can embed environmental assessment within routine project activities, reduce reliance on specialist resources, and prevent the isolation of LCA as a siloed expertise.

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2.01.T03 Scalable and Trustworthy Automated LCA: Balancing AI Efficiency with Expert Credibility

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Life Cycle Assessment (LCA) is rapidly transitioning from a specialized analytical tool to a cornerstone of regulatory compliance and corporate decision-making, driven by frameworks such as the EU Digital Product Passport. However, traditional manual LCA workflows remain resource-intensive and difficult to scale for organizations manaing large and diverse product portfolios. To tackle this challenge, automation and AI tools are emerging as critical enablers, yet their adoption raises questions about methodological rigor, transparency, and alignment with evolving standards.

Our approach leverages AI and proprietary algorithms as 'co-pilots' to automate repetitive tasks while preserving expert oversight. By connecting seamlessly to existing business systems (ERP, PLM, flatfiles) and standardizing data exchange, we enable organizations to scale LCA across thousands of product references without sacrificing accuracy or depth. Pre-established models allow practitioners to rapidly generate assessments for entire product ranges, while suppliers can refine the model thanks to a dedicated data enrichment system. This way, experts focus their efforts on validation, refinement, and interpretation rather than manual data entry. To safeguard transparency and trust, every AI-assisted analysis is accompanied by a Reliability Index which evaluates data completeness, assumptions and proxies quality. This structured evidence base ensures the automated process remains fully auditable. All hypotheses generated by AI are documented in the LCA model, and flagged for expert review with clear visualizations of data sources and gaps. Automated error detection highlights inconsistencies in data sources, ensuring that practitioners can quickly identify and address potential issues. This human-in-the-loop approach ensures that while automation accelerates the

process, final decisions remain grounded in expert judgment. Combined with framework agility, automated LCAs can meet methodological and regulatory standards without manual adjustments.

While AI significantly reduces the time required for LCA, human oversight remains indispensable, particularly for complex scenarios. Ongoing work focuses on expanding LLM testing across sectors to refine accuracy and explore automated sensitivity analyses. Ultimately, this approach illustrates how automation, transparency, and expert collaboration can scale LCA to meet the demands of modern regulatory and corporate sustainability goals.

Disclaimer/Disclosure: Real-world deployments in sectors like agrochemicals, textile, and retail demonstrate the platform's ability to support portfolio-level eco-design and compliance, for catalogs comprising thousands of references. We aim to present a case study if the customer agrees to.

2.01.T04 From Sparse Descriptions to Structured Inventories: A Tiered LLM Framework for Transparent Automated LCA

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LCA is increasingly needed for value-chain reporting, regulatory compliance, and eco-design. Conventional workflows remain difficult to scale because they require expert judgment in goal-and-scope definition, inventory compilation, background data mapping, and uncertainty interpretation. Recent large language model (LLM)-based tools can accelerate selected tasks but remain fragmented. As a result, their current use in LCA is vulnerable to opaque assumptions, proxy misuse, and unverifiable inventory choices. We propose a tiered, human-in-the-loop agentic workflow for automated LCA that links user-supplied information to model defensibility.
The framework is organized around three levels of information availability. The first level (Screening) provides the minimum comparability core for a rapid indicative estimate: activity or product-system identity, functional unit, broad geography, impact category, and high-level system boundary. The second level (Structured Scope) adds the qualitative inventory structure but no process quantities or emission factors. The third level (Foreground-Enhanced) adds process-specific activity data, material and energy quantities, emission factors, and direct-emission or physical-flow records for hotspot processes, together with explicit missing-input flags. The downstream automated LCA workflow then fills remaining background or proxy components and claculates the impacts.
To test whether tiered information improves automated LCA defensibility, the study integrates two interconnected components: a structured extraction benchmark and an automated, agentic LCA workflow. First, a dataset of published, open-access LCA case studies is leveraged to extract three progressively richer information tiers from full texts and supporting materials. Second, these inputs are processed through an LCA agentic workflow that executes goal-and-scope interpretation, inventory structuring, background process matching, and calculation setup. We further conduct a controlled comparison across the three information tiers to quantify how the level of user-supplied input shapes overall workflow performance. Outputs at each tier are evaluated against the published case studies along impact-score agreement and inventory completeness. Our results provide a transparent foundation to determine when automated LCA suffices for screening, when detailed foreground data is required, and where expert intervention remains indispensable.

2.01.T05 Efficiency and Effectiveness in AI Applications for LCA: Current Trends and Potential Improvements

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Applications of artificial intelligence (AI) in life cycle assessment (LCA) have significantly increased in recent years, both in academia and in industry. As expected in technological developments, many applications present trade-offs

between efficiency and effectiveness, where the former is how fast is a task done and the latter is how robust is the task completion. We aim at assessing whether current applications address the most challenging tasks in LCA and if they do so with an acceptable balance between efficiency and effectiveness.

We perform a literature review of academic and industrial AI-LCA applications. Each application is characterised based on the LCA tasks that it tackles. Then, we analyse what are critical bottlenecks in LCA and whether current AI applications can be helpful.

A review of 148 AI-LCA applications shows that 55% of academic applications predict LCA impacts based on inventory data. Conversely, 82% of industrial applications focus on mapping inventory flows to the most relevant secondary data points to obtain the related LCA impacts. While the former practice may seem more efficient because it bypasses traditional LCA steps, it comes at the expense of effectiveness as it is often impossible to validate predictions. The latter practice shows a narrower focus, which can lead to improvements in both efficiency and effectiveness.

Like traditional LCA, AI-LCA applications are limited by the quality and availability of primary and secondary inventory data. One third of academic AI-LCA applications estimate missing inventory data, albeit often with poor auditability practices. Checking that consistent choices are applied throughout the inventory modelling is another major bottleneck in LCA, yet there is no effort to automate this task. AI applications that are not designed for auditability even worsen this issue.

We assess strengths and weaknesses of current practices, while also showing that more targeted work is needed to automate and ease current bottlenecks in LCA studies. Future work includes a semi-quantitative assessment of efficiency and effectiveness of the reviewed solutions.

2.01.P - Accelerating and Safeguarding Automated LCA: Scalability with Transparency, Trust, and Regulatory Alignment

2.01.P-We016 Extending Knowledge Graph-Based Life Cycle Assessment Toward Interoperable Product System Modelling

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Life cycle assessment (LCA) is increasingly used to support European sustainability initiatives. In practice, however, it remains heavily reliant on specific software tools. Consequently, data structures and calculation methods often cannot be readily reused, which limits transparency, interoperability and the integration of LCA into digital systems such as digital product passports.
This study extends an existing approach in which LCA data and calculations are represented in a system-independent and machine-readable way using knowledge graphs. A knowledge graph functions here as a structured data model that explicitly represents processes, flows and impact indicators, as well as their relationships, thereby enabling consistent data integration and query-based analyses across different data sources and applications.
In previous work, the ORIENTING Life Cycle Sustainability Assessment ontology was evaluated as a basis for this approach. It was instantiated using data from the European Reference Life Cycle Database, including characterisation factors for climate change. To enable quantitative modelling, the ontology was extended to represent numerical values and units. Tabular data are transformed into a graph-based structure, allowing LCA information to be directly queried and aggregated.
The novelty of this work lies in extending the approach to additional sub-domains of the ontology, moving towards the representation of complete product systems. A key challenge is the integration of such systems, as this requires modelling complex dependencies between processes, recursive supply chain links, and the consistent mapping of reference flows and functional units in a machine-readable way. The approach is evaluated using standard LCA tasks,

including the analysis of input and output flows and the calculation of climate change impacts.
The findings demonstrate that knowledge graph–based representations can improve interoperability and transparency of LCA data and support their integration into emerging digital infrastructures, contributing to more scalable and automated sustainability assessments.

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2.01.P-We018 Enhancing Robustness in Life Cycle Assessment: A Comprehensive Uncertainty and Sensitivity Analysis of Composite Manufacturing Processes in Aviation

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The robustness of Life Cycle Assessment (LCA) for emerging technologies depends heavily on the quality of input data and the quantification of uncertainties. Existing LCA studies often generalise the manufacturing of composite parts, neglecting the ecological differences between various production technologies and the inherent uncertainties in process data. This study addresses this gap by conducting a detailed, comparative LCA of five manufacturing processes for a composite aircraft component, focusing on inventory validation, uncertainty quantification and sensitivity analysis.
Based on an upper wing shell, geometrically approximated from a long-range wide-body airplane model using Common Parametric Aircraft Configuration Schema (CPACS), five manufacturing processes are modelled and evaluated. The analysis follows ISO 14040/44 standards, utilising the Brightway Framework and the ecoinvent database. A key focus is on a comprehensive uncertainty and sensitivity analysis, employing Monte Carlo simulations and a variance-based global sensitivity analysis (GSA) with Sobol indices to assess the robustness of the results and identify key influencing parameters. Furthermore, the modelled manufacturing processes are compared to the generic ecoinvent dataset for “vacuum infusion moulding” to assess the representativeness of such generic datasets.
The results reveal that autoclave-based processes exhibit significantly higher environmental impacts across the 16 assessed impact categories of the EF 3.1, primarily due to high energy consumption and nitrogen usage during the curing cycle. Notably, the comparison to the generic “vacuum infusion moulding” dataset shows significant discrepancies, highlighting how generic datasets can mask specific environmental hotspots and increase uncertainty. The GSA confirms that specific input parameters are the dominant contributors to result variance, demonstrating that process-specific primary data is essential for transparent and robust LCA outcomes.
The study concludes that differentiated, process-specific modelling of the manufacturing phase is crucial for accurate LCAs of emerging composite technologies. The identification of environmental hotspots provides a quantitative basis for targeted process optimisation and highlights the need for high-quality, transparent primary data to reduce uncertainties in future assessments. Ultimately, the study provides a methodological foundation for trustworthy an roubust automated LCA.

2.01.P-We019 A systematic procedure for quick life cycle inventories on chemicals

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Background:
A common hurdle in everyday life cycle assessment (LCA) practice is the limited coverage on industrial chemicals by life cycle inventory (LCI) databases. Often this limitation is overcome by practitioners using dubious proxies, chosen from what is available in such databases. Here we present a systematic procedure for LCA practitioners to quickly develop LCIs for chemicals with a cradle-to-gate scope, using the ecoinvent database in the background.

Methods:

The first step is to establish a mass balance; this is achieved by defining a balanced synthesis stoichiometry with one or more synthesis steps, a yield for each step and an account of excess reagents and reaction by-products. Acid and base by-products are assumed to require neutralization, while the resulting salts are linked to disposal. Excess reagents and organic by-products are modelled as pollution in wastewater, using dedicated LCIs developed for this purpose, where the reference flow is 1 kg organic carbon, 1 kg nitrogen, 1 kg water, etc. Whenever a production process obtains additional co-products, a decision is made on whether they are recovered (requiring system expansion/allocation) or disposed of as waste.
Utilities and infrastructure are determined for an 'average' chemical, with specific energy figures for two chemical classes: inorganic and organic chemicals, while amounts are dependent on the number of reaction steps required in the synthesis.
All this information is then linked to appropriate background datasets in ecoinvent. A common situation is that a needed reagent is not covered by the database, requiring in turn the development of an additional LCI for this reagent, using this same procedure.

Results:
This procedure has been tested in a research project where LCIs for 52 chemicals have been developed, including 9 inorganic and 43 organic chemicals. As an example, the cumulative greenhouse-gas emissions per kg chemical, calculated in SimaPro with ecoinvent 3.10, range from 2 to 74 kg CO2e, with mean values of 6 kg CO2e for inorganic chemicals and 17 kg CO2e for organic chemicals.

Conclusions:
The developed procedure has proven useful to develop LCIs for otherwise missing chemicals in databases such as ecoinvent. The effort is relatively low, in the order of 1 hour per chemical. A key aspect in this procedure is the establishment of a balanced stoichiometry, which can benefit from the use of artificial intelligence tools such as ChatGPT or Perplexity, among others.

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2.01.P-We020 From Efficiency to Scale: Practical Lessons and Risks in Automating Life Cycle Assessment for Industrial Applications

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The growing demand for environmental information across entire product portfolios has made the automation of Life Cycle Assessment (LCA) a relevant topic for industry research. While elements of LCA automation have been used in practice at Essity for several years, current challenges extend beyond accelerating individual studies towards enabling the reliable and scalable production of LCAs for decision-making, product development, and customer requests.
This contribution presents practice-based insights into LCA automation based on industrial experience at Essity Hygiene and Health AB, highlighting key challenges, risks, and enabling factors.
Automation efforts typically pursue two complementary objectives: increasing LCA efficiency through improved organization and reuse of data and models, and enabling the mass production of LCAs using standardized, parameterized model templates. Although increasing volumes of operational and supplier data are available, automation exposes critical dependencies on data ownership, structure, and governance. LCA practitioners often do not control enterprise data sources, and changes in data formats, collection processes, or supplier information can undermine automated workflows and result consistency. Close collaboration with data-owning functions and early integration with IT systems therefore emerge as essential prerequisites.
Automation further simplifies user interaction with the model, enabling access for a broader user base while simultaneously increasing the risk of the model being perceived as a black box. While these approaches support wider adoption, they also raise the risk of misinterpretation when users lack insight into model assumptions and limitations. As manual review becomes infeasible at scale, automated verification procedures, plausibility checks, and consistency

analyses are required to maintain result quality.
Finally, the contribution highlights the importance of user training and expectation management when deploying large, parameterized LCA models. Sustained interaction is required to interpret outcomes correctly, and clear communication of intended use and limitations is critical, particularly during early deployment phases. Overall, LCA automation offers substantial benefits industrial value when data governance, transparency, validation, and organizational alignment are treated as core design principles.

2.01.P-We021 Enabling Life Cycle Inventory Development Through Digital Product Passports and FAIR Data Practices in Industrial Contexts

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Digitalization is increasingly recognized as a key enabler for improving data quality, transparency and scalability in life cycle assessment. At the same time, emerging policy initiatives, such as digital product passports (battery passport) are introducing new requirements for how life cycle inventory data are generated, managed and exchanged across complex industrial value chains.
In this work, we address the challenge of translating digitalization concepts into practical approaches for strengthening life cycle inventory development in industrial contexts, with the focus on stationary, grid-scale battery applications. While digital product passports and automated data flows are frequently discussed at a conceptual level, their effective integration into life cycle assessment workflows remains limited by data interoperability issues, fragmented information systems and inconsistent data governance practices.
This work explores how digital product passports, combined with FAIR (Findable, Accessible, Interoperable, Reusable) data principles, can support more robust, efficient and reusable life cycle inventory development. A structured, practice-oriented framework is proposed, focusing on the alignment of product-level data structures, interoperability between information systems and the automation of data collection processes relevant for life cycle assessment.
The approach draws on industry experience in sustainability data management and life cycle assessment in the context of stationary battery systems. The findings highlight methodological choices, organizational considerations and enabling factors, rather than specific tools or commercial solutions. The work demonstrates how digital approaches can improve life cycle inventory completeness, traceability and reusability, while also supporting more dynamic and prospective life cycle assessment applications.
The findings illustrate how digital approaches can improve life cycle inventory completeness, traceability and reusability, while also supporting more dynamic and prospective life cycle assessment applications. This work is relevant for industry, and method developers of digital product passports. By situating the discussion within stationary battery applications while maintaining a transferable perspective, this work contributes to ongoing discussions on automated LCA, data governance and the role of digital infrastructures in advancing transparent and decision-relevant life cycle assessment.

2.01.P-We022 Web-based Platform for Managing and Exchanging Primary Data and Product-system Models for Life Cycle Assessment

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Life Cycle Assessment (LCA) is a well-established methodology for the quantification of environmental impacts. Recently, its application has shifted toward scalability and automation to address the analysis of extensive product and service portfolios within companies. However, this accelerated growth must not compromise the transparency, quality, and reproducibility of primary data and product-system models. This work presents the development of a web-based platform that enables flexible, multi-format primary data inputs for the creation, management, and exchange of product-system models. This architecture facilitates the adaptation of such models into the specific outputs required by international regulations and frameworks that incorporate LCA as a requirement.

The platform's functionality is demonstrated through a case study of the distilled spirits sector in Mexico. In this context, LCA is essential for complying with diverse national and international regulations while simplifying data management across the value chain. Furthermore, the platform allows users to evaluate data quality through indicators such as completeness, reliability, and geographical, technological, and temporal correlations. Consequently, users can discern which regulations or frameworks are supported by the available data and identify existing limitations.

Managing primary data and product-system models through this centralized approach illustrates how the interoperability of information between stakeholders can be simplified. Notably, the platform facilitates selective exchange, sharing only the specific data required by each stakeholder. By enabling structured management, the platform allows for identifying similarities and differences in modeling approaches for similar product-systems, providing a robust basis for informed decision-making. Ultimately, this framework serves to train AI models for automated mapping and impact assessment, ensuring consistency across diverse environmental modeling scenarios.

2.01.P-We023 A Framework for Screening-Level Quantification of Climate Impacts in Agrochemical Industry

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The progressive restriction of degrees of freedom in process design with the increasing level of chemical process development highlights the need to be able to perform environmental sustainability assessments at early development stages as a key prerequisite to climate-conscious decision-making when designing new chemical processes. To tackle this objective, several approaches were formulated over the past two decades to introduce simplifications when performing a life cycle assessment of emerging technologies, such as exclusion, inventory data substitution, and qualitative expert judgement.
Within this context, a high-level framework and an internal web-based tool were designed to support screening-level life cycle assessments of chemical processes in fine chemical industry, leveraging an approach built around reaction mass balances, complemented by modular inventory blocks for energy, waste treatment, and direct emissions based on proxy data stemming partially from open literature and partially from internal data from processes at manufacturing scale. Building on previous research attempting to close the gap between technology experts and sustainability practitioners, the core feature of the newly developed software is the ability to capture life cycle inventories in a form that is familiar to process chemists, significantly lowering the barrier to life cycle assessments and enabling thus direct contributions from process technology experts. The proposed framework allows a streamlined modeling of different process design options, which can then be translated into cradle-to-gate climate impacts with minimal support from sustainability experts. Given the high degree of uncertainty at such early development stages, the tool is able to generate order-of-magnitude estimates thanks to the introduction of simplifications associated with the impact of raw materials, energy, and waste treatment.
Such a modeling solution enabled us to obtain preliminary insights on the climate impact of a wide set of active agrochemical ingredients ranging from simple heterocyclic structures to complex multi-step synthesis routes, enabling hotspot analysis and, ultimately, sustainability-informed chemical process design. Notably, we found that the screening-level results correctly identify the qualitative hotspot pattern observed in more detailed assessments, despite the limitations associated with the use of proxy data.

2.01.P-We024 Improving the Accuracy of Life Cycle Assessment Data Augmentation for Chemical Data Gaps

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Life cycle assessment (LCA) is the standard for quantifying environmental impacts of chemical systems, yet its application to complex fine chemicals is often hindered by significant data gaps in commercial databases. To overcome this, we recently presented the Augmented Life Cycle Assessment (AuLCA) algorithm, which integrates chemical reaction networks with mass-based propagation and first-principles energy estimations to predict the life cycle impacts of missing substances.
While bulk chemicals are well represented in databases, fine chemicals typically involve complex multi-step syntheses,

where solvent use easily exceeds reagent mass by orders of magnitude, contributing to the global warming potential (GWP). Estimating solvent impacts at scale is currently hindered by the high solvent variability and quantity, as well as scarcity of reliable data. Here we refine the gate-to-gate emissions prediction of AuLCA by integrating refined energy estimation, such as solvent recovery energy in separation, and a predictive framework for solvent and yield estimation. Initially, reaction solvent impacts were neglected, due to the data scarcity. Therefore, we trained a random forest model on industrial-grade data to predict solvents for reactions, while PAS 2090 standards inform yield and solvent quantity to enhance the accuracy of the resulting GWP.
Our results indicate that for fine chemicals, involving multi-step syntheses, solvent impacts are the dominant environmental driver. Incorporating these into AuLCA significantly improves the accuracy of the predicted GWP. Moreover, the cumulative process mass intensity (PMI) was found to align with GWP for solvent-heavy systems, providing a useful screening indicator. However, high-impact reagents require more detailed assessment as they are not captured properly by the PMI. A key finding is the high impact of specific solvents like tetrahydrofuran (THF). Despite its relatively high GWP, THF remains a dominant choice in synthesis due to its versatile solvating power.
Our results demonstrate that refining gate-to-gate emissions estimates is critical for enhancing the reliability of impact predictions. Our refinements allow for more transparent benchmarking, enabling the identification of greener synthesis alternatives during early-stage research. Future work will focus on data clustering to pinpoint solvent hotspots and evaluating alternatives to facilitate more sustainable chemical production.

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2.01.P-We025 Beyond Keyword Search: Knowledge Graph–Driven LLM Retrieval for Life Cycle Inventory Data

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Life cycle assessment (LCA) is undergoing rapid digitalization, yet key steps such as identifying appropriate life cycle inventory datasets remain largely manual, time-intensive, and dependent on keyword-based search interfaces. These limitations hinder the accessibility, transparency, and reproducibility of LCA, particularly for complex or non-English search queries.
This study presents GreenGraph, an AI-integrated framework that advances the digitalization of LCA workflows through knowledge-graph-driven semantic retrieval. The approach transforms a large life cycle inventory database into a structured graph linking activities, products, locations, and impact methods, and combines lexical search, semantic embeddings, and large language model–based reranking. By leveraging graph-structured context, the system enables more precise interpretation of user queries and disambiguation of structurally similar datasets, supporting more reliable dataset selection.
The framework is evaluated using an expert-validated benchmark of 200 practitioner-oriented queries across multiple levels of complexity and languages. Compared to a conventional keyword-based interface, the proposed approach significantly improves retrieval performance, with a 125% increase in mean reciprocal rank and a 185% increase in top-ranked correct results. Performance gains are particularly strong for non-English queries, highlighting the potential of AI-driven tools to broaden accessibility. Results further show that integrating graph context into large language model reasoning is critical for improving precision beyond conventional hybrid search.
Beyond performance improvements, this work demonstrates how AI and knowledge graph technologies can underpin the development of intelligent, interactive LCA tools that support data exploration, interpretation, and decision-making. By enabling more intuitive and context-aware access to background data, the approach contributes to the transition from static LCA workflows toward dynamic, digitally integrated systems that enhance the usability and impact of life cycle thinking.

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2.01.P-We026 LLM to streamline LCA: a case study on benefits and challenges for an ex-ante LCA in particle board production

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The rise in environmental issues and sustainability awareness has forced industry to develop more sustainable products, making sustainable alternatives more accessible and affordable. More stringent regulations for manufacturers have also increased in the demand for quantifiable sustainability assessments like Life Cycle Assessments (LCA). However, LCAs, in particular ex-ante LCAs, are associated with major challenges such as data availability, uncertain value chains and time intensity. Digital technologies, in particular artificial intelligence (AI), can help address these challenges. AI can be broadly separated into two types: machine learning (ML) and large language models (LLM). Multiple studies have already proven that ML-models can support LCA in all four phases, whereas the ability of LLMs to support LCA has not yet been proven.
This study develops multiple prompts for LLMs to streamline the LCA work of an innovative, bio-based adhesive currently under development using Few-Shot-Learning (FSL) for prompt engineering. FSL enables models to learn and generalize information based on a very small number of training examples included in the prompt. Eight prompts are engineered including production process description, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), upscaling from laboratory to industrial scale, hotspot identification, sensitivity analysis and interpretation of results. The prompts are tested twice: once without any project specific data and a second time with project data. The validity of the results of the LLM is then verified by technical and LCA experts to explore the use of LLM to transform LCA practice while safeguarding scientific robustness and credibility.
Preliminary results show that without project specific data LLMs only provide initial ideas on potential production processes, but cannot be used for LCI, LCIA or interpretation, as resource use is product dependent, environmental characterization factors are mostly behind paywalls not accessible to AI and interpretation needs valid information from the LCI and LCIA. However, when LCI and characterization factors are provided to the LLM, it can be used for the LCIA as well as the interpretation of results, hotspot identification and sensitivity analysis. The results for upscaling production are based on assumptions made by the LLM in both scenarios and cannot easily be verified but do offer an initial insight into potential efficiency increases.

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2.01.P-We027 Demystifying LCA-Automation: Five Persistent Myths Examined Through Industrial Practice

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Regulatory frameworks including the Product Environmental Footprint (PEF) and Digital Product Passports (DPP), combined with mounting value chain demands for Product Carbon Footprints (PCFs), are compelling chemical companies to generate life cycle assessment (LCA) results at scale. Automation is the only viable path – yet widespread scepticism about its feasibility and validity continues to delay adoption.
This presentation directly confronts five myths that prevent companies from acting:
Myth 1: "Our data is not good enough." Enterprise systems for financial accounting already record the process inflows and outflows that form the basis of life cycle inventory (LCI) modelling. What companies capture for cost accounting and corporate reporting can be systematically reused for LCA, provided the methodological rules of each applicable framework are correctly reflected.
Myth 2: "Automation sacrifices methodological rigour." Manual LCA introduces inconsistent practitioner choices across portfolio-wide assessments. An apparent optimization at the product level can be readily achieved when the

implications for the aggregate portfolio are excluded from the analysis. Automation enforces a holistic approach and uniform modelling rules, improving consistency, reproducibility, and auditability.
Myth 3: "AI can simply generate an LCA from a product description." LCA requires traceable, defensible inventory data – not plausible-sounding estimates. While AI can assist with data mapping, classification, and gap identification, using it to generate inventory data without validation produces confident but unreliable results. Use of primary data, and human-in-the-loop oversight remains essential.
Myth 4: "Scaling LCA requires prohibitive effort." The perceived barrier is largely organisational. Direct integration with existing enterprise systems eliminates redundant data collection and makes portfolio-wide calculation tractable.
Myth 5: "Automated results lack transparency and will not be accepted." Explicit governance structures – covering validation workflows, data quality evaluation, and audit trails – make automated LCA more defensible than inconsistent manual studies.
Each myth is examined through a case study with Afton Chemical, a global specialty lubricant additive and fuel manufacturer, where automated LCA was deployed across the global product portfolio. The evidence consistently shows that the barriers to LCA automation are not technical – they are perceptual.

2.01.P-We028 Digitalising LCA While Strengthening Its Human Dimension: The Role Of The LCA Practitioner In The Age Of AI

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LCA is being rapidly reshaped by artificial intelligence, machine learning, interoperable data systems, and other digital tools. These developments offer major opportunities to improve efficiency, reduce costs, and increase the transparency and scalability of LCA practice.

This perspective argues that the AI age is not only a technical shift, but also an opportunity to rethink the role of the LCA practitioner. If digital tools can take over more repetitive and procedural tasks, practitioner effort can be redirected toward activities that often determine whether an LCA becomes useful and credible in practice: framing the right questions, ensuring data quality and contextual relevance, engaging stakeholders, and interpreting and communicating results in ways that support action.

From this follows a broader question for the field: what kind of future do we want for LCA? One possible direction is a more automated and standardised practice, well suited to routine reporting and procedural compliance. Another is an AI-enabled practice in which automation creates more space for dialogue, co-creation, stakeholder learning, and value-chain improvement. There may not be one correct answer, but this debate is increasingly necessary if we are to safeguard the purpose of LCA and make meaningful use of AI. Further research is also urgently needed to better understand what future LCA practitioner roles will look like, how to determine what is suitable and sufficient stakeholder engagement, and how to follow up on LCAs post competition. It may be time to reconsider the need for a 5th phase of the LCA methodology: one focusing on the human element and supporting the implementation of outcomes.

Digitalisation therefore should be understood not only as a means of automating assessment, but also as a chance to strengthen its human dimensions. In this future, the practitioner becomes less of a manual operator and more of an interface between digital tools, robust evidence, and engaged stakeholders. Paying greater attention to this evolving role can help ensure that AI-enabled LCA delivers not only faster results, but also more legitimate, useful, and transformative outcomes.

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2.01.P-We029 Integrated Web-Based Dashboard Features to Streamline the Creation of Reliable Environmental Sustainability Assessments

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The demand of most companies for reliable life cycle assessments (LCAs) is increasing substantially due to new requirements from frameworks such as the European Corporate Sustainability Reporting Directive. Scalable automation strategies and experts' knowledge are needed to deal with this growing demand. There are challenges in meeting these needs, however, since there is limited discussion of the benefits and limitations of the developed automation strategies, and a mismatch between the number of LCA experts and the level of third-party auditing requirements.
To address these challenges related to methodological rigour, we need to:
1. Integrate reliable bridges between data sources and digital tools
2. Make experts' knowledge computer-understandable
3. Show how these aspects may support more people with limited expertise to create LCAs that align with the requirements of various standards.

We thus propose to present how:
1. A digital ecosystem with application programming interfaces (APIs) can be built to offer integrated, scalable, and reliable access to various LCA data sources and digital tools.
2. A knowledge graph (KG) offers a computer-understandable representation of experts' knowledge on the content of LCA data sources and how they may be consistent with the requirements of various standards.
3. A web-based dashboard, often found in enterprise resource planning (ERP) tools, may offer consistency checks when companies are carrying out LCA studies on their organisations.

Key aspects of these propositions, their potential benefits, and limitations will be described to offer insights into possible future development pathways for scalable digital architectures that can enable consistent use of various foreground and background data sources while respecting diverse regulations and frameworks. Various features will be presented with a working dashboard prototype demonstrating the solution's viability.
Overall, we can conclude that these propositions meet the needs for transparent and trustworthy automation procedures through open-source descriptions of APIs and a KG, while ensuring secure data exchanges. However, the comprehensiveness of the solutions will require more effort to include further data formats and LCA standards in the future. As a follow-up, more work is required to test options for reliably integrating artificial intelligence (AI) solutions into the proposed digital ecosystems; nonetheless, some ideas will be discussed.

2.02 - Advancing LCA of Digitalization, ICT and AI: Methodological Developments and Case Studies

2.02.T01 naKnow: A New Collaborative Knowledge Base on Semiconductors and Electronic Components for Digital LCA

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The environmental performance of digital technologies requires robust and transparent assessment methods. Life Cycle Assessment is widely used, yet its application to the digital sector remains constrained by limited availability of reliable and up-to-date data, especially for semiconductors and key electronic components.
This project addresses the lack of high-quality environmental data, which leads to large uncertainties and limits the identification of effective eco-design strategies across the digital value chain. These limitations affect both industrial decision-making and public policy design.
The objective is to develop an open and expert knowledge base that provides structured environmental modeling data for key electronic components. The project focuses on five component categories: silicon wafers and derived

components, printed circuit boards, displays, optical sensors, and hard disk drives.
The approach combines scientific literature review, cross-analysis of existing models, and laboratory-based physico-chemical analyses. For each component category, the project documents manufacturing processes, value chain structures, and material composition. It also develops representative Life Cycle Inventory datasets, including quantified uncertainty ranges.
Preliminary results indicate that combining literature data with laboratory measurements improves consistency in material composition estimates and supports refinement of environmental models. The project aims to reduce uncertainty in key parameters and impact estimates to below 50% for representative components.
The project also supports the formation of an open community involving researchers, industry, and institutions. An association structure is planned to ensure governance and long-term maintenance of the knowledge base.
The main conclusion is that an open, shared knowledge base can improve data quality and consistency in digital LCA, enabling more reliable eco-design and policy decisions.
The study is relevant for advancing environmental assessment in the digital sector. It provides a structured foundation for improving transparency, supporting eco-design tools, and enabling broader adoption of data-driven sustainability practices.

2.02.T02 Comparing Life Cycle Assessment Approaches for ICT Hardware in Building Automation

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Digital technologies are increasingly adopted in buildings, yet the environmental impacts of the underlying ICT hardware are rarely assessed from a life cycle perspective. Conducting life cycle assessment (LCA) of electronic devices remains methodologically challenging due to complex supply chains, limited availability of supplier-specific data, and the sensitivity of results to modelling assumptions.
This study addresses these challenges by applying and comparing five distinct LCA approaches to a building automation controller device weighing 0.25 kg, with a nominal power of 5 W and a lifetime of 15 years. The approaches include 1) a detailed component-level inventory, 2) material-based inventory using X-ray, 3) subsystems-based inventory using Proxy subsystem datasets, 4) a parameter-based method grounded in a “simplified LCA” framework, 5) material-based inventory using proxy device information. All approaches share a consistent system boundary, covering raw material extraction, manufacturing, transport, use phase (657 kWh electricity), and end-of-life treatment, and are modelled in SimaPro using ecoinvent v3.10.
The results show that estimates of global warming potential vary significantly across approaches, ranging from 34.6 to 62.3 kg CO2 eq over the entire lifecycle, reflecting the influence of modelling assumptions, manufacturing energy allocation, and data source selection. As no single approach is universally superior and each involves trade-offs in terms of data availability, modelling effort, transparency, and uncertainty, it is not possible to decide which is preferable at this point.
These findings contribute to the methodological development of LCA for electronic devices and provide a practical reference for researchers and practitioners assessing ICT hardware used in building digitalization and other applications.

2.02.T03 Investigating the Material Use and Resource Impacts of the Information and Communication Technology and Entertainment and Media Sectors

Anna Furberg[1], Nina Lövehagen[2], Jens Malmodin[2], Ragul Kanna Manoharan[1], Tomiwa Onaleye[1] and Göran Finnveden[1] (1)KTH Royal Institute of Technology, (2)Ericsson AB

The widespread adoption of digital technologies has increased the interest in the environmental sustainability of the Information and Communication Technology (ICT) and Entertainment and Media (E&M) sectors. Knowledge on environmental and resource impacts associated with the material use of these sectors are important to promote sustainable practices. However, so far, studies on the ICT and E&M sectors’ resource impact have been limited. The

aim of this study, which was recently submitted to a scientific journal, is to estimate the material use and related cradle-to-gate resource as well as climate impact of the ICT and E&M sectors in 2020 applying life cycle thinking and life cycle assessment (LCA) methodology. This study combines top-down and bottom-up approaches, building on a previous study for 2015, to provide three different estimates, including (i) the material use of selected materials in the ICT and E&M sectors in 2020, (ii) the cradle-to-gate resource impact related to the material use and (iii) the cradle-to-gate climate impact related to the material use. In total, 30 materials were selected, including metals, rare earth oxides, cardboard, ceramics, glass and plastics. The results from this study show that the ICT and E&M sectors accounted for about 0.5% of the total global selected materials' use in 2020. For certain critical materials, however, such as indium, gallium, and germanium, these sectors accounted for up to 75-86% of the global use of these materials. Thus, the ICT and E&M sectors are clearly influencing the global demand for some specific materials. Depending on the impact assessment method and scenario applied, the resource impacts of the ICT and E&M sectors material use are significant (at 2-9% of the total global resource impact of the selected materials). Their contribution to the total global climate impact of the selected materials, however, is rather limited (at about 1%). These results indicate that the ICT and E&M sectors have a more significant resource impact than what their share of total global material use of the selected materials would suggest and highlight the need for assessments beyond climate impacts. This study is marked by uncertainties and the estimates provided should be considered as coarse rather than precise. Still, the estimates provide valuable insights into the overall scale and impacts of material use within these sectors.

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2.02.T04 Assessing the Environmental Impacts of AI for Sustainability: LCA of an In-House-Built AI-Powered Team Assistant for Renewable Energy, Operations, and Market Intelligence

Lina Plataniti[1], Bram van de Glind[1], Marcin Rutecki[2], Synnove Rubach[2] and Kari-Anne Lyng[1] (1)NORSUS, (2)Becour

The usefulness of custom-made AI assistants to support business operations is widely recognised and such systems are increasingly adopted by companies. This case study concerns an AI assistant developed by an SME operating as a global energy attribute certificates provider. The AI assistant is built in alignment with the company's sustainability values and used as a key support for day-to-day operations. To ensure the responsible use of AI, the company sought to measure the system's energy and resource consumption, assess its overall environmental impacts, and estimate its carbon footprint. However, AI service providers typically disclose little about energy use or underlying infrastructure including data centre location, materials, and water consumption, limiting transparency considerably. To address the lack of energy consumption data, the company developed an energy and emissions calculator as part of a dedicated research project. The calculator collects latency and token count, applying literature-sourced factors for energy consumption and carbon intensity to estimate electricity use and corresponding emissions. Life Cycle Assessment was then applied for a holistic environmental assessment of the AI system, taking energy values and token counts from the calculator as input values. The LCA model includes the main three components of AI systems: data centres, networks, and end-user devices. The calculator proved instrumental in building the lifecycle inventory, as it covers data gaps from providers. The inventory was supplemented with data from literature and provider information on location of data centres. The calculator provides an overview of the number of observations, tokens, energy use, CO2 emissions and costs. Water consumption has been estimated through global Water Usage Effectiveness. The LCA results are indicating the contribution of each component of the AI system to its overall environmental impacts, encompassing both embodied and operational emissions. The preliminary results indicate the significance of data centre infrastructure and energy use in AI systems of this type. The CO2 quantities estimated by the calculator and the LCA model are comparable. This study highlights the challenges posed by limited transparency and lack of information from technology providers, which hinder the application of LCA to AI systems, and presents the actions taken to overcome

them.

2.02.T05 Early-Stage Material and Design Evaluation Aligned with the EU Ecodesign for Sustainable Products Regulation: A Battery Case Study Integrating Environmental, Economic, and Mechanical Performance

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Sustainability is becoming a key design criterion alongside technical performance and cost, reinforced by the EU Ecodesign for Sustainable Products Regulation (ESPR). However, comprehensive environmental assessments are typically conducted late in product development, when design flexibility is limited and changes are costly. Early design decisions—especially material selection and product architecture—largely determine life cycle impacts.
This work presents a method to enable early-stage, integrated evaluation of material and design options by linking technical, environmental, and economic criteria within a unified decision framework. The approach combines simplified Life Cycle Assessment (LCA), engineering-based mechanical modeling, and basic cost estimation to support rapid, data-driven decision-making in the conceptual phase. Sustainability is operationalized through measures like “sustainability costs,” . This concept is one option enabling direct comparison with economic metrics.
To ensure usability for non-experts, the method emphasizes low-effort data input and fast modeling of value chains. Digital tools, including machine learning and large language model–based guidance, support technical users like development engineers in navigating unfamiliar domains and generating consistent assessments without requiring deep LCA expertise.
A battery housing for electric vehicles serves as a case study. A surrogate model abstracts key functional requirements, enabling rapid evaluation of design alternatives. Simplified mechanical load cases are used to estimate structural performance and material demand across different material options. These results feed directly into an LCA to quantify environmental impacts such as global warming potential for material selection.
The results demonstrate that combining mechanical modeling with streamlined LCA enables meaningful differentiation between material choices early in development. The approach improves transparency of trade-offs between environmental impact, cost, and performance, supporting more informed and aligned decisions with European sustainability objectives. It provides a practical pathway to embed life cycle thinking into early product design and contributes to advancing LCA application in industrial decision-making.
The method also enables structured documentation of sustainability-related decisions throughout product development and alignment with emerging digital product passport requirements.

2.02.P - Advancing LCA of Digitalization, ICT and AI: Methodological Developments and Case Studies

2.02.P-We030 Estimating the Global Impact of Artificial Intelligence

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Although the idea of artificial intelligence has been introduced long time ago and we have been able to follow the technical developments it enables, e.g. in medicine, the wide public started interacting with AI on a large scale after the introduction of ChatGPT in November 2022. Since then, the adoption of AI, especially generative AI, has exploded. Usage of AI varies from generation of images and videos for entertainment, establishment of businesses based on AI-generated media, throughout everyday assistance in summarising one’s emails, suggesting corrections in reports, sorting applicants in the hiring process, and even utilisation of AI workforce.

Despite this exponential growth, how the AI impacts the environment is not well known. First life cycle assessment (LCA) studies have emerged in the past year, although understandably with their limitations. For instance, Association Green IT (2025) has estimated the global impact of AI across the 16 impact categories of Environmental Footprint methodology, but identifies potential for improvement, especially when it comes to modelling more types of AI servers

(on top of the Nvidia H100SXM Tensor core graphics processing unit (GPU)), more detailed location of data centres hosting AI servers, specific electricity mix based on AI data centres around the world, inclusion of third-party networks and users, as well as calculating additional indicators.

Similarly, Falk et al. (2025) have calculated cradle-to-grave impacts of manufacturing and training GPUs in two locations (France and USA), focusing on training of two models. Hubblo has recently published a calculator and background data for computing the environmental impact of seven GPUs.

Thus, building on this recently published research, this LCA study aims to calculate the global impact of AI with an improved resolution, considering different hardware used, more accurate location of data centres based on Lehdonvirta et al. (2024), and specific electricity mix based on this location. This will also allow for conducting sensitivity analyses in terms of GPU chosen and the hosting location – currently, only 32 countries host AI data centres, but how would the impact look if they were spread out similarly to regular data centres?

2.02.P-We031 Implementing Catena-X Dataspace Principles for Interoperable PCF Exchange in Semiconductor Supply Chains

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Semiconductor manufacturing involves complex and globally distributed supply chains with significant upstream emissions from materials, equipment, and infrastructure. Generating consistent product carbon footprint (PCF) information across these supply chains remains challenging due to fragmented data structures and limited interoperability between supply chain actors.

This contribution presents a framework for structured PCF data exchange in semiconductor supply chains, developed in the context of Semiconductor-X, a Manufacturing-X initiative. The approach enables harmonised PCF assessment and data exchange across semiconductor manufacturing processes while preserving company-level data sovereignty.

At the core of the approach is a semantic environmental data model embedded in digital twins using the Asset Administration Shell (AAS). Environmental information remains stored locally at participating companies but can be exchanged in a structured way via Catena-X-compliant dataspace mechanisms.

The approach builds on Catena-X technical standards and the Catena-X Rulebook. It implements the One-Up-One-Down principle, enabling sequential exchange of PCF information between upstream and downstream actors through standardised request–response mechanisms. This allows environmental data to be linked across both vertical and horizontal stages of the semiconductor value chain, including front-end fabrication as well as back-end assembly and test processes.

The methodology aligns with the Partnership for Carbon Transparency (PACT) and Together for Sustainability (TfS) guidelines, supporting harmonised PCF practices across supply chains and strengthening interoperability across industries.

The framework is demonstrated on representative semiconductor manufacturing process chains, showing how sequential PCF aggregation across supply chain stages can be operationalised within a dataspace setup. The presentation reports the final methodological framework and discusses its potential to enable interoperable PCF calculations and improved Scope 3 transparency in semiconductor manufacturing systems.

2.02.P-We032 From cradle to algorithm: a review of AI and Machine Learning integration in LCA towards

circular economy transition.

Marco Frey[1] and Monia Niero[1] (1)Sant'Anna School of Advanced Studies

Life Cycle Assessment (LCA) is the standard methodology for evaluating the environmental impacts of Circular Economy (CE) strategies. However, LCA studies face some challenges: the scarcity of primary data, high implementation costs, and their predominantly retrospective nature limit effectiveness in the complex and dynamic contexts of the circular economy.

Machine learning (ML) and artificial intelligence (AI) offer promising solutions to these problems. The aim of this review is ito nvestigate how the integration of AI and ML into LCA can improve the implementation and effectiveness within CE strategies.

The methodology follows the PRISMA guidelines. Searches were conducted using Scopus and Web of Science, combining keywords across three domains: LCA, digital technologies (AI-ML) and CE. Following screening and eligibility evaluation based on predefined inclusion criteria, 21 peer-reviewed articles were selected.

The results show that AI and ML interact with LCA in different ways, with different implications for CE. In some studies, ML improves the Life Cycle Inventory phase by estimating primary data, enabling more accurate assessment of complex circular systems and reducing dependence on generic databases. In others, predictive models trained on LCA output allow rapid ex ante impact estimation, making LCA compatible with early-stage circular product development, where design choices on material selection and product configuration determine circularity outcomes. A further configuration uses LCA results as input to ML-driven optimisation creating frameworks that simultaneously balance technical performance and environmental impacts. This promotes the implementation of CE strategies such as resource narrowing, closed-loop material recovery, and carbon emissions reduction. Finally, dynamic ML models fed with real-time data enable continuous LCA updates, supporting service models and the management of circular systems.

Critical challenges remain: the black-box nature of AI, the absence of standardised protocols, and limited validation in a real industrial context. Future research should prioritise transparency in AI-LCA models, develop shared methodological frameworks, and extend these approaches to complex circular business models. The integration of AI and ML in LCA can transform LCA from a static verification tool into a complete decision-support infrastructure for the transition towards CE.

2.03 - Innovative LCA Visualisation Approaches and Advances in AI-Integrated Digitalisation

2.03.T01 Digital Tool for Preliminary Life Cycle Assessment: Supporting Non-Experts to Visualise Methodological Choices for Reliable Studies

Francesco Barilli[1] and Didier Beloin-Saint-Pierre[1] (1)Swiss Federal Laboratories for Materials Science and Technology (EMPA)

Background
Early Life Cycle Assessment (LCA) is increasingly important in research as it helps assess the environmental impacts of novel materials, technologies, and systems before major design and investment decisions are made.

Challenge
Preliminary LCA remains difficult at early stages, especially when systems are not yet fully defined. Key information is held by domain experts, while consistent and comparable study framing requires LCA methodological expertise. Limited expert support restricts access to early studies and creates a barrier to reliable decision support during early project design.

Addressing the Challenge
We propose a web-based tool that translates standards-based LCA requirements into guided support for early-stage studies. The tool provides a visual interface that researchers, with limited expertise in LCA, can use to enter system-specific descriptions (e.g., functional unit).

Approaches and Results
The tool helps address three aspects that require expert knowledge when conducting early LCA: the selection of the most appropriate standard, the system modelling choices, and the disclosure requirements. The tool is grounded in ISO 14040/44 and the ILCD Handbook, combining the global ISO LCA basis with ILCD's more prescriptive European guidance. The considered methodological elements are translated into machine-readable reporting elements within a knowledge graph (i.e., ontology). They include: intended application, functional unit, system boundary, system modelling choice, impact categories, and reporting format. These elements are implemented in a "dynamic" questionnaire that automatically adapts the question paths based on provided answers, explains concepts, and blocks inconsistent combinations. The tool thus brings clarity and consistency to methodological choices through a user accessible visual interface.

Conclusions and Relevance
The proposed digital questionnaire improves consistency, traceability, and comparability of early-stage LCA setups. It supports more comparable studies by guiding researchers through methodological choices that typically require LCA expertise and by structuring outputs for later review and reuse. This establishes a basis for connecting the questionnaire output with other digital tools and for future automated report generation across different standards and reporting contexts. The approach is relevant for sectors such as construction, where region- and standard-specific LCA requirements are important.

2.03.T02 Advanced LCA Visualisation with Real-World IoT Data for Circular Supply Chains

Friedrich Halstenberg[1] (1)GreenDelta

Digitalisation is reshaping Life Cycle Assessment (LCA) by enabling real time data integration and intuitive visualisation that make complex environmental information accessible to a broader audience. This contribution presents how a dynamic, web based LCA visualisation platform is applied within the DigiEcoTrays project to assess reusable plant trays using real field data collected through RFID technology. By capturing tray movements and use phase behaviour directly from the logistics chain, the project generates high resolution operational data that can be fed seamlessly into any openLCA model and visualised through an interactive, user friendly interface.
A key strength of the platform is its ability to make LCA insights understandable for consultants, operational stakeholders, and non LCA practitioners. Instead of navigating complex modelling environments, users explore environmental performance through advanced visualisation modules, including sunburst diagrams for system structure, contribution trees for hotspot identification, and Sankey diagrams for flow analysis. Most prominently, the geospatial mapping feature visualises RFID tracked logistics routes and regional impact patterns, enabling users to interpret transport related environmental burdens in a spatially explicit and intuitive way.
The platform's modular architecture supports any product system and can be connected to diverse data sources, making it suitable for real time applications, digital product passport integration, and AI enhanced analytics such as automated data quality checks or predictive modelling.
By demonstrating how real world IoT data and interactive visualisation can make LCA more transparent, accessible, and operationally relevant, this contribution aligns with the session's focus on innovative digitalisation and AI supported LCA practices. The reusable plant tray case illustrates how dynamic data and intuitive visual tools can strengthen circular business models and improve decision making across supply chains

2.03.T03 Towards Semantic Search and Other AI Application for LCA Using Text Embeddings and Vector

Storage

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1. Introduction

Life cycle assessment (LCA) databases comprise large collections of process descriptions and exchanges. This work proposes the use of dense text embeddings to enable semantic retrieval of LCA process data within a standard database environment. Process metadata (e.g., name, reference product, location, and classification) are transformed into structured textual representations and encoded into embeddings. The resulting embeddings are intended to be stored in a PostgreSQL database extended with vector support (pgvector), enabling similarity search through nearest-neighbour queries based on cosine distance.

2. Materials and Methods

A reproducible pipeline is designed to integrate embedding generation, storage, and querying. The study explores how different text representations of LCA processes influence embedding quality and retrieval behaviour and will compare semantic search results with conventional keyword-based approaches using illustrative examples.

3. Results and Discussion

The current results show that by using a simple text embedding model, it is possible to retrieve relevant activities from an EcoInvent database. Next steps are: 1) Finetuning of the text representations, 2) Using different embeddings models, 3) Finetuning of the database querying method for better search results, and 4) implement it into an end-to-end AI assisted workflow.

4. Conclusions

The study demonstrates the feasibility and relevance of semantic methods for enhancing the usability of LCA databases. Beyond improving data discoverability, this work serves as an initial step towards more advanced artificial intelligence applications in LCA, including retrieval-augmented generation (RAG), AI-supported LCI generation and AI assistants.

For example, a user prompt such as “add 5000 kilograms of steel” can be translated into a workflow where a corresponding steel-producing activity is retrieved and linked to a selected process with the specified amount. The main contribution lies in accurately retrieving the relevant activity, which can feed downstream steps that convert user prompts into actions within an LCA application.

2.03.T04 A Coupled Digital Twin and LCA Framework Applied to Microalgal Biorefineries

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Conventional LCA approaches are typically static and resource-intensive, which restricts their applicability to dynamic systems. In such systems, changing operating conditions require models that are both flexible and highly automated. In parallel, industry is increasingly adopting digitalization through real-time data acquisition, automation, and the use of digital twin, a virtual counterparts of physical systems. Embedding LCA within these digital frameworks makes it possible to perform dynamic, data-driven sustainability assessments.

This study presents the development of a coupled Digital Twin and LCA framework that explicitly captures both data variability and process variability, while also enabling automated calculations. The framework is demonstrated in the context of microalgal production, a system known for its substantial variability arising from meteorological conditions, geographic location, and operational scale. Given this operational variability, it is necessary to adapt the LCA not only with respect to input parameter values, but also regarding the model structure itself and particularly the selection of activities included under different operating scenarios. To address this need, we developed a data collection guideline specifically intended for the creation of a parameterized and digitalized LCA model. The guideline accounts for variability effects, prioritizes components already implemented in the production system, and identifies key sources of variability, which are then translated into model parameters. Interviews with technology developers clarified the existing level of digitalization and data integration, ensuring that the LCA model builds upon and integrates smoothly

with current data systems. The parameterized LCA model is coupled with a digital twin of the production facility, enabling more dynamic assessment and improved decision support. A semantic schema is employed to map primary process data to secondary datasets and LCA model components, facilitating automated reasoning and model reconfiguration. Finally, the implementation of the data mapping and the interface with LCA software (Brightway) are described through a functional and logical system architecture. Overall, the proposed approach enables automated LCA implementation through a software-based microservice that can be integrated into existing industrial IT infrastructures via suitable communication interfaces.

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2.03.T05 Safe Spaces for Unknown Cases: Developing Multivariate LCA.

Stuart Walker[1] (1)University of Sheffield

Life cycle assessment has been used to assess the impact of products and process for over fifty years. It is undeniably useful, enabling comparison between products and the identification of hotspots.
However, it has limitations. Current LCA methods require us to know the path a product will follow through its life, including how it will be treated at the end of life. Even using sensitivity analysis, determining the impact of a product with unknown end of life is challenging.

This work addresses this problem using a new LCA paradigm, with the working title “Multivariate LCA”. It represents a step change in LCA, by enabling models to consider many outcomes and provide impact results as multi-dimensional safe operating regions, identifying cases with the highest risk of environmental impact and enabling design optimisation for reduced impact.
Initial work is focussed on the Wastewater system. Interaction, chemical persistence and biodegradable products complicate the system and lead to highly complex interactions, which influence end of life impacts but cannot be represented by current LCA methods.

Consider a cleaning product washed into the drain. Its end of life has countless permutations: It will mix with other products, interact with materials, travel through a variety of locations, all anywhere on a temperature and pH spectrum depending on environmental conditions. Per- and polyfluoroalkyl substances (PFAS), polymers in liquid formulation (PLFs) and products may be mixed, separated or transported, biodegradation may be accelerated or inhibited, and degraded material may lead to eutrophication or many other outcomes.

The method identifies universal parameters and hyperparameters, and attributes multivariate impact factors to these by taking data from global sources, including climate models, real-world test data and existing LCA databases. A computational tool links materials, products and processes to these parameter sets, calculates multivariate impact spaces and incorporates temporal changes and impact risk. The user can search for high or low impact end of life scenarios, identify any critical cases to avoid, and see target areas for impact reduction.

The dataset will be open source and dynamic, linked to source data for continuous updating and trend modelling. This work is ongoing, but case study projects are in development and will be ready for presentation in late summer 2026.

AI was not used to conceptualise, draft or write this abstract.

Disclaimer/Disclosure: AI was not used to conceptualise, draft or write this abstract. The project itself will use

machine learning tools, but is an LCA project, not an AI project using LCA as a case study.

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Track 3: Policy integration and decision support through life cycle approaches

3.01 - Advancing Integrated Sustainability Assessment in Healthcare: Methods and Decision-Support for Policy, Hospitals and Industry

3.01.T01 Cradle-to- grave Life Cycle Assessment of vaccines as an informative tool towards Sustainable Procurement of more environmentally friendly vaccines for Low- and Middle-Income Countries (LMICs)

Lale Lee[1], Lucie Flauder[2], Sebastien Taillemite[2] and Jean-Pierre Amorij[1] (1)UNICEF, (2)ECOVAMED

One of UNICEF's core missions is to provide children and adolescents with uninterrupted access to life-saving vaccines and help them grow in an environmentally, socially, and economically sustainable world. In line with UNICEF Guidance on Sustainable Procurement, UNICEF strives to positively influence the vaccine supply chain towards practices aligned with sustainability principles while recognizing vaccine security as priority.

Market assessments revealed vaccine manufacturers, especially in developing countries, have a relatively low sustainability maturity and recently started their comprehensive sustainability journey. In particular, the adoption of methodologies of Life Cycle Assessment and Product Carbon Footprint assessments is at its infancy.

UNICEF executes a pilot program to develop Life Cycle Assessment (LCA) for five vaccines with an "outside-in" approach, including the identification of environmental hotspots and key abatement levers as well as assess technical and financial implications of key abatement levers. The LCAs cover multiple-impact categories or climate change impact category only and are conducted in accordance with the ISO 14040-14044 Standards and the newly developed PAS 2090:2025 Product Category Rules for Pharmaceuticals.

The results of this study shows significant variations in environmental impact per dose for cradle-to-gate life cycle, depending on the type of vaccine (oral, injectable, monovalent, trivalent, pentavalent, single and multi-dose vials, type of vial and device, energy used in manufacturing, drug substance, cell culture yields, drug product manufacturing productivity, and vaccination scheme). An assessment of factors such as logistics (e.g., inbound airfreight), cold chain set up for in-country distribution and storage, vaccine use phase, and wastage rates revealed key hotspots for the carbon footprint of vaccines for gate-to-grave. The project is still in progress to identify and quantity environmental impact abatement levers with final conclusions available in Q3 2026.

Future dissemination of all findings and the vaccine specific LCA methodology developed in the project will be highly valuable for vaccine manufacturers, logistics providers, procurement agencies and regulators to drive and support sustainability improvements for vaccines while not compromising vaccine access in Low- and Middle-Income Countries.

3.01.T02 Integrating LCA into Industrial Decision-Making: Three Use Cases from Cytiva

Emma Linhäll[1], Hassan Safa[1], Per-Mikael Åberg[1] and Lorna Starmer O´Farrel[1] (1)Cytiva Sweden AB

Life cycle assessment (LCA) is increasingly embedded in Cytiva's decision-making processes, supporting both strategic and operational choices across product development and manufacturing. This abstract presents three industrial case studies that illustrate how LCA data is used to guide decisions in real-world settings.

The first case focuses on new product development where prospective LCA was applied early in the design of a chromatography resin. By modeling environmental impacts before finalizing the product design, the team identified key hotspots and implemented eco-design changes that significantly reduced the cradle-to-gate footprint. This proactive use of LCA enabled informed trade-offs and aligned product development with sustainability objectives from the outset.

Second, for an existing product family, retrospective LCA results were used as the foundation for a cross-functional brainstorming and continuous improvement program. Cradle-to-gate LCA data revealed key contributors to carbon emissions, which in turn guided the ideation and prioritization of process improvement initiatives. A structured "carbon reduction funnel" methodology was employed — assessing feasibility, effort, and impact — leading to prioritized actions integrated into ongoing operations.

The third case highlights the usefulness of LCA as a decision-support tool during a process redesign. Faced with manufacturing constraints, the R&D team applied a structured design-of-experiments approach that identified multiple operating windows yielding comparable product quality. LCA scenario modeling compared the environmental impacts of these alternatives, and optimal operating conditions was selected by balancing robustness, manufacturability, and footprint—resolving the manufacturing constraints while also improving the environmental impact. Moreover, the retained model supports a "variable recipe" approach, enabling operating conditions to be revisited as data, assumptions, or environmental factors change.

Together, these cases illustrate how LCA can be utilized as a decision-support tool across different stages of the product and process lifecycle. Rather than serving solely as a reporting mechanism, LCA is used to inform design, prioritize improvements, and guide adaptive manufacturing strategies.

3.01.T03 Operationalising Pharmaceutical LCA Under Data Scarcity: A Proxy-Inventory Framework for Decision-Support in a Small-Molecule Case Study

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Challenge
Life Cycle Assessment can support sustainability decisions in healthcare, but its use for small-molecule pharmaceuticals is limited by incomplete data. Drug substance manufacturing can dominate impacts through long routes, solvent use, reagents and waste treatment. Upstream chemicals are often absent from LCA databases, and supplier or manufacturing data may be unavailable during development. This limits reliable hotspot screening and prospective LCA evidence for Safe and Sustainable by Design decisions.

Addressing the Challenge
PAS 2090 was used as the reference document for pharmaceutical LCA, guiding inventory modelling, default values and transparent reporting. However, PAS 2090 provides limited guidance on how to select and justify proxy inventories for chemicals without direct database coverage. To address this gap, we developed a structured source-selection and proxy-inventory framework. Tested on a developed antibiotic with F. Hoffmann-La Roche AG, the framework handles incomplete route information and generates an LCI resolved to available database datasets.

Approaches and Results
The manufacturing route was mapped by inventory ingredients and materials, and each input was matched against LCA datasets. For chemicals without direct database coverage, the framework guided the proxy and LCI creation by retrieving evidence from Reaxys, patents and literature, and ranking sources by data reliability and completeness, including stoichiometry, yields, solvents, reagents, relevance and plausibility. To increase data retrieval and interpretation, AI-assisted support was used to parse reaction descriptions, complete stoichiometric calculations, and verify mass balances. PAS 2090 defaults for energy, solvent, water and waste were applied where primary or source-specific data were unavailable, providing a replicable basis for screening and refinement.

Conclusions and Relevance

The case study shows how PAS 2090 can be operationalised with the proposed framework when process data and database coverage are incomplete. By converting route information into LCI data, it enables hotspot analysis of chemical routes and refinement as data improves. The framework improves data availability for prospective assessment and shows how LCA supports SSbD by identifying hotspots linked to materials, solvents, reagents and waste.

3.01.T04 Towards a Common Standard for Pharmaceutical LCAs: Comparison of PAS 2090 and French Medicine Carbon-Score

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Regulatory developments across Europe are fundamentally reshaping the life cycle assessment (LCA) landscape for pharmaceutical products – transforming it from a voluntary exercise to a potential procurement requirement. As these direct regulations come into force, delivering robust and consistent LCA results is becoming essential for pharmaceutical companies to comply with evolving legislative requirements and remain competitive in the European market.

The only standard dedicated to guide conducting LCA on pharmaceuticals – PAS 2090:2025 – was published by the British Standard Institution (BSI) at the end of 2025. Meanwhile, a methodological guidance for pharmaceutical products LCA with a specific focus on Product Carbon Footprint (PCF) has been proposed in France in response to the increasing incorporation of PCF requirements in pharmaceutical procurement. However, this guidance (referred to as 'medicine carbon score') is not fully aligned with the PAS 2090 standard.

In this study, we aim to compare the PAS 2090 standard and the French medicine carbon footprint assessment, identify key differences in methodological approaches and reporting requirements and their impact on the PCF and overall time and effort needed to compute the PCF. To illustrate these aspects, we apply both methodologies to two case studies, using data from industrial practice, and see overall differences in PCF outcomes, link these differences to specific methodological divergences, and discuss their practical implications for industry stakeholders across different stages of LCA execution and PCF reporting.

The findings of this study underscore the importance of adopting a common standard for pharmaceutical LCAs when implementing new country-specific regulations. Methodologies that are not aligned with established standards may significantly increase both the costs and complexity associated with conducting LCAs for medicines.

Moreover, this fragmentation complicates European harmonization, hindering regulatory alignment, and effective assessment of pharmaceuticals' environmental impacts.

3.01.T05 Sustainability Assessment of Single-Use Small-Scale Bioreactors: Integrating Environmental, Economic, and Circularity Metrics to Support Better Sustainable Design Decisions

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Single-use bioreactor vessels are gaining popularity in biopharmaceutical processes due to their cost-effectiveness and operational advantages. Composed primarily of polymeric components, they reduce capital and operating costs relative to traditional stainless steel or glass vessels by obviating cleaning and sterilisation procedures and minimising cross-contamination risks. Despite rapid adoption, there is limited understanding regarding their environmental, economic, and circularity impact profiles to inform sustainable design policies and industry practices.
This study presents an approach, based on an industrial case study, to assess the environmental, economic and circularity impact of single-use small volume bioreactor vessels by integrating a cradle-to-grave Life Cycle Assessment (LCA), Circularity Assessment (CA), and Life Cycle Costing (LCC). The integrated methodology provides a holistic

sustainability product-category specific profile. The LCA was informed by primary inventory data from Sartorius, supplemented by the Ecoinvent v3.11 database and literature. The CA was conducted using the Material Circularity Indicator (MCI) method. Finally, the LCC followed a similar cradle-to-grave approach, incorporating materials, manufacturing, assembly, logistics, and end-of-life (EoL) costs. Analysis utilised primary cost data from procurement records, complemented by process-based estimates for in-house manufacturing, labour, and energy, evaluated under best-, worst-, and average-case scenarios.
LCA results show that the manufacturing phase, specifically material production for the vessel body and lid has the highest carbon footprint, followed by EoL and use phase impacts. Circularity remains limited and almost linear mainly due to current disposal practices and materials type. LCC results indicate that externally sourced components and labour-intensive assembly are the major cost contributors.
Overall findings suggest that light-weighting polymer assemblies, consolidating components via AM or incorporating design for disassembly to facilitate cleaning and recycling could significantly reduce environmental impacts. Cost optimisation should prioritise in-house production of high-cost components and reduce labour through design consolidation and assembly automation. This study builds the evidence base of sustainability profiles to inform policies, such as Ecodesign for Sustainable Product Regulation (ESPR), and improve industrial design practices.

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3.01.P - Advancing Integrated Sustainability Assessment in Healthcare: Methods and Decision-Support for Policy, Hospitals and Industry

3.01.P-We034 Life Cycle Assessment of Pharmaceuticals: Analysis of Current Methodological Guidance and Outlook for Further Development

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Efforts to further develop and harmonise life cycle assessment (LCA) methods for pharmaceutical products have grown in momentum in recent years. With mounting evidence of the environmental impacts resulting from the production, use and disposal of pharmaceutical products, methods and tools that provide visibility and usable insights throughout the pharmaceutical life cycle are sought-after. Recent publications, such as the PAS 2090:2025, outlining product category rules for the LCA of pharmaceutical products, and France's carbon footprinting methodology for medicines are gaining traction. With these current high-profile developments and the push toward harmonisation, it is a key point in time to reflect on the body of methodological guidance documentation now available for LCA in the pharmaceutical sector and whether it fulfils the sector's potential use cases for LCA.

This study provides an analysis of methodological guidance documents for LCA of pharmaceuticals to date, consisting of formal and informal standards and guidelines, and scientific literature. First, the methodological approaches outlined in the literature were mapped to the methodological elements of the ISO14044:2006 framework. A comparison between the literature was then conducted, to identify methodological approaches with higher and lower agreement among method documents. In parallel, a series of structured discussions with experts in industry and academia were conducted, in which potential use cases – or purpose for LCA – in the sector were identified. The compatibility of methodological approaches in the literature was then evaluated against the set of use cases identified in the expert consultations.

The identified use cases could be clustered under the headings, 'reporting and communication' and 'improvement of

products and processes'. The outcomes indicate a convergence in methodological approaches over time, and a greater focus on LCA as a tool for reporting and communication. Although partly aligned with the identified use cases for LCA in industry, there is noticeably less harmonised methodological guidance available for the use of LCA as a tool for the improvement of pharmaceutical products and processes. The analysis, therefore, offers an outlook for potential next steps toward harmonisation in this method space.

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3.01.P-We035 How to Include Circularity in Pharmaceutical Sustainability Assessments: Bridge Between Industry and Academia.

Lotte Neckebroeck[1], Lieselot Boone[1], Delphine De Smedt[1] and Jo Dewulf[1] (1)Ghent University

Sustainability assessments in the pharmaceutical sector have traditionally focused on environmental impacts, often complemented by economic and social aspects. Recently, however, additional concepts such as circularity have gained increasing attention within the sustainability field (e.g. EU Horizon project Orienting). Circularity refers to improving resource efficiency and minimizing waste through strategies such as reuse, recycling, and recovery. Despite the growing relevance, this concept is still broadly defined and is not yet systematically integrated into pharmaceutical sustainability assessments.

Applying circularity in the pharmaceutical sector presents specific challenges. Pharmaceutical production is characterized by strict regulatory requirements, complex global supply chains, and high quality standards, which can limit the straightforward implementation of circular strategies that are more common in other industries. This highlights the need to better understand how circularity can be considered alongside traditional sustainability dimensions.

This framework will be developed using both a top-down (literature study) and a bottom-up approach (stakeholder workshop). By involving industry it can be explored how circularity can be incorporated into sustainability assessments within the pharmaceutical industry. The stakeholders involved are both from industry and academia. A key objective will be to discuss how circularity can be defined in this context and to identify what should be included when assessing it, both in terms of life cycle stages to be covered (pharmaceutical supply chain versus entire pharmaceutical value chain) and in terms of substances (e.g. circularity of solvents within the pharmaceutical supply chain versus circularity of packaging material along the entire value chain).

The discussion aims to get a clearer and more practical understanding of how circularity is to be integrated into pharmaceutical sustainability assessments. The main goal is to have a well-founded methodological framework tailored to the pharmaceutical industry that integrates circularity into sustainability assessments.

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3.01.P-We036 Sustainability Assessment of Shifting from Multiple-Use to Single-Use Gastrointestinal Endoscopes: A Triple Bottom Line Perspective

Mojtaba Ahmadinozari[1] and Stuart Coles[1] (1)University of Warwick

Background:

The adoption of single-use medical devices in healthcare is increasing, particularly in gastrointestinal endoscopy, where reducing cross-contamination is a key concern. This shift from multiple-use to single-use endoscopes has implications beyond clinical performance, requiring evaluation across environmental, economic, and social dimensions.

Methods:
A mixed-methods approach was used to assess the sustainability implications of this transition. Environmental impacts were evaluated through a cradle-to-grave life cycle perspective, focusing on global warming potential. Economic outcomes were assessed using cost analysis and modelling from a healthcare system perspective. Social and clinical aspects, including infection risk, technical performance, and stakeholder perspectives, were examined through evidence synthesis and qualitative analysis.

Results:
The shift toward single-use endoscopes was associated with increased environmental impacts due to repeated manufacturing and disposal, compared to the distributed impacts of multiple-use devices over repeated cycles. Reprocessing contributed to environmental burdens but remained lower than those associated with single-use systems. Economically, single-use endoscopes resulted in higher per-procedure costs, with limited evidence of proportional improvements in outcomes. From a social and clinical perspective, both approaches demonstrated comparable technical performance. Infection risks remained low across both systems and were not fully mitigated by single-use devices, as some infections are patient-related. Stakeholders expressed confidence in existing reusable systems, while also recognising the importance of sustainability considerations.

Discussion:
The findings highlight the trade-offs associated with transitioning from multiple-use to single-use endoscopes. While single-use devices may address specific operational concerns, their broader sustainability implications are less favourable when evaluated across all three dimensions.

Conclusions:
A shift from multiple-use to single-use gastrointestinal endoscopes presents challenges for sustainability. A comprehensive, multi-dimensional assessment is essential to inform balanced and context-sensitive decision-making in healthcare systems.

Relevance
This study provides a replicable TBL methodology for assessing medical device transitions and contributes critical evidence for sustainable procurement decisions in healthcare.

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3.01.P-We037 Environmental Sustainability Assessment of the Flemish Population-Based Colorectal Cancer Screening Program

Bente Verhaegen[1], Lisa Van Wilder[1], Lieselot Boone[1], Jo Dewulf[1] and Delphine De Smedt[1] (1)Ghent University

Colorectal cancer (CRC) remains a major health concern, highlighting the importance of effective screening programs to improve survival, reduce incidence and mortality, and limit the need for costly invasive treatments with associated environmental implications. As healthcare accounts for 4.4% of global greenhouse gas emissions, integrating environmental sustainability into the organisation of cancer screening programs, alongside health impact and costs, is essential to align public health with sustainable development. The aim of this study is to estimate the environmental

impact of the population-based CRC screening program in Flanders and to compare it with an opportunistic screening scenario without organised screening. By comparing these approaches, the study assesses whether organised population-based screening programs can provide environmental benefits in addition to established health and cost advantages by life cycle assessment (LCA). A detailed care pathway was mapped, visualising all steps in both CRC and opportunistic screening, from invitation to treatment & follow-up. For each step, input and output flows were identified and quantified based on literature and the Ecoinvent 3.9 database. Observational data from the Flemish population were used to estimate transition probabilities within the care pathway and to quantify the number of individuals in each step. The LCA was conducted using the ReCiPe 2016 Midpoint (H) V1.08 method. We assessed whether the environmental impact of CRC screening is offset by reduced use of invasive downstream cancer treatments compared to opportunistic screening. Preliminary results for the screening phase of the pathway indicate that colonoscopies account for approx. 78% of the total carbon footprint of the population-based program, corresponding to 17 kg CO_2eq per colonoscopy. This shows that medical procedures are the main contributors to the program's environmental impact, consistent with literature reporting footprints of 20-400 kg CO_2eq for complex procedures. Preventing more invasive treatments through organised screening may therefore lead to net environmental benefits. Next steps include estimating the downstream impact of treatment & follow-up in both screening scenarios. This study will bring insights into the environmental benefits of population-based CRC screening, supporting policy decisions and enabling targeted improvements to align preventive healthcare with sustainable development goals.

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3.01.P-We038 Emergency Department Care for Suspected Sepsis: A Life Cycle Assessment for Sustainable Hospital Decision Support

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Healthcare systems need actionable evidence to reduce the environmental burden of acute care, yet detailed assessments of emergency department pathways are scarce. We evaluated whether life cycle assessment (LCA) can identify practical priorities for lower-impact care for patients with suspected sepsis in the emergency department and support hospital decision-making.
The functional unit is the treatment of a patient with suspected sepsis in the emergency department of a Dutch academic hospital. Data was collected for ten patients with a mix of direct observation and surveys. Life cycle impact assessment included ReCiPe midpoint indicators and endpoint indicators. Waste generation was also tracked. Contribution analysis identified major hotspots, which guided emergency department staff in the development of mitigation scenarios and in testing realistic improvement options.
Treating one patient generated a mean 0.82 kg non-hazardous solid waste, 45.7 kg CO2-eq, and led to 7.53 × 10-5 disability-adjusted life years, or about 40 minutes of healthy life lost from environmentally mediated effects. Human health damage was dominated by staff transport (29.9%), heating, ventilation, and air conditioning (23.2%), and patient transport (19.9%), with smaller contributions from personal protective equipment and other consumables and diagnostics. The combined mitigation scenario reduced estimated damage to human health by 23.5% and damage to ecosystems by 32.9%. The largest reductions came from renewable energy for heating, ventilation, and air conditioning, lower-carbon staff commuting, renewable electricity for imaging, and replacing single-use isolation gowns with reusable alternatives. Widening the system boundaries from the emergency department towards pathway-level sustainability assessment might show a higher impact due to medicines in some treatment scenarios. However, LCA modeling of medicines is limited.
This study shows that LCA can move beyond quantification toward decision support for emergency care. For hospitals and policymakers, the main leverage points are energy sourcing, staff mobility, and procurement of reusable products.

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3.01.P-We039 The Impact of Care Pathway and Contextual Variability on the Environmental Footprint of Prostate Cancer Treatment in the Netherlands

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Healthcare aims to improve human health but also has a substantial environmental footprint that can unintentionally harm planetary health. Prostate cancer is one of the most frequently treated cancers in men. As curative treatment options for low- and intermediate-risk disease have comparable clinical outcomes, environmental sustainability may be a relevant additional consideration in decision making.

Life Cycle Assessment (LCA) is increasingly applied in healthcare, but results are often based on single institutions, potentially limiting their relevance. This study assesses how care pathway and contextual variability in prostate cancer care affects LCA outcomes.

A process-based, cradle-to-grave LCA was conducted for two curative treatment pathways for localized prostate cancer in the Netherlands: robot-assisted laparoscopic prostatectomy and conventional external beam radiotherapy. Scenario analyses were performed using data from three to four Dutch hospitals across different regions, focusing on key environmental hotspots: patient travel, energy use, and disposable materials. In addition, an exploratory, illustrative location-based travel scenario was modelled to represent a patient perspective in sparsely populated regions, using hypothetical patient postal codes combined with actual hospital locations.

Substantial variability in environmental impacts was observed between hospitals. In most hospital-level scenarios, radiotherapy had a higher environmental footprint than surgery. Preliminary analyses suggest that observed practice and contextual variability can lead to differences of up to approximately 30% in carbon footprints for both treatments. Across these scenarios, variability in energy source was the dominant driver, with transitions from grey to green electricity yielding the largest differences in environmental impact.
In the illustrative travel scenario, travel-related emissions were substantially higher for prostatectomy in sparsely populated regions due to long distances to centralized surgical centers, while radiotherapy remained available closer to home. Under these context-specific conditions, radiotherapy exhibited a lower carbon footprint than prostatectomy.

These findings demonstrate that care pathway and contextual variation can substantially influence environmental outcomes. Incorporating context- and care-pathway–specific parameters into LCA may provide more decision-relevant insights for hospitals, policymakers, and patients.

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3.01.P-We040 From evidence to consensus: defining key indicators for social sustainability assessment in healthcare

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Background.Sustainability in healthcare has largely focused on environmental and economic dimensions, while social sustainability remains insufficiently defined and operationalized. However, issues such as equitable access, labour conditions, and societal impacts are essential for achieving sustainable healthcare systems. This study aims to develop a comprehensive set of indicators to assess social sustainability across healthcare and pharmaceutical life cycles. Methods. A systematic literature review was conducted using Scopus and Web of Science, complemented by grey literature and international frameworks. Indicators were included if transferable to healthcare. A multi-step selection process was applied, including materiality assessment and a two-stage scoring based on relevance, acceptability, and

achievability/interpretability. A Delphi study with multidisciplinary experts was conducted to validate indicators and select appropriate metrics.
Results.From 267 indicators identified across 37 sources, 33 were retained across five social impact categories: patient and wider society's health and well-being, fundamental principles and rights at work, access to healthcare, antimicrobial resistance in humans, and human toxicological impact. The Delphi study demonstrated strong consensus (≥60%) for most indicators. Preferred metrics included disability-adjusted life years (DALYs) for morbidity and disease burden (72.2%), availability of essential medicines for access to healthcare (88.9%), workers in forced labour conditions for labour rights (77.8%), and healthcare resource use (94.4%). For a minority of indicators, consensus was not reached in the first round, necessitating a second Delphi round. Expert reflections highlighted methodological considerations regarding attributional versus consequential scope, potential conceptual overlap between indicators, and the need to split combined indicators into distinct constructs.
Discussion.This study provides a validated set of social sustainability indicators tailored to healthcare and pharmaceuticals. The findings demonstrate the feasibility of integrating social dimensions into sustainability assessments while highlighting the need for flexible and context-sensitive application. The proposed indicators support life cycle–based evaluations and can inform health technology assessment and policy decisions. Future work should focus on practical implementation and integration with environmental and economic dimensions.

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3.01.P-We041 Carbon-Neutral Healthcare: Insights from Deriving Long-Term GHG Emission Trajectories for an Austrian General Hospital

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European healthcare confronts demographic ageing and the accompanying surge in medical demand. Hospital-based inpatient and outpatient care represent the most resource-intensive sectors within healthcare systems. At the same time, EU and Austria's national climate policy impose stringent decarbonization targets on Healthcare organizations until 2040 and 2050.
In collaboration with a mid-sized Austrian general hospital and municipal authorities, we developed a comprehensive GHG emission trajectory extending to 2050. We established an GHG emission inventory based on the GHG Protocol. Considering a future perspective until 2050, we derived foreground projections for activity data from expected medical demand and statistical analysis. Transport-related activities from inpatient, outpatient, and visitor flows were estimated using an agent-based transport model. For background data, we applied prospective scenarios using premise, modified LCA datasets and projected GHG emissions through 2050.
To assess future mitigation potential, we engaged hospital stakeholders to gather planned measures and evaluated their GHG reduction impact. Results indicate that part of planned measures exhibit limited long-term effectiveness or poor data availability regarding their GHG reduction potential. To address the gap between externally induced scenarios, we proposed an enhanced emission trajectory toward net-zero by integrating measures from national decarbonization strategies and proposed additional interventions.
The hospital's projected emission trajectory was benchmarked against applicable national climate targets, providing management boards and public authorities with a clear picture of policy-relevant impacts. Results are structured according to company reporting standards and nationally defined fields of action for healthcare providers. Our analysis confirms the critical importance of addressing pharmaceuticals and direct emissions as dominant GHG drivers, while commonly referred categories such as food and waste are of comparatively minor relevance to the cumulative GHG emissions.

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3.01.P-We042 Environmental hotspots in intensive care pathways for critically ill sepsis and trauma patients: a process-based life cycle assessment

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Healthcare systems are under increasing pressure to reduce environmental impacts. Since life cycle assessments (LCA) in healthcare are often restricted to a single product or procedure, understanding of environmental burdens is limited at the level of care pathways, particularly in high-intensity settings such as intensive care units. This study quantifies the environmental footprint of intensive care unit admission for sepsis and trauma patients and identifies hotspots to support hospital-level decision-making and sustainability strategies.

A comprehensive cradle-to-grave LCA was conducted for the intensive care stay of patients with trauma and patients with sepsis, two prevalent pathways in acute care. Primary data were collected at a Dutch academic hospital, including detailed resource tracking per admission for variables such as energy use, medical disposables and reusables, pharmaceuticals, diagnostics, linen, medical gases, waste treatment, and transport of staff and visitors.

Energy use, medical disposables, and transportation were key environmental hotspots in intensive care pathways. Energy use associated with heating, ventilation and air-conditioning, modelled using the Dutch energy mix, dominated the contributions to greenhouse gas emissions. In contrast, staff transport, visitor transport and medical disposables were the largest contributors in fine particulate matter, carcinogenic and non-carcinogenic toxicity, terrestrial acidification and land use. Only twelve of 90 administered pharmaceuticals had available environmental impact data, indicating major gaps in healthcare LCAs. Results on mitigation potentials for renewable energy supply, air treatment optimization, transportation alternatives, and reduced use of disposable products will be available in October.

This process-based LCA demonstrates how environmental burden shifts across clinical processes and highlights actionable levers for hospitals and health care professionals, including procurement, infrastructure, and prescribing decisions. The findings support integration of environmental metrics into clinical and operational decision-making to reduce intensive care unit related emissions without compromising care quality.

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3.01.P-We043 Estimating the Environmental Impacts of Adopting Health Technologies at the Care Pathway Level: A Case Study on Continuous Glucose Monitoring

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Introducing new health technologies affects the environmental impacts of the care pathways they support. However, these impacts are often overlooked in attributional LCAs, which focus on improving environmental performance at the product level.

This research aims to address the following question: “How can we estimate the environmental impacts of adopting new health technologies at the care pathway level?” Addressing this question may benefit from insights in Health Economics, where established decision-making tools can be adapted to incorporate environmental impacts.

Health Economics aims to optimize healthcare resource allocation to meet population needs. It commonly relies on cost-effectiveness analysis, which evaluates the trade-off between the costs of new health technologies and their health outcomes. This trade-off is expressed through the incremental cost-effectiveness ratio (ICER), which helps decision-makers assess the value for money of new healthcare interventions. A well-established approach for estimating ICER is the use of Markov models, which simulate disease progression, treatment effects, and costs across discrete health states. In cohort simulations, each state accumulates costs and health outcomes over time, which are then aggregated to compute the ICER.

To address our research question, we propose augmenting conventional Markov models by incorporating an environmental dimension. Specifically, we assign a quantified environmental impact, in $kgCO_2eq$, to each health state, alongside economic costs and health outcomes. As it is not possible to do this for all Markov models found in the Health Economics literature, we focus on a specific case study as an illustrative example. The selected case study is continuous glucose monitoring (CGM) devices for diabetes management, for which a Markov model already exists. Integrating $kgCO_2eq$ at the health-state level requires conducting dedicated LCAs or deriving monetary-based emission estimates from healthcare costs associated with each state. By simulating this augmented model and aggregating impact estimates, we estimate the total $kgCO_2eq$ emitted or avoided at the care pathway level through the introduction of CGM devices.

The two main challenges of this research are: 1) reconstructing a robust Markov model and 2) collecting environmental data for each state. At the SETAC Symposium 2026, we will present these methodological challenges in further detail and initial results from the case study.

3.01.P-We044 Development and Validation of a Standardized LCA Methodology for Healthcare Pathways: The CLEAR-Path Framework

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Healthcare systems contribute substantially to environmental impacts, yet robust and comparable methods to assess the footprint of care pathways remain limited. Existing life cycle assessments are heterogeneous in scope, system boundaries, and indicators, and are often resource-intensive, limiting reproducibility and comparability.

This study presents the development of CLEAR-Path, a standardized life cycle assessment methodology tailored to healthcare pathways, focusing on methodological robustness, transparency, and validation. The objective is to establish a reproducible framework for multi-indicator environmental assessment at pathway level.

The methodology follows ISO-based LCA principles across four phases. In the goal and scope phase, key choices—including system boundaries, functional units, and a minimum indicator set—are defined through stakeholder engagement and a structured Delphi process with clinicians, LCA experts, and policymakers.

In the inventory phase, a modular life cycle inventory framework is constructed using reusable “building blocks” representing common healthcare activities (e.g. procedures, diagnostics, inpatient stays). Modules are parameterized using hospital data, literature, and background databases. Where primary data are unavailable, proxy approaches are applied and evaluated. Data inputs are categorized into quality tiers, and uncertainty is explicitly characterized.

Validation is central to the study. For selected pathways, the modular approach is compared with detailed process-based LCAs (“gold standard”) to assess agreement in total impacts, hotspot identification, and ranking of processes.

Sensitivity and uncertainty analyses evaluate the influence of proxy assumptions and data variability. Reproducibility is assessed through application across multiple sites.

Initial applications include pathways in surgery, gynaecology, and dialysis, enabling evaluation across care settings. Results are expected to show that a modular, proxy-based approach can approximate detailed LCAs while reducing data requirements, with transparent uncertainty ranges.

This demonstrates that a modular, validated and uncertainty-informed approach can provide a robust basis for healthcare pathway LCA. The framework enables consistent and reproducible pathway assessments and complements ongoing efforts focused on implementation and decision-making.

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3.01.P-We045 Comparative Life Cycle Assessment of a Bench-scale Trastuzumab Manufacturing Process of Different Cultivation Conditions for Process Intensification

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Monoclonal antibodies (mAbs) remain the predominant modality for the treatment of various diseases. Trastuzumab is a mAb used for the treatment of HER2-positive breast and stomach cancers. Notwithstanding, the production process of mAbs in mammalian cells such as Chinese Hamster Ovary (CHO) cells remains a very resource- and energy-intensive process. In the context of mounting regulatory and societal pressures to defossilize the pharmaceutical industry, therefore, it is imperative to quantitatively assess the environmental impacts of these bioprocesses in order to enhance their environmental performance. Life Cycle Assessment (LCA) provides a standardized framework for the quantification of such impacts across the entire production chain, thus supporting evidence-based decision-making.

In the present study, an LCA is conducted on a 10 L bench-scale Trastuzumab manufacturing process, encompassing both the upstream (cell culture phase) and downstream (mAb purification and formulation) operations. The primary objective of this study is to identify environmental hotspots and to quantify the contribution of these operations to multiple impact categories, including climate change, water use and freshwater ecotoxicity.
A secondary objective is to evaluate how process intensification, by implementing different cultivation conditions, influence the overall environmental sustainability performance. To achieve this objective, a comparison is made between two fed-batch cultivation process conditions. Firstly, a baseline process was conducted, with a cultivation duration of 10 days at a constant temperature (37 °C). Secondly, an extended 14-day process was initiated, which incorporated a temperature shift from 37 °C to 32 °C on day five. This strategy is commonly employed to enhance cell performance and mAb product yield. The inventory data were compiled from experimental bench-scale runs and supplemented with background datasets for energy, media components and consumables.

The findings are intended to provide an empirical basis for identifying the key parameters required to reduce the environmental footprint of mAb manufacturing. Moreover, it establishes a benchmark for evaluating emerging process intensification strategies, including continuous bioprocessing and novel purification technologies. By embedding LCA into early-stage process development, this work contributes to the design of more sustainable and resource-efficient mAb manufacturing platforms.

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3.01.P-We046 The environmental impact of using digital display labels in clinical trials

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Before new drugs are brought to market, their safety and efficacy are investigated in clinical trials. These are inherently complex in terms of operational, regulatory and logistical aspects, and often take place within global networks spanning multiple sites. Although they are essential, they are known to have a big environmental impact. One way to make this more environmentally sustainable is to introduce digital display labels (DDLs) to replace conventional paper labels. DDLs offer greater flexibility within the clinical supply chain by enabling variable product information (e.g. expiry date) to be updated, reducing the burden of relabelling. However, DDLs are electronic devices that require critical raw materials and contribute to electronic waste.

The aim of this study is to investigate how the environmental impact changes when a DDL is used in clinical supply chain instead of a standard paper labelling system. This study uses a Phase III clinical trial of a specific drug product as a case study.

Life cycle assessment is used to evaluate the impact at both product and system level. The functional unit (FU) corresponds to one dose of drug product administered to a single patient during a multi-site clinical trial. The life cycle stages include drug manufacturing, packaging and label production, packing and labelling, repackaging during distribution, use at clinical trial, and transport and end-of-life treatment. Data was provided by a pharmaceutical manufacturer, supplemented by data from literature and ecoinvent v3.9. Impacts were assessed using Environmental Footprint v3.0, focusing here on climate change.

The impact of the paper label is negligible compared to that of the DDL, which is mainly determined by the circuit board (71%) and the e-ink display (21%). However, at system-level, preliminary results suggest that, thanks to greater efficiency and thus a lower amount of drugs needed to administer a single dose, a saving of 12% per FU can be achieved by using the DDL. The main phases contributing are drug production (59 and 52%) and transport (23% and 20%) for the paper label and the DDL clinical supply chain, respectively.

This study shows that it is important to take the device's function into account when evaluating the environmental impact of electronic healthcare devices, highlighting the need for system-level evaluations.

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3.01.P-We047 Decision Support for Clinical Practice – Screening Life Cycle Assessment of Laryngoscope Systems in German Hospitals

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The healthcare sector accounts for about 4.4% of global greenhouse gas emissions, with single-use medical devices raising particular concerns. While patient safety remains paramount and decisions are taken within economic constraints, environmental impacts are still difficult to integrate into clinical decision-making due to lacking robust life

cycle assessment data for many medical products and processes.
This study addresses the need for accessible environmental decision support in hospital procurement by applying a screening Life Cycle Assessment (LCA) to different types of laryngoscopes used in real-life German hospital settings. Available in multiple configurations regarding technical features and reprocessing, they are used daily in clinical practice. Yet, their environmental performance has not been systematically assessed and compared under actual clinical conditions in Germany.
Six scenarios were assessed, covering conventional and video laryngoscopes with single- and multi-use options and cleaning methods including disinfection bath, heat-water sterilization, and wipes. Primary data were collected from three German hospitals within the clinical "COVALENT randomized, controlled multicenter trial". The functional unit was 100 intubations. Nine impact categories were assessed using CML 2001, January 2016.
Results show that the disinfection method is the dominant driver of environmental performance for multi-use devices – at times outweighing multi-use benefits. Multi-use laryngoscopes reprocessed in disinfection bath showed the highest global warming potential (110 kg CO2 eq.), while the lowest was achieved by a multi-use system using wipe disinfection (24 kg CO2 eq.) – despite incorporating single-use blades. Single-use options showed comparatively higher resource depletion, especially when electronic components such as monitors were involved. No single option performed best across all impact categories.
These findings show that reusable devices realize their circular-economy potential only when cleaning and reprocessing are adequately addressed. Multi-use systems can outperform single-use options when paired with optimized, low-impact disinfection procedures. By translating complex LCA results into scenario-based guidance, this study offers a practical framework for hospital procurement teams and managers to identify hotspots and prioritize procedures, supporting more informed and evidence-based environmental decision-making in clinical practice.

Disclaimer/Disclosure: This research was conducted in the context of the clinical Conventional versus video-assisted laryngoscopy for perioperative endotracheal intubation (COVALENT) randomized, controlled multicenter trial.

3.01.P-We048 Applying Life Cycle Assessment to Clinical Cohort Data: A Comparison of Dialysis and Conservative Kidney Management

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Environmental sustainability has become an increasingly important component of quality care, yet it is rarely integrated into healthcare decision-making. A relevant case study for this integration is the treatment choice for older patients with kidney failure, where the choice between dialysis and conservative kidney management is based on shared decision-making between the patient and doctor. To integrate environmental sustainability into patient- and policy-level treatment decisions, this study applies a comparative life-cycle assessment to the DIALOGICA cohort. DIALOGICA is an observational study following 809 patients ≥65 years old with kidney failure and compares clinical outcomes, quality of life, and costs of dialysis and CKM treatment.
A comparative LCA was conducted in accordance with ISO 14040/44, using ReCiPe 2016 for impact assessment and background processes from Ecoinvent v3.11. The system boundary starts from inclusion, just before kidney failure is reached (eGFR between 20-15), and captures the care consumption of a patient over 48 months. The care consumption is modeled through building blocks and includes dialysis access creation, dialysis sessions, hospital and general physician consultations, and hospitalizations. Dialysis sessions are modeled to reflect a mix of modalities (center hemodialysis, home hemodialysis, automated peritoneal dialysis, and continuous ambulatory peritoneal dialysis) present in the DIALOGICA cohort. Inventory data was collected from UMC Utrecht and Radboudumc.
This study adopts two complementary perspectives of the environmental impact. A treatment analysis considers patients who chose CKM or dialysis and remained on that trajectory, informing shared decision making. An intention to treat analysis categorizes patients by their initial treatment choice regardless of subsequent switching, to support data-driven policy evaluation. Scenario and sensitivity analyses are performed to identify environmental impact

mitigation strategies, such as switching from treatment or modality, or changing travel modes and distances.
By applying life cycle assessment to clinical cohort data, this study demonstrates an innovative framework that is transferable to other clinical research and presents an important step toward integrating environmental sustainability into healthcare evaluations.

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3.01.P-We049 Environmental Life Cycle Inventory of Diagnostic Processes in Healthcare Pathways: Coverage and Quality of Existing Literature

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Hospitals are complex systems comprising many interacting processes, materials, and energy flows. A growing body of literature addresses the environmental impact of healthcare pathways, products, and individual processes in hospitals. However, this body of work is highly heterogeneous in scope, system boundaries, focus and, data availability. It is challenging and interesting to assess to what extent existing studies can collectively support the development of a modular and data-granular life cycle inventory (LCI) representation of a hospital. Making an overarching framework, based on inventory data rather than impact results, would help to structure existing and future research. As a starting point, the purpose of this study is to systematically review how laboratory and imaging diagnostic processes are represented in existing environmental and life cycle–oriented studies of care pathways.
Methodologically, a modular framework that structures hospital activities into hierarchical process groupings, combining clinical and process engineering perspectives is developed, based on literature and validated by experts. Clinical laboratory and imaging diagnostic processes are clustered under diagnostic testing. For this cluster, environmental and life cycle–oriented studies related to hospitals and care delivery pathways, extending beyond healthcare products assessments, are reviewed. The reviewed articles are assessed based on the processes they address and on whether, and to what extent and level of detail, they report inventory data suitable for compiling mass and energy balances.
The first result is a LCI-based modular framework that embeds the reviewed process cluster and that structures further research. Second, the study is expected to identify which diagnostic testing processes are documented with data suitable for inventory compilation in the existing literature. It will also show which processes contain data gaps or are limitedly documented.
The modular framework will provide a basis for extending the analysis to additional hospital processes, enabling a more coherent representation of hospital activities and supporting the identification of resource-intensive processes of potential environmental relevance. The outcome of this study is not a compiled literature-based inventory, but an overview of literature coverage and gaps that improves understanding of where inventory-relevant knowledge already exists and identifies priorities for future research.

3.01.P-We050 Standardizing Healthcare Life Cycle Assessment: A Cross-Border Approach for Integrated Sustainability Decision-Making

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Life cycle assessment (LCA) is increasingly used to support sustainability transitions in healthcare, yet current applications remain difficult to compare, reproduce, and integrate into decision-making. Key methodological challenges include incompatible formats, high data requirements, inconsistent clinical pathway definitions, and limited transferability across settings. Finally, the reliance on complex academic language frequently hinders patient comprehension, thereby restricting meaningful patient involvement in decisions concerning sustainable treatment pathways.

This study aims to develop a standardized LCA-based methodology that enables robust and comparable sustainability assessment of healthcare pathways across hospitals and national contexts. A cross-border comparative approach is applied, examining variation in the clinical pathways of uterine fibroids, pelvic organ prolapse and uncomplicated gallstone disease in peripheral and academic hospitals in the Netherlands and Germany. Differences in clinical procedures and hospital environments are systematically identified and evaluated with respect to their environmental impact and subsequently integrated into the framework, enabling the development of a method that is broadly applicable across diverse healthcare settings. The method includes the development of standardized reporting guidelines and a centralized database to improve access to and reuse of LCA results. In collaboration with patient organizations, strategies are co-created to communicate environmental outcomes and integrate them into shared decision aids.

The proposed framework is expected to improve consistency, accessibility, and transferability of healthcare LCAs, enabling meaningful comparison across settings. The first results will be available in October.

This work advances methodological innovation in healthcare LCAs by providing a standardized, accessible, and decision-support-oriented framework. By translating environmental outcomes into simplified sustainability indicators, the framework enables patients and healthcare professionals to incorporate sustainability considerations into treatment decisions. It further supports policymakers, hospitals, health professionals and industry in embedding sustainability in clinical and procurement decisions, contributing to reduced healthcare-related environmental impacts while supporting broader societal and health benefits.

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3.01.P-We051 Integrating Life Cycle Assessment and Health Technology Assessment: A Stakeholder-Informed Framework for Environmental Impact of Healthcare Pathways

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Healthcare systems contribute substantially to environmental impacts, yet existing assessment approaches remain fragmented and poorly aligned with decision-making frameworks. While Life Cycle Assessment (LCA) is widely used to quantify environmental burdens, its application to healthcare pathways is inconsistent and rarely integrated with Health Technology Assessment (HTA), limiting its relevance for policy and clinical decision-making.

This study addresses this gap by developing a methodological framework that integrates LCA with HTA to enable robust and decision-relevant environmental impact assessment of healthcare pathways. The objective is to identify key methodological requirements and establish a structured approach aligned with HTA principles.

A mixed-methods approach is applied. First, a targeted review of current LCA applications in healthcare pathways is conducted to identify methodological inconsistencies and limitations. Second, stakeholder interviews with clinicians, policymakers, and researchers are performed to define decision-relevant requirements. Third, a Delphi process with LCA and HTA experts is ongoing to build consensus on system boundaries, data sources, and modelling assumptions.

Preliminary findings indicate substantial variability in system boundary definitions, limited consideration of long-term care consequences, and lack of standardisation in data integration across studies. Early results from stakeholder engagement highlight the need for harmonised methodological choices that reflect real-world practice variation and support integration into HTA frameworks.

Based on these insights, an initial framework structure is proposed, combining LCA modelling principles with HTA requirements, including alignment with cost structures, time horizons, and decision contexts. The framework aims to

improve comparability, transparency, and applicability of environmental assessments in healthcare.

This work advances methodological integration between LCA and HTA and provides a foundation for incorporating environmental sustainability into healthcare decision-making, supporting clinicians, policymakers, and patients in evaluating treatment options beyond clinical and economic outcomes.

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3.02 - Exchanging Primary Supplier Data Along the Value Chain – Approaches, Leanings and Challenges for Supplier Engagement

3.02.T01 Why do Supplier-specific PCFs Often Lack Comparability: Lessons from Multi-Output Chemical Processes.

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Companies increasingly request supplier-specific product carbon footprints (PCFs) for their LCA studies and Scope 3 accounting. Yet PCFs received are frequently not comparable, even when suppliers seek to align with existing standards, because methodological choices remain insufficiently standardized.

We demonstrate this challenge using a chemical-sector case study where a supplier operates a multi-output process and is required to report PCFs to downstream customers. Different ISO 14040/44-compliant choices for handling multifunctionality are shown to substantially shift the reported PCF, creating uncertainty in downstream companies' scope 3 accounting.

The case study examines, using company-specific data, a chemical process producing two outputs , both requiring further processing before becoming marketable. ISO 14067 standard & Together for Sustainability (TfS) PCF guidelines were followed to select appropriate approach to handling multifunctionality. Subdivision is not feasible due to tightly coupled unit operations. System expansion is possible but sensitive to counterfactual definition; in practice (as in this study) it is difficult to identify what is substituted. Allocation is therefore commonly applied. Following TfS, economic allocation is selected instead of mass allocation when the market value between the co-products differs substantially. However, this alters the system boundary as economic allocation as economic value is only defined after downstream upgrading steps, requiring inclusion of these processes in the allocation. This is debated, as it implies allocating certain downstream specific (nonshared) inputs across co-products, which is against the principle of subdivision. Hence, the modelling choice is unambiguous and there is no sufficiently prescriptive guidance to resolve these tensions, leaving the modelling choice to practitioner judgement.

This study compares supplier-specific PCFs derived approaches for handling multifunctionality that may reasonably be selected under current guidance – system expansion, mass allocation and economic allocation – and shows that PCF differs significantly depending on the methodological choices. These findings underscore the need for more detailed, scenario-aware guidance on the treatment of multi-output processes; without it supplier-specific PCFs are unlikely to be methodologically aligned or meaningfully comparable, limiting their usefulness for assessing upstream climate mitigation effort.

3.02.T02 Managing Missing Primary Operational Data in Dependency-Aware LCA: Lessons From the Rittershoffen Geothermal Plant

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Life Cycle Assessment (LCA) increasingly relies on primary data from industrial operators to improve data quality and decision support. Yet operational or joint datasets are often unavailable, incomplete, or not exchanged at the level required for dependency-aware uncertainty analysis. This matters because many LCA models contain physically or structurally linked parameters, while uncertainty workflows commonly assume independent inputs. In global sensitivity analysis (GSA), this can distort uncertainty propagation and rankings when dependencies are present.

This contribution asks how dependency-aware LCA can remain defensible when operational data needed to estimate correlations are unavailable, using the Rittershoffen deep geothermal heat plant as a case study. The initial objective was to characterize dependencies from operational data and formal dependence modelling. However, limited operator data prevented estimation of correlation structures. Rather than reverting to fully independent sampling, we developed a limited-data approach applicable when only nominal values, minimum–maximum ranges, and model equations are available.

The work first identifies critical parameters using screening and GSA. It then computes finite-difference Jacobians and dimensionless elasticities to describe how each parameter affects the impact result. Cosine similarity between elasticity vectors identifies parameters with similar model behavior. These groups are interpreted as structural driver families rather than empirical correlations. Dependency scenarios are constructed among the resulting driver groups and propagated through the model. Shapley-style variance attribution compares driver importance under independent and dependency-informed assumptions.

Applied to Rittershoffen, dependency-informed scenarios changed the ranking of critical drivers compared with independence-based sensitivity analysis and conventional variance-based rankings such as Sobol. This indicates that dependency assumptions can affect uncertainty propagation and which parameters appear most important for data collection and decision support. The approach does not replace supplier or operator data, but provides a strategy for avoiding unrealistic independence assumptions, documenting structural relationships, and identifying the primary data most valuable for future engagement. More broadly, the work shows how LCA practitioners can maintain robustness when primary data exchange remains limited.

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3.02.T03 Market averages may obscure structural supply chain uncertainty in LCA and Scope 3

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Companies conducting product-level LCA, PCF and Scope 3 reporting have to decide which purchased goods require primary supplier data and which can rely on secondary market-average datasets. Engaging suppliers across thousands of inputs is rarely feasible, yet decisions about where to seek supplier data typically rely on significance analysis using generic averages, rather than quantitative analysis of the supply chain for specific goods. The current approach often relies on market activities from databases such as ecoinvent to derive initial estimates, with uncertainty around the estimate characterised through the pedigree matrix approach as a single-peaked distribution centred on the weighted average.

We argue this approach for deriving significance can systematically misrepresent uncertainty for goods supplied by diverse production processes, with consequences for supplier engagement strategy. Where supplier production routes for the same good differ substantially in environmental intensity, the true distribution may have multiple peaks or be much wider than the default approach suggests, and the weighted average may fall in a region where no real supplier operates. In these cases, primary supplier data is essential. In markets where production routes are similar in environmental intensity, the market-average is adequate and supplier engagement efforts may be better directed

elsewhere.

We are developing a weighted-sampling methodology that decomposes ecoinvent market activities into their constituent production routes and resolves geographical and technological uncertainty by sampling from each route in proportion to its market share, implemented in Brightway2. We apply it to 16 widely consumed market activities spanning primary metals, energy carriers, chemicals, and construction materials, comparing each resulting emission factor distribution against the conventional pedigree-only approach and separating total variance into within-route and between-route components.

We anticipate the results will support a prioritisation framework based on route heterogeneity and purchasing frequency, indicating for which kind of good primary, supplier-specific data is methodologically necessary and where market-averages are defensible. The aim is to give LCA practitioners and Scope 3 teams a quantitative basis for improving supplier data collection processes across diverse procurement portfolios.

3.02.T04 Collaborative LCA in Battery Value Chains: Insights from Stakeholder Workshops Around Primary Data Exchange

Exchanging primary supplier data for Life Cycle Assessment (LCA) across complex supply chains remains difficult in practice, especially as confidentiality concerns frequently limit what actors are willing to share. The battery sector exemplifies this challenge, with actors spanning mining, cell manufacturing, assembly, and recycling, each holding critical primary data they are reluctant to provide. However, with the Carbon Footprint declaration and Digital Battery Passport required by the new EU Battery regulation (EU 2023/1542), there is a growing regulatory pressure to report environmental performance based on primary data.

This contribution draws on the development of a collaborative LCA platform for the battery value chain to examine stakeholder priorities around primary data exchange. The platform operates as a parametrised configurator to facilitate LCA for non-experts: for each life cycle stage and production sub-step, users input flow quantities and select relevant parameters (process type, geography, transport), which are automatically linked to an EU 2023/1542 and ISO 14040/44 compliant Life Cycle Inventory database built for the tool. For a collaborative LCA, suppliers can be invited directly to contribute their own process data within the model, with a governance mechanism that restricts the project owner's access to raw supplier inputs while preserving full use of results in the overall model, a design response to the confidentiality concerns that routinely block supplier engagement in practice today.
In the design stage of the platform, stakeholder workshops are conducted to validate design priorities and verify that the tool addresses real-world constraints.

We present findings from the first two stakeholder workshops around user experience, confidentially architecture, and background data, mobilising over 30 actors across the battery value chain. Participants from different tiers of the supply chain help capture diverging perspectives on what makes a collaborative LCA tool both safe enough to use and practical enough for users without LCA expertise. These constraints and insights are then integrated into the platform development and the underlying inventory database. Results highlight that confidentiality governance, primary data verification, and interface simplicity are perceived as equally important as background data quality for an effective deployment of the tool.

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3.02.T05 Ensuring Data Quality in a Shifting Landscape: Challenges and Opportunities in Supplier LCI

Collection

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Essity is a global, leading hygiene and health company. Every day, our products, solutions and services are used by a billion people around the world.
High quality primary supplier data has become essential for Essity's LCA work, Scope 3 reporting and meeting growing customer expectations. Based on extensive experience across diverse material categories, this contribution explores the practical challenges of securing reliable and comparable LCI data from suppliers.
Although Essity maintains long-standing relationships with pulp suppliers, obtaining robust LCI datasets remains challenging. Even in this more regulated sector, incoming data often require extensive quality checks that can significantly modify initial values. For new suppliers, Essity's multi year internal LCI database is critical for validating plausibility and ensuring consistency. For other materials, where Essity sources smaller volumes and regulatory requirements are less stringent, data collection becomes even more difficult. These suppliers frequently lack LCI experience, resulting in higher variability and lower quality.
At the same time, Essity observes a clear trend: suppliers increasingly prefer to provide product carbon footprints rather than full LCI datasets. This shift is driven by the growing focus on less resource-intensive carbon accounting due to its alignment with SBTi reporting requirements. However, different types of environmental assessments require varying levels of data detail and transparency. When suppliers start using product carbon footprints as a quicker substitute for full LCI datasets, several issues can arise, including reduced insight into underlying processes, fewer methodological options for analysis, and lower comparability across suppliers. This shift risks oversimplifying environmental performance when consistent, and methodologically robust data is essential for credible decision making.
These experiences reinforce why primary LCI data remains Essity's preferred approach. By contributing these insights, we aim to support the development of harmonized approaches for primary supplier data exchange and advance consistent, scalable use of supplier specific LCI data across value chains.

3.02.P - Exchanging Primary Supplier Data Along the Value Chain – Approaches, Leanings and Challenges for Supplier Engagement

3.02.P-We052 A Collaborative Systematic Review of LCA data formats: Benefits, Limitations, and Silos

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At the Brightcon 2025, Départ de Sentier highlighted three fundamental life cycle assessment (LCA) data-related challenges (findability, maintenance, and flexibility) and decided to focus on three solutions: vocabulary, models, and data. Although the community recognizes the need for FAIR (findable, accessible, interoperable and reusable) principles in LCA data, the landscape remains fragmented regarding these principles. To the best of our knowledge there exists no systematic review of LCA data formats. This gap creates a dual risk: it leaves LCA practitioners without a roadmap to navigate software and data format silos, and it prevents developers from leveraging historical design choices to inform future data formats development. Furthermore, most of the studies discussing LCA data formats seem Western-centric biased, potentially overlooking significant data format developments from East Asia and the Global South.

This study provides the first systematic review of LCA data formats. We include 100+ studies in the review to summarize the benefits, limitations, and silos of current data formats. The raw data and resulting visual representations will be available on GitHub. We aim at making this work collaborative. Through this open-source collaborative public repository, we invite the LCA community to expand the review beyond Western-centric sources. This ensures that the findings remain relevant as new LCA methodology, database and software emerge globally, directly supporting the goal of identifying and overcoming data silos in sustainability practices.

3.02.P-We053 Developing Regionalized Construction Life Cycle Inventories from Primary Supplier Data

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Construction life cycle assessment depends on reliable inventory data, but many studies still rely on generic datasets that do not reflect local production conditions. This is a significant limitation for primary construction materials, where results can vary by region because of differences in raw material sourcing, fuel use, electricity grids, production technologies, transport modes, and recycled content.

This presentation shares progress and lessons from a Canadian initiative to develop national and provincial average life cycle inventory datasets for construction materials. The work focuses on direct engagement with industry associations and their material producers to collect primary production data and convert facility-level information into representative (industry-average) datasets for use in life cycle assessment, environmental product declarations, procurement, and research.

The approach combines primary data collection, technical review, aggregation rules, and database formatting requirements. Data requested from suppliers includes production volumes, raw material inputs, fuels, electricity, process emissions, waste flows, transport information, and other material-specific parameters. The work also requires decisions on minimum participation thresholds for regional averages, treatment of outliers, alignment with product category rules, and the level of detail that can be shared publicly without exposing commercially sensitive information.

Several lessons have emerged. Supplier engagement is strongest when the purpose of the data request is clear, the reporting burden is limited, and participants can see how the resulting datasets will support credible environmental product declarations and future low-carbon procurement. The main challenges are not only technical. They include inconsistent data formats, different metering practices across facilities, limited access to upstream supplier information, confidentiality concerns, and the difficulty of balancing transparency with data protection.

The findings show that primary supplier data exchange for construction materials requires both sound life cycle assessment methods and careful governance. A practical pathway is needed to move from confidential plant-level data to regional datasets that are robust, reusable, and trusted by practitioners. These lessons are directly relevant to other sectors seeking to replace generic background data with supplier-informed inventories along complex value chains.

3.02.P-We054 Environmental Impacts of Bridal Fashion: A Supply Chain and Life Cycle Assessment Study

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While the fashion industry continues to contribute to global environmental problems, an increasing number of consumers seek products that align with their sustainability values. This research focuses on bridal fashion and presents a case study of a Belgian bridal dress designer. Bridal designers face the challenge of assessing the environmental performance of their products and communicating this as part of their value proposition.

The sustainability strategy of the designer in this case study is linked to the ambition of working with short supply chains, emphasizing regional sourcing and regionally made materials. The first aim of this study was therefore to investigate and map the textile and trims supply chain of a representative wedding dress from the designer's collection, to assess whether the supply chain can be considered short. Spatial material flow mapping was used to identify key actors, origins, and transport steps.

In a second step, the environmental performance of the wedding dress was quantified using a Life Cycle Assessment (LCA) based on the Environmental Footprint method, including production and packaging of the final dress. By weight, the dress consists mainly of polyester (over 50%) and viscose (around 40%). Despite the designer's ambition, the supply chain analysis showed that 95% of the dress fabrics by weight originated from Asia, indicating a long upstream supply chain. The LCA results showed that packaging materials account for approximately 30% of the total single score impact. For the dress itself, the most relevant impact categories were climate change, particulate matter formation, fossil resource use, acidification, and mineral and metal resource use. Environmental hotspots were identified in fiber production (26%), yarn production (14%), fabric production (37%), and confectioning (18%), with notable contributions from viscose fiber production and transport between the designer and tailor using a petrol vehicle.

Scenario analyses were conducted to assess alternatives under the designer's control, including hanger material, fabric waste end-of-life treatment, and transport modes. Fabric substitution scenarios were not considered, as material choices must balance sustainability with design-related quality requirements. Future research could explore how environmental impacts might be reduced through earlier material-related design decisions and strategies to increase use intensity, such as modular design or designing for reuse.

3.03 - From Decommissioning to Design: Integrating Circular Economy into LCA of Energy Systems.

3.03.T01 Power Infrastructure Lifespans and End-of-Life Dynamics for Circular Energy System Design

Renewable energy is central to decarbonisation strategies, driving rapid deployment of wind, solar, and other low-carbon technologies. While life cycle assessment has improved understanding of emissions and material demands during construction and operation, end-of-life phases remain comparatively underexplored. This gap is critical, as decommissioning and replacement of energy infrastructure determine environmental impacts and opportunities for material recovery, site reuse, and industrial system transformation. This study examines the role of infrastructure lifespans as a key determinant of end-of-life material flows and system-level circularity. It addresses a central question: how do real-world operational lifetimes of power-generation assets shape the timing, scale, and characteristics of decommissioning, and what are the implications for integrating end-of-life considerations into future energy system design? A harmonised dataset of empirical lifespans across major power-generation technologies is compiled and compared with reported technical design ranges. This comparison enables the identification of assets operating below, within, or beyond expected lifetimes, providing a consistent basis for characterising infrastructure turnover. Preliminary findings indicate substantial variation in operational lifetimes across technologies, leading to asynchronous and uneven end-of-life material flows. These dynamics influence the feasibility of circular strategies, including secondary material supply, infrastructure repowering, and site reuse, and highlight constraints related to timing and scale. The study demonstrates that infrastructure lifespans are not fixed technical parameters but rather system variables that mediate the interactions among deployment, decommissioning, and circularity. Integrating empirically grounded lifespan dynamics into energy system planning and life cycle assessment can improve the evaluation of end-of-life strategies and support more effective policies for material reuse, infrastructure repurposing, and just transitions.

3.03.T02 Incorporating European Union Policies into Prospective Life Cycle Assessment of Solar Photovoltaics Deployment to 2050

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The large-scale deployment of solar photovoltaic (PV) panels required to meet European Union (EU) national energy and climate plans (NECP) is expected to increase pressure on critical raw materials (CRM) and future waste management. Existing directives on waste electrical and electronic equipment (WEEE) and new policies on CRM and net zero industry are expected to influence the future environmental impacts (EI) of solar PV.
To assess these implications, a prospective life cycle assessment (LCA) informed by material flow analysis (MFA) is performed. Five scenarios are defined according to the extent of implementation of relevant EU policies, ranging from a 'no new policy' case to ambitious targets of decarbonization, eco-design, CRM security, and circularity. Evolution of PV stock over 2025-2050 is modelled consistently with time-dependent foreground inventories and future-projected background systems.
MFA results indicate that over 8 million tonnes more of PV waste can be recycled during the studied period following the combined implementation of the WEEE Directive and the CRM Act. Around half the mass of materials required for solar capacity expansion, primarily glass and aluminium, can be obtained from recycling even under ambitious scenarios. Efficient recycling allows 45% of silicon and 76% of silver demand for PV panels to be met. In contrast, eco-design strategies (e.g. lifetime extension and reuse) show reduced flow into recycling, increasing dependence on primary material by 4-5% to meet NECP targets.
Expected improvement in manufacturing (such as thinner wafers) can yield up to 39% reduction of cradle-to-gate

impacts by 2050. Despite this and the increased recycling capacity, production remains to be the primary hotspot across the life cycle of PV panels. Recycling yields net credits across all impact categories studied, except in human toxicity due to residual waste. Despite its small mass contribution, the avoided impacts from recycled silver contribute to 69% and 86% of credits in climate change and material resource impacts, respectively.
Results show that current policies enable significant recycling of PV panels at their end-of-life, mitigating the impacts of expanded solar energy deployment. Potential policies on eco-design and rapid decarbonization should be aware of the implications to material availability and trade-offs in environmental sustainability. Future work is planned to expand this analysis to wind energy and other technologies.

3.03.T03 From Life-Cycle Assessment to Interdisciplinary Insights: Intertwined Dimensions of Fessenheim Nuclear Power Plant Decommissioning from its Human-Environments Observatory

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A Human-Environments Observatory (OHM in French) is an interdisciplinary research framework for studying anthropized socio-ecosystems. The OHM Fessenheim focuses on the impacts of the 2020 closure of the Fessenheim Nuclear Power Plant (NPP) and its forthcoming decommissioning (scheduled for 2026), which together are reshaping the territory's socio-ecological trajectory and driving profound environmental, social, economic, energy, and political implications.

This presentation aims to convey the diversity of knowledge production within the OHM Fessenheim and the science–society interactions it fosters. A survey of 80 stakeholders between 2024 and 2025 aimed to determine the potential roles of an academic observatory for decommissioning (Labat et al. 2026). It highlighted the need to formalize interactions between researchers, institutions, and operators, particularly regarding access to data generated by the latter. It underscores the challenges of this contested industrial sector, where divergent stakeholder interests tend to limit collaboration to strictly regulatory matters.

Regulatory impact studies for NPP decommissioning follow an Health and Environmental Risk Assessment approach, and Life-Cycle Assessment (LCA) is not mandatory. In the Fessenheim case, LCA studies (Iguider et al. 2024, Robineau et al. 2025) were therefore initiated by academia, which influenced their access to data, methodological choices, interpretation, and diffusion of the results.

Moreover, the immediate decommissioning policy interferes with an under-specified legal framework regarding the reuse of buildings. It thus shapes institutional bodies expectations. Indeed, the operator' decommissioning plan mobilized life-cycle thinking to suggest partial reuse of the buildings for the "Technocentre" project, a very-low-level waste recycling installation planned on the Fessenheim site - but not yet approved. The suggestions were skeptically received by the French Environmental Agency reviewing the plan. Critically, their arguments were made on a purely legal basis, not an environmental one.

By identifying these key interacting tensions, and their potential resolution, we aim to clarify the path towards better integration of both circular economy and LCA into decommissioning practices.

Labat et al. 2026. Riséo. 2026.2 (to be published).
Iguider et al. 2024. Int J LCA. DOI: 10.1007/s11367-024-02315-9
Robineau et al. 2025. Sci Total Environ. DOI: 10.1016/j.scitotenv.2025.179200

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3.03.T04 Beyond Maximum Recovery: Stress-Testing Circularity, Environmental Impacts, and Material Criticality at End-of-Life for Offshore Wind

Célestin Demuytere[1], Jo Dewulf[1] and Gwenny Thomassen[1] (1)Ghent University

As early European offshore wind farms (OWF) approach their End-of-Life (EoL) phase, decisions on dismantling, recycling, and repowering are becoming pressing. These decisions shape material recovery, environmental burdens, and exposure to raw material supply risks. Sustainability assessments typically apply material flow analysis (MFA), circular economy (CE) metrics, life cycle assessment (LCA), and material criticality through separate frameworks. Their integration remains uncommon, particularly at EoL while conclusions are drawn from limited point estimates, without consideration of effects in other methodologies or under plausible parameter variation.
Prior analysis (MFA-CE-LCA) of a North Sea OWF compared four EoL scenarios: a baseline, minimal removal, maximal removal, and an alternative design. While collection rates ranged from 5% to 88%, no single scenario dominated across all decommissioning dimensions. Maximal recovery reached high collection rates, yet environmental gains showed signs of saturation as additional recovery targeted materials with lower avoided burdens.
Building on this framework, criticality introduces a third dimension while the robustness of the prior conclusions is examined in three steps. First, the four scenarios are reproduced and a criticality score is derived using the CriticS method, complementing the CE and LCA indicators. Characterisation factors focus on the steel alloying elements (Cr, Ni, Mn), Cu, Al, and precious metals. Second, input parameters are varied within case study-relevant and expert-informed ranges. These include retrieval and recycling efficiencies, background energy mix, and transport distances. Stress tests cover interactions while a breakpoint analysis identifies parameter values at which scenario dominance or trade-off direction could reverse. Third, baseline conclusions are classified as robust, contingent, or fragile, depending on whether they hold across, depend on identifiable conditions within, or reverse inside the explored parameter range. The analysis aims to identify parameter conditions under which each EoL strategy retains its advantages, shifting OWF EoL evaluation from point-estimate rankings towards threshold-informed decision support. It also extends integrated EoL assessment with a criticality lens that has so far remained outside approaches for offshore wind, supporting sector preparedness for upcoming decommissioning waves where rare earth dependencies will add to its complexity.

3.03.T05 Wind Turbines as Material Assets: Rethinking Circularity at End of Life

Jennifer Hawkin[1] and Fanran Meng[1] (1)University of Sheffield

Wind energy is central to global decarbonisation, but it is also a rapidly expanding materials system. Modern wind turbines use large volumes of tonnes of steel, concrete, composites, copper, and rare earth elements. As the first large-scale deployments from the early 2000s approach the end of their design lives, the sector faces a growing wave of decommissioning and repowering. End-of-life volumes are expected to increase non-linearly, creating an urgent need to manage material flows effectively.

While much of a turbine’s mass, particularly steel and copper, can be readily recycled, the core challenge lies in material complexity. Composite blades, typically made from thermoset resins, are difficult to recycle and often downcycled or disposed of. Foundations are frequently left in situ, and material recovery is further complicated by limited standardisation and incomplete data on turbine composition. These technical barriers are compounded by economic and system constraints: virgin materials often remain cheaper than recycled alternatives, logistics costs are high, and responsibilities across the value chain are fragmented.

At the same time, current industry practices and incentives do not consistently align with circular outcomes. Repowering decisions, for example, are often driven by economic gains from higher-capacity turbines, but can accelerate material turnover and waste generation in the near term. Although innovation is emerging, including

recyclable blade materials, alternative designs, and improved tracking of material flows, these solutions have yet to scale.

This work reframes wind turbines as long-lived material assets rather than purely energy-generating infrastructure. It argues that achieving circularity in the wind sector requires coordinated changes across design, policy, and business models, including design for disassembly, high-value recycling pathways, and stronger alignment between economic and environmental incentives. Without such changes, there is a risk that the sustainability gains of wind energy could be undermined by growing material impacts at end of life.

3.03.P - From Decommissioning to Design: Integrating Circular Economy into LCA of Energy Systems.

3.03.P-We055 When Does Methane Pyrolysis Become Competitive? A Sensitivity-Informed Life Cycle and Total Cost Assessment of Hydrogen Pathways

Yuchen Zhang[1], Justin Prabowo[1], Yangyang Wang[1], Zhiyan Lee[1] and Yuan Chen[1] (1)School of Chemical and Biomolecular Engineering, The University of Sydney

Methane pyrolysis is increasingly discussed as a low-carbon hydrogen production route, but its environmental and economic competitiveness depends strongly on conversion efficiency and treatment of the solid carbon co-product. This study develops a harmonised cradle-to-gate life cycle assessment and total cost comparison for methane pyrolysis, steam methane reforming, steam methane reforming with carbon capture and storage, and water electrolysis, using a consistent functional unit of 1 kilogram of hydrogen delivered at 200 bar. A unified life cycle inventory is implemented in SimaPro and assessed using ReCiPe 2016 midpoint indicators and monetised endpoint indicators to support decision-making. The analysis further tests how avoided-product credit for marketable carbon black changes the relative performance of methane pyrolysis. Results indicate that methane pyrolysis without co-product credit only approaches the greenhouse gas performance of conventional steam methane reforming at near-complete methane conversion, whereas inclusion of avoided-product credit substantially improves performance and can bring methane pyrolysis close to steam methane reforming with carbon capture and storage under favourable conditions. Total cost results show that competitiveness is highly sensitive to methane conversion, electricity carbon intensity, and carbon market assumptions. The study demonstrates how harmonised modelling and sensitivity-informed interpretation can improve the use of life cycle approaches for decision support in emerging hydrogen energy systems.

3.03.P-We056 End of Life Management for Solar Panels

Jennifer Hawkin[1] and Fanran Meng[1] (1)University of Sheffield

The global deployment of photovoltaic (PV) systems is accelerating rapidly, with installed capacity rising from ~0.04 TW in 2010 to ~1.6 TW in 2023, and projected to reach ~6 TW by 2030. However, this expansion is geographically uneven, and prevailing market and regulatory structures shape the extent to which circularity can be achieved. Without intervention, several challenges may undermine the sustainability of PV deployment, including lifecycle emissions, the transboundary export of waste, regional concentration of critical materials and manufacturing capacity, emerging material risks, and growing geopolitical dependencies.

At the same time, circular economy strategies present significant opportunities to mitigate these risks. These include reducing lifecycle emissions, alleviating material supply constraints, and fostering new industries and economic value from end-of-life (EOL) systems. While prior reviews have largely focused on recycling technologies, broader circularity strategies (such as lifetime extension, reuse, and system-level design) remain underexplored, particularly in relation to non-technical barriers and enablers.

Here, we provide a comprehensive review of both technical and non-technical dimensions of PV circularity. We examine material use and technology trends, panel composition and critical materials, waste generation projections,

and the role of markets, business models, and policy frameworks. We further assess circular strategies, including reuse, refurbishment, and recycling, alongside design approaches that enable circularity. Regional differences and future deployment scenarios are considered throughout.

This review addresses key questions regarding the extent of material supply risks and geopolitical dependencies, the environmental and economic case for increasing PV circularity, the influence of market structures on EOL management, and the effectiveness of existing policy frameworks. The findings aim to inform policy and industry strategies to reduce future deployment constraints, minimise unjust waste practices, and support a more resilient and sustainable global PV system.

3.03.P-We057 Environmental Life Cycle Assessment of Offshore Wind Power: Results from a Systematic Review

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Offshore wind farms are a key renewable energy technology for decarbonization, but the environmental performance should be assessed across the full life cycle, not only during operation. This study systematically reviews environmental life cycle assessment (LCA) research on OWF published between 2010 and 2026 using the PRISMA framework. The objective is to identify persistent environmental hotspots and methodological patterns across the literature and to develop a framework. Data were extracted from 99 studies, including 75 LCAs, and 24 review articles covering geographical scope, system boundaries, functional units, life-cycle stages, impact categories, and environmental indicators. The studies are concentrated in China, Europe (North Sea), UK & USA, while other countries are barely represented. Most studies assessed OWFs in general, while fewer focused separately on floating or fixed-bottom types. The manufacturing stage is consistently identified as the main contributor to environmental issues, followed by raw material extraction. Operation and maintenance have comparably low impacts. However, the impacts associated with this stage are mostly biodiversity-related indicators linked to operational and site-specific marine contexts. Climate change is the most consistently assessed impact category, with most reported values ranging from 6.5-30 g CO2 eq/kWh, followed by acidification, eutrophication, freshwater and marine ecotoxicity, particulate matter, and human toxicity, with major contributions linked to steel, concrete, and composite-intensive components. The review also reveals substantial variation in methodological choices, particularly in system boundaries and impact category coverage, limiting direct comparability across studies, which highlights that OWF environmental LCA is expanding, but direct comparability is still limited. Therefore, there is a clear need for a framework to enable consistent comparison of results to support decision-making in OWF.

3.03.P-We058 Environmentally Strategic Decommissioning of Gas-Cooled Nuclear Reactors Led by Life Cycle Assessment

Jesse Farrell[1], Laurence Stamford[1] and Anthony Banford[2] (1)University of Manchester, (2)United Kingdom National Nuclear Laboratory

Decommissioning of the UK's Advanced Gas-Cooled Reactor (AGR) fleet is a project beginning imminently which is expected to cost £20 billion and last into the 22nd century. This will be one of the country's largest nuclear decommissioning projects, covering 14 reactors at 7 sites across the country. To date, environmental impact assessments have been either qualitative or based on general construction industry norms, and there is potential for more in-depth analysis to yield environmental and economic opportunities. Similarly, much prior life cycle assessment (LCA) literature has focused on front-end activities like construction and the fuel cycle, leaving decommissioning underexplored.

This project is using lifecycle assessment and lifecycle costing to compare the baseline decommissioning scenario (deferred dismantling of the reactor structure) with other strategies such as immediate dismantling and in-situ

decommissioning (permanent encasement in concrete). Additionally, hotspots identified will guide recommendation of smaller-scale improvements e.g. usage of sustainable construction materials. Sensitivity analysis will consider the impacts of delays in the project and in supporting projects, which has been a common issue in the UK nuclear sector.

Findings of all of these will be reported back to the Nuclear Decommissioning Authority the government body responsible for all UK decommissioning activities and Nuclear Restoration Services, the company which will be carrying out the work.

In addition to the direct opportunities to advise on the best methods for AGR decommissioning; this research can inform good practice for decommissioning projects abroad. It will also be one of very few LCAs focusing specifically on nuclear decommissioning and can help inform future policymakers on the environmental impacts that can be expected.

The work presented at this conference will be the findings from the initial model of the baseline decommissioning scenario and sensitivity analysis.

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3.04 - From Earth to Space: Enhancing Life Cycle Assessment for Sustainable Space Activities

3.04.T01 Application of PEF method in the space sector: lessons learned and challenges to overcome

An De Schryver[1], An Vercalsteren[2], Jean-Loup Rondeau[3] and Carolin Spirinckx[2] (1)PRé Sustainability, (2)Flemish Institute for Technological Research (VITO), (3)NovaSpace

The space sector is a unique sector, which has exceptional long production/development times with little to no mass production lines. The environmental impact of space missions is as such not only driven by material use, but also by R&D and testing. Moreover, space missions create not only environmental impacts on Earth, but also at higher atmospheric altitudes and space. This makes the application of standard LCA methodologies or the PEF methodology very challenging.
With the aim to establish a standardised method for assessing and reducing environmental impacts across the EU space sector, in October 2024 the development of the Product Environmental Footprint Category Rules for the space sector (PEFCR4Space) took off. Members of the Technical Secretariat, consisting of representatives from the European Commission (DG DEFIS and JRC), the space sector and LCA/PEF experts , worked during 1.5 years to develop a first version of horizontal modelling rules for the space sector and specific vertical rules for 6 sub-categories. During this process, over 30 expert meetings took place in which numerous space sector-specific issues and challenges were discussed. Examples of specific points of attention are: the FU which is rather a service than a product in scope, the complex products and supply chains, the broad scope of activities and processes covered (such as test models and R&D activities), the exceptional geographic and temporal boundaries, the relevant environmental impacts and elementary flows missing in standard LCA and PEF methods, the very specific end-of-life activities and the limited availability of company-specific data.
The learnings over these 1.5 years were large. While a practical and applicable PEFCR is in the make, not all challenges were overcome and recommendations for the next version of the PEFCR are being identified. This presentation will outline the learnings and recommendations both from the perspective of the process and of the content for (i) future PEF methodology developments, as well as for (ii) future updates of the PEFCR4Space. These recommendations are based on learnings from the technical secretariat and working group meetings, the modelling of the market averages for each sub-category, stakeholder feedback during the first open consultation, and the first review round of the PEFCR and sub-category studies.

3.04.T02 Evolving Data and Modelling Approaches in Iterative LCA for Space Missions

Stefanie De Smet[1], Lise Asscherickx[1], Ariane Bouilly[2] and Enrico Tormena[3] (1)VITO, (2)Airbus Defence and Space GmbH, (3)ESA

Life cycle assessment is increasingly used to support sustainability decision-making in complex, high-technology sectors. In the space industry, its application is challenged by long development timelines, evolving designs, and limited data availability. This presentation analyses how data availability evolves across development phases and how this influences methodological choices and modelling approaches in life cycle assessment.

At equipment level, early-phase assessments typically rely on proxy data derived from material declarations, while later phases allow the integration of more detailed models that include manufacturing, assembly, integration, and testing processes.
At component level, generic proxy datasets are commonly applied in early stages. As development progresses, targeted data collection enables refinement of these proxies by adjusting key parameters or subcomponents, improving representativeness without requiring fully detailed primary data models.

These methodological choices and differences in data granularity can significantly influence impact estimates and hotspot identification. This presentation further shows how these evolving approaches affect impact results at system level, when moving from simplified to more detailed models. Particular attention is given to the trade-off between model complexity and LCI data collection effort, as well as strategies to improve efficiency and consistency in iterative assessments.

3.04.T03 Simplified Life Cycle Assessment of a Battery Module for Reusable Launch Vehicles – Methodological Choices and Initial Results

Mathieu Udriot[1], Marnix Verkammen[1], Guillaume Bonneau[2], Angel Iglesias[2] and Jan-Steffen Fischer[1] (1)EcoDeltaV Sàrl, (2)Almatech SA

Space industries — from primes to smaller SMEs in their supply chains — must now comply with environmental requirements from space agencies. Additional regulations like the European Space Act are expected around 2030, and some companies are already including an environmental criteria in their multi-objective design process.
In this context, Almatech is developing, together with its partners, an innovative battery module for reusable launch vehicle applications. The solution is based on a multifunctional additively manufactured structural frame, combined with battery cells and a health-monitoring approach. Compared with conventional battery architectures, the concept aims to reduce integration complexity, improve maintainability, and enable refurbishment and repeated use, which are seen as key levers for lowering environmental impacts in reusable launcher operations.
The purposes of the simplified Life Cycle Assessment study conducted by EcoDeltaV on the battery module are three-fold: 1) better understand the environmental hotspots of the product's lifecycle with its added functionalities, 2) find areas where ecodesign could be applied to reduce the impacts, and 3) investigate the potential environmental benefits of the aforementioned key levers at system level.
This presentation covers the LCA steps applied to the battery module, the assumptions, and the adapted methodology to consider the reusability aspect at system level, when the product is integrated in the operations of a reusable launch vehicle. This use case aligns with ongoing European LCA and ecodesign methodological progress, including with the expected harmonization between the PEFCR4space and ESA LCA guidelines in their latest versions. The usability of the recent ESA handbook update, the limitations of the study, and the challenges faced to apply simplified LCA at equipment and system levels are discussed.

3.04.T04 Leveraging Uncertainty Assessment for Insight into Space System Life Cycle Assessments

Jason James[1], Amanda Filie[1], Ann Michelle Morrison[2], Achim Wechsung[2], Ryan Harrington[2], Shana Diez[3], Nicholas

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Life cycle assessment (LCA) of space systems remains a developing field with limited publicly available process data and inconsistent methodological boundaries. The European Space Agency's LCA guidelines and recent space-specific LCA conference forums continue to stress the need for transparent, harmonized frameworks that capture the full environmental footprint of launch vehicles. To address this gap, SpaceX has undertaken a first-of-its-kind process-based LCA of greenhouse gas emissions (GHG) for Starship, which will be the first fully reusable two stage launch vehicle.

For the preliminary cradle-to-grave GHG life cycle model for Starship, the life cycle inventory (LCI) was assembled using both primary process data provided by SpaceX and secondary data from the ecoinvent database. This study quantified the uncertainty around material and energy flows of the LCI, such as variation in fuel consumption during engine acceptance testing and variation in electricity use for manufacturing processes. Through Monte Carlo sampling of the statistical distributions that characterize variation in primary processes—coupled with ecoinvent's pedigree matrix scores for secondary data—uncertainty analysis was used to constrain the plausible GHG footprint of Starship and identify the processes with the greatest contributions to variation in the total footprint.

While this study is ongoing, preliminary results indicate that testing of energy-intensive manufactured parts, such as acceptance testing of rocket engines, substantially contributes to the carbon footprint of rockets. By increasing the lifetime of these GHG and energy intensive components, fully and rapidly reusable space vehicles can provide significant reductions in GHG emissions. The framework developed herein establishes a replicable process based methodology aligned with emerging European guidance and ISO standards, supports harmonized assessment of space launch systems, and underscores the importance of considering complete life cycles when developing policies and standards for low impact space access.

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3.04.T05 Parametric LCA for Space

Constellations of LEO satellites, used mainly for telecommunications and imaging, are growing exponentially (EPRS, Sept. 2025). If the sector continues on this trajectory, more than 100,000 LEO satellites will be in orbit by 2030, compared with around 10,000 today (ESA 2025). As well as raising questions of sovereignty at European level this expansion is causing environmental concerns. Indeed, the impacts remain difficult to assess for many reasons: the complex chemistry of the stratosphere, very different from that of the troposphere, making it difficult to produce reliable impact factors; a lack of transparency from industry players regarding manufacturing processes; and the absence of methodological standardisation within the sector, amongst others.

The PEFCR4Space framework will establish a methodological framework and ensure comparability across studies. However, it does not (yet) address concerns regarding data confidentiality.
Currently, the studies carried out by the sector's stakeholders are considered too sensitive for their results to be shared externally. However, many players in other industries (such as telecommunications) offer services that rely on space infrastructure. They therefore need access to this footprint data to be able to carry out an end-to-end LCA of their services, which is currently impossible.

To address this need, we have recently produced environmental data for satcoms (LEO satellites and launchers) for ADEME.

We see great potential for parametric LCA in the space sector and, as we have done for the digital sector, we wish to develop parametric models for this sector. For over three years now, Resilio has been developing its own

environmental database for IT, ResilioDB. This dynamic parametric approach makes it unique as it offers far greater transparency and makes updates much easier.

The problems in the space sector this approach addresses? It provides a variable level of granularity, depending on the user's level of information.
How? By pre-filling the model with default values for the parameters. For the time being, these are drawn from the literature, but eventually they will be supplied directly by the industry for even greater precision (using average, benchmark value to ensure data confidentiality). Users with access to highly detailed information can change the default values to better reflect their reality, whilst others will have access to average data (admittedly imperfect, but transparent and reliable).

3.04.P - From Earth to Space: Enhancing Life Cycle Assessment for Sustainable Space Activities

3.04.P-Tu016 Life Cycle Assessment of the Copernicus CO2M Flight Calibration Unit Developed at the Centre Spatial de Liège

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The space industry is experiencing an ecological awakening, mainly led by European stakeholders. The Life Cycle Assessment (LCA) methodology was deemed the most suitable to evaluate the environmental impacts of space activities. Centre Spatial de Liège (CSL) does not have any LCA expertise, and has thus decided to take the lead by conducting its first LCA on the Copernicus CO2M Flight Calibration Unit (FCU) within the context of a Master's thesis at Université de Liège. This study aimed to reveal the potential barriers that prevent CSL from performing an LCA under proper conditions, and the environmental hotspots linked to CSL's activities.

A cradle-to-gate approach was used, since CSL's responsibility ends at the delivery of the three flight models to Thales Alenia Space (TAS), its prime contractor. The LCA database and handbook developed by ESA were intensively used to conduct this LCA, as well as the first draft of the PEFCR4Space. The functional unit is "three flight FCU models delivered to TAS". Since the second and third flight models are still under development, the impacts linked to the first flight model will be extrapolated to the other two flight models.

The main challenge that was encountered in this LCA was the lack of primary data at CSL, since the entire organisation of the facility was not designed to facilitate primary data collection. This proved to be an issue for the modeling of CSL's ISO 7 clean room, which is often a hotspot in similar LCA's due to its major electricity consumption. Furthermore, given the size of the clean room (15 500m3), many projects are constantly present in the clean room, rendering the allocation problem very complex.

The study is still being carried out, but environmental hotspots should be linked to office work (commuting and electricity/heating) linked to the development of the FCU and manufacturing, assembly, integration and testing activities, the electricity consumption linked to both clean room usage and production of liquid nitrogen for TVAC testing. Another hotspot should be caused by the use of PTFE powder for the production of the diffusers of the FCU.

The findings of the study will be publicly shared, to help other space LCA practitioners, and feed the ESA database. Suggestions for ecodesign at the level of CSL will be made, as well as recommendations on the organisation of both projects and facility to ease primary data collection and increase the accuracy of future LCA's.

3.04.P-Tu017 Assessing Readiness for Implementing Life Cycle Thinking and Ecodesign in Space Projects: A Cross-Sector Benchmarking Analysis

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Technological Research (VITO), (2)Novaspace GmbH, (3)ESA Strategic Sustainably Office, European Space Agency (ESA)

The European space sector is increasingly integrating environmental sustainability into its programmes, with life cycle assessment (LCA) and ecodesign playing a growing role in addressing environmental impacts and identifying opportunities to reduce them. However, embedding these approaches consistently across complex space projects remains a challenge, particularly in the context of emerging policy and evolving sector requirements.

This work examines how sustainability ambitions can be translated into actionable practices within space programmes. It establishes the current status of LCA and ecodesign in the space sector and benchmarks it against similar industries, including automotive, construction, and battery technologies. The analysis aims to understand how LCA and ecodesign are implemented in practice and to identify transferable insights to support the space sector in their integration in the context of emerging ecodesign policy.

To support this analysis, a cross-sector benchmarking was carried out based on literature review, expert input, and stakeholder interviews. Sources were analysed and mapped across sectors to compare implementation practices and maturity levels. The assessment was structured along key dimensions covering governance and requirements, implementation and engineering integration, stakeholder and supply chain aspects, and programmatic impacts and challenges.

Results show that while LCA practices are increasingly standardised, ecodesign maturity varies significantly and is strongly driven by regulatory frameworks and governance structures. Programmatic impacts such as cost, schedule, and resource implications are predominantly reported qualitatively, reflecting limited availability of harmonised quantitative data. Leading sectors achieve effective implementation through early integration into design phases, strong coordination, and standardised data frameworks.

The analysis also indicates that the space sector has already established key enabling elements, including LCA guidelines, databases, and an emerging ecodesign policy supported by centralised governance. These elements position the sector to advance implementation, while highlighting the need to align methods, strengthen data flows, and support supplier engagement.

This study provides insights into the readiness of the space sector to operationalise life cycle thinking and ecodesign, supporting their more systematic integration in complex engineering programmes.

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3.04.P-Tu018 Deployment Feedback On OASIS: A Parametric Environmental Assessment Tool For Orbital Systems

Xavier Loizillon[1] and Eric Lorigny[2] (1)SCALIAN, (2)CNES

Developed within CNES, the french space agency, OASIS (Orbital projects: Assessment of Simple environmental Impact Software) is a parametric tool designed to rapidly estimate the environmental impacts of space systems from the early design phases. It relies on the consolidation of Life Cycle Assessment (LCA) data from internal projects and sector-wide references, addressing the uncertainty and low maturity of input data at this stage.

Based on a limited set of technical parameters (mass, system architecture, mission profile, ground and launch segments), the tool provides order-of-magnitude impact estimates—particularly for carbon footprint—while ensuring methodological consistency across projects. To date, 30 projects have been assessed, contributing to the continuous

enrichment of the database and the expansion of the covered scope.

OASIS also includes model sharing and data capitalization features, enabling efficient feedback loops and convergence of assumptions across teams. The tool is currently being evaluated by major space stakeholders (ESA, Airbus, Thales…) to strengthen its robustness and support the harmonization of practices.
With a modeling time of less than one hour and computation time of a few seconds, OASIS enables the systematic deployment of environmental quantification at portfolio level. The results support cross-cutting analyses (benchmarking, sensitivity analysis, identification of key drivers) and provide an operational lever for implementing eco-design strategies and low-carbon roadmaps, for example, through the annualization of emissions associated with a portfolio of projects.

3.04.P-Tu019 The Environmental Footprint of Space Activities: an EU Perspective on Scientific State of Play, Challenges and Opportunities

Antoinette Ott[1], Thibaut Maury Micolier[2], Vera Pinto[2] and Fulvio Ardente[1] (1)European Commission - Joint Research Centre (JRC), (2)European Commission - DG DEFIS

While acknowledging that space activities are essential for the European Union and can improve sustainability on Earth, one must also consider the environmental impacts they generate over their life cycle. These effects are not yet well characterised, highlighting the need to develop a common methodological framework for environmental assessment. In that context, the EU Space Act proposal incorporates a Sustainability pillar building on the Environmental Footprint method recommended by the European Commission, based on Life Cycle Assessment (LCA). Applying this framework to space activities requires a holistic view that (i) spans the full life cycle of a mission and (ii) captures emerging impacts specific to space systems. Existing LCA methodologies don't yet adequately model several aspects, such as energy intensive tests, specific materials and equipment, emissions into the upper layers of the atmosphere, and impacts on the orbital environment and astronomical observations. This limitation hinders trade-offs, such as between the orbital domain and the Earth environment. The interlinked system formed by these impacts, and the associated risk of burden shifting across life cycle stages, underscores the need to assess how this could be integrated into the LCA methodological framework.
This presentation proposes to critically review existing scientific literature, aggregating available facts and figures and exploring potential inclusion of relevant emerging environmental aspects related to space activities within the LCA framework. The presentation will be organised following the standardised LCA structure: goal and scope definition, to inventory, impact assessment, and completing it with further perspectives.
Outcomes are expected to highlight pathways to improve LCA for space systems. They will emphasise the need for further scientific research on high-altitude emissions, and to potentially develop specific metrics that characterize uncertain or insufficiently quantified effects of space activities on e.g. ecosystems or shared resources. The findings are expected to contribute to LCA standardisation for space systems, supporting a more robust and holistic approach while enabling its operational implementation.

3.05 - From Ecodesign to E-Waste Reduction: Applying LCA to Enable Environmentally Sustainable Electronics

3.05.T01 Integrating User Behavior into Life Cycle Assessment

Mayra Montoya Flores[1] and Maria Ljunggren[1] (1)Chalmers University of Technology

Household appliances are an essential part of daily life. Their production demands a variety of resources, while their life cycle is characterized by continuous and diverse interactions with users from the moment they are purchased, throughout their use, and until their final disposal. However, the complexity and the implications of these interactions are rarely reflected in Life Cycle Assessment (LCA) studies of household appliances. Instead, it has been seen that most studies rely on assumed use parameters with limited consideration of real-world use patterns. Given the

widespread use, resource intensity, and strong dependence on consumer practices of these products, user behavior plays a pivotal role in shaping their life-cycle environmental impacts and represents a significant opportunity for impact reduction through integrating behavioral insights into product design and environmental assessment frameworks.
Within this context, this study analyzes different user behaviors associated with dishwasher use, explores how these behaviors can be assessed within the LCA framework, and concludes on the implications for dishwasher design and development. The scope follows a cradle-to-grave approach, analyzing user behaviors across acquisition, use, and divestment phases of dishwasher ownership to examine a wide range of behavioral patterns across the product lifecycle. The research focuses on user behavior in Sweden and the Netherlands and is carried out in collaboration with industrial design and product development researchers and two European appliance manufacturers that provide primary data to support both behavioral and environmental analyses.
Findings indicate that regional factors, particularly electricity supply, as well as detergent use and appliance technical lifetime are crucial in shaping the environmental performance of dishwasher user behavior patterns. In particular, the relative contributions of detergents and electricity use, and the resulting implications for sustainable design priorities, vary significantly depending on the electricity mix. A shorter technical lifetime further shifts impact distribution, increasing the relative importance of manufacturing and end of life stages within the overall life cycle. These findings provide an initial basis for developing a systematic approach to incorporating real-world behavior practices and their variability into LCA which can support product designers in early-stage product and service development.

3.05.T02 Assessing the Environmental Impacts of Technical Refresh Cycles in Data Centers Using LCA

Parvathi Maya Thampi[1], Jon Summers[1] and Annie Wyon[1] (1)Research Institutes of Sweden AB (RISE)

In data centers, periodic technology refresh drives server replacement to improve performance and efficiency. As a result, many functional servers are decommissioned and recycled before reaching their full engineering lifetime, accelerating equipment turnover and raising sustainability concerns. Despite the increasing sustainability concerns and climate goals, the environmental impacts of large scale technology refreshes remain insufficiently studied in the industry. This study applies life cycle assessment to evaluate the environmental impacts of massive technical refreshes. A cradle-to-grave LCA was conducted for a data center under alternative technology refresh cycles of 2, 4, and 6 years where the the functional unit is 1000 million ssj_ops per year over a 10-year period. A constant non - AI workload is assumed to compare the different refresh scenarios based on evolution in the CPU technology over the 10 years, to factor in improvement in performance and efficiency. The scope includes only servers, while supporting infrastructure and electrical equipment are excluded to limit complexity. LCI and operational data were derived from publicly available sources, using hardware inventory and performance data representative of servers deployed between 2012 and 2025. Impacts were assessed using the Environmental Footprint 3.1 method across seven impact categories: climate change, water deprivation, abiotic depletion potential (ADP), fossil resource use, ozone depletion, eutrophication, and acidification. The results indicate that a 6-year refresh cycle has overall lower environmental impacts than the 2-year and 4-year cycles, due to reduced number of servers to deliver the same workload over the 10 year study period. Across scenarios, the use phase dominates impacts in the climate change, fossil resource use, and acidification categories, reflecting the influence of operational energy consumption. The manufacturing phase dominates impacts in ozone depletion, eutrophication, and ADP. For ADP, manufacturing accounts for nearly the entire life-cycle impact, with contributions of other phases being negligible. The end-of-life phase contributes marginally to most impact categories, with water deprivation as an exception. This study supports data center operators by providing quantitative evidence on the environmental impacts of technology refresh strategies, enabling more informed refresh decisions.

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3.05.T03 Life Cycle Sustainability Assessment of Formal Pyrometallurgical and Informal Open Burning Recycling for Gold and Copper Recovery from E-Waste

Saumya Kumar[1], Judith Apsley[1] and Laurence Stamford[1] (1)University of Manchester

The growing consumption of electronic devices has led to unprecedented levels of e-waste, which can serve as a secondary resource containing precious metals and copper essential for circular material recovery, making efficient recycling critical for advancing circular economy transitions. Recycling occurs through formal centralised facilities and informal dispersed operations in developing countries. Among formal methods, pyrometallurgical smelting is the most used approach and open burning is the most common informal method. The environmental performance of both pathways has not been compared in peer-reviewed literature using identical waste inputs and consistent inventory frameworks, creating a knowledge gap. This research develops a comparative LCA of formal pyrometallurgical and informal open burning recycling of waste printed circuit boards. Both pathways rely on thermal processing but operate under vastly different conditions: controlled high-temperature smelting with emission controls versus uncontrolled combustion. We applied Doka's waste-specific lifecycle inventory model to generate composition-specific emission profiles, enabling comparative assessment where comprehensive empirical data is unavailable. Using ReCiPe 2016 across 18 midpoint impact categories, the assessment covers four scenarios spanning two recycling technologies and two regional electricity backgrounds. India is examined as a high e-waste-generating economy where informal recycling dominates, making it relevant for assessing the environmental implications of introducing formal recycling. Europe serves as the formal recycling baseline, and a fully renewable electricity scenario tests the influence of grid decarbonisation, with all scenarios benchmarked against primary production. Formal pyrometallurgical recycling generates substantially lower impacts than open burning, with reductions in human toxicity and ecotoxicity of around an order of magnitude. The electricity background strongly affects climate change results, with formal recycling in India generating up to twice the climate impact of the European case, while the renewable scenario reduces it further. Compared with primary production, formal recycling cuts climate impacts by up to 90% with order of magnitude improvements in toxicity and resource use. These findings support recycling formalisation, grid decarbonisation, and technology transfer as strategies for advancing circular economy transitions in e-waste management.

3.05.T04 Closing the Loop: The Role of Life Cycle Assessment in Optimising End-of-Life Strategies for Point-of-Care Medical Devices Abstract

Sabine Lengger[1], Emily Bezerra[2], Johanna Zikulnig[1] and Mani Teja Vijjapu[2] (1)Silicon Austria Labs GmbH, (2)Silicon Austria Labs

Point-of-care (PoC) medical devices are playing an increasingly vital role in decentralised healthcare, enabling rapid diagnostics and monitoring in clinical and home settings. However, their growing adoption—often characterised by short product lifetimes, single-use components, and strict hygiene requirements—raises significant sustainability challenges, particularly at the end-of-life (EoL) stage. Addressing these challenges is essential to align healthcare innovation with Europe’s circular economy ambitions and policy frameworks such as the European Green Deal and the Ecodesign for Sustainable Products Regulation.

Here,we investigate the role of LCA in supporting environmentally sound EoL strategies for PoC medical devices. Building on insights from the EECONE project, we apply an LCA approach to evaluate alternative end-of-life pathways, including recycling, refurbishment, component reuse, and safe disposal. Our case study focuses on a representative PoC devices, a diagnostic readers for glucose monitoring, with particular attention to embedded electronics, batteries, and materials (including CRM).

The results highlight critical trade-offs between infection control requirements and circularity strategies, showing that while material recycling can recover valuable resources, environmental benefits can also be achieved through minimisation of material use, reuse, and refurbishment where feasible within regulatory constraints. Increasing miniaturisation and integration of energy-efficient components can hinder disassembly and material recovery, shifting environmental burdens toward waste management.

We further explore how LCA can inform design-for-disassembly, material selection, and modular architectures to improve EoL outcomes without compromising device performance or safety and assess the potential of digital tools

such as the Digital Product Passport to enhance transparency on material composition and support more effective collection and treatment systems for medical electronics.
The study concludes with recommendations for integrating EoL considerations into the design and development of PoC medical devices, highlighting the need for closer alignment between healthcare regulations, circular economy policies, and sustainability assessment methods. By positioning LCA as a decision-support tool across the full life cycle, this work contributes to reducing e-waste and advancing environmentally sustainable healthcare technologies in Europe.

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3.05.T05 Repair or Replace? Lessons Learned from the LCA of Smartphone Lifetime Extension Strategies

Jáchym Judl[1], Aida Hosseinian[1] and Laura Sokka[1] (1)Finnish Environment Institute (Syke)

Smartphones, and other hand-held smart electronic devices, play an essential role in our lives. They have effectively replaced other products, such as music players, navigators, or cameras. Their manufacturing is complex, requires a wide range of materials, especially metals, and is energy intensive. As smartphones are small and light products, their environmental impacts per device are quite low. At the same time, the market penetration of smartphones is very high and their average lifespan in western societies is short, typically reported as 2-3 years. Maximizing the lifespan reduces the system-wide environmental impacts of smartphone use by lowering the demand for new production and limiting e waste generation.

In our study, we apply life cycle assessment (LCA) to evaluate environmental implications of smartphone lifetime extension strategies. Two smartphones, one mid-range and one high-end, were disassembled to determine component and material compositions. The inventory was reflected with existing studies and completed with the ecoinvent database to estimate the impacts of the devices' production. Repair, refurbishment, and end of life recycling scenarios were defined with Finnish business actors and are based on the geographical context of the study. The presented results are used to assess environmental trade-offs and benefits associated with circular economy strategies of smartphones, with emphasis on lifetime extension.

We further discuss methodological limitations in applying LCA to rapidly evolving electronic products, such as outdated background datasets and limited data on repair and refurbishment processes. Furthermore, the allocation of production impacts between multiple product's lives and the potential of used devices to avoid new ones are discussed. These issues are strongly linked to the challenges in communicating LCA results for circular electronics.

Our results indicate potential environmental benefits of repair and refurbishment, particularly for components with relatively low replacement impacts – such as the display and the battery – presuming these actions lead to an effective extension of the product's lifetime. The findings support the importance of ecodesign strategies that balance durability, reparability, and environmental performance in smartphones. The discussion of methodological insights contextualizes the reliability of LCA results for smartphones and similar products.

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3.05.P - From Ecodesign to E-Waste Reduction: Applying LCA to Enable Environmentally Sustainable

Electronics

3.05.P-We059 A Cradle-to-Grave LCA-Based Comparison of Traditional and Modular Data Centre Power Supply Units

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Data centres are becoming an increasingly central part of today's digitalised society. Power supply units (PSUs) are critical components of data centre servers associated with extensive e-waste production. Conventional server PSUs are integrated, fan-cooled and limited in circular opportunities, leading to full replacement upon failure. Modular PSU architectures with standard replaceable cells have been proposed to address these challenges by eliminating active cooling, enabling partial replacement and reducing redundancy.
This study presents a comparative life cycle assessment (LCA) of a traditional server PSU and a modular PSU developed in an academic context in two designs: research design with cell redundancy and industrial-optimised design with minimal material. The study considers the conversion of 750W of output power throughout an 8-year lifetime in France. Use-phase modelling includes typical and full-load conditions, as well as two scenarios with zero or one failure. The environmental impacts (EI) are evaluated using ecoinvent and the Environmental Footprint 3.1 reference package in SimaPro.
Results show that the use phase dominates the EI for all designs, primarily due to electricity losses. Despite higher manufacturing EI mainly associated with printed wiring boards and integrated circuits, the modular PSUs achieve substantially lower life-cycle EI across most categories owing to higher conversion efficiency and the elimination of fan power. In terms of freshwater ecotoxicity (part 2 and inorganics), freshwater eutrophication, ozone depletion and resource use of minerals and metals, the modular research design shows the biggest EI out of all three products. This is largely associated with electricity use and the integrated circuits. The industrial modular design consistently performs best, reflecting lower material demand. It shows 15% lower climate change impact at full load than the traditional unit, and up to 60% lower at typical load. Sensitivity analysis on electricity mix and failure assumptions indicates that the relative ranking of designs is robust.
The findings highlight improved efficiency and reduced auxiliary power demand as key improvements for lowering PSU life-cycle impacts. This study lays the groundwork that may inform future assessments with wider scope including circular scenarios and illustrates how LCA can support eco-design decisions and guide development paths for designers.

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3.05.P-We060 Environmental Assessment of UHF RFID Tags: A Life Cycle Approach

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The electronics industry contributes significantly to global carbon emissions, which makes it important to better understand the environmental impact of the technologies we produce and use. One area of growing interest is the identification sector, particularly Ultra-High Frequency (UHF) Radio Frequency Identification (RFID) technology, which is manufactured in very large quantities and continues to expand rapidly. As demand increases, there is a need to explore more sustainable design options and materials.

In this study, three different UHF RFID tag designs are analyzed and compared. The first tag uses a graphene based antenna on a paper substrate, the second uses a copper based antenna on a paper substrate, and the third combines a

copper based antenna with a polyamide substrate. A cradle-to-gate Life Cycle Assessment (LCA) is carried out to evaluate the environmental impact of each design, focusing on stages from raw material extraction to manufacturing.

The analysis is based on primary data collected from project partners, supported by secondary data from the ecoinvent v3.11 database. The study follows the ISO 14040 and ISO 14044 standards for LCA. In addition, sensitivity and uncertainty analyses are performed to ensure the reliability of the results. The results provide insight into how different material choices affect the overall environmental impact of UHF RFID tags across various stages of their cradle-to gate life cycle. In particular, the comparison highlights the potential of alternative materials to reduce the environmental footprint of these widely used devices.

3.05.P-We061 Greener PCB Production: The Potential of the Thickness Reduction on the Carbon Footprint

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Printed circuit boards (PCBs) in automotive electronic control units (ECUs) contribute significantly to the environmental footprint of vehicles due to energy- and resource-intensive manufacturing. Reducing the environmental impact of PCBs is therefore important for lowering the carbon footprint (CF) of automotive electronics.

This study quantifies the potential CF reduction achievable through design and production changes for multilayer PCBs used in ECUs. A cradle-to-gate life cycle assessment (LCA) was performed using a commercial LCA software tool. The system boundary covers raw material extraction and production (including copper, glass fiber, resins and process chemicals), manufacturing of FR4 and CCL cores, and the full PCB fabrication process with associated electricity use and overheads.

This study focuses on the environmental impact of the reduction of the PCB thickness (from 1,6 mm to 1,2 mm) which alone leads to around 5% lower cradle-to-gate CO2-eq emissions per panel, maintaining the same functionality and reliability requirements. The potential of this optimization in combination with other CF reduction scenarios, such as the use of low carbon emission energy mix (Austrian mix) in PCB manufacturing and the substitution of primary copper by recycled copper, showcase a great reduction on the emissions.

These findings highlight the strong influence of material intensity, electricity mix and secondary raw materials on the climate performance of automotive PCBs. The results provide practical guidance for designers, manufacturers and original equipment manufacturers to reduce the carbon footprint of ECUs while limiting e-waste and overall resource use.

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3.05.P-We062 Life Cycle Assessment of Silicon Carbide Power Transistors From Two Alternative Production Routes

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Silicon carbide (SiC) semiconductor transistors can operate at higher efficiencies and in harsher conditions than silicon devices. SiC device production has larger energy requirements than conventional silicon devices, implying a risk of higher environmental impacts when these devices are used. Two different production routes for SiC wafer are currently

used in industry. They differ regarding how the SiC material is produced as well as in how the SiC boule is grown. One route produces SiC via the Acheson process and then grows the boule using physical vapor transport (PVT). In the other route, SiC production and boule growth occur in the same process, called high temperature chemical vapor deposition (HTCVD).
Using the life cycle assessment (LCA) the environmental impacts of SiC device production can be compared to their performance during their use phase. However, LCA data for SiC electronics is scarce. This cradle-to-gate study investigates the production of one discrete, packaged power electronic transistor covering both SiC wafer production routes, as well as front-end and back-end processing. A silicon device is also assessed in similar fashion to provide comparison to the SiC devices. Data for the SiC wafer production was collected both from literature and from environmental permits of existing manufacturers. Front-end processing data for silicon and SiC was retrieved from manufacturing site environmental declarations. The impact categories assessed are climate change impact and material resource use.
Results show that SiC wafer production has larger environmental impacts than Si wafer production. This is the case for both Acheson-PVT and HTCVD routes. The environmental burden added by the front-end processing stage is larger for silicon than for SiC devices. After back-end processing, the impact of the three packaged devices is similar. Devices produced with the Acheson-PVT route have a larger impact than silicon devices, but the difference between them is relatively minor. However, an SiC device produced with the HTCVD route has 17% lower climate change impact and 6% lower material resource use than a silicon device.
Production of SiC power transistors can result in a lower environmental impact than comparable silicon-based devices, depending on the production route followed. Applications using SiC devices may have lower environmental impacts than those using Si, even if their improved performance during the use phase is not considered.

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3.06.A - From Science to Action: Advancing LCA for Consumer Transparency, Policy Integration, and Inclusive Decision-Making

3.06.A.T01 Improving Robustness and Interpretability by Applying an Uncertainty-First Approach to LCA

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Life cycle assessment (LCA) is widely used to inform policy, industry, and innovation decisions. However, LCA results are often communicated as single-score outcomes, which obscure underlying uncertainty and variability, limit interpretability beyond expert audiences, and may lead to overconfident or misleading conclusions and decisions. These challenges are particularly pronounced when assessing emerging technologies: systems that are still under development or scaling lack industrial-scale data, requiring the use of future-oriented inventories that introduce additional assumptions and data gaps.

This work proposes an uncertainty-first approach to LCA that improves both robustness and communication. Uncertainty (arising from limited knowledge) and variability (reflecting inherent system heterogeneity) are systematically identified, classified, and quantified across all stages of the assessment, based on established LCA uncertainty frameworks and a critical review of published LCA studies. Types are differentiated between choice, data, and model uncertainty, while nature is differentiated between aleatory and epistemic uncertainty. We also examine if the practitioner conducting the LCA can reduce or fully quantify the uncertainty sources. For sources that are most common across LCA studies, a quantification and modelling approach is proposed.

Rather than compressing results into single impact category scores, all these sources of uncertainty and variability are propagated through the model to generate a distribution of possible outcomes, as well as the contribution of each source, which is reported as the primary result. To support decision-making, we propose methods best suited to

translating this outcome space into interpretable insights, such as conditions that need to be true in order to achieve a desired impact.

The proposed framework enhances transparency by making assumptions, data gaps, and system variability explicit, and improves robustness by shifting the focus from potentially misleading point estimates to a reliable range, while supporting more interpretable communication of results. By presenting results as outcome spaces rather than single scores, “uncertainty first” LCA can better inform regulatory processes, decision-making, and broader societal discussions. It facilitates clearer communication to non-expert stakeholders and supports comparability across studies.

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3.06.A.T02 From Research to Industry to Policy - Integrating Microplastics in LCA in the Apparel and Footwear Sector

Emilie Carasso[1] and Alban Fournier[2] (1)2B Policy, (2)Ecobalyse

The prevalence of plastics in the environment has grown exponentially these past decades, leading to microplastics being found in most ecosystems on the planet. The textile sector being perceived as a significant emitter of microplastics in the environment, integrating their impact in product environmental footprints has become a necessity. This has, however, progressively emerged as a methodological challenge.

This presentation explores how microfibres (including microplastics) were integrated both into the Apparel & Footwear Product Environmental Footprint Category Rules (A&F PEFCR) and the French single environmental score (“environmental cost”) framework, highlighting the parallel pathways taking microfibre impact assessment from research papers to assessments at scale.

This process first relied on a broad state-of-the-art assessment. It connected the A&F PEFCR Technical Secretariat and the French Government with leading LCA research initiatives (notably CIRAIG and the Plastic Footprint Network), while also mobilising expertise from standardisation bodies working on testing protocols (European Outdoor Group, ISO committees) and from operational databases on fibre release (The Microfibre Consortium). This collective work confirmed the need to address not only synthetic fibres but also microfibres of natural origin.

By the end of 2024, two distinct but complementary interim approaches were adopted, leveraging different strengths and weaknesses of the currently available science
- The French Government implemented a semi-quantitative but more holistic method, allowing microfibre impacts to be incorporated directly into the environmental cost
- The A&F PEFCR Technical Secretariat adopted a more limited (both from a life cycle stages and an environmental compartment coverage perspective) quantitative LCA-based approach aligned with Environmental Footprint principles, although not yet integrated into the EF single score.

This presentation will explore the competing priorities which led to the decisions taken in the two approaches, which are both taking the impact of microplastics closer to their robust integration in multi-criteria life cycle assessment.

Disclaimer/Disclosure: We'll have 2 presenters, Alban Fournier and Emilie Carasso. I've listed them both as authors as I couldn't add more than 1 presenter

3.06.A.T03 Overview of Potential Technical Advancements in Environmental Footprint Methods

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The Environmental Footprint (EF) methods represent a reference Life Cycle Assessment (LCA) framework in the EU for assessing the environmental impacts of products and organisations across their life cycles. Since their conception in 2013, the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) have supported the assessment of sustainable production and consumption in research and innovation, policymaking, corporate accountability.
The Joint Research Centre (JRC) supports the continuous evolution of the EF methods through scientific developments, addressing the different elements of LCA: goal and scope definition, interpretation phase, life cycle inventory modelling rules, reference package, life cycle impact assessment and data guidance. This work aims to seek a balance between policy needs, scientific advancements, and implementation challenges, defining widely applicable solutions.
Such evolutions are based on the review of scientific developments, discussions with domain experts and engagement with experts of the EF Technical Advisory Board (TAB) and other stakeholders.
The present work aims to share most recent scientific developments to inform the potential development of EF methods. These are structured in three main blocks addressing (a) life cycle inventory (e.g. enhancing the Circular Footprint Formula, improving accuracy and transparency of GHG emissions and removals accounting); (b) life cycle impact assessment (e.g. potential introduction of new impact categories and updates for other impact categories); and (c) data (e.g. updated Data Quality Rating framework). Moreover, these developments aim also to contribute, as far as possible, to the European Commission's goal towards simplification and harmonisation.
These developments are expected to help the applicability of EF methods to support EU policy and other market and research initiatives. JRC is also working in identifying remaining limitations, thereby supporting future research and longer-term development of the EF methods and, overall, LCA.

3.06.A.T04 Linking Pro-Environmental Behaviour Scales with Life Cycle Impacts: Evidence from Household Consumption in Chile

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Pro-environmental behaviour (PEB) has been widely studied as a key determinant in reducing environmental impacts and is frequently used to guide public policies and sustainability strategies. However, a gap remains regarding the relationship between the degree of pro-environmental behaviour and the actual environmental impacts associated with individuals. In this context, this study analyses, for the first time, the relationship between pro-environmental behaviour scales and the life cycle environmental impacts of individuals. To this end, 100 in-person household surveys were conducted in Temuco, Chile, integrating two validated scales: the 13-item PEB scale (Larson et al., 2015) and the 19-item Pro-Environmental Behavior Scale (PEBS) (Markle, 2013). In addition, information on food, water, energy, and transport consumption was collected, enabling modelling of household-related flows. Based on this, a life cycle assessment (LCA) was conducted in accordance with ISO 14040/44, using as the functional unit the annual consumption of one inhabitant (2025). Modelling was performed in SimaPro PhD 10.4 using the ReCiPe Midpoint (H) method. Instrument reliability was assessed through internal consistency analysis, confirming validity in the Chilean context.
Results show no consistent relationship between pro-environmental behaviour and environmental impacts. No clear trends were observed across the 18 impact categories. In 12 categories, individuals with very low behaviour showed

higher impacts, whereas in 5 categories the opposite occurred. Intermediate levels (low, medium, high) accounted for 60–80% of impacts relative to peak values. High uncertainty was observed across all categories, with variations up to 1000% for stratospheric ozone and 200% for land use, reflecting substantial variability in household consumption patterns.
In conclusion, the results do not support the assumption that individuals with higher pro-environmental behaviour achieve better environmental performance. These findings question the use of such indicators as proxies of individual environmental performance and highlight the need for instruments that better capture actual consumption and its impacts.

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3.06.A.T05 Effects of country specific supply chain modelling for guiding biodiversity assessment of construction materials

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Background and challenge
The biodiversity crisis requires urgent action. In Denmark, it is leading to growing policy and industry interest in using life cycle assessment (LCA) for biodiversity impacts. However, biodiversity assessment differs from other impact categories in that it integrates multiple ecosystem pressures and is strongly dependent on spatial location and resolution. Therefore, this study investigates how generic versus country specific supply chain inventories influences biodiversity impacts for commonly used construction materials.

Methods
Four commonly used construction materials, wood, concrete, steel and CLT, are evaluated using LCA based on inventory data from Ecoinvent, with ecosystem quality assessed through four different life cycle impact assessment (LCIA) methods. Generic inventories for concrete, reinforcement steel and mineral wool are represented by global market mixes, while sawn wood is modelled using a European mix. Material inventories are adjusted to reflect country-specific conditions, including electricity, heat and waste mixes, national production processes, and modified forestry for sawn wood.
Ecosystem quality is used as indicator for biodiversity impact using three LCIA methods: Impact World+, LC Impact (excluding ecotoxicity), and ReCiPe. Additionally, EN 15804 indicators were translated to biodiversity impacts using ReCiPe characterisation factors, acknowledging limitations related to the coverage of biodiversity pressures, such as land occupation.

Results
Country specific modelling substantially alters biodiversity impact results compared to generic inventories. Reinforcement steel shows a 79-90% lower biodiversity impact, while mineral wool and sawn wood exhibit moderate differences. For concrete, both the magnitude and direction of change depend on the LCIA-method used. EN 15804 based results consistently indicate reduced biodiversity impacts across all materials, diverging from trends observed in LCIA methods covering ecosystem quality.

Conclusions and relevance
The findings demonstrate that both supply chain modelling choices and LCIA method selection can lead to divergent biodiversity conclusions with direct implications for policy and decision support. As a result, research should be directed to improved understanding of inventory representativeness, method limitations, and regional characterisation is critical to avoid misleading conclusions in building LCA and to support robust policy integration.

3.06.B - From Science to Action: Advancing LCA for Consumer Transparency, Policy Integration, and Inclusive

Decision-Making

3.06.B.T01 Are Environmental Indicators Just? Analysis and Framework for Assessing the Justice Dimension of Environmental Indicators

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The perceived (un)fairness of environmental policy measures is commonly identified as one of the most significant barriers to their implementation and adoption. Hence, the question of who causes environmental impacts and who suffers from them is crucial. Every robust environmental impact and sustainability study must consider all relevant environmental impacts. In an LCA study, the issue of inclusiveness and equity can (should) be explicitly considered in the definition of the research question, the design of the methodology, and in the interpretation.
But other factors affecting the results and their interpretation remain hidden. Many justice/injustice issues are already embedded in standard LCA methodologies for calculating indicators and are rarely reflected in routine decision-making. What, how, where, and when the applied indicators measure often determines our interpretation and can illuminate or hide the issues of justice. Thus, the dimension of justice should be reflected both in the development and application of environmental indicators. However, contemporary literature does not offer any coherent framework for such a reflection.
In this contribution, I aim to conduct a comprehensive analysis of the dimensions of justice influenced by the choice and design of environmental indicators. Relevant theories of (environmental) justice and the basic dimensions of justice are identified with emphasis not only on intra-generational distributive justice, but also on issues of inter-generational and inter-species justice. Different schools of moral philosophy are reflected (e.g., utilitarian, teleological, deontological) as well as perspectives of local and indigenous peoples. The aim of this research is to create a general framework for a comprehensive analysis of the dimensions of justice and its influence on the choice of indicators in environmental studies. The validity and applicability of this framework will be demonstrated in a case study using various LCA characterization methodologies and indicators. The choice of a suitable indicator is a matter of balancing different criteria. The main goal of this contribution is to introduce justice as one of the crucial criteria to be considered by the LCA community.

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3.06.B.T02 Democratizing Life Cycle Assessment: Challenges and Opportunities for Broad Adoption

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Context and challenges

Life Cycle Assessment (LCA) is a key tool for assessing the environmental impacts of products and services. However, its use remains largely confined to expert communities due to its technical complexity. In a context where environmental challenges require actionable solutions, there is a growing need to evolve LCA toward broader usability, addressing sustainable design, regulatory compliance, and transparency. The key challenge is to democratize LCA while preserving scientific rigor and methodological robustness.

Democratizing LCA to foster its adoption among businesses
LCA tools have a role to play in bridging the gap between novice and expert users. The solution enables LCA studies with expert-level reliability by relying on robust methodological frameworks. Its collaborative design supports cross-functional use beyond sustainability teams, allowing product designers to integrate environmental considerations early in the development process through dedicated features for scenario exploration, while access to full methodological depth is still possible. Clear visualizations and indicators facilitate both internal and consumer communication, without compromising analytical detail. Agility is also a key to foster LCA adoption within different business teams: ability to switch from a framework to another without manual adjustment enhances decision-making while making reporting

easier.

Real-world impacts
LCA now becomes a transformation lever by embedding environmental considerations into decision-making and fostering collaboration across teams, thereby enabling eco-design practices, as shown in several use cases. It also simplifies consumer transparency through its built-in alignment with major frameworks, combined with tailored communication tools, including sector-specific environmental scores and regulatory environmental disclosures.

Conclusion, limitations and perspectives
This approach has the potential to transform LCA into a decision-support tool for action. However, it requires ensuring robust and reliable results regardless of user expertise to avoid misinterpretation and greenwashing risks. Its impact also relies on adoption by non-expert users within companies and among consumers. Future work will focus on collaboration with policy-makers to make frameworks interoperable in order to reinforce LCA's adoption as key tool for businesses.

Disclaimer/Disclosure: With their agreement, we'll be happy to present one ore two customer use-cases during the oral presentation to highlight how LCA democratization helps businesses to integrate LCA in daily R&D or product design activities and encourages a transparency approach towards consumers by integrating voluntary frameworks such as French Environmental Labelling.

3.06.B.T03 Same LCA Score, Different Sustainability? From "LCA+" towards a Multidimensional Sustainability Assessment Framework

Yanne Goossens[1] (1)Thünen Institute

Life Cycle Assessment (LCA) is widely used to quantify the environmental impacts of food products and increasingly underpins sustainability labels and decision-support tools. To enable large-scale product assessments, simplified approaches often rely on generic life cycle inventory data. As a result, products with different production practices may receive identical environmental scores, limiting differentiation between similar products and reducing usefulness for decision-making by consumers, food chain actors and policymakers.

This study explores how products with identical generic LCA scores can be differentiated by integrating complementary information beyond conventional LCA modelling. While LCA provides a scientifically robust basis for assessing environmental performance, sustainability of food products depends on additional dimensions that cannot be derived from environmental footprints alone. A conceptual assessment framework was therefore developed that combines environmental LCA indicators with complementary sustainability dimensions, including production system characteristics (e.g. organic versus conventional), animal husbandry standards, agri-environmental measures, labour conditions along the supply chain, nutritional quality, and alignment with food system transition objectives. The framework combines generic baseline datasets with more specific product-level information, allowing differentiation between products while maintaining scalability across large product portfolios.

Rather than treating these aspects as simple add-ons to an environmental core metric, the framework conceptualises sustainability as a multidimensional construct in which environmental performance assessed through LCA constitutes one important dimension among several complementary perspectives. The framework was applied to selected food products sharing identical generic LCA scores but differing in these attributes. Results demonstrate that integrating complementary indicators enables more nuanced product differentiation while maintaining both scalability across a wide product portfolio as well as transparency regarding methodological choices.

The findings contribute to ongoing discussions on translating life cycle results into actionable sustainability information. By embedding LCA within a broader multidimensional assessment architecture, the study provides

insights for the development of consumer-facing sustainability scores that support informed decision-making.

Disclaimer/Disclosure: Acknowledgements
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3.06.B.T04 Operationalising Sustainability with Key Performance Indicators as LCA Complementary Tools for Businesses and Policy-makers: Maximum Energy-use Threshold in Controlled Environment Agriculture.

Shiwei Ng[1], Olaf Hinrichsen[2] and S Viswanathan[3] (1)TUMCREATE Ltd, (2)Technical University of Munich, (3)Nanyang Technological University

Life Cycle Assessment is an elaborate effort requiring significant investment of time, financial and human resources. To enable strategic decisions for regulation or operational strategies, key performance indicators tracking resource use intensity of an operation can provide early indication of whether sustainability claims can be achieved, before embarking on an LCA. This is important to enable non-experts in identifying unsustainable operating conditions quickly and act as a transparent industry benchmark. One example of a resource use/ key performance indicator important to many industries is energy use. Particularly for new technologies in computing (data centres) and agri-food (controlled environment agriculture - CEA).

Here, we present the Maximum Energy-use Threshold (MET) as a measure of operational prudence in resource use, such that the emissions from energy use would be lower than the emission incurred by current system. To demonstrate this approach, the MET was calculated for CEA, where the potential for intensive agriculture is plagued by high energy use threatening fiscal and environmental viability.

For different countries, the MET operationalises sustainability claims while considering local context. We found that given the current state of CEA, it is feasible for CEA of leafy greens in land-locked countries with lower grid emissions or growing short shelf-life produce to be a lower carbon option. Having more renewable energy in future grids helps, but it will not be the sole enabler of low carbon CEA without energy use improvements. Lastly, CEA of high energy use crops such as wheat or soyabean can be supported if agricultural land substitution and restoration is considered.

The MET could be institutionalised to encourage sustainable CEA. Through integration with policy levers such as incentives and licence to operate or scale, policy-makers can promote sustainable CEA technologies. This approach complements LCA because operation fulfilling the MET would be worthwhile investing resources for a detailed environmental impact assessment while operations not fulfilling MET would not require an LCA to ascertain its inferior environmental attributes.

This simplified indicator approach converts scientific outputs into guidance that can go beyond CEA and into many industries. Other relevant indicators could also be explored for different industries, depending on which parameters are the primary contributors of environmental impact.

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3.06.B.T05 Five Shades of Circularity: A Multi-Indicator Framework

Cristian Pérez-Hernández[1], Pieter Nachtergaele[1], Sophie Huysveld[1] and Jo Dewulf[1] (1)Ghent University

The shift towards a circular bioeconomy requires a shared understanding of what circularity truly means. Currently, a fragmented landscape of definitions and a lack of standardised metrics make it difficult to translate scientific findings into the robust evidence required to inform policy and industrial strategy. This work presents a novel product-level circularity assessment methodology specifically tailored for high-TRL bio-based products. Grounded in Material Flow Analysis, this framework provides a unified modelling approach that shifts from current basic indicators only relying on material tracking towards a suite of five complementary, life-cycle-thinking based indicators: Circular Input Content, Circular Output Content, Utility Factor, Cascading Performance of Inputs, and Cascading Performance of Outputs.

A significant scientific contribution of this methodology, and a key differentiator from existing frameworks such as ISO 59020 or the Material Circularity Indicator (Ellen MacArthur Foundation, 2019), is the explicit integration of functional value preservation. Rather than monitoring mass-based flows alone, this methodology introduces an additional analysis layer to track how this value is maintained as resources cascade through multiple life cycles. This distinction ensures that 'downcycling' is not misrepresented as high-quality circularity. Aiming for broad applicability, the methodology employs a semi-quantitative scoring system. This translates the complex value dimension into a simplified measure, fostering ease of adoption for different stakeholders.

By deriving all metrics from a single MFA model through a dedicated characterisation of inputs, outputs, cascading performance, and product utility relative to industry benchmarks, the methodology unifies diverse circularity aspects into a cohesive framework. The resulting scores can allow companies to generate transparent, verifiable information for both B2B and consumer communication. Furthermore, these insights can also feed into transparent sustainability reporting and emerging regulatory requirements, such as the Digital Product Passport (DPP), providing a robust data foundation to support market transparency. Ultimately, this methodology offers a dual benefit: it provides scores with the scientific rigour essential for robust policymaking, and it offers a clear framework for manufacturers to quantify and communicate their circular economy contributions to both B2B and end consumers.

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3.06.C - From Science to Action: Advancing LCA for Consumer Transparency, Policy Integration, and Inclusive Decision-Making

3.06.C.T01 Harmonizing Life Cycle Assessment to Enable Sustainable Consumption and Eco-Design in the Cosmetics Industry

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The EcoBeautyScore (EBS) framework is a science-driven initiative aiming at standardizing environmental evaluations in the cosmetics industry by leveraging Life Cycle Assessment (LCA). Developed in accordance with the European Commission’s Product Environmental Footprint (PEF) methodology, EBS measures 16 midpoint environmental impact categories throughout the entire product’s life cycle. By applying normalization and weighting, EBS aggregates these impacts, facilitating consistent product comparisons within specific product segments.
EBS established a unified methodological approach among industry participants. Dividing products into functional groups ensures fairness in comparison, while standardized usage scenarios minimize variability unrelated to product

formulation. This harmonization is critical for robust benchmarking and transparent environmental communication, empowering consumers to make more sustainable choices.
At the heart of EBS is the creation of a harmonized database covering ingredients, packaging components and activity data. Due to the wide variety of cosmetic ingredients, a prioritization process identifies ingredients with the highest environmental impact. Advanced modeling, such as the MSS-HC5 method for freshwater ecotoxicity, addresses gaps in current datasets, avoiding no-data, no-impact situations.
To make LCA results easily accessible to non-expert, EBS converts them into an A–E scoring system for use by both consumers and manufacturers. These scores are based on statistically representative product portfolios, reflecting actual market conditions. The scoring system transforms complex LCA findings into practical insights, supporting eco-design strategies that target key environmental hotspots.
Analysis of almost 2,000 products underscores the significance of differentiating life cycle stages: the use phase is most impactful for rinsed-off products, while packaging and ingredient end-of-life are most critical for leave-on products. These results highlight the necessity for tailored eco-design approaches and more nuanced impact modeling for each product segment.
EBS shows how unified methodologies, shared databases, and standardized evaluation processes can foster ecoconception into industry operations. By promoting comparability, transparency, and scientific rigor, developed assessment and scoring system becomes a powerful tool for guiding eco-friendly product design and supporting sustainable consumption in the cosmetics sector

3.06.C.T02 Identifying, Understanding and Addressing the UK LCA Skills Gap.

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LCA Skills are essential for supporting the transition to net zero. But what exactly do we mean by LCA Skills, and who needs them?

The UK Life Cycle Assessment Regulatory Science and Innovation Network (LCA-RSIN) is a network of UK academics, industry, regulators and policymakers. In 2025 and 2026, the network undertook a two-part study on skills in the UK LCA sector. The first phase aimed to identify whether the perceived skills “gap” exists in reality, and the second aimed to identify what actions are required to close such a gap, if it does exist.

To enable this work, a typology of LCA skills was created. This skills typology consists of 7 skills specific to the application of LCA: Life Cycle Thinking; Commissioning an LCA; Conducting an in-depth LCA; Interpreting an LCA; Communicating an LCA; Reviewing and Verifying an LCA; Developing LCA Methodology; and 3 core skills critical to good LCA practice: Critical Thinking; Research Integrity; Collaboration.

Through interviews, questionnaires, and workshops with members of the UK LCA community, the first phase of the work revealed that the existence of a skills gap is supported by evidence. The work identified and outlined 3 broad and interrelated gaps: UK Graduate Skills; Life Cycle and Critical Thinking; Awareness of LCA.

Each of these skills are relevant to different LCA stakeholders across a variety of sectors at varying levels of proficiency. Aside from LCA professionals, policy actors and industry management were identified as key targets for LCA upskilling.

This contribution will present in detail the typology of LCA Skills, the methodology used to understand and ascertain the presence of skills, and will outline the identified UK LCA skills gap. Furthermore, we will present proposals to address the skills gap. We argue that partnerships with universities, industry actors, policymakers, and other important stakeholders are necessary to address these gaps, and we offer 7 recommendations to this effect intended to expand LCA literacy, embed life cycle thinking, and strengthen UK Higher Education provision, to support the transition to Net Zero. Though based in the UK, the findings of this study are highly relevant across Europe and around the world.

Disclaimer/Disclosure: This work was undertaken through the UK Life Cycle Assessment Regulatory Science and Innovation Network (LCA-RSIN), which was funded by Innovate UK. The project formally ended in March 2026 but will transition to become the UK LCA Network. The work was supported by the University of Sheffield Grantham Centre for Sustainable Futures.

3.06.C.T03 Integrating Life Cycle Assessment into Public Procurement Practices: a Digital Framework for EU Tenders

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Green Public Procurement (GPP) is increasingly recognised as a strategic policy instrument to steer markets towards more sustainable production and consumption patterns. However, despite its conceptual alignment with life cycle thinking, the practical integration of Life Cycle Assessment (LCA) into public procurement procedures remains limited due to methodological complexity, data scarcity, and the absence of operational decision-support tools.
This study investigates how LCA can more effectively support GPP goals by addressing both methodological choices and key implementation barriers.
To this end, a digital GPP support tool was developed and implemented to integrate LCA-informed criteria directly into European e-Procurement processes, based on the mandatory eForms standard. The tool assists contracting authorities during the pre-awarding phase by identifying relevant EU-defined GPP criteria and evaluating the environmental implications of their inclusion in procurement notices. The consequences of a selected GPP requirement were assessed through a consequential LCA, aimed at determining whether its adoption would result in a net reduction or a trade-off in environmental impact across key categories.
A case study based on a public furniture procurement demonstrates how the proposed framework improves transparency, consistency, and usability in LCA-based environmental evaluation, enabling more traceable and comparable assessment of competing bids.
The present work contributes to the development of life cycle thinking within the context of European public procurement workflows. It offers a methodological framework and a deployable digital tool for contracting authorities, with the potential to strengthen the role of LCA in GPP practice across Europe.

3.06.C.T04 Advancing Sustainable Policy Integration: Insights from Collaboration on Life Cycle Approaches Among Swedish Government Agencies

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As the demand for life cycle expertise continues to grow across society, and as policies and legislation increasingly require a life cycle perspective on environmental impacts, the Swedish Life Cycle Center launched a collaboration for Swedish government agencies in 2016. Today, this 10-year structured, and unique partnership includes 13 agencies and more than 40 participants, creating an established forum for continuous dialogue, knowledge sharing, and joint initiatives related to life cycle methodologies and policy integration.

The participating agencies play important roles in developing policies and regulations at both national and EU levels and have gained significant benefits from this partnership. In addition to exchanging knowledge, the collaboration enables agencies to participate in activities organized by Swedish Life Cycle Center, helping them build expertise and broaden their professional connections.

This presentation highlights the results of this collaboration by exploring both how the network operates in practice and the value it has created in strengthening life cycle knowledge within Swedish government agencies and policies. The

group functions as a platform where government agencies exchange experiences, deepen their understanding of life cycle approaches, and work together on shared initiatives and policies.

The presentation will demonstrate how life cycle thinking is being implemented in practice within these agencies, and into policies, with examples from different areas. The presentation will also highlight concrete achievements and illustrate how the collaboration has strengthened the capabilities of Swedish government agencies. It will also include findings from a research project on the need for life cycle competence among government agencies now and in the future.

3.06.C.T05 Beyond Market Failure: A Rationale for Life Cycle Policy

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Environmental policymaking is traditionally informed by the market failure framework, which postulates that a theoretical "perfect" market with well-informed participants yields the best possible allocation of resources and thus the highest welfare. Market failures are deviations from this ideal, leading to lower welfare, and may be categorised and matched to appropriate responses (e.g., taxes to address externalities).
However, governments increasingly implement life cycle policies, whose merit cannot be explained through the market failure framework, since the policies derive from environmental science rather than economics. Life cycle policies intervene in one stage of the product life cycle to prevent or reduce harm in another stage of the life cycle, often across space and time, based on the systemic interactions across the product life cycle.
This study develops a framework uniquely suited to justify life cycle policy interventions. We identified and abstracted problems and solutions in life cycle policymaking through three complementary methods: literature review of the institutional scholarship on life cycle thinking, a workshop with life cycle practitioners on policy choices, and systematic review of stated justifications for major life cycle policies.
We find that life cycle interventions are preferred when they give decisionmakers more leverage than traditional measures because of systemic interactions. For example, whole life carbon regulation for buildings gives policymakers at the planning stage, such as city governments granting building permits, leverage over embodied and operational emissions, which they would have much less control over through traditional measures.
We also identified major justifications for not pursuing life cycle interventions, including a possible lack of quality life cycle inventory data, risk of gaming by market actors, lack of skills and capacity in the public and/or private sector, and regulatory burden. As such, our framework presents life cycle policymaking as a trade-off between the benefits of systemic leverage and the challenges associated with model complexity and reliance on data.
The outcome of our study is a decision-making framework akin to the market failure approach but tailored to life cycle policymaking. The framework enhances the ability of decision-makers to bring life cycle science into action by evaluating the potential role of life cycle interventions in addressing a given policy problem.

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3.06.P - From Science to Action: Advancing LCA for Consumer Transparency, Policy Integration, and Inclusive Decision-Making

3.06.P-We063 Aligning Modelling Choices with Study Goals in LCA of Recycling: Enhancing Interpretation and Decision-making.

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Life cycle assessment (LCA) is used to support decision-making, communication, and policy development. However, LCA results are highly sensitive to modelling choices, which can lead to different, and sometimes conflicting, interpretations of environmental performance. This represents a challenge for translating LCA outcomes into clear,

actionable insights for non-experts and risks undermining comparability and transparency.

This study investigates how key methodological choices influence LCA results and their interpretation in the context of recycling systems. Recycling represents a particularly complex case, as it simultaneously fulfils waste management and production functions, it can deliver multiple products and involves multiple life cycles. As a result, choices related to functional unit selection, co-product multifunctionality, and end-of-life modelling can significantly affect outcomes.

Using a case study of an innovative chemical recycling value chain for the aluminum–polymer layer of post-consumer beverage cartons, we evaluate the impact of three methodological dimensions: (i) functional unit selection (waste vs product perspective), (ii) co-product modelling via system expansion (substitution vs basket of products), and (iii) end-of-life modelling approaches. The results show that these choices influence the magnitude and interpretation of impacts. For example, adopting a product-based functional unit leads to higher absolute impacts compared to a waste-based perspective, while the basket of products approach yields higher results than substitution due to system expansion by addition rather than subtraction. However, analysis of the results shows that these methodological choices serve different purposes. For example, the basket of products approach better represents system-level performance, whereas substitution reflects product-level comparisons.

Thus, beyond these numerical differences, our findings highlight that modelling choices shape the message communicated by LCA results. Based on this analysis, we propose a set of practical recommendations to align methodological choices with three common recycling LCA study goals: evaluating waste management systems, production systems, or specific products. By explicitly linking modelling choices to LCA goals and communication objectives, this work contributes to improving the interpretability, robustness, and responsible use of LCA in decision-making contexts.

3.06.P-We064 When Does LCA Give Reliable Guidance? Convergence and Decision Fragility in Life Cycle Assessment of Industrial Waste Upcycling

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Life Cycle Assessment (LCA) is increasingly used to guide circular economy decisions, yet the same upcycling practice can yield conflicting environmental conclusions depending on which methodological framing is applied. Without knowing under which conditions those differences matter for the final recommendation, practitioners, policymakers, and companies risk acting on guidance that is scientifically fragile without being aware of it.
This study investigates under which industrial upcycling conditions alternative LCA framings converge on the same recommendation, and under which conditions they produce decision fragility or reversal. The distinction matters for anyone relying on LCA results to justify circular economy investments, procurement decisions, or policy measures.
This paper tests whether specific case characteristics can predict when the choice of LCA method changes the environmental conclusion and when it does not, across a set of Danish industrial upcycling cases. Cases are selected based on four characteristics expected to drive sensitivity: how homogeneous the residual material is, how well its function is preserved in the new application, how clearly it displaces a primary material in the market, and how intensively it is processed. Cases range from straightforward upcycling applications to complex ones where materials are heavily transformed and displacement is uncertain.
Each case is assessed against a consistent decision question: is diverting a residual material stream to a specific upcycling application environmentally preferable? Two modelling framings are applied, a cut-off approach treating residual inputs as burden-free and a shared upstream responsibility approach, and robustness is evaluated through decision reversal indicators.
Cases with homogeneous materials and limited transformation are expected to give stable results regardless of the method used. Cases involving heterogeneous inputs or uncertain displacement are expected to show sensitivity and potential reversal. Intermediate cases are expected to reveal what specifically triggers the shift.

The study contributes a practical screening framework that helps practitioners and decision-makers anticipate when LCA can be trusted as a basis for action, and when greater caution is needed.

3.06.P-We065 Framing LCA results for PFAS-contaminated water treatment as net human health benefit (NHHB) analysis

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Conventional LCA results can struggle to cut through the media noise. This is especially true when the results of alternative options are only comparable to one another rather than framed in a more absolute way in relation to human health. This is particularly evident in the case of drinking water contamination by per- and polyfluoroalkyl substances (PFAS). PFAS exposure is linked to immune dysfunction, developmental delays, hormonal disruption, and certain cancers. Conventional drinking water treatment plant (DWTP) process is ineffective at removing PFAS, driving the development of innovative technologies (granular activated carbon, ion exchange resin, others).
LCAs have often taken a limited, relative approach to assessing health effects. Given the resource intensity and associated impacts of these technologies, knowledge gaps remain regarding the most sustainable water treatment approach. To support policy development, it is meaningful to ask whether PFAS removal in fact results in a net human health benefit when assessed from a life cycle perspective.
We applied LCA to evaluate human health impacts of 2 treatment trains for PFAS-contaminated water. The functional unit is delivery of 1m³ of treated drinking water with PFAS-4 concentration below 4ng/L. Both midpoint and endpoint human health impacts are assessed. To complement conventional LCA, a NHHB approach was developed to assess whether the avoided PFAS-4–related human health impacts achieved through water treatment outweigh the life cycle impacts induced by DWTP. In the NHHB, to enable a more comprehensive evaluation of the potential range of impacts from direct PFAS ingestion through drinking water, two characterization factors (CF) based on effect factors derived from 1)rodent studies and 2)epidemiological data were applied.
In conventional LCA using rodent-derived effect data, the potential benefits of removing PFAS from drinking water are smaller than the potential impacts generated by the DWTP. However, when CF derived from human epidemiological data is used, the benefit of treatment increases by several orders of magnitude. This work suggests that changes in how the life cycle inventory and impact assessment are framed can make LCA results more meaningful, but these changes also raise important methodological questions, particularly regarding how the choice of effect factors affects consistency and representativeness when assessing human health impacts from direct exposure to contaminants.

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3.06.P-We066 Addressing Attributional–Consequential Inconsistencies in Circular Footprint Formula and Proposed Modifications for Improved Consistency – A packaging material case study

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The Circular Footprint Formula (CFF) under Product Environmental Footprint (PEF) framework aims to model waste and recycled materials, and to allocate environmental burdens and credits to users and producers of such flows in uniform and justified way. The CFF consists of material, energy, and disposal parts. With the current version of CFF, the PEF framework combines elements of attributional and consequential LCA through the use of substitutions of primary materials and energy. This hybrid formation creates methodological inconsistencies, including reliance on market-based assumptions and challenges in interpreting results within the attributional context. This study examines

the methodological implications of the CFF and proposes two modified versions of CFF to improve consistency in attributional LCA study. The first modification removes E*v substitution along with QSout/Qp. The second modification replaces E*v with Ev, thereby eliminating explicit substitution assumptions while allocating the primary material impacts between the previous and next life cycle with A factor. In the energy part of the formula, substituted energy is removed in both of the modifications and impact of energy recovery is allocated between different life cycles with factor B. The performance of these formulations is evaluated against the baseline CFF and cut-off approach using selected case studies.
All four approaches were applied in a LCA case study of cold cut meat packaging. The packaging material consists of 80% recycled polyethylene terephthalate (PET) and 20% virgin PET. The whole life cycle from cradle to grave was considered, including raw material production, conversion, filling, transportation, and mechanical recycling and energy recovery as end-of-life options. The functional unit of the study is the consumption of 1 kg of cold cut meat by the consumer within the shelf life of the packaging. Primary data has been collected from package producer and cold cut meat producer, concerning energy and material inputs and outputs, whereas the secondary data has been collected from different scientific articles. The results of the study are interpreted through EF 3.1 impact assessment methods. This work is part of larger SCORE development work under LIFE-IP project (PlastLIFE), which aims to develop a harmonized LCA methodology in line with PEF for food packaging.

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3.06.P-We067 From Data Burden to Decision Value: Right-Sizing Primary Data Granularity in Food-Waste LCA

Silvia Schütz[1] and Gudrun Obersteiner[1] (1)University of Natural Resources and Life Sciences (BOKU)

The collection of primary data for the life cycle inventory is challenging, particularly in balancing methodological robustness with feasibility. Data granularity must be sufficient to yield reliable results, yet feasibility constraints often shape what can be collected. LCA practitioners must decide case by case, under specific circumstances (e.g., funding, budget, and stakeholder support), how much detail is necessary. Striking this balance is essential to avoid stakeholder fatigue and to ensure that primary data are gathered efficiently and meaningfully.
In the context of food waste LCA, data granularity is a key consideration. High-granularity information on food waste composition (at the food-item level) is often lacking. Quantification methods such as food waste diaries or composition analyses can provide data at this level; however, these investigations are time-consuming and costly. For this reason, this study evaluates how primary data granularity affects carbon footprint estimates of household food waste and identify the minimum viable. Emission factors can be applied at different aggregation levels—ranging from item- or dish-specific to broader categories such as animal-based, plant-based, and cereal-based foods.
Within the Horizon Europe CARE project, more than 70 households across Finland, Norway, Sweden, Germany, and Estonia participated in a 14-day observation. Participants recorded quantities and types of edible food disposed in structured food waste diaries. In total 1,200 entries were collected. Each entry recorded mass and a textual description; entries were mapped to two parallel life cycle inventory models - (i) High-granularity model: item-/dish-specific emission factors, (ii) Low-granularity model: aggregated food-category emission factors (e.g., ruminant meat, non-ruminant meat, dairy, fish, cereals, bakery, vegetables, fruit, mixed dishes) and results compared.
The study aims to identify a feasible path to robust results at the lowest practical cost, minimizing respondent burden while maintaining decision-relevant accuracy. High-resolution household diaries combined with product-specific emission factors can reveal actionable hotspots for shifting consumer behaviour. Results inform tailored advice for participating families and provide a scalable approach for policy and consumer interventions targeting the most emission or resource-intensive waste fractions.

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3.06.P-We069 User-centered Life Cycle Engineering Tool for Robust Decision Making in Development Processes

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Life cycle assessment (LCA) is key to designing a sustainable future. In industry, LCA is still mostly used as a retrospective reporting tool, informing customers or consumers about the environmental impacts of a product or process. With increasing regulatory pressure and self-set targets to mitigate environmental impacts, a shift from using LCA to implementing life cycle engineering (LCE) in the industry becomes necessary. With LCE, the consideration of environmental impacts becomes integrated in the design and development of processes and products. For a successful implementation of LCE, the process needs to include different stakeholders, such as designers and developers, and be oriented on their available data on the input side as well as present the results suitable for decision making by non-LCA experts. The implementation of LCE in the industry can be facilitated by a user-oriented LCE tool for robust decision making in industrial development. A user-centered development and low-threshold access to the tool ensures usability by non-LCA experts. Thus, a user-centered LCE tool can bridge the gap between complex data needed for implementing LCE and clear insights for decision making in the development process. Our work showcases the concept for such an LCE tool, focusing on the key elements of the concepts such as the user-interface, the included models and the visualization of results and how to design these key elements in a user-oriented way. For the design of the user-interface, it is important to analyze which inputs the involved stakeholders can provide in which format. The included models need to be developed and parametrized based on the insights of the involved stakeholders. The visualization of results needs to be oriented on the knowledge level of the involved stakeholders as well as on their decision-making context. A prototypical implementation of such a user-oriented tool for the automotive industry will be presented.

3.06.P-We070 Integrated Impact Assessment Approach for Safe and Sustainable by Design of Advanced Materials: Focus on economic dimension

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Although the European Commission has proposed a unified SSbD framework, its practical implementation is difficult. Within this context, the Horizon Europe SUNRISE project develops an Integrated Impact Assessment Approach (IIAA) to support industry SSbD strategies by combining safety, environmental, social, and economic dimensions at different level of assessment (Tiers) and helping close the gap between scientific evidence and real world decision making. While the IIAA evaluates safety and sustainability dimensions, this contribution focuses on the assessment of economic aspects across the SUNRISE tiered approach which is composed of three main Tiers. Tier 1 involves simplified SSbD assessment via a qualitative screening to identify ‘hot spots of safety and sustainability concerns. Tier 2 represents an intermediate SSbD assessment employing (semi)quantitative analysis for ranking and prioritization of SSbD design alternatives, while Tier 3 involves a quantitative assessment of safety & sustainability for design alternatives identified in the prior tiers as being ready for scale-up. Economic assessment is introduced in Tier 1, where users respond to guiding economic questions that support early-stage R&D by prompting qualitative and semi-structured reflections. This helps innovators identify cost-related hotspots, feasibility constraints, and potential trade-offs alongside safety and environmental considerations. Tier 2 strengthens this perspective through a semi-quantitative weight-of-evidence approach, where preliminary cost indicators are combined with environmental and social signals to support prioritisation of design alternatives.
Tier 3 sees the results of a full quantitative economic evaluation through conventional Life Cycle Costing (LCC). A dedicated SUNRISE tool links midpoint LCA results—whether generated using Environmental Footprint or ReCiPe methods—with monetary valuation coefficients, allowing users to estimate the economic cost of environmental

burdens. These monetised externalities are then integrated with traditional LCC results to produce an environmental LCC, offering a more comprehensive economic basis for decision-making. The tool also includes functionality for adjusting valuation coefficients for inflation to ensure temporal consistency.
Across all tiers, results are visualised through clear graphical outputs to facilitate interpretation and communication.

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3.06.P-We071 Linking LCA to Policy: PROMETHEE Based Prioritization of Bioeconomy Options in Central and Eastern Europe

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The transition towards a bioeconomy aligns closely with the European Green Deal and the United Nations Sustainable Development Goals, as it seeks to decouple economic growth from resource depletion and environmental degradation while fostering low-carbon technologies and new economic opportunities. This requires a comprehensive, cross-sectoral approach that takes into account agriculture, forestry, aquaculture and biotechnology, whilst incorporating key products such as food, feed, wood and bio-based materials. Furthermore, planned activities must be aligned with national policy contexts and the priorities of stakeholders. A key challenge is determining which bioeconomy alternatives should be prioritized, as each country has unique framework conditions (e.g., agricultural/forestry resources, energy mix) requiring tailored recommendations.
To address this, a multiple criteria decision analysis (MCDA) approach has been applied within the Horizon Europe-funded project CEE2ACT supporting 10 countries in Central and Eastern Europe. A system-wide framework was developed to enable like-for-like comparison of heterogeneous bioeconomy pathways, evaluating 24 bioeconomy options (i.e. sectoral intervention pathways represented by specific implementation scenarios) spanning food, feed, wood, energy, bio-based products, and ecosystem services.
Quantitative data was used to assess environmental impacts, such as fossil and water resource use and greenhouse gas savings, by comparing each bio-based alternatives to the corresponding status quo using an LCA approach. Expert judgement was used to assess social and economic indicators such as consumer acceptance and willingness to pay, job creation potential, domestic biomass as well as renewable energy production. The PROMETHEE method was employed to aggregate preference flows to rank alternatives in each country. These results inform the development of national roadmaps and action plans.
By linking life cycle results directly to prioritization and roadmap development, the work closes the gap between methodological advances and implementation, supports innovation and ESG alignment, and strengthens evidence-based policy and industry strategies in diverse national contexts. The presentation will detail the methodology, stakeholder engagement and communication approach, and country-specific outcomes, for how LCA-based insights can guide responsible investment, policy design, and consumer-oriented interventions.

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3.06.P-We072 Matching SSbD Framework and ESPR Digital Product Passport Requirements: the case study of Flooring Systems with Recycled Rubber Granulate

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The end-of-life management of plastics remains a significant environmental challenge due to their high production volumes and persistence in the environment. Several polymers significantly contribute to ecosystem contamination and potential release of hazardous chemicals, causing toxicological effects on biodiversity and human health. Extending

material (re)use through recycling and circular strategies is therefore essential to support sustainable transitions and mitigate also potential ecotoxicological effects of plastics and their chemical additives.
This study, developed within a European Union (EU)-funded project aimed at implementing circularity and sustainability of solutions and services within SMEs (Small and Medium-sized Enterprises), presents a case study of flooring systems with incorporation of rubber granulate obtained from end-of-life tyres and shoe soles. The objective is to assess the environmental performance of this material and identify how recycled material can improve product sustainability and support ecodesign strategies in these construction applications.
Life Cycle Assessment (LCA) was conducted according to International Organization for Standardization (ISO) 14040/14044, using the ReCiPe (2016) method, SimaPro Craft software, and the Ecoinvent 3.11 database. Applying a streamlined cradle-to-gate approach, flooring systems with recycled rubber granulate were modelled using primary data (material, energy consumption and waste generation). Four scenarios, involving both virgin and recycled material (end-of-life tyres and shoe soles), were compared.
Results indicate that the application of rubber granulate from recycled tyre can reduce climate change impacts by up to 75%, compared to virgin raw materials, highlighting strong potential for decarbonisation. However, critical trade-offs, particularly in the collection, transport, and processing of secondary materials, which can also significantly affect human toxicity, were identified.
The findings highlight the role of LCA in supporting policy implementation and decision-making processes by identifying environmental hotspots, guiding ecodesign improvements. Furthermore, the results align with the compliance and sustainability requirements of the Ecodesign for Sustainable Products Regulation (ESPR), Digital Product Passport (DPP) Regulation, improving transparency and stakeholder communication, and thereby fostering future sustainability-related certifications of the products.

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3.06.P-We074 Decoupling Plastic Packaging from Fossil Feedstocks for increasing European Sustainability and Resilience

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Driven by the EU's Packaging and Packaging Waste Regulation (PPWR), the plastic packaging sector faces an urgent directive to shift from a linear to a circular economy given its environmental burdens. While "virgin-like" polymers can be produced via chemical recycling, a make-up is still required to account for losses throughout the plastic lifecycle. Relying on fossil feedstocks leads to climate burdens and high dependence on foreign imports, highlighting that defossilization and resilience of the sector can go hand in hand but require a synergistic approach that couples recycling with renewable feedstocks. However, multiple renewable technologies could be selected to defossilize chemicals production, raising the fundamental question of which ones and to what extent should be deployed at scale. This research addresses this key challenge in the transition: deciding which technology portfolio to invest in.

The polymer landscape becomes increasingly complex. This complexity is driven by a wide variety of feedstock options (such as naphtha and biomass), different recycling routes (mechanical, biochemical and thermochemical), and different polymer types, including conventional and non-drop-in (NDI) options. To address these complexities, we developed a superstructure reflecting 47 different pathways within the European plastic packaging sector. Further, we

apply multi-objective life cycle optimization (LCO) employing the recently developed PULPO framework to identify trade-offs between environmental and economic impacts, while respecting technical constraints like biomass availability and recycling limits.

First results indicate that the cost optimal solution for the plastic packaging sector can save up to 20% of the polymer cost, and lower global warming potential (GWP) by 40% through incorporation of mechanical and chemical recycling. Moving along the Pareto front, the GWP can be further lowered by utilizing more biomass and can shift into carbon negative values, when implementing NDI plastics into the economy. While this increases cost, there are still solutions that are competitive with the business-as-usual case and are completely independent of fossil imports. These findings suggest that NDI plastics are a critical lever for climate goals and European resilience. Future work will further explore the financial-environmental trade-offs across varying legislative and market scenarios to provide a roadmap for sustainable plastic packaging value chains.

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3.06.P-We075 Quantifying Packaging-Induced Product Losses in Life Cycle Assessment: A Risk-Based Modelling Framework

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Product loss is an important but difficult-to-quantify variable in Life Cycle Assessment (LCA) of packaging systems. Although packaging is designed to protect the product, packaging-related losses are often omitted or modeled using generic assumptions. Default loss rates in the European Commission's Product Environmental Footprint guidance are defined by product category rather than packaging type, highlighting the need for a detailed approach. This gap can affect the interpretation of comparative LCAs, especially when the environmental burden of the contained product exceeds that of the packaging.
This study presents a structured, risk-based framework to quantify packaging-induced product losses and integrate them into LCA models. The approach combines a systematic literature review, empirical production data, expert elicitation, and industry interviews (n=34), supported by a standardized Product Loss Risk Matrix.
The framework applies a function–characteristic–failure logic. Product protection requirements are linked to packaging characteristics and supply-chain failure modes. For each failure mode, probability (P) and impact (I) are assessed using calibrated 1–5 scales based on defined frequency and severity ranges. These are combined (P×I) to estimate loss rates. Case studies were evaluated by expert panels (n=17), and results are reported as medians with confidence intervals using a hierarchical data preference scheme.
The framework was applied to five case studies: heavy-duty sacks (cement and mineral fertilizer), rigid cosmetic packaging (body cream), pallet stretch wrap, and collation shrink. Losses for industrial bulk goods remain below 1% for high-water-barrier polymer systems but rise when moisture protection or mechanical resistance is insufficient. For viscous cosmetics, use-phase emptiability dominates losses and exceeds logistics-related losses tenfold. For collation shrink and pallet wrap, failure does not always cause product loss, as these formats serve secondary and tertiary roles; loss rates are below 0.6% and 1.4%, respectively.
Integration into LCA demonstrates that even small differences in product loss rates can significantly change comparative impact assessment outcomes when raw material production and product manufacturing environmental impacts are high. The proposed framework supports more robust LCAs and better decisions in sustainable product–packaging design and policy.

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3.06.P-We076 Comparative Life Cycle Assessment of Packaging Materials for Relocation: Supporting Circular Economy Transitions Under the Packaging and Packaging Waste Regulation

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The Packaging Waste Regulation (PPWR), entering force in 2025, mandates full recyclability of all packaging by 2030 and establishes minimum recycled content thresholds for plastic packaging, creating urgent compliance pressure across logistics-dependent industries. Despite this regulatory context, the mobility and relocation sector, a globally distributed logistics segment generating substantial per-shipment packaging waste, remains largely absent from the LCA literature. Existing comparative packaging LCA studies focus predominantly on food and retail applications, leaving decision-makers in the mobility and relocation sector without evidence-based guidance for sustainable procurement.

This study presents a cradle-to-grave comparative LCA of a range of packaging configurations for corporate relocation, spanning conventional fossil-derived materials, bio-based alternatives, and paper-based systems across key packaging functions. The analysis is grounded in sector-specific operational context and covers contrasting product models representative of the diversity of items transported during relocations.

The study addresses circularity and resource efficiency at the material selection level, examining how substituting fossil-derived packaging with bio-based or paper-based alternatives affects environmental performance across the full life cycle, including trade-offs where mass penalties from alternative materials may influence transport-phase emissions. The findings highlight the importance of considering full life cycle impacts when evaluating packaging alternatives in logistics systems. Integration of environmental and economic metrics is designed to produce decision-relevant outputs applicable across the broader mobility sector and transferable to other logistics contexts where packaging specifications remain largely unexamined.

This work contributes evidence relevant to both PPWR compliance and circular economy transitions in an under-researched logistics application, demonstrating how LCA, when integrated with industry-specific operational data, can bridge methodological rigor and practical decision-making in alignment with the symposium's aim of advancing life cycle approaches in support of European sustainability initiatives.

3.06.P-We077 Circular Product Design: Mapping Regulations and Product Characteristics to Life Cycle Impacts

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In response to increasing resource scarcity, environmental pressures, and the growing complexity of global supply and manufacturing networks, regulations and policy initiatives have become central to promoting product circularity. These include requirements on durability, repairability, recycled content, and end-of-life management. Within the European Union, the European Green Deal and the Ecodesign for Sustainable Products Regulation are key drivers. While these strategies aim to extend product lifespans, interdependencies between design characteristics within product architectures remain insufficiently addressed. Moreover, the combined environmental effects across the life cycle are not well understood, particularly regarding trade-offs between repair and energy efficiency improvements in newer product generations.

This study applies a systematic literature review of European regulations, standards, and circular design approaches, complemented by an analysis of life cycle assessment (LCA) methodologies and circularity indicators. The focus is on linking design characteristics to environmental impacts across the life cycle. A systematic mapping is developed to bridge policy objectives and engineering design practice, integrating LCA indicators such as climate change impacts and cumulative energy demand.

A reference model of product elements is established, including assemblies, components, interfaces, fastening technologies, and repair information. Based on this model, repairability, circularity, and LCA indicators are decomposed into components such as disassembly effort, reversibility of joints, spare part availability, and life cycle impacts. These are mapped to design characteristics along two dimensions: direct relationships and interdependencies across system levels.

The results show that environmental performance is context-dependent and requires a life cycle perspective. LCA indicates that repair is not always preferable, especially when newer products offer significant efficiency gains. At the same time, design strategies that enhance repairability may introduce trade-offs with material efficiency or production impacts. The framework identifies these trade-offs and highlights the need to integrate repairability metrics with LCA-based evaluation.

The approach supports systematic assessment of circular design requirements by linking policy objectives, indicators, and design parameters with life cycle impacts.

3.06.P-We078 Comparative Sustainability Assessment of Fish Boxes in Europe

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The Packaging and Packaging Waste Regulation (PPWR) introduces binding reuse targets for transport packaging in the European Union (EU), including fish boxes used for the distribution of fresh fish. In this context, EUMEPS and representatives of the fish industry commissioned us to evaluate the consequences of moving away from single-use Expanded Polystyrene (EPS) fish boxes and to assess whether alternative packaging systems would deliver environmental, economic, and social benefits for the EU fish sector.

We performed a comparative sustainability assessment of five fish box solutions used (or potentially used) to transport fresh fish in the EU: single-use EPS, reusable EPS, cardboard, insulated reusable polypropylene, and non-insulated reusable high-density polyethylene. We defined the functional unit as the transport and protection of 1 kg of fresh fish on ice during one distribution step in the EU.
Environmental impacts were quantified through a peer reviewed LCA conducted in accordance with ISO 14040/14044, covering the 16 impact categories recommended in the European PEF framework. Economic costs, and social impacts related to labour demand were assessed in parallel.
To support an integrated comparison across the three dimensions of sustainability, results were aggregated into a common metric expressed in euros per functional unit. Environmental impacts were monetised to estimate the current and future global burden caused by emissions and resource use (“cost of inaction”), while social impacts were monetised using the social value of job creation.

Under the assumptions applied, the single-use EPS box shows the lowest aggregated sustainability impact for distribution distances above 200km. Sensitivity analyses identify distribution distance as a key influencing parameter, reflecting the importance of return logistics and insulation performance for reusable and alternative systems.
While PPWR reuse targets aim to increase circularity in transport packaging, our study suggests that a rapid or systematic shift towards reusable fish box systems may lead to higher environmental impacts, in addition to higher costs for the fish industry, when realistic logistics and distribution constraints are accounted for. The results support evidence-based discussions on PPWR implementation, combining long-term quantitative comparisons with a qualitative analysis of short- and medium-term transition challenges.

Disclaimer/Disclosure: EUMEPS (The European Manufacturers of Expanded Polystyrene) and representatives of the fish industry in Europe have commissioned this study.

3.06.P-We079 Extended PEF-wise Dutch Environmental Food Database for 3000 Products

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In 2016, the Dutch Environmental Food Database was launched at the Dutch National Institute for Public Health and the Environment (RIVM) providing environmental impact data for food products alongside nutritional information. This public database was expanded throughout the years. Its latest version (2024) contains 400 food products and covers six environmental impact categories. The database, together with the Dutch food consumption survey, is being used to estimate the impact of the Dutch food consumption.

The RIVM and Wageningen University and Research (WUR) have further developed this database, aiming to make the method compliant with EC's Product Environmental Footprint (PEF) methodologies (European Commission, 2021), allowing inter-category comparisons of food products. The number of food products is being extended to about 3,000 products across 26 product groups. The results cover 16 environmental impact categories for 10 life cycle stages.

The methodology uses a mass-based functional unit and cradle-to-grave system boundary. Updated (international) cultivation data, quality data from Dutch cultivation, animal husbandry and processing data were added, as well as data quality ratings per food product. The final life cycle stages are modelled using PEF default approaches and, where possible, replaced by Dutch-specific data (e.g., food loss). EF3.0 datasets were not available, limiting full PEF(CRs) compliance. Each food product considers a specific market mix or individual country of origin, packaging type and preparation method. The database is accompanied by a public method report and data report, also identifying life cycle hotspots per food product group.

Key aims of the database are to: estimate the impact of the Dutch food consumption, support a reduction of the environmental impact along the food supply chain, inform sustainable policy development, and provide a solid base for comparing across food product categories for future environmental labelling. It is also being used for research purposes; another abstract explores the relation of the database with the Planetary Boundary approach for the food system.

This database supports the availability of publicly available environmental impact data of food products, which is essential in the transition to a more sustainable food system. On one hand it provides food companies with a reference for their own products and on the other hand can help more sustainable consumer choices.

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3.06.P-We080 Exploring the Environmental Impact of Dutch Food Consumption in Relation to the Planetary Boundaries

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The current food system is under pressure and contributes substantially to several global environmental problems. It will be a challenge to provide about 10 billion people healthy and sustainable food by 2050. The concept of the Planetary Boundaries (PB) defines the safe operating space for human development based on nine critical ecological processes. Based on this concept the EAT-Lancet Commission derived boundaries specifically for the worldwide food production. These boundaries provide an important frame of reference for policy making. Therefor we explored comparing the life cycle analysis (LCA) outcomes of the Dutch food consumption with the PB on the national scale, based on the allocation principle of 'equal per capita'.

RIVM monitors the environmental impact of the Dutch food system based on food consumption surveys for over 2000 people aged 1-79 years, combined with LCA results across six different impact categories for over 400 food products. We showed that the current database enables a comparison of the impact of the Dutch food consumption for four of the nine PB, i.e. climate change, land use, blue water use, and biogeochemical flows (N as well as P).

Comparing the environmental impact of yearly Dutch food consumption of the Dutch population with the Planetary Boundaries for food systems on a national scale , two impacts clearly exceed their Planetary Boundary: climate change and N-eutrophication of marine water. The CO2-eq emissions were estimated to be 1.03 tonnes per person per year, whereas a PB for the Netherlands was derived of 0.63 tonnes per person per year. N-eutrophication of marine water was calculated to be 13.0 kg per person per year, being well above the derived PB of 6.95 kg per person per year. The other Planetary Boundaries in this study (i.e. blue water use, land use and P-eutrophication of fresh water) were not exceeded.

In this study, we made a first exploration of the ability to couple LCA impact data of Dutch food consumption with the Planetary Boundaries for food. Although not yet complete, the results indicate that the concept of PB provide a valuable reference framework to relate absolute LCA data to the severity of environmental impacts when considering the carrying capacity of our planet on country level. This overview enhances communication about emerging environmental issues with stakeholders and the public and facilitates policy making regarding absolute sustainability.

3.06.P-We081 Integrated Analysis of Environment, Nutrition, and Affordability for Building a Sustainable Individual Diet in Japan

Food systems are a major driver of environmental degradation and a key determinant of human health, and previous research and policy efforts have primarily evaluated dietary patterns from environmental and nutritional perspectives. However, achieving practical solutions and enabling behavioral change requires economic feasibility, along with policy frameworks that support gradual transitions toward target diets rather than immediate shifts.
This study aims to provide an evidence base for designing incremental shifts toward sustainable diets in Japan by simultaneously considering nutritional adequacy, environmental impact, and affordability. To do so, we attempt to quantify current dietary patterns, related nutritional adequacy, and environmental impacts that are disaggregated into detailed food categories while considering consumption context, including home-cooked meals, eating out, and ready-made foods. Nutritional adequacy is assessed against dietary reference intakes to identify imbalances, while environmental impacts are quantified using life cycle assessment (LCA), focusing on greenhouse gas (GHG) emissions.
Based on these analyses, dietary scenarios are also constructed as incremental shifts to gradually increase the intake of nutrient-dense, low-impact unprocessed vegetables and fruits, which are associated with a higher environmental impact and health risk, as well as processed meats and meats, sweets, and indulgent beverages. The economic implications of each transition step are evaluated by comparing food costs before and after dietary changes. This enables the visualization of how sustainability improvements and associated costs evolve along transition pathways.
The results are expected to clarify the trade-offs among nutrition, environmental sustainability, and affordability, thereby making it easier for individuals to choose sustainable diets. Furthermore, by explicitly linking stepwise dietary changes with their cost implications, this study provides insights into how policies can promote more realistic and widely adoptable dietary shifts.

3.06.P-We082 Applying Input Output (IO)-Models for Agricultural PCF Calculation – Potentials and Limitations

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Background and challenges:

Carbon footprint accounting for agricultural products is required for climate smart food policies and food labelling, yet diverse data and methods limit comparability of results.
While international standards for bottom-up LCA-based Product Carbon Footprints (PCFs) leave many methodological choices open, top down macro-economic input output (IO) models may contribute to harmonization providing a consistent methodological and statistical data framework.

Our approach:
We compare two IO-based models, the Common Agricultural Policy Regional Impact (CAPRI) model and EXIOBASE 3, with respect to their methods, data sources and results regarding PCF. We deduce potentials and limitations of IO-models to contribute to harmonization of agricultural PCFs, and fields of application of the two IO-models in particular.

Methods and Models:
We chose CAPRI and EXIOBASE since they are both used frequently for assessing GHG-emissions of food / agricultural production and generic footprint calculation at EU membership level. The carbon footprint module of the CAPRI model comprises an IO model that converts activity-based greenhouse gas emissions to roughly 50 PCFs. EXIOBASE (version 3.9.4) provides environmentally extended multiregional IO-tables and by applying the Leontief inverse calculates PCF for 13 agriculture related items. We compare (i) the PCF results with those of bottom-up LCAs; (ii) emission factors and data sources of both models for emission hotspots (feed, manure, etc.) and (iii) lists of non-agricultural inputs, e.g. industrial products and services.

Findings / Hypotheses:
CAPRI and EXIOBASE yield similar carbon footprint values for pork, raw milk and wheat at the EU-membership level, which tend to be slightly lower than PCFs from common LCA databases such as Agribalyse. Our hypothesis is that IO-models capture the dominant hotspots despite higher aggregation and solve allocation issues consistently. Differences arise because CAPRI provides finer agricultural detail, whereas EXIOBASE reflects broader industrial input streams.

Conclusions and relevance:
The climate footprint modules of CAPRI and EXIOBASE each provide a largely consistent, low effort reference for nationally representative food PCFs, with different foci. As such, they may contribute to harmonization and comparability, e.g. for food labelling. Additional potential arises from delivering time series and combining different sustainability criteria.

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3.06.P-We083 Is Wine the Fruit of a Sustainable Production? Environmental Impact Assessment of Belgian Vitiviniculture Before and After Agroecological Practices, Based on Primary Data

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Emerging cool-climate wine production is a scientific field that presents unique opportunities and challenges, particularly in the context of climate change modelling and sustainability quantification. While agroecology has been studied and subsidized in traditional wine-growing regions, its application to northern European viticulture remains largely unexplored.
This study firstly evaluates the baseline environmental impact of Belgian vitiviniculture through a Life Cycle Assessment (LCA), conducted prior to the implementation of agroecological interventions at both vineyard and winery

levels. Secondly, applicable agroecological practices and concepts as defined in alignment with EU Horizon and Farm2Fork directives and relevant regenerative farming data will complement the inventory for comparative analysis. The Belgian case study functions as a reference model for emerging cool-climate wine regions in Europe, specifically Denmark and the Netherlands. The research systematically analyses the benefits and trade-offs associated with the adoption of agroecological practices and proposes methodological approaches to address these trade-offs. Scenario analysis is employed to identify and support optimal strategies for accelerating the uptake of best practices across varying spatial and temporal scales.
The inventory is based on primary data collected directly from wine producers, encompassing operational practices and company-own documentation. In addition, the study highlights the role of creative multi-stakeholder scenario development as a participatory tool in sustainability transitions. The Belgian case study enables the identification of critical environmental hotspots in both field and production processes that differ from those in traditional wine regions, including cultivar selection, plant protection strategies, canopy management, and energy use in winemaking. Furthermore, the research explores cost-reduction opportunities in terms of working time, raw materials, fuel consumption, and synthetic inputs, alongside eco-enhancing measures ranging from ecosystem-based approaches to advanced techno-digital automation. The findings contribute to the refinement of existing Product Environmental Footprint guidelines by incorporating factors specific to cool-climate viticulture, thereby supporting more context-sensitive sustainability assessments.

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https://www.agroecologypartnership.eu/en/projects/emcoclim-viti

3.06.P-We084 Shifting Protein Intake in Belgium: Potential Health and Environmental Impacts

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Background: A high consumption of animal-based protein is characteristic of Western diets but contributes substantially to both environmental pressure and diet-related health risks. In response, several initiatives have been launched to promote a shift towards more plant-based diets. One such initiative in Belgium, the Flemish Green Deal Protein Shift, recommends a transition to a 40:60 animal-to-plant protein ratio. The potential environmental and health benefits of this transition have not yet been quantitatively assessed. This study, therefore, aims to evaluate the impacts of such a dietary shift in Belgium, providing evidence to support more effective and targeted food policy measures.
Methods: The Belgian diet was modelled using data from the Belgian National Food Consumption Survey 2022-2023 (FCS 22/23). Health impacts were assessed using a comparative risk assessment framework, focusing on major health outcomes, including type 2 diabetes, cardiovascular diseases and certain types of cancers. Environmental impacts associated with food consumption and production were evaluated using life cycle assessment. To assess the potential effects of a dietary protein shift, a subsample was identified within the FCS 22/23 of individuals consuming the 40:60 animal-to-plant protein ratio. This sub-sample was used to model the impact of the potential transition.
Results: Preliminary findings indicate that shifting towards a 40:60 animal-to-plant protein ratio improves health outcomes associated with key dietary risk factors, including high red and processed meat intake and low fruit and vegetable consumption. Most environmental impacts associated with the modified diet were reduced, with approximately 20% reduction in climate change compared to the current diet.
Conclusions: A dietary protein shift could help reduce the environmental and health impacts of food consumption in Belgium. However, the effectiveness of initiatives such as the Green Deal Protein Shift depends on broader structural support. The results of this study highlight the important benefits of such dietary transitions and provide quantitative evidence to support stronger policy measures and targeted interventions aimed at enabling and accelerating this shift.

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3.06.P-We085 The Use of a Farm-level LCA Calculator for Small-scale Dairy Systems in the Cross-border Region of Spain and France

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The dairy sector is facing growing market pressures to demonstrate its environmental sustainability. However, Life Cycle Assessment (LCA) remains largely inaccessible for small-scale producers due to limited financial and technical resources. In response, LCA calculators have emerged as a solution (e.g., GLEAM (FAO), FarmAhead (Arla Foods)) to bridge the gap between a full LCA evaluation and user-friendly tools that facilitate the assessment and communication of results to producers.

This study assessed the potential environmental impact of four small-scale cheese producers in the cross-border region of Spain and France to identify hotspots and mitigation strategies. For three producers, impacts from farm and processing stages were calculated using the LCA calculator CAP2'ER. For the fourth producer, who purchases milk from one of these farms, the impacts from cheese production were modeled using OpenLCA with Ecoinvent v3.10 as background data, incorporating the result of climate change related impacts from milk production previously calculated with CAP2'ER.

The findings show that CAP2'ER facilitates data collection by combining a user-friendly questionnaire with default values for unavailable data with an integrated impact assessment methodology. This supports data collection, the development of life cycle inventories, and methodological consistency in a sector with data collection barriers, complex biological processes, and high variability. Additionally, it allows for benchmarking of the results, which helps farmers better understand and compare their assessments. However, these benefits come with constraints for the alignment with standards, such as PEF, and for modeling atypical systems.

Using OpenLCA for the processing phase allows a more detailed model of artisan cheese production and further stages. However, there are difficulties in the harmonization of results due to the underlying methodological assumptions and modeling of the calculator, even though effective mitigation options emerge from interactions between the farm and processing stages, such as valorising whey as fertiliser.

One significant conclusion of this study is the importance of adapting LCA approaches to the characteristics of small-scale cheese producers, understanding how different solutions can adapt to different realities and produce meaningful results for decision making towards more sustainable dairy systems.

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3.06.P-We086 Visualizing Biophysical Limits of Battery Production for Policy Integration

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Digital battery passport stakeholders have expressed their preoccupation regarding the critical need for transparent and representative sustainability data. Moreover, current use of deterministic data compromises the robustness of decisions in relation to the inherent variability embedded in LCA calculations and absolute sustainability downscaling methodologies. Uncertainties are further exacerbated when assessing emerging technologies and evolving supply chains in a future context via prospective LCA, all the more pertinent to the battery ecosystem. We highlight the need for life-cycle thresholds for battery production that take into account embedded uncertainties and reliable process data. Therefore, the goal of the present work is to demonstrate that the comparison of prospective impact distributions (generated from granular life cycle inventories with propagated uncertainties) against absolute sustainability target distributions can provide feasible life-cycle impact thresholds for battery regulations. We introduce two existing

statistical tools to compare probability density distributions, the Hellinger and Wasserstein distances, in order to better characterize the overlap between the estimated future impact and target distributions. We convert such metrics into a more accessible risk of non-exceedance, quantified in percentage. We then provide visualizations of impact and target distributions overlap as an intuitive pathway for non-expert decision-makers to explore life-cycle threshold setting within regulations. We assess the potential of introducing technical improvements in prospective background life cycle inventories (i.e. augmenting recycled content of battery metals and upgrading mineral processing pathways) for increasing the overlap between the battery's projected impact and its target distribution. We repeat the forward-looking analysis for the years 2030, 2035, 2040 and 2050. Our results visually demonstrate the need for concerted technological and demand-side mitigation measures (i.e. reduction in vehicle fleet) in order to achieve battery production within planetary boundaries. We hope our proposed methodology can inform higher-tier performance classes to be set in the EU battery regulation and analogous regulations for other industrial sectors.

3.06.P-We087 Cradle-to-Gate LCA of Carbon Nanotube Production: Hotspot Analysis and Low-Carbon Strategies

This study conducted a cradle-to-gate life cycle assessment (LCA) of carbon nanotube (CNT) production to quantify its environmental profile and identify key priorities for sustainability improvement. Following ISO 14040 and 14044 standards, the study modeled the production of 1 kg of CNT, encompassing raw material extraction, input transport, and manufacturing processes, while excluding use and end-of-life stages. The functional unit was defined as 1 kg of CNT used as a conductive material. Environmental impacts were calculated using GaBi software by integrating gate-to-gate inventory data with Ecoinvent v3.10 and applying the CML 2001 (Aug 2016) impact assessment method. Six midpoint categories were evaluated, with the carbon footprint serving as the primary sustainability indicator. The life cycle inventory (LCI) was developed from an integrated dataset combining site-specific data from an international producer with three literature-based datasets for CVD-based production. For 1 kg of CNT, the global warming potential was determined to be 1.02 x10^2 kg CO2 eq. Contribution analysis revealed that the manufacturing stage dominated the carbon footprint (83.4%), followed by pre-manufacturing (16.6%), while transport contributed less than 0.1%. Electricity was identified as the critical hotspot (83.4%), followed by argon (8.6%) and the carbon precursor (4.3%). Scenario analysis indicated that replacing the grid mix with photovoltaic electricity could reduce the carbon footprint by up to 79.3%, whereas substituting ethylene with bio-ethylene yielded a 4.8% reduction. The study also highlights methodological limitations. Due to the integration of site-specific and literature data, the environmental profile of the individual producer could not be fully isolated. Furthermore, direct benchmarking against international datasets remains challenging due to the scarcity of transparent gate-to-gate inventories. Future research should prioritize the development of process-level inventory datasets and company-integrated data management systems to support more rigorous benchmarking and the "Safe-and-Sustainable-by-Design" of nanomaterial production.

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3.06.P-We088 A Dual-Economy LCA Framework for Allocation in Absolute Sustainability Assessment

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Life Cycle Assessment (LCA) informs decision-making, yet most applications struggle to translate complex environmental results into actionable guidance on what should be prioritized, reduced, or reorganized. This challenge is particularly acute when distinguishing between essential 'needs' and non-essential 'luxury' consumption within the planetary boundaries. To bridge this gap, we developed a modular dual-economy framework by partitioning the safe and just operating space, at the sectoral level, into a needs-based Base Economy and a wants-based Space Economy. By combining the sector-resolved LCA with normative provisioning baskets and transition scenarios, this framework

allows to translate biophysically planetary constraints into interpretable allocation keys and service-level trade-offs. Our first results show that Base and Space Economies are shaped following different provisioning logics and exhibit environmentally heterogeneous sectoral structures. Consequently, the allocation keys for production and consumption vary significantly across different environmental categories and between the two economies. Scenario projections up to 2060 further indicate that that ecological space for non-essential consumption is rarely available. Climate-compatible provisioning of essential 'needs' (the Base economy) can emerge only under completely defossilized supply chains in the Base Economy or through defossilization combined with the carbon dioxide removal. Even for pathways staying within the safe climate boundary, residual space remains constrained, with climate gains often accompanied by bottlenecks regarding safe nitrogen emissions and mineral resource use. This highlights the need for multi-indicator transparency to avoid burden shifting in policy design.
The framework attempts to enhance decision-making by quantifying industrial scale compatible with meeting human needs within planetary boundaries as well as the ecological space available for non-essential activities. Moreover, public luxury (e.g., shared mobility) delivers much higher service levels than private alternatives under the same ecological budget. Ultimately, our research here recasts sustainability not merely as impact reduction, but as a transparent strategy for allocating scarce ecological space, providing a scientific basis for environmental social governance reporting, eco-design, and consumer communication

3.06.P-We089 Decision Support for Circular Transitions in Remote Islands: Linking Local Specialties to Regional Resilience

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Remote islands face acute vulnerabilities, including demographic decline, resource scarcity, and economies reliant on external imports. Transitioning to a robust, self-sufficient circular economy is essential for long-term sustainability. To achieve this, isolated regions must foster endogenous development by transforming local resources into high-value specialty products. However, policymakers and consumers lack high-resolution evidence to understand how steering toward these localized circular models alters global greenhouse gas (GHG) emissions and local economic resilience across geographical tiers.

We investigate how expanding specialty markets and internalizing supply chains may steer the Goto Islands, Japan, toward a circular economy. We combine macro-economic scenario analysis with granular micro-environmental assessments. The primary method is a nested multi-regional input-output (MRIO) model connecting city, prefectural, and global economic scales. Utilizing primary empirical data from interviews, we precisely disaggregated standard input-output sectors to model niche industries, local beef, seafood, and camellia oil, to quantify their specific contributions to the local economy.

Utilizing this framework, we will evaluate the systemic socio-economic and environmental impacts of import substitution scenarios where intermediate agricultural goods are produced locally rather than imported. Concurrently, a rigorous LCA will be applied to quantify the expected GHG reduction benefits of specific grassroots actions, such as adopting sustainable packaging materials within the fishery sector. Furthermore, a comparative analysis between island-produced and foreign-imported camellia oil will be conducted to provide transparent data for consumer choice and regional branding.

The integrated assessment is expected to reveal significant structural transformations in not only global GHG emissions but also regional employment generation and economic ripple effects resulting from localized supply chains. The nested MRIO model will effectively capture macro-level shifts in socio-economic indicators, while the independent LCA isolates emission reductions driven by grassroots initiatives undetectable in aggregate data. This research aims to provide a robust analytical framework for inclusive decision-making, demonstrating how steering local industries toward circular strategies optimizes both the environmental and economic profiles of resource-constrained regions.

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3.06.P-We090 Assessing Sustainability in Metal Additive Manufacturing: A Decision-Support Tool

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Evaluating the sustainability of different systems is challenging, particularly when environmental and economic dimensions are jointly considered. Life Cycle Assessment (LCA) evaluates various environmental impacts expressed in different units. The integration of Life Cycle Costing (LCC) further increases analytical complexity and complicates the aggregation of criteria. Recent literature highlights a growing interest in approaches that combine LCA and LCC frameworks. Multi-criteria Decision Analysis (MCDA) has been widely recognised as a robust and flexible method, enabling transparent and structured evaluation of multiple criteria and supporting informed decision-making.

MCDA has been applied to assess sustainability across a range of sectors, including energy, building, and construction. However, the literature remains limited within the metal manufacturing sector. To the best of the authors' knowledge, no previous study has considered MCDA for the sustainability assessment of large aluminium parts produced by metal additive manufacturing (AM). To address this research gap, the present study proposes a decision-support tool for the metal AM sector, aimed at supporting product developers' decision-making during the early stage of part development.

The tool was developed by integrating sustainability and technical indicators, including energy consumption, multi-functionality, carbon footprint, human toxicity, resource scarcity, and production costs. The environmental indicators were assessed using the LCA framework and a cradle-to-gate approach, while production costs were evaluated through the LCC analysis under the same system boundaries and assumptions. Then, the scenarios were ranked using several aggregation and weighting methods, namely the Weighted Sum Model, VIKOR, Technique for Order Preference by Similarity to Ideal Solution, and the Analytic Hierarchy Process. The MCDA tool was validated through a real-world case study from the aerospace sector and complemented by sensitivity and uncertainty analyses to assess the robustness of the results. Overall, the findings showed that AM outperform conventional machining.

This work addresses a critical gap in decision support at early design stages, contributing to the advancement of sustainability assessment in metal AM. This tool integrates technical performance with life cycle environmental and economic criteria, enabling robust design decisions for the manufacturing of large aluminium parts.

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3.06.P-We091 Absolute Assessment of Abiotic Resource Depletion of Urban Blocks

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Existing eco-design tools based on LCA are mostly used as comparative tools to select the best variant. However, they need to better represent the level of ambition needed to achieve strong sustainability, for instance thanks to absolute environmental assessment as a complement to existing comparative environmental assessment.

The concept of absolute environmental sustainability assessment (AESA) is to assess the life cycle impacts of the project or nation or sector on an absolute scale by comparing its impacts to a threshold reflecting absolute

sustainability. Among existing approaches, planetary boundaries (PB) have been made operational using AESA and LCA in recent years. The PB framework does not include boundaries for resources, which holds an important instrumental value to humanity.

The objective of this work is to investigate how to incorporate the preservation of abiotic resources into an absolute framework for building eco-design tools. Existing global boundaries from the literature have been downscaled to the building level, using a first equal per capita sharing principle and a second based on spending for housing. It was then applied to an illustrative case: a French single-family energy-efficient house (heating needs <1kWh/m²), built from bio-based materials and housing four people.

Critical analysis of existing methods shows that they mostly focus on the depletion of natural stocks, disregarding dissipation, thereby failing to fully account for circular economy practices. Resource boundaries per resource type have been computed for 25 abiotic resources, mostly metals, coming from 13 methods. The values vary widely for the same resource across references. As an example, resource boundaries for aluminium range from 0.1 to 28.3 kg/building*year (for housing four people), while the projected house requirement over the building lifespan is 6.33 kg/building*year.

Further research will be conducted to integrate dissipative flows and dissipative uses in the building sector to better reflect circular economy practices and to consider both resources from geological reserves and from urban mining. Other downscaling methods will be investigated to enable the evaluation of other building types (schools, offices, etc.) and thus evaluation at the urban block scale. The approach can ultimately be integrated into building eco-design tools, enabling professionals to look beyond regulatory compliance and towards absolute environmental sustainability.

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3.06.P-We092 Fulfilling Human Needs within Planetary Boundaries: A Review of Downscaling Global Environmental Budgets to Provisioning Systems

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Current strategies for fulfilling human needs drive global environmental degradation, with impacts likely to intensify if left unmitigated. It is therefore necessary to establish maximum consumption levels for provisioning systems for individuals or households that fulfil their needs, e.g. housing, mobility and food. These maximum levels should be derived from the global Earth's biophysical limits, for instance from the planetary boundaries framework, which defines global environmental budgets such as carbon budgets. A key challenge lies in translating these global environmental budgets to the level of individual's or household's provisioning systems. This requires downscaling, whereby a share of the global environmental budget is allocated to a specific system.
This study systematically reviews how global environmental budgets can be downscaled to provisioning systems that fulfil human needs at the level of individuals or households. While downscaling is commonly applied in absolute life cycle assessment and reviewed mainly at country level, this study advances the literature by centering specific provisioning systems that fulfil human needs, the ultimate purpose of consumption.
The findings highlight the methodological complexity of the downscaling process where a sequence of analytical and normative choices leads to a wide range of possible outcomes. Most studies apply a two-step downscaling approach: allocating budgets first to a subpopulation and subsequently to a specific provisioning system. The review identifies proportional discrepancies of e.g. carbon budget for individuals for housing provisioning, where differences up to a factor of 18 are identified, predominantly caused by different allocation methodologies. The study identifies critical gaps, including the limited adoption of a multi-need perspective, and provides methodological foundations for establishing a need-based maximum level of consumption. These insights advance the operationalization of sustainable consumption within planetary boundaries, offering a first step for integrating human needs and environmental limits in

research and policy.

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3.06.P-We093 Life Cycle Approaches For Chemical Technology Selection: Enabling Informed Decision Making For Chemicals and Fuel Production Technologies

In this work we show how the use of life cycle approaches for carbon footprinting could influence behavioural and consumer decision-making within the chemical plant technology industry for sustainable fuel production.
When selecting a sustainable technology route for chemical or fuel manufacture, meeting the threshold carbon footprint for legislation can be crucial in securing a profitable venture. This directly correlates economic feasibility with the carbon footprint of the produced commodity. Some efforts have been made to create public calculators e.g., UK low carbon H2 fuel emissions calculator but for many fuels and chemicals it is left up to the customer or technology supplier to estimate.
To enable informed decision consumer decision making for in Catalyst Technologies we have created several simple tools to calculate carbon footprints of chemicals across different technologies. This requires:

- mass and energy balance data of prospective plants
- public and proprietary datasets for emission factors
- geographic specificity
- scenario and sensitivity analysis including feedstocks
- understanding of different legislative requirements and thresholds

Using these tools we can provide more insight for consumers of our chemical technology. Examples include sharing hotspots and “must haves” as well as identifying high risk choices. We will showcase some of the results from the tools and how our commercial teams can use the tools with prospective customers.

3.06.P-We094 Defining Net-Zero Buildings through Product-Level Life Cycle Strategies

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The concept of net-zero has been adopted in numerous frameworks and sustainability targets in the building sector. However, it remains unclear how the net-zero concept can be applied at a product level, since net-zero buildings mostly refer to the operational energy use, rather than the embodied emissions of the construction products.

This study examines how product-level life cycle assessment (LCA) can support the understanding of net-zero on a building scale by analysing various scenarios of individual construction products. The study analyses how decisions related to the products would impact the total emissions of the building. The methodology combines a literature review of net-zero strategies for construction products with LCA modelling. Strategies are considered at two levels: material and design, which can demonstrate that achieving a net-zero product requires a combination of approaches focusing on both production and design sides. Some strategies at a material level include increased recycling rate, carbon capture and storage plant, and the use of fossil-free energy; meanwhile, design strategies can be the use of bio-based alternatives. To assess the results at a building scale, a representative building has been chosen as a case study, in which the main materials were evaluated under various strategies.

This study illustrates how net-zero buildings must integrate both operational energy improvements and embodied emissions from the construction products, emphasising the importance of product-level decisions. By clarifying how net-zero concepts can be applied at the product level, this study gives an insight into how product-level strategies can influence net-zero outcomes at the building scale.

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3.06.P-We095 Safe and Sustainable by Design (SSbD) Functionalized MXenes: Environmental Impacts Comparison through Life Cycle Assessment (LCA)

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MXenes are a class of advanced 2D materials composed of transition metal carbides, carbonitrides and nitrides. The SAFARI project aims to enable the SSbD production and utilization of MXenes, covering the whole supply chain, from precursors' preparation to final applications (biosensors, conductive inks and electromagnetic interference (EMI) shieldings). A key step is the functionalization of MXenes, which enables the tailoring of their surface chemistry to achieve the desired properties and performance characteristics for their intended applications. In SAFARI, titanium-based MXenes (Ti MXenes) were functionalized using metallic nanoparticles (Cu, Ag and Ni) and polymers (PVA, PPy, PANI, PEDOT and APTES) via an ultrasonication assisted process (U/S).

The objective of this study is to determine the environmental impacts of functionalized Ti MXenes production process via LCA assessment, in order to identify hotspots and improvement opportunities, thereby supporting the innovation process. An LCA was carried out following the ILCD handbook and ISO14040 methodology. The assessment was performed using SimaPro v10.1, with the Ecoinvent 3.10 database and the Environmental Footprint 3.1 method. The functional unit was defined as 1 g of functionalized Ti MXenes, and the scope was Cradle-to-Gate. Primary data were collected from the production process, including inputs, outputs, waste streams and energy requirements.

The environmental impacts associated with the production of functionalized Ti MXenes are ranked as follows, listed from highest to lowest impact: Ag, APTES, Cu, PPy, PANI, PEDOT, Ni and PVA. The impact of Ti MXenes functionalized with Ag is 3.3, 5.6, 10.5, 10.6, 11.9 and 12.2 times higher than APTES, Cu, PPy and also PANI, PEDOT, Ni and PVA, respectively. Regarding Ti MXenes functionalized with Ag, the majority of the environmental impact is associated with the category Resource use, minerals and metals (82.51%), followed by Climate change (3.99%), Resource use, fossils (3.49%) and Eutrophication, freshwater (3.39%).

This study highlights the critical importance of material selection in the MXene functionalization process in determining the environmental impacts of the production process. Thus, the implementation of SSbD principles in the tailoring routes of MXenes is a critical step toward ensuring the safe and sustainable production of these materials.

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3.06.P-We096 Integrating Life Cycle Assessment and Life Cycle Costing for Cleaner Production in AOD Refining of Stainless Steel: A Scenario-Based Evaluation

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The Argon Oxygen Decarburization (AOD) process is a key step in stainless steel (SS) production, yet its environmental and economic performance remains insufficiently resolved at the process level. This study addresses the need to identify environmental hotspots and cost-effective decarbonization strategies within AOD refining. A combined LCA and LCCosting approach is applied to evaluate the impacts of key process inputs, including reductants

(ferrosilicon/Al), inert gases, and flux. Scenario analysis is used to assess the influence of mass-based parameter variations relative to a baseline configuration. The methodology relies on database-driven inventory data and midpoint impact assessment, complemented by simplified cost calculations for 1 ton of SS. Preliminary results show that the reduction stage dominates environmental impacts, with FeSi contributing up to 90% of particulate matter formation. Argon contributes the most to energy resource use due to its high consumption rate, despite its lower energy intensity per unit mass. Climate change impacts are primarily driven by upstream emissions from input materials rather than direct process emissions. From a cost perspective, the baseline scenario ranks among the lowest-cost configurations, while nitrogen substitution reduces both environmental impacts and operational costs. Mixed reductant use yields lower impacts compared to single-reductant scenarios. Overall, the study confirms that raw material inputs and their consumption rates are the primary drivers of both environmental and economic performance in the AOD process. Reductant selection and inert gas composition emerge as critical parameters for optimization, while flux variations play a comparatively minor role. The substantial generation of AOD slag suggests that its valorization represents a complementary pathway for improving system sustainability, although this aspect requires further investigation. The relevance of this study lies in its contribution to bridging the gap between system-level assessments and process-level decision-making in stainless steel production. By integrating LCA and LCC within a scenario-based framework, the study provides actionable insights for industry stakeholders seeking to implement cost-effective decarbonization strategies. Furthermore, it highlights the need for improved primary data and process-specific modeling to enhance the accuracy and applicability of environmental assessments in metallurgical processes.

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3.06.P-We097 Guidelines for Social Life cycle Assessment of Hydrogen Valleys

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Hydrogen valleys are multi-actor projects that cover the entire hydrogen value chain in a limited geographical area. These valleys may include activities ranging from the production of green hydrogen to its end-use. Hydrogen end-uses include its use as a fuel or an energy vector, or as a feedstock for industry, including the production of steel and chemicals. Hydrogen may also be exported outside the valley. Due to the variety of activities that may be covered and the potential difference in maturity between these, hydrogen valleys are complex systems.
The Clean Hydrogen Joint Undertaking (JU) is a public-private partnership that funds research and innovation projects in hydrogen in Europe, including hydrogen valleys. Some of the funding calls launched by the JU require funded projects to assess their environmental impacts by conducting life-cycle assessments. Many projects have extended their assessment to include a social life-cycle assessment. However, given the wide range of activities covered by hydrogen valleys and the different scopes these may cover, conducting a (S)LCA on hydrogen valleys is not trivial.
Therefore, the JRC and PRe Sustainability have produced a set of recommendations on conducting social life-cycle assessments for hydrogen valleys by adapting state-of the art methodologies to the hydrogen value chain. The recommendations cover the typical elements of social life-cycle assessments, such as the choice of goal and scope, the indicators that practitioners should assess, and the data collection procedure. These integrate insights gained from consultations to hydrogen valleys from various European countries.
In the coming year, these recommendations will be tested and consolidated into guidelines that hydrogen valleys can use to assess their social impact.

3.06.P-We098 From CE Assessment to Best Practice: A Nano-Level Case Study of Data-Driven Circular Product Design

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Implementing circular economy strategies at product (nano) level is often constrained by life cycle data gaps, fragmented data sources, and limited data competences in organizations, yet requires translating complex assessment results into concrete design decisions. We build on a nano-level case study of a manual dishwashing detergent concentrate refill system, in which life cycle assessment and material and product circularity indicators were applied to alternative packaging configurations.
Prior analysis showed that environmental impacts of both product systems compared are dominated by the use phase, while packaging design, especially recycled content and reusage, drives differences in circularity. Combining circularity indicators with environmental impacts indicates that introducing concentrate refills can reduce most impacts and increase circularity compared to the conventional product system, whereas additional refill cycles unintuitively reduce circularity scores, revealing limitations of the applied metrics.
Using this quantitative dataset and previous insights, we develop an optimized best-practice product system that aligns circularity and environmental performance.
Our approach integrates circular strategies (e.g. reduce, reuse and recycle), scenario analysis, and digital assessment with the data competences needed to generate and interpret results. It follows a repeatable sequence from problem definition, functional unit and system boundary setting followed by data collection, modelling, indicator calculation, and integrated interpretation.
The resulting best-practice product system provides a transparent, data-driven redesign pathway for concentrated consumer products and helps organizations manage trade-offs between circularity metrics and environmental indicators, while illustrating how detailed product-level studies can inform systematic guidance for data-driven circular product development beyond this specific application. In essence, this contribution integrates best practices for collecting, managing, and analyzing product-related data to support redesign for higher circularity and improved environmental performance.

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3.07.P - From Waste to Resource: Life Cycle Perspectives on Recycling, Recovery and Treatment

3.07.P-Tu020 Environmental assessment of a building board for circular construction made from recycled materials

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The RECOB2 project, part of the Walloon platform REMIND (Reverse Mineral Industry in Wallonia), aims to develop an innovative construction panel composed of over 70% recycled materials (paper fibers, crushed sand, and binders such as lime or alternatives like biomass ash). This material, intended for the building renovation and insulation markets, is part of a circular economy approach by valorizing waste (recycled paper, demolition sands, ...) and reducing the environmental footprint compared to traditional processes.
A Life Cycle Assessment (LCA) compliant with ISO 14040/44 standards as well as EN 15804 + A2 (2019) was conducted to evaluate the environmental impacts of the RECOB2 building board, from raw material supply to its end of life. The environmental impact indicators were compared to those of a conventional product (wood fiber panel). The Environmental Footprint 3.1 method was used for this assessment, the modeling was carried out using Simapro 10.3.0.1 software. A cradle-to-grave approach was followed, and the inventory is based on primary data collected from project partners and supplemented by the Ecoinvent 3.11 database as a secondary data source. The functional unit is 1 m2 of floor covering with thermal conductivity of 0,10 W/(m.K) over a 50-year lifespan. The end-of-life scenario assumed is 50% recycling, 30% reuse, and 20% landfilling.
The final results identify manufacturing (A3) as the main hotspot module, primarily due to Belgium's electricity residual mix, followed by end-of-life disposal (C4) due to landfilling. The climate change indicator (including module

D, "benefits and loads beyond the system boundary") is 3.19 CO2 eq/m2.
This study aimed to use LCA as an eco-design tool to highlight the hotspots of different choices in terms of technologies and materials, and to support the circular economy transition in the construction sector.

3.07.P-Tu021 Life Cycle Assessment of End-of-Life Artificial Turf: Hotspots and Optimization in Recycling Systems

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End-of-life artificial turf poses a growing environmental challenge due to its heterogeneous material composition, decades-long weathering exposure, and contamination from organic and inorganic substances. While recycling is technically feasible, the ecological trade-offs between mechanical, chemical, and thermal recovery pathways remain poorly quantified.
This study evaluates the environmental impacts of artificial turf recycling using an attributional life cycle assessment (LCA). The analysis, conducted with Ecoinvent APOS and the Activity Browser, applies the avoided burden approach to assess material recovery benefits and the superstructure method to model complex recycling networks. Key aspects include:
a) Comparison of mechanical, chemical (pyrolysis), and thermal recycling,
b) Sensitivity analysis of transport logistics on the life cycle inventory,
c) on-site sand reuse from decommissioned turf as a strategy to minimize transport emissions and preserve virgin resources
d) Identification of hotspots (e.g., energy demand, emissions).
Preliminary results indicate that thermal recovery currently outperforms alternatives environmentally, primarily through farer transportation ways to recycling companies. However, reduced transport distances or advances in mechanical processing could shift this balance. The study aims to pinpoint critical hotspots and propose targeted measures to improve the ecological and economic feasibility of artificial turf recycling.
By providing a systematic LCA framework for this understudied waste stream, this work advances circular economy strategies in sports infrastructure and offers transferable insights for other complex plastic waste systems. Findings will inform policy recommendations and industrial best practices to minimize environmental burdens while maximizing resource efficiency.

3.07.P-Tu022 Life Cycle Assessment of Pyrolysis-Based Feedstock Recycling as an Enabler for Circular Polymer Value Chains

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Global plastic demand and associated greenhouse gas emissions continue to rise. To reduce greenhouse gas emissions, the polymer industry needs to reintegrate polymer waste into chemical value chains through the implementation of recycling pathways. Pyrolysis-based feedstock recycling offers a promising recycling pathway as chemical recycling technologies are currently at low technology readiness levels. However, high energy demand and environmental impacts associated with energy supply might dwarf the environmental benefits of pyrolysis-based feedstock recycling compared to virgin polymer production with subsequent thermal end-of-life treatments. Therefore, a life cycle assessment for polymers is required to determine whether feedstock recycling via pyrolysis represents a viable option and is worth the additional energy input. Yet, current literature lacks an environmental assessment of pyrolysis-based feedstock recycling.

This study identifies conditions under which pyrolysis-based feedstock recycling is environmentally beneficial compared to virgin polymer production with subsequent energetic thermal treatment for specific polymer types. To this end, we 1) create a parameterized stoichiometric process model of the pyrolysis process to quantify energy demand and product distribution, and 2) perform a life cycle assessment for evaluating the environmental impacts of the polymer

value chain with feedstock recycling via pyrolysis.

In the results, we quantify the energy demand required to establish circular value chains and explore the pyrolysis process parameter space under which feedstock recycling is environmentally preferable over virgin polymer production with energetic thermal treatment for specific polymer types. Our findings provide polymer-specific guidance on whether - and under which process parameter conditions - pyrolysis-based feedstock recycling is environmentally beneficial to enable circular value chains.

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3.07.P-Tu023 Environmental Benefit of Hydrogen Production from Waste Silicon: A Case Study of the Semiconductor Industry

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To achieve the goal of global net-zero emissions by 2050, integrated solutions that combine resource circularity with environmentally friendly strategies are essential. Hydrogen, owing to its high energy density and its ability, can be served as a high-temperature heat source and a critical chemical feedstock, that is widely regarded as an essential pathway to achieving net-zero. As a global hub for the semiconductor industry, substantial amounts of silicon-containing wastes are generated annually. In fact, the waste silicon can be recovered and converted into hydrogen via hydrolysis, which may contribute to a lower environmental footprint while advancing a circular economy. Therefore, this study aims to understand the environmental performance of waste silicon slurry to hydrogen production through life cycle assessment (LCA) approach. The LCA was conducted based on the ISO 14040 standard using SimaPro 10.1.0.6 software and the IPCC 2021 GWP100 method. The functional unit of the assessment is defined as the production of 1 kg of hydrogen, and the system boundary is set as cradle-to-gate. According to the IPCC results, the total global warming potential (GWP) is 0.21 kg CO_2 eq/kg H2, with water use during the production process as the main environmental hotspot (0.15 kg CO_2 eq/kg H2), followed by energy use (0.06 kg CO_2 eq/kg H2). For comparison, the GWP of conventional hydrogen production via steam methane reforming (SMR) is 11.98 kg CO_2 eq/kg H_2. The substantially lower GWP potential obtained in this study is mainly attributed to the use of waste silicon as the feedstock, for which does not have any environmental impact within our system, and the process does not require additional chemical reagents. In conclusion, the hydrogen produced through this waste-silicon-based route can be further integrated with industrial supply chains and applied to high-value materials, thereby signifying its carbon-reduction potential and circular-economy value, and accelerating progress toward a sustainable net-zero future.

Keywords：hydrolysis; waste silicon; environmentally friendly; resource circularity

3.07.P-Tu024 Life Cycle Assessment of Energy-saving Wastewater Treatment Systems

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Wastewater treatment is essential for sustaining water. While improving water quality, these processes simultaneously impose environmental burdens through resource and electricity consumption during construction, operation, and sludge treatment. To implement an appropriate wastewater treatment process that balances water quality improvement with environmental impact, it is crucial to analyze wastewater treatment process using Life Cycle Assessment.

Down-flow Hanging Sponge (DHS) is an energy-saving technology that purifies wastewater using microorganisms in sponge carriers. It has been implemented in Japan, India, and Egypt, demonstrating high organic removal efficiency. Although electricity consumption is a primary driver of environmental impact in wastewater treatment, DHS is expected to have low impact due to its low electricity demand. However, there are no studies that have evaluated and compared the environmental impacts of wastewater treatment using DHS.

This study evaluated the operational environmental impacts of two DHS-based wastewater treatment systems—

Primary Sedimentation Basin (PSB) + DHS and Up-flow Anaerobic Sludge Blanket (UASB) + DHS using LIME3, a Life Cycle Impact Assessment (LCIA) method. These systems were compared with Oxidation Ditch (OD), which is widely utilized in Japan.

LCIA results showed that the monetary-based environmental impact of PSB + DHS system was 0.132 US$, primarily due to sludge incineration and the discharge of treated water containing nitrogen and phosphorus. UASB + DHS system's impact was 0.149 US$, driven by treated water discharge and unrecovered methane volatilization. OD process had an impact of 0.116 US$, indicating that the DHS systems had a larger environmental impact in this research. However, an integrated evaluation considering both environmental impact and electricity consumption shows that PSB + DHS system represents the most optimal configuration in this research.

These results indicate that while DHS-based systems offer energy-saving advantages, they impose higher environmental impacts than conventional methods. Because these impacts primarily stem from nutrient-rich treated water, utilizing it for irrigation can transform environmental burdens into regional benefits through resource recovery. Since environmental impacts are highly site-specific, technology selection must move beyond single-focus metrics toward multi-faceted evaluations that account for local conditions and regional needs.

3.08 - LCA Challenges & Opportunities in the Fast-Moving Consumer Goods (FMCG) Industry

3.08.T01 THE ROLE OF LCA IN SUPPORTING ENVIRONMENTAL CLAIMS

Martijn van Hövell[1] and odile koenders[2] (1)SGS, (2)sgs

Presentation preference : Oral presentation

The new directive on Empowering Consumers for the Green transition (ECGT) is a European consumer-protection directive and part of the European Green Deal. It amends the Unfair Commercial Practices Directive and the Consumer Rights Directive with the objective of preventing greenwashing and misleading sustainability claims.

From September 2026 onwards, companies targeting EU consumers may no longer use:
- Vague or generic environmental claims unless they can be clearly and verifiably substantiated and verified
- Self-designed sustainability labels
- Sustainability labels that are not based on a transparent certification scheme with independent third-party verification, or that are not established by a public authority.

This presentation explores how the role of LCA is expanding beyond its current use where well-developed LCA standards and PCRs are made for specific products. In particular, it examines how LCA functions within the context of sustainability labels and certification schemes, such as Type I environmental labels under ISO 14024, where LCA forms an integral part of the label’s methodology. In this context, the purpose, structure and constraints of an LCA differ from those commonly applied by EPD operators working under general methodological guidelines or PCRs.

The presentation highlights key differences between LCA practice within certification frameworks and with current PCR systems, including predefined system boundaries, prescribed indicators, comparability requirements and verification procedures. It discusses how these differences influence data and modelling choices, documentation requirements and the role of verification.

By using LCA as a part of certification and sustainability communication, the presentation shows how LCA is becoming a central mechanism for preventing unsupported environmental claims. The new directive points to new ways how LCA can be applied: moving from direct use of LCA results (as in EPDs) to environmental labels where LCA plays an important role in substantiating sustainability claims as broader certification scheme.

3.08.T02 Development of an LCA-based method for assessing the environmental impact of fragrance

concentrates: application to cosmetic products

Kévin Lafaye[1], Jacques L'Haridon[2], Carlos Javier Reyes Solis[3], Elodie Schaffner[4], Anne Tirilly-Badie[5] and Quentin Vincent[5] (1)EVEA, (2)L'Oreal, (3)INP Ensiacet, (4)MANE, (5)L'Oréal

Fragrances are an essential part of products from our daily lives, they are found in cosmetics, detergents, pharmaceuticals and many others. They typically consist of a complex mix of several dozens of ingredients from different origins and obtained with different processes. Evaluating their environmental impacts by life cycle assessment (LCA) is therefore complex and tedious, as their exact composition is one of the best kept secrets of the industry.
To tackle these challenges, a clustering method of ingredients composing fragrance concentrates has been developed. Representative fragrance ingredients of cosmetic products were chosen and classified in clusters based on their production processes and the origin of raw materials, leading to 72 ingredients grouped into 9 clusters. Each ingredient was modeled by LCA and used to calculate the average carbon footprint and global environmental score for each cluster, the latter being obtained from the 16 indicators and the normalisation and weighting factors recommended by the European Commission's Product Environmental Footprint approach. By breaking down a fragrance concentrate into these clusters, it is possible to assess its carbon footprint and global environmental score while respecting the confidentiality of the composition.
This new approach would make it possible to better calculate the proportion of the fragrance concentrate in the cosmetic product's environmental impact. Although some ingredients might have very high carbon footprints, the evaluated fragrance concentrates, representative of those used in the main categories of cosmetic products, show values in line with other specialty/advanced chemicals. In addition, the carbon footprints and global environmental scores of these concentrates calculated from cluster data, ranging from 10 to 20 kgCO2eq / kg and 1 to 3.5 mPt / kg, respectively, are consistent with values calculated directly from the specific composition of concentrates.
This work is a first step towards a better environmental evaluation by LCA of fragrance concentrates. The LCA of the selected fragrance ingredients are mainly based on primary data but some secondary data and hypotheses are still needed to fill in gaps, thus the authors invite the industry to contribute collectively to the strengthening of this method. By sharing more specific data about the ingredients, the clusters' representativeness and robustness would be improved and so the evaluation of the fragrance concentrates.

3.08.T03 Diapering and Beyond: Bridging the Gap Between Consumer Product Use Experience and Behavioral Modelling in LCA

Jordyn Francisco[1], Maria Fernanda Gonzalez[1], Caleb Gravesen[1], Frank Wiesemann[1], Christina Endres[1] and Ioannis Hatzopoulos[1] (1)Procter & Gamble

Comprehensive Life Cycle Assessment (LCA) is imperative for sustainable consumer product design. However, conventional LCAs often oversimplify or neglect the consumer use phase, relying on static assumptions that fail to capture the real-world intricacies of consumer behavior. This presentation will highlight the challenges of this approach and showcase opportunities for more robust use-phase assessments, focusing on P&G's experience with disposable absorbent products.

Addressing the 'use phase' involves complex factors like consumer habits and in-use product performance. This necessitates moving beyond static models to a nuanced approach that models distinct consumer behavioral segments. In this example, we see how one segment's behavior can be discretionary, allowing for optimized product use with minimal environmental consequence. In contrast, another segment's behavior was directly driven by product performance limitations (e.g., leakage), compelling more frequent product use and associated impacts like increased laundering. This requires a variable functional unit approach compared to a standard fixed functional unit, which better reflects how product performance directly influences a product's life cycle impact.

P&G integrates these diverse behavioral insights into holistic decision-making, showcasing leading thought in comprehensive LCAs. This presentation shares our learnings from use-phase assessments for complex consumer products and outlines our approach, calling for industry collaboration to advance behavioral and performance-based

modelling in LCA.

3.08.T04 Polyethylene Packaging Generally Shows Lower Life Cycle Impacts than Alternatives in Europe and the United States, Despite Different End-of-Life Allocation Methods

Manfred Tacker[1], Elizabeth Avery[2], Tasja Hafner-Kuhn[1], Emma Lawrence[2], Andrin Gstöhl[1], Marius Rauch[1], Experience Nduagu[3], Kirti Richa[3], Timothee Roux[4] and Rafael Auras[5] (1)Circular Analytics TK GmbH, (2)Trayak, (3)ExxonMobil Technology and Engineering Company, (4)Exxon Mobil Corporation, (5)School of Packaging, Michigan State University

Packaging plays an essential role in protecting and preserving products but is increasingly scrutinized for its environmental footprint. In Europe, policy initiatives such as the Packaging and Packaging Waste Regulation promote reducing packaging, reusable systems, and substituting materials. Life cycle assessment (LCA) is important for evaluating whether these strategies decrease overall environmental impacts or simply shift burdens across different environmental impact categories.

This study compares the life-cycle environmental impacts of polyethylene (PE) packaging with those of alternative materials, including paper, metals, and glass, in the U.S. and EU markets. A cradle-to-end-of-life LCA comparing functionally equivalent packaging systems (excluding use-phase effects such as product loss or shelf-life changes) was conducted for five common PE packaging applications. Twenty-four comparative cases were assessed for Europe and twenty-one for the United States, including both single-use and reusable packaging systems. Impact assessment followed regional methodological practice, applying the Product Environmental Footprint method with the Circular Footprint Formula for European cases and IMPACT World+ with cut-off modelling for the United States.

Despite these different end-of-life allocation approaches, results across both regions show consistent directional outcomes. In Europe, PE-based packaging generally exhibits lower potential environmental impacts than alternative materials across most indicators. For single-use systems, PE packaging showed lower impacts in 68% of comparisons for global warming potential, 64% for water use, and 45% for fossil resource use, and in 82–95% of comparisons for acidification, land use, and freshwater eutrophication. Results from the U.S. show a similar pattern, with PE packaging demonstrating lower impacts in about 79% of comparisons for global warming potential and more than 80–95% of comparisons for land occupation and freshwater eutrophication.

The findings converge across regions supports the robustness of conclusions, despite methodological differences in impact assessment and end-of-life allocation. Overall, the findings indicate that replacing PE packaging with alternative materials may increase environmental impacts across several categories, depending on the application. These results stress the importance of life-cycle–based data when developing packaging policies and material substitution strategies.

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3.08.T05 Navigating End-of-Life Complexity: Perspectives on Formulated and Assembled Consumer Products

Caleb Gravesen[1] and Binod Neupane[1] (1)Procter & Gamble

Effective End-of-Life (EoL) assessment is imperative for sustainable consumer product design. This presentation will highlight consumer product industry challenges and opportunities on EoL assessments, focusing on P&G's experience derived from a portfolio of both formulated and assembled consumer products.

For formulated products, addressing "down-the-drain" EoL involves complex factors like ingredient specific properties, degradation kinetics, and wastewater treatment plant (WWTP) efficacy. This necessitates granular, ingredient-specific data which has driven P&G to help lead tool development like the Wastewater LCI (WWLCI) tool. This tool employs ingredient-specific physicochemical properties and environmental fate for detailed EoL impact assessments, offering a scientifically robust advancement over generic databases and directly informing product development.

Assembled products encounter distinctly different EoL challenges including: regional data outages in solid waste management scenarios, the challenge of accurately assessing the End-of-Life fate for specific components within an assembled product (e.g., in diaper recycling, understanding how each material like the superabsorbent polymer, non-wovens, and elastic components are individually managed and processed at EoL, and the subsequent environmental impacts) and lack of material-specific LCI data for novel materials. Such gaps mandate robust upstream design integration and iterative data collection-product development feedback loops so that product development and EoL solution exploration can mutually inform each other.

P&G integrates these diverse EoL insights into holistic decision-making, showcasing leading thought in comprehensive EoL assessments. This presentation shares our learnings from EoL assessments for complex formulated and assembled products and outlines our approach, calling for industry collaboration to advance EoL modelling in LCA.

3.08.P - LCA Challenges & Opportunities in the Fast-Moving Consumer Goods (FMCG) Industry

3.08.P-Tu025 Avoided Emissions Case Study: Reducing Use-Phase Environmental Impacts in the Dishwashing Business

LCAs show that, for many consumer products, the use phase drives most of the environmental impact. Peer-reviewed 2023 cradle to grave LCAs of dishwashing and laundry, presented at recent SETAC conferences and published in Mankad et al. (2025), conclude that the use phase accounts for over 60% of the total carbon footprint. While P&G's 2030 and 2040 climate targets cover operations and supply chain emissions, the company recognizes the importance of the use phase and helps consumers reduce impact through innovations in cold-water washing and short cycles.
P&G recently joined a World Business Council for Sustainable Development (WBCSD) pilot on Avoided Emissions (AE) to showcase low-carbon solutions. WBCSD defines AEs as GHG reductions outside a company's operations enabled by its products. They are calculated by comparing a low-carbon solution with a conventional alternative, with the difference representing emissions avoided. The WBCSD publication "Climate Solutions in the Consumer Goods Sector: An Avoided Emissions UK Case Study" (April 2026), based on the aforementioned peer-reviewed LCA, shows a 31% reduction in global warming in the UK when switching from auto to short dishwasher cycles (<55 min), driven by lower energy use and enabled by a high-performance cleaning product. Combined with UK consumer data, the study estimates 8.8 kt CO_2e AE between 2022 and 2025 and highlights positive impacts in other areas such as particulate matter, fossil resource use and water scarcity.
The concept of AE complements traditional corporate carbon accounting by showing how companies contribute to broader decarbonization beyond their value chain. Many companies invest in climate actions outside their value chain that are not captured in traditional GHG inventories. To address this gap, the GHG Protocol is developing the Actions and Market Instruments (AMI) framework, expected in 2027, to standardize mitigation reporting and support decarbonization efforts. It introduces a four-statement structure: physical and market-based GHG inventories, a GHG impact statement, and non-GHG indicators, with AE included under the GHG impact statement using consequential accounting.
This work highlights significant contributions to global warming reduction, shows how AE is gaining traction in industry while being incorporated by the GHGP to incentivize decarbonization, and illustrates how low-carbon solutions beyond the value chain enable sustainable consumer choices.

3.08.P-Tu026 Towards Strategic Implementation of Renewable Value Chains in Personal Care Products

Jaleesia Amos[1], Nadia Malinverno[1], Claudia Som[1], Tim Börner[1] and Florian Glaus[2] (1)Empa, (2)dsm-firmenich

Climate change is the biggest challenge of our time. Industry is well aware of the responsibility to having a part to play in the sustainable transformation. Many companies have set powerful programs of climate action across value chains, e.g. dsm-firmenich has set ambitious, integrated climate targets to reduce carbon footprints of their product portfolio

validated by the Science Based Targets Initiative (SBTi) comprising the goal of net-zero emissions, across scopes 1, 2, and 3, by 2045.
For the cosmetics industry, the net-zero target comprises a transition to renewable raw materials. In the framework of a joint effort of Empa and dsm-firmenich, within the ACHIEVE project, we are addressing this challenge by developing a forward-looking, probabilistic model that assesses the current and future availability of sustainable feedstock. This includes evaluating biomass side streams and waste streams and identifying GHG-intensive chemicals that offer high potential for substitution. The task also involves analysing competitive dynamics related to the chemical composition of various feedstocks and defining key chemical building blocks.
The methodological novelty of this work lies in combining prospective feedstock availability modelling with prospective life cycle assessment (LCA), and cross-sector competition analysis.
The net-zero potential and environmental footprints of bio-based chemicals will be assessed by means of LCA and compared to fossil-based products in the market and carbon capture and utilisation (CCU)-based (current and future) alternatives. In addition to analysing the development of new technologies, estimating the costs of process transformations, and assessing the energy requirements of proposed strategies, we are aiming to identifying which levers are relevant along the value chain focusing on the upstream elements (cradle-to-gate), to predict positive changes to the system and unleash the potential for net zero.
In this contribution we will highlight the currently identified gaps and biggest obstacles that need to be addressed to achieve the target. We present gaps that have arisen from the crucial stage of identifying viable product categories suitable for biomass substitution based on data availability for biomass feedstock. Our work represents initial findings from ongoing model development.

Disclaimer/Disclosure: This research isconducted within the ACHIEVE project (Pathways to ACHIEVE net-zero target for hard-to-abate Swiss emissions), funded by the Swiss Federal Office of Energy (SFOE) under the SWEET programme. The ACHIEVE consortium is coordinated by Empa. For more information, see www.sweet-achieve.ch.

3.09 - Life Cycle Assessment of Hard-to-Abate Transport Sectors: Shipping, Aviation, and Heavy-Duty Road Transport

3.09.T01 How to Quantify Aviation Impacts on Human Health?

Félix Pollet[1], Thomas Planès[1], Olivier Jolliet[2] and Alexis Laurent[2] (1)Institut supérieur de l'aéronautique et de l'espace (ISAE)-Supaero, (2)Technical University of Denmark (DTU)

Non-CO_2 effects from aviation emissions at altitude represent a major yet insufficiently integrated component of environmental assessments. These effects include climate forcings from contrails, nitrogen oxides (NO_x), water vapour, and aerosols, as well as air quality impacts via particulate matter and surface ozone formation. Despite better scientific understanding, their consistent integration into life cycle assessment through robust characterisation factors is still lacking.

This study addresses this gap by (i) proposing a modelling framework to quantify human health impacts of aircraft emissions, (ii) operationalising this framework through the development of characterisation factors linking unit emissions to health damages, and (iii) evaluating current and future impacts of global aviation through scenarios.

The approach combines atmospheric chemistry-transport simulations, climate modelling, and health response functions to capture the effects of emissions at altitude. In addition to characterisation factors applicable to present-day aviation, prospective factors are derived to reflect future changes in atmospheric conditions and population distribution. These factors are applied to aviation scenarios from the International Civil Aviation Organization (ICAO), enabling their assessment beyond a carbon-centric perspective.

The results indicate that emissions from 2019 international aviation account for a global burden of 2.6 million

disability-adjusted life years (DALYs), or 0.5 μDALY per passenger-kilometre. These findings suggest that international aviation contributes 0.3% of global air pollution damages, and 3% of climate-related health impacts from 2019 greenhouse gas emissions. By 2050, under scenarios primarily targeting CO_2 reductions, NO_x are projected to become the second-largest contributor to near-term health damages (100-year horizon), after contrails. However, CO_2 remains dominant over longer time horizons (500-year horizon).

Overall, this work provides a consistent and operational framework for integrating both CO_2 and non-CO_2 aviation effects into life cycle impact assessment. It supports the development of more comprehensive environmental strategies and highlights the importance of addressing non-CO_2 emissions to effectively reduce the sector's total human health burden.

3.09.T02 Life Cycle and Absolute Sustainability Assessment of Individual Transportation Patterns in Denmark

Marion George[1], Weinan Yan[2], Kerstin Von Borries[1] and Olivier Jolliet[1] (1)Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark (DTU), (2)Department of Environmental and Resource Engineering, Technical University of Denmark (DTU)

Transportation accounts for about a quarter of Denmark's total greenhouse gas emissions and plays a key role in the country's climate strategy, which targets climate neutrality by 2050 compared with 1990. This project examines the environmental and health impacts of individual transportation behaviors in Denmark and brings an absolute perspective to assess the current status as well as three alternative scenarios.

Drawing on national survey data, the travel patterns of 11 686 interviewees were analyzed through three scopes: distance, transportation mode and trip purpose. Environmental and physical activity data were added to evaluate individual life cycle impacts and health benefits from physical activity associated with daily trips. Potential improvements were then studied through theoretical alternative scenarios.

Results show that half of the Danes travel less than 14 km daily, with 80% of these trips mainly walked or biked. The distance travelled is identified as the most influential parameter in the selection of a motorized mode of transportation. For most impact categories, non-motorized and public modes lead to lower environmental impacts than individual vehicles. In addition, walking or cycling results in a net health gain when considering the physical activity involved.

The median transportation-related climate change impact is 1 kgCO2e/cap/day. Meanwhile, the share of safe operating space economically allocated to domestic daily transport is 0.36 kgCO2e/cap/day (0.58 kgCO2e/cap/day with the grandfathering approach), reached by 39% of the daily trips. This percentage rises to 51% in a scenario where car trips under 10km are biked, and 42% when all private vehicles are considered electric. However, changing the current car fleet for electric cars would induce an important burden shifting, reducing the pressure on climate change by 49% but increasing it on land use by 47%, among others.

In conclusion, individual transportation behaviors affect the environment in a highly unequal way, mostly due to the distances travelled daily, and the interlinked mode selected. The pressure is also uneven in terms of category considered; while current policies promote electric vehicles to reduce carbon emissions, these are more impactful from, among others, a land use or a resource perspective. This study further highlights clear co-benefits between environmental sustainability and health, with low-impact transportation modes also delivering health gains.

3.09.T03 Decarbonising Heavy-Duty Road Transport: A Life Cycle Assessment of Diesel, BEV, and FCEV under Alternative Energy Pathways

Gaia Gentilucci[1], Antonella Accardo[1], Marzieh Mohammad Hosseinzadeh Golabchi[1] and Ezio Spessa[1] (1)Polytechnic

of Turin

Road transport accounts for one fifth of total greenhouse gas emissions in the European Union and continues to grow, making it a key target for decarbonisation policies. However, reducing impacts in heavy-duty transport remains challenging due to long distances, high energy demand, and infrastructure constraints. This study aims to assess the environmental performance of conventional and zero-emission heavy-duty trucks using Life Cycle Assessment (LCA) approach.
A cradle-to-grave system boundary is adopted including raw material processing, manufacturing, use, maintenance and end-of-life phases. The assessment is performed using SimaPro v9.4, with Ecoinvent v3.8 as the background database, and the EF 3.0 impact assessment method covering 16 impact categories. Two diesel configurations are analysed, representing regional and long-haul operations, and compared with two zero-emission prototypes developed by an European OEM: a Battery Electric Vehicle (BEV) for regional use (i.e., 400 km range) and a Fuel Cell Electric Vehicle (FCEV) for long-haul applications (i.e., 750 km range). For the fuel cell option, four hydrogen production pathways are considered: Steam Methane Reforming (SMR), SMR with carbon capture and storage, Alkaline Electrolysis (AE) using the European electricity mix, and AE powered by offshore wind. For the battery electric configuration, four electricity mixes (i.e., European average, Norway, Malta, and Italy) are compared, reflecting different shares of renewable energy.
Results show that energy supply pathways are the main driver of life cycle impacts in zero-emission vehicles. Across most scenarios, the well-to-tank phase dominates both carbon footprint and most impact categories, reflecting the burden of fuel and electricity production. In contrast, raw material acquisition is the main contributor to mineral and metal resource use and becomes increasingly relevant in low-carbon electricity scenarios, such as wind-based BEVs. This shift indicates that as decarbonisation improves, impacts move upstream in the life cycle. Electrification alone does not ensure impact reductions unless coupled with low-carbon energy systems The analysis provides evidence to support integrated policy design and industry strategies for heavy-duty transport decarbonisation.

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Polytechnic of Turin.

3.09.T04 Are Aviation Transition Scenarios Compatible With Planetary Boundaries? A Regionalized Absolute Environmental Sustainability Assessment

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Despite growing scrutiny of aviation's environmental footprint, regional aviation transition scenarios have yet to be assessed against absolute ecological limits. Building on our team's prior work (the first absolute environmental sustainability assessment (AESA) of global civil aviation futures, which revealed that even ambitious decarbonization scenarios transgress planetary boundaries for climate change and biosphere integrity, and that demand management is an indispensable lever alongside technological transition) the present study extends this framework to the regional scale.
Regional differentiation is essential: divergent traffic growth trajectories, historical contributions to global impacts, and uneven access to feedstocks for alternative energy carriers (AECs) mean that a globally aggregated assessment can mask the heterogeneity that matters most for just and effective transition strategies.
We evaluate region-specific aviation scenarios, using prospective LCA databases built with the premise package. Environmental pressures are characterized across five planetary boundaries (climate change, biosphere integrity, freshwater use, biogeochemical flows, and stratospheric ozone depletion) and compared against regionally and sectorally allocated safe operating space budgets. Allocation draws on the Fulfilment of Human Needs approach to operationalize distributive justice in the sharing of environmental budgets.

Our results reveal sharp contrasts between regions. Some face tighter sustainability constraints due to high historical impacts and limited renewable and biomass resources: North America and Europe retain a disproportionate share of global environmental pressure through 2050. Others may pursue relatively lower-impact pathways, though several face structural AEC constraints as projected biokerosene demand exceeds regional biomass availability. AECs may shift, rather than eliminates, environmental pressure across planetary boundaries.
This work suggests that absolute environmental sustainability in aviation is only approachable through regionally differentiated strategies, considering specific historical contributions, feedstock availability, development status, and aviation use intensity. As demonstrated in our global-scale AESA, this region-scale study shows that technological solutions alone cannot close the sustainability gap, and that questioning the level of aviation demand itself remains an essential and unavoidable part of the transition.

3.09.T05 Are shipping and aviation decarbonization regulations measuring the right thing?

Shan Zhang[1] and Fayas Malik Kanchiralla[1] (1)Chalmers University of Technology

Shipping and aviation are widely considered as hard-to-abate sectors because of their high energy demand, dependance on fossil fuels, and limited near-term alternatives to energy-dense fuels. According to the European Commission, aviation accounted for approximately 2% of global CO2 emissions in 2022 and remains the fastest growing transportation sector. Without additional mitigation measures, ICAO projects that international aviation emissions could triple by 2050 relative to 2015 levels. International shipping faces a comparable decarbonization challenge: the 2023 IMO aims for net-zero GHG emissions from international shipping by 2050. A range of decarbonization pathways has therefore been proposed for both sectors, including operational measures such as route optimization, improvements in engine and energy efficiency, electrification for short-distance applications, and the use of alternative fuels.
Regulation plays a central role in the low-carbon transition in both shipping and aviation. However, existing regulatory frameworks remain methodologically heterogeneous. Current regulations address different aspects of decarbonization, including fuel carbon intensity, fuel-blending requirements, operational emissions pricing, and technical efficiency. This diversity creates uncertainty about whether regulating fuels, vehicles, or operators can effectively deliver emission reductions at the level of the transport service. For example, fuel-based functional unit (in gCO2-eqMJ) was proposed by ICAO's CORSIA and IMO-related carbon footprint calculation guidelines. Such functional unit does not capture ship- or aircraft-level operational efficiency. Consequently, they are insufficient for evaluating the climate performance of a ship or aircraft delivering a given transport service. This limitation may undervalue efficient propulsion systems while making inefficient systems using low-carbon fuels appear more favorable than they are for delivering transport services.
This study maps and compares sustainability-related regulations in the shipping and aviation sectors. It highlights inconsistencies and limitations in current regulations and aims to provide decision-makers with a structured overview and supports the development of more coherent regulatory framework to support the sustainable development of these sectors.

3.09.P - Life Cycle Assessment of Hard-to-Abate Transport Sectors: Shipping, Aviation, and Heavy-Duty Road Transport

3.09.P-Mo046 From the Brazilian Semiarid to Europe: Carbon Footprint and GIS-Based Assessment of Agave Alcohol-to-Jet Sustainable Aviation Fuel

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The European Union has positioned sustainable aviation fuel (SAF) as a central strategy for aviation decarbonization through ReFuelEU Aviation and the revised Renewable Energy Directive (RED). Although synthetic fuels will play an

increasing role, bio-based SAF remains essential in the short and medium term to ensure supply security. At the same time, RED and CORSIA impose strict sustainability criteria, requiring substantial greenhouse gas (GHG) reductions and safeguards against land-use change and food competition.
Meeting these targets requires diversification of feedstocks beyond conventional sources such as UCO, animal fats and sugarcane ethanol. In Brazil, Agave tequilana emerges as a promising alternative for the semiarid region, characterized by high temperatures, low rainfall, and limited suitability for traditional crops. Due to its crassulacean acid metabolism (CAM), agave has high water-use efficiency and can accumulate significant biomass under conditions unsuitable for sugarcane cultivation.
This study presents the first carbon footprint assessment of alcohol-to-jet (ATJ) SAF produced from agave cultivated in Bahia's semiarid region and exported to Europe. The analysis follows the CORSIA LCA methodology, combining primary unpublished data from the BRAVE Program with literature, ecoinvent and GREET databases. The modeled supply chain includes cultivation, ethanol production, ATJ conversion at the RNEST refinery in Pernambuco, maritime transport to Rotterdam, and final distribution to Amsterdam airport. Particular attention was given to land-use implications, considering the potential classification of agave cultivation as low indirect land-use change (iLUC) risk due to its suitability for degraded pasturelands.
GIS-based analyses were also developed to identify suitable cultivation areas, estimate biomass yields, and assess soil carbon balance. Results indicate significant potential on degraded pasturelands and low-productivity anthropized areas, minimizing competition with food production while leading to carbon sequestration. Agave-based SAF has, therefore, potential to comply with both CORSIA and EU sustainability requirements, positioning the Brazilian semiarid region as a new frontier for low-carbon (even carbon negative) SAF supply.

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3.09.P-Mo047 Absolute Environmental Sustainability Assessment of Bio-based Transport, Chemistry Sector and Wood Construction Scenarios in Germany

Matthias M. Welker[1], Matthias Jordan[1], Walther Zeug[1] and Daniela Thrän[1] (1)Helmholtz Centre for Environmental Research (UFZ)

Abstract
The bioeconomy is promoted as a concept that enables sustainable green growth by enabling the substitution of fossil resources with regenerative ones. The term encompasses several different visions. Depending on whom one asks, the bioeconomy promises either regional autarky, sufficiency within planetary boundaries, or climate-neutral global supply chains. With this work we aim to make those different visions tangible and assess their environmental implications. We answer the research question: Which environmental impacts result from different future visions of the bioeconomy? We will present early results of answering this research question for the chemistry and transport sector in Germany. The results are achieved based on the following three methodological steps.
First, linking bioeconomy visions to the biomass-use optimization model BenOpt (Jordan et al. 2023). In previous work the model scope has been extended to additionally include material uses of biomass. In this work we will present three bioeconomy scenarios representing three different visions: a regional, a sufficiency-based and a global bioeconomy. Second, we soft-couple the biomass utilization pathways to life cycle inventories derived from literature and databases. This enables us to present life cycle assessment results of those bioeconomy scenarios. Third, we will conduct an absolute environmental sustainability assessment to determine not only which of the expressed scenarios and visons might be the most sustainable. We will also answer the question which vision is sustainable enough, in order to remain within biophysical limits (Bjørn et al. 2020).
The studies novelty consists out of the integration of bioeconomy scenarios for multiple sectors and their environmental assessment against planetary boundaries. With this the presented work will assess the bioeconomy's capability to deliver goods and services within biophysical limits, lays the ground work to extend the assessment to

further sectors and discuss necessary methodological adaptions. Discussed future potential additions include social and regional assessment, as well as integration of optimization within biophysical limits.

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3.09.P-Mo048 Expanding Coverage of the ecoinvent Background Database: Implementation of a New Road Transport Model for Multi-Powertrain, Region-Specific Life Cycle Inventory Generation

Mattia Clementi[1], Enkeled Hoxha[1], Lucia Valsasina[1], Thomas Sonderegger[1] and Avraam symeonidis[1] (1)ecoinvent Association

The diversification of road transport powertrains, encompassing battery-electric (BEV), hybrid-electric (HEV), compressed natural gas (CNG), and liquefied natural gas (LNG) vehicles, has accelerated over the past decade. Yet background LCA data has not kept pace: existing inventories lack the powertrain granularity and geographic specificity needed to accurately represent the circulating fleet across different markets and supply chains. This mismatch introduces systematic uncertainty in comparative LCA studies and limits the reliability of transport-related policy analyses.

To address this challenge, the Road Transport Model (RTM) was developed by ecoinvent in collaboration with INFRAS. This model provides a structured methodology to collect, process, and translate region-specific data into life cycle inventory datasets suitable for use in background databases. Consistent boundary conditions are applied across all vehicle classes, with powertrain-specific parameterization, enabling direct benchmarking between drivetrain options under equivalent assumptions. Regionalization is achieved through the integration of driving behaviour, regionalised supply chain, and country-specific fuels and road quality indexes. Environmental impacts are reported at a system level (e.g. frame, cabin), enhancing transparency and supporting targeted hotspot identification across the full vehicle system.

Application of the RTM reveals meaningful differentiation in use-phase environmental profiles across powertrain types and diverse national contexts, underscoring the importance of geographic specificity in transport LCA. This is illustrated by the BEV case, where electricity supply mix emerges as a dominant factor when comparing the environmental impact to conventional ICE vehicles. The resulting datasets are designed for direct integration as background transport datasets, enabling more representative and disaggregated life cycle modelling across a range of transport use cases. Current limitations, notably the absence of temperature-dependent performance modelling, are acknowledged, while future developments are directed towards expanding geographic coverage and operationalizing the model for broader application.

3.09.P-Mo049 Methodological considerations in defining the Functional Unit for the Life Cycle Assessment of ship energy storage systems: a case study

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abstract Poster presentation: Hybrid Energy Storage Systems (HESS), combining Battery Energy Storage Systems (BESS) with high power devices such as supercapacitors or superconducting magnetic energy storage (SMES), are promising options for maritime decarbonization. Life Cycle Assessment (LCA) can quantify environmental trade offs between hybrid solutions and battery only configurations. Yet robust comparisons critically depend on how the product system function, and the corresponding functional unit (FU) are defined. The LCA literature on maritime electrification

shows high heterogeneity and limited standardization in FU selection, which can yield divergent results and hinder comparability. Several studies do not explicitly report a FU, while others use non ISO consistent references (e.g., “lifetime emissions” or “carbon footprint”) rather than a quantified performance. When defined, FUs are often purely time or energy based (e.g., years of operation, annual energy demand, kWh consumed), describing power system operation but not the ship’s delivered transport/service function. This weakens functional interpretability and cross study consistency. Therefore, this work addresses the challenges of defining an appropriate FU and product system boundary for LCA of maritime HESS.
Within the European V ACCESS project, an LCA (ISO 14040/14044 and BS EN 50693 compliant) evaluates the potential impacts and benefits of HESS combining BESS with supercapacitors or SMES in marine applications. The FU is defined as 1 hour of vessel operation provided by the energy storage system, assessed over a 30 year service life. The FU is motivated in methodological terms by highlighting its advantages for representing the intended function and ensuring comparability, while also discussing the limitations and potential inappropriateness of commonly used alternative references. On this basis, the LCA is developed exclusively using the proposed FU to compare a BESS only baseline with hybrid HESS across representative missions.

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3.09.P-Mo050 Linking Life Cycle Assessment and Techno-Economic Cost Functions for Bio-Based Aviation Fuels from Perennial Grasses in Europe

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The integration of economic aspects into life cycle assessment (LCA) is essential to support decision-making for sustainable aviation fuels (SAF), yet consistent approaches linking environmental performance, production potential, and cost remain limited. In particular, spatially explicit assessments of bio-based aviation fuels are rarely connected with pathway-specific techno-economic insights in a consistent and comparable framework.
This study evaluates aviation fuels produced from switchgrass and miscanthus cultivated on abandoned cropland in Europe using a life cycle assessment framework. Fischer–Tropsch and alcohol-to-jet conversion pathways are assessed under different land and water management conditions, including scenarios with carbon capture and storage. The analysis quantifies environmental impacts and estimates the potential contribution of these systems to European aviation fuel supply.
To integrate economic dimensions, we link life cycle results with techno-economic cost information from recent literature. Reported minimum jet fuel selling prices and capital intensity ranges are harmonised and converted to energy-based units, enabling consistent comparison with the estimated fuel outputs. This approach allows the translation of spatially explicit fuel potentials into indicative cost ranges and supports the exploration of trade-offs between environmental performance, production scale, and economic feasibility.
By combining environmental, resource, and cost perspectives, the proposed framework enables a more comprehensive assessment of bio based SAF pathways. The results provide improved decision support for evaluating the role of bio based aviation fuels in Europe’s decarbonisation strategies.

3.09.P-Mo051 Infrastructure-Driven Environmental Trade-offs of Hydrogen Deployment in Short-Haul European Aviation: A Life Cycle Assessment

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Hydrogen is increasingly proposed as a decarbonisation pathway for aviation, yet its feasibility is strongly coupled to

infrastructure requirements that differ across transport segments. While long-haul deployment could concentrate fuelling systems at a limited number of hub airports, short-haul aviation, often identified as the most viable entry point, would require hydrogen infrastructure across a dense and spatially distributed airport network. This raises a key policy question: whether infrastructure expansion undermines the life cycle benefits of hydrogen aviation.

This study applies consequential life cycle assessment (LCA) to evaluate hydrogen supply to aircraft across the EU-27 and the UK. The functional unit is 1 MJ of fuel delivered at the aircraft tank, with a cradle-to-gate boundary covering hydrogen production, distribution, and airport-level infrastructure. A supplementary cradle-to-grave comparison is included to contextualise use-phase differences relative to fossil Jet-A.

Airport infrastructure is modelled using a stratified classification of jet-capable airports, with representative hydrogen supply configurations defined for each class. These include compression or liquefaction, storage, and on-site distribution. The analysis explicitly accounts for continuous energy demands associated with hydrogen handling, including liquefaction and boil-off management. Three production pathways are evaluated: current-state hydrogen (SMR-dominated), a projected 2050 European mix coupled with electrolysis, and a green hydrogen scenario.

Results show that infrastructure-related emissions are non-trivial and scale with network expansion. While low-carbon hydrogen reduces upstream production impacts, infrastructure and operational energy demands remain significant. Consequently, net environmental performance is highly sensitive to assumptions on infrastructure scale, utilisation rates, and electricity system carbon intensity.

The findings highlight a structural trade-off: hydrogen deployment is most operationally feasible in short-haul networks where infrastructure requirements are largest, and most infrastructure-efficient in long-haul contexts where feasibility is constrained. This has direct implications for policy frameworks such as ReFuelEU Aviation, demonstrating the need for LCA to explicitly integrate infrastructure scaling and energy system interactions when assessing emerging aviation fuels.

3.09.P-Mo052 Hydrogen emissions and their contribution to the global-warming impact of current industrial processes

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Hydrogen released to the atmosphere acts as an indirect greenhouse gas because it lengthens the atmospheric lifetime of methane and promotes the formation of tropospheric ozone and stratospheric water vapor. Consequently, the prospective hydrogen economy has been examined closely to ensure that a transition to hydrogen-based technologies delivers the anticipated climate benefits. By contrast, existing industrial processes that already use or emit hydrogen—ranging from oil-and-gas operations to the production of commodities such as chlorine or metals—have received considerably less scrutiny.

In this study, we analyzed the latest ecoinvent database (version 3.12) to identify all processes that record hydrogen emissions to air. We then quantified the change in global-warming impact of the associated products when the global-warming potential (GWP) attributed to those hydrogen emissions is changed from 0 to 11.6 kg CO2e/kg H2. The results indicate that, for many products, the inclusion of hydrogen-related impacts leads to a noticeable increase in their overall GWP. For example, the GWP of sodium chlorate used in paper manufacturing rises from 29 % to 136 % of the original value, depending on the geographical location, while the GWP of cobalt production increases by roughly 25 %.

The analysis also reveals that hydrogen emissions are likely under-reported in the database; key sectors such as oil-and-gas extraction presently lack any hydrogen-emission entries. These findings highlight the need for a systematic

review of LCA databases to incorporate hydrogen emissions and for impact-assessment methods to account for the indirect GWP of hydrogen.

3.09.P-Mo053 Life Cycle Assessment and Life Cycle Costing of Using Ammonia in Different Ship Power Train Systems.

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The shipping sector accounts for around 3% of the global greenhouse gas emission and also the emission of different air pollutants, including sulfur oxides, nitrogen oxides, particulate matter, and hydrocarbons. Energy transition shall not only reduce greenhouse gas but also to improve the sustainability of the shipping sector. Ammonia is considered one of the potential cost effective low-climate marine fuel. However, the environmental impact and economic value of the transition depend on ammonia production pathway and ship power conversion system (e.g. engines and fuel cells). The study employs life cycle assessment and life cycle costing to understand the environmental and economic trade-offs of using ammonia produced from different production routes including grey-ammonia, blue ammonia, biomass ammonia, electro-ammonia, biomass with carbon capture ammonia, and biogas-ammonia. The climate impact result shows that biomass with carbon capture has the highest reduction potential with negative climate impact (250% reduction rate). However, the negative climate impact depends on the source of the biomass. Electro-ammonia on the other hand has 90% GHG reduction compared to fossil diesel, provided electricity is from wind power. Grey ammonia on the other have increases the life cycle climate. Blue ammonia can be a transitional solution with the 40% GHG reduction compared to fossil diesel. The use of biomass for ammonia production will create an additional environmental burden on acidification potential, land use, and eutrophication (terrestrial and freshwater). Electro-ammonia produced using electricity from wind power will have an increased impact on human toxicity and resource use. The use of ammonia in engine without abatement technologies, can potentially increase environmental impacts like eutrophication and acidification and may limit GWP reduction due to nitrous oxide emissions. Fuel cell offers one of the most environmentally sustainable solutions for ships however, due to high investment cost fuel cell technology have high life cycle cost compared to engine for same ammonia choice. With regards to the fuel production cost, bioCCS ammonia, and electro ammonia have higher life cycle cost indicating the transition comes economic trade-offs.

3.10 - Modelling Product Lifetime Extension to Support Circular Economy

3.10.T01 When Does Repair Pay Off? Integrating Time into Circular Economy Environmental Assessment

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Global electronic waste is rising rapidly, with 62 million tonnes generated in 2022 — an 82% increase since 2010 — posing urgent challenges for sustainable resource management. Circular economy (CE) strategies, including repair, are widely promoted to extend product lifetimes and reduce environmental impacts. Life cycle assessment (LCA) is the dominant method for evaluating such strategies at the product level. However, LCA's static nature limits its capacity to capture temporal dynamics, which can critically alter environmental conclusions for time-sensitive products such as electrical and electronic equipment (EEE).

This study investigates how incorporating temporal dynamics into environmental assessment changes repair-versus-replacement outcomes for consumer electronics. Using a smartphone as a case study, we conducted LCA for three repair scenarios — battery, display, and printed wiring board — and a new device production scenario. Drawing on life cycle impact assessment (LCIA) results, we developed an equilibrium-based equation that integrates timing of failure into the comparison of repair and replacement options. The equation identifies a threshold point in a product's lifespan at which the environmental impacts of repair and replacement are equivalent, enabling time-explicit decision support.

Results show that static LCA consistently favours repair but can overstate its environmental advantage. When temporal dynamics are incorporated, outcomes depend critically on both what is being repaired and when the failure occurs. For

components with high emission ratios relative to the full device — such as the printed wiring board — the threshold favouring replacement is reached early in the product lifespan. For components with low emission ratios, such as the battery and display, repair remains preferable throughout most of the designed lifespan. These findings vary across impact categories, underscoring the importance of multi-category trade-off analysis.

This research provides a novel, LCA-compatible decision tool applicable to any EEE product with a defined lifespan. The findings challenge simplified assumptions about repair as a universally beneficial CE strategy and call for the systematic inclusion of time in environmental assessments to support more robust and accurate conclusions.

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3.10.T02 When Reuse Backfires: Consequential Modelling of Second-Hand T-Shirts in the Netherlands

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Product lifetime extension through reuse is a key circular economy strategy to reduce environmental impacts and resource use. Given the high burdens of the production phase, clothing reuse is generally considered beneficial because it partially replaces demand for new garments. Environmental assessments typically account for demand replacement, which is a primary consequence on the consumer side, but typically overlook secondary consequences, such as respending triggered by second-hand purchases, which may counteract the initial environmental benefits. This study quantifies how including both primary and secondary consequences of clothing reuse influences the net environmental impacts. We conduct a consequential cradle-to-grave life cycle assessment (LCA) integrated with environmentally extended input-output (EEIO) analysis, using a Dutch case study. The functional unit is defined as provision of a T-shirt for a typical consumer over one year, compared to the counterfactual of a new T-shirt providing the same function. We develop a life cycle inventory based on empirical data from a survey of Dutch second-hand t-shirt users, national statistics, the ecoinvent database, and scientific literature on clothing LCAs. Demand replacement for new clothes is determined using four methods: self-reported demand replacement, purchasing motivations, purchasing behavior, and product condition assessment. This approach aims to reduce biases inherent to self-reported data. Respending is modelled using EEIO, accounting for changes in household expenditure patterns triggered by second-hand purchases. Preliminary results show that demand displacement reduces environmental impacts by 30% to 90%, while respending may lead to rebound effects between 39% and 217%, with burden shifting occurring across impact categories. The results are sensitive to demand replacement and respending behavior. Overall, reuse is beneficial; however, the environmental benefits may be offset when respending redirects spending towards high-impact goods and services such as electronics, furnishings, and the hospitality industry. By taking a systemic, change-oriented perspective, this study provides methodological insights for integrating consumer behavior change in textile reuse LCA. Accounting for secondary effects can provide a more nuanced picture of the potential consequences of emerging circular systems and, consequently, better guidance on how to facilitate sustainable reuse behavior.

3.10.T03 Environmental Trade-Offs Between Reusable and Recyclable Packaging for Large Appliances: A Comparative Life Cycle Assessment

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The transition toward a circular economy has increased interest in reuse strategies, particularly for packaging systems. However, the comparison between the environmental performances of reusable and recyclable packaging remains highly context-dependent. Therefore, our study addresses the key question: “under which conditions does reuse outperform recycling (and vice versa) for washing machines”?
This question arose under the framework of the Packaging and Packaging Waste Regulation (PPWR). The initial PPWR proposal set an ambitious target requiring 90% of transport packaging for large household appliances to be

reusable. However, strong industry opposition led to the removal of this target in the final regulation, reflecting the need for robust, evidence-based guidance.
A comparative Life Cycle Assessment (LCA) was conducted across four realistic European distribution scenarios for washing machines, combining different sales channels and transport modes. A breakeven point analysis evaluated the Climate change impact of reusable versus recyclable packaging as a function of transport distance. This approach enables comparison of the two packaging solutions not only for the scenarios considered, but also for other potentially relevant contexts. The assessment was extended to 16 impact categories and complemented by sensitivity analyses on reuse cycles and packaging weight.
Results show that reusable packaging becomes environmentally competitive only under specific conditions: relatively short transport distances (approximately below 425 km for road transport and up to 750–860 km for intermodal transport) or a high number of reuse cycles (around 45–70). Reducing the weight of reusable packaging significantly improves performance, highlighting design optimization as a critical factor.
From a policy perspective, the findings provide relevant evidence for the debate on the PPWR. They suggest that targets promoting reusable packaging may not be environmentally justified for large appliances, where transport-related impacts and reverse logistics play a dominant role. This analysis shows that supporting intermodal transport infrastructure and promoting innovation in lightweight designs are effective strategies to reduce environmental impacts of reusable packaging. Policy frameworks should therefore adopt a context-specific approach based on LCA, considering the most sensitive parameters influencing the performance of reusable and recyclable packaging.

3.10.T04 From Single-Use to Reusable Medical Devices: Life Cycle Assessment of ECG Lead Sets Across Circular Scenarios

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Healthcare systems are increasingly challenged to reduce environmental impacts while maintaining high standards of patient safety. Electrocardiogram (ECG) lead sets are widely used medical devices, yet their environmental performance under different use and reprocessing strategies remains insufficiently understood.
This study evaluates the environmental performance of four ECG lead set value chains: one single-use configuration and three reusable configurations involving direct reuse, local hospital reprocessing, and specialised external reprocessing. The functional unit (FU) is defined as one ECG lead set (five leads) used for patient monitoring, with reusable systems modelled over a lifetime of up to 200 uses. A cradle-to-grave life cycle assessment was conducted using the Environmental Footprint v3.1 method, covering climate change, acidification, resource use (minerals and metals), and water use. The system boundaries include raw material extraction, manufacturing, packaging, distribution, use, cleaning and reprocessing, and end-of-life treatment. Background data were sourced from ecoinvent v3.11 database.
Production dominates environmental impacts in single-use and one-cycle configurations across all categories. When extended to 200 cycles, reusable systems show a clear shift in hotspots, with cleaning and reprocessing becoming the main contributors, accounting for more than two-thirds of impacts in some cases.
For climate change, the single-use system reaches approximately 97 kg CO2 eq/FU over 200 uses. Reusable systems significantly reduce impacts, ranging from about 5.8 to 18.8 kg CO2 eq/FU depending on the reprocessing strategy. The lowest impacts are achieved with local hospital reprocessing due to lower material intensity in cleaning.
These results highlight that while reuse can substantially reduce environmental impacts, its effectiveness depends largely on the efficiency of reprocessing systems. Therefore, it is essential to optimize cleaning protocols to maximize the environmental benefits of circular strategies applied to medical devices.

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3.10.T05 New Pathways to Map the Environmental Footprint of the European Average Wardrobe: Connecting

Life Cycle Assessment With Consumer Behaviour

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Consumption of textiles has continuously grown within the European Union during the last decades, resulting in an increasing sustainability footprint derived from impacts during production – mostly localised on low-income countries –, use and management of constantly higher amounts of textile waste – this being largely externalised towards developing countries. This trend is expected to continue in the future, based on a consumption pattern driven by fast-fashion behaviour, recently reinforced by widespread use of online purchasing platforms and shorter fashion cycles induced by social networks, particularly relevant for younger generations. Extended Producer Responsibility (EPR) schemes appear as a suitable tool to overcome this situation, as well as a valuable opportunity to enhance circular business models. However, effective implementation of EPR faces significant challenges: lack of reliable data, regulatory fragmentation, coordinating multiple stakeholders with divergent interests, while also addressing the socio-economic and environmental impacts of supply chains. Current environmental assessments about clothing focus on production stage, often using a static product-based functional unit (FU), for instance: a single piece of garment or given amount of apparel. A more dynamic approach is here proposed, making use of a user-based FU to encompass consumer behaviour. Existing published data were taken to model an average European wardrobe representing per capita clothing consumption.
Different profiles were adopted to ensure an accurate representation of European consumers. Main demographic variables identified were: gender, age, purchasing power and geographical area. The work illustrates how life cycle inventories are structured and differentiated across these profiles, also considering clothing typology and composition. Moreover, it offers a more rigorous explanation of population behaviour in terms of social patterns and inequalities, since these influence opportunities and resources available, as well as norms to follow. Furthermore, the use phase of clothes was represented by inputting key aspects, such as average garment usage and washing cycles. Upon this foundation, the obtained LCA results will allow to establish future projections of population behaviour to be linked with the effects of EPR application, thus allowing to link environmental evidence to relevant strategic decisions, supporting policymakers, businesses managers and consumers.

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3.10.P - Modelling Product Lifetime Extension to Support Circular Economy

3.10.P-Mo055 Next life or next guess? Inventory data quality in LCA of second- and third-life EV battery repurposing

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Repurposing electric vehicle batteries (EVBs) for second- and third-life applications represents a product lifetime extension strategy with potentially significant environmental benefits. Life cycle assessment (LCA) is the dominant tool for quantifying these effects, but the credibility of such assessments hinges on the quality of inventory data. This study presents a comparative LCA of repurposing EVBs under two inventory scenarios: one based entirely on secondary data, and one incorporating primary data collected from an ongoing research project for foreground processes where empirical measurements were available. The study demonstrates that for the parameters that could be measured directly, the two scenarios produced largely consistent environmental results, indicating limited sensitivity to the data source for these inputs. However, key hotspots, particularly the recovery rates for critical raw materials (CRM) in the cathode and recycling process yields, remain dependent on secondary data because robust primary estimates require demonstration- or commercial-scale operation. These findings show that uncertainty analysis is essential for interpreting LCA results where key recovery and recycling parameters remain empirically constrained. They also

support the development of credible circularity claims for CRM-containing products such as EVBs under emerging Extended Producer Responsibility (EPR) and Ecodesign for Sustainable Products Regulation (ESPR) frameworks.

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3.10.P-Mo056 From First to Second Life: A Life Cycle Approach to Circular Battery Pack Design

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Battery systems are central to the European Union's transition toward climate neutrality, with increasing attention given to opportunities for reuse, repair, and efficient disassembly to further reduce environmental impacts. However, these aspects are not yet systematically integrated into electric vehicle battery pack design, limiting their practical implementation.

EU policies such as the Regulation (EU) 2024/1781 and the EU Battery Regulation increasingly promote life cycle-oriented design approaches, which reinforce the need to embed circularity into product development. Despite this, current battery pack designs remain largely optimized for first-life performance, consequently creating a gap between policy ambitions and practical implementation. The key challenge is therefore to integrate circularity strategies into battery pack design while maintaining performance and material efficiency across multiple life cycles.

To address this challenge, this study adopts a design-oriented approach that applies circularity principles at the component level within a battery compartment. It focuses on four key strategies: reuse of recycled cork for second-life cell holders, development of reusable wood-based structural components, use of thermally reversible adhesives to enable controlled disassembly, and integration of phase change materials into the cell holder to extend cell lifetime.

The environmental performance of the different design strategies is assessed using life cycle and circularity assessments. While such strategies are expected to improve circularity performance, their implications for overall environmental performance remain uncertain. Additionally, focus is placed on the application of different circularity indicators that enable the comparison of different circularity strategies, allowing identification of the most beneficial approaches as well as potential trade-offs.

This study supports the application of life cycle approaches in product design by demonstrating how circularity strategies can be integrated at the component level of battery packs. The findings provide practical insights for implementing life cycle-oriented design in line with the Regulation (EU) 2024/1781 and the EU Battery Regulation, supporting the transition toward more sustainable and circular battery systems.

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3.10.P-Mo057 Enhancing End-of-Life Decisions for E-Cargo Bikes through LCA and Field Failure Data Integration

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E-cargo bikes are increasingly used in urban transport and are considered a promising option for reducing transport-related environmental impacts. However, the production phase dominates life cycle greenhouse gas emissions, making product lifetime and end-of-life (EoL) management key determinants of overall environmental impacts. While circular economy strategies offer potential to improve resource efficiency, the selection of appropriate EoL options remains challenging due to limited availability of component-specific and condition-based information.
This study presents a life cycle assessment (LCA)-based decision framework to identify environmentally optimal EoL strategies for e-cargo bike components. The approach follows an attributional LCA perspective and considers multiple impact categories, including climate change and resource use. A central element is the integration of primary field data on component-specific failure modes and degradation behavior, enabling condition-based estimation of remaining useful life and differentiation between EoL options such as reuse, refurbishment, remanufacturing, and recycling.
The framework is demonstrated for a bicycle stand component, selected due to its high observed failure frequency and robust data availability. Despite its relatively low mass, the bicycle stand contributes approximately 6% to the total climate change impact, primarily due to its aluminium content, highlighting its relevance as a decision variable for EoL optimization.
By linking condition-based assessments with LCA results through parameterized EoL scenarios, the model enables the identification of strategies that minimize environmental burdens under consistent system boundaries and functional unit definitions. The results illustrate how integrating real-world usage data into LCA supports informed, component-level decision-making and enhances circular economy strategies. Future work will extend the approach to additional components and system-level optimization.

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3.10.P-Mo058 Decision-Support for Product Lifetime Extension: Scenario-Based LCA Modelling of Maintenance for the Manufacturing Industry

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Maintenance-driven product lifetime extension (PLE) receives higher priority in circular economy (CE) framework hierarchy, despite its environmental impacts' quantification remains much less studied than those of recycling. Decision-makers, practitioners, or experts in the life cycle assessment (LCA) field face a recurring challenge when evaluating PLE: extending service life increases cumulative environmental impacts while reducing impact intensity, defined as the environmental impact per unit of production or impact per year of service, making it unclear how to judge the environmental performance. This study analyzes industrial process equipment with a service lifetime 17% below the industry average and dominant with use-phase impacts, applying scenario-based LCA modelling to model maintenance-driven PLE supported with computational modelling for the future extended lifetime scenarios. These scenarios allow comparing between the total environmental impacts and impact intensity. Results demonstrate a clear pattern: cumulative impacts continue to increase with longer product use through maintenance, while impact intensity decreases up to 58% within climate change and other significant impact categories. This decrease in impact intensity occurs because manufacturing impacts are distributed over more years and more production units, which improves resource efficiency. Scenario-based LCA supported with computational modelling shows the trade-offs between different lifetime strategies visible, rather than assuming lifetime extension is always beneficial or detrimental. The environmental benefit of lifetime extension depends on product type and context, highlighting the need for case-specific evaluation. These findings underscore the importance of lifetime-oriented circularity indicators and scenario-based modelling for evaluating circular economy strategies. It supports practical, policy-relevant life cycle-based decision-making for making sustainable product developments.

3.11 - Qualitative Life Cycle Studies: Exploring and Analysing the Practical Meaning of LCA

3.11.T01 Understanding Variations in Life Cycle Policymaking Through a New Classification.

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Life Cycle Thinking (LCT) is increasingly used across jurisdictions and sectors to regulate environmental impacts. Existing studies highlight that Life Cycle Assessment (LCA) is knowledge-intensive and challenging to implement in policymaking, due both to the complexities of life cycle data and modelling and to difficulties in communication and implementation of LCA results.

This review synthesises academic literature from the past 20 years that classify different forms of LCT use in environmental policymaking. The review aims to answer the following questions: what forms of LCT use exist in policymaking; where, when, and how is LCT employed within policy processes; what kind of life cycle approaches are more common in policymaking; and how prevalent is life cycle based policymaking relative to other forms of environmental policy.

The review combines an academic literature review with a qualitative analysis of policy documents using legislative databases to assess the prevalence of different types of LCT use across countries and sectors. The geographic scope is global and will be followed by a comparison with policy frameworks within the European Union, with a particular focus on construction policies.

Building on existing classifications of LCT use, the review introduces an additional category to capture recent cases in which LCT is mandated directly through policy instruments and requires LCA practice. This improved classification is applied to the construction sector to demonstrate how it supports the interpretation of diverse policy frameworks, such as the Ecodesign Directive and the Energy Performance of Buildings Directive.

The review highlights a gap in theoretical understanding of the different forms of LCT use in policymaking, and the institutional factors that shape these choices. It concludes with a research agenda to advance theoretical and empirical work on the evolving role of LCT in environmental policymaking, and sheds light on potential opportunities for strengthening the use of life cycle approaches in European policy frameworks.

3.11.T02 Beyond Efficiency: How Social Values Shape Functional Value Retention in a Solar Panel Reuse Case

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Circular economy (CE) interventions are often promoted as win-win-win solutions for sustainability on economic, environmental and social dimensions. Unfortunately, their social dimensions, such how a product's value is retained and distributed and the social values surrounding the actors involved in a product chain, remain poorly understood. One such CE intervention facing this issue is the solar panel reuse chain in the Netherlands, which is the focus of this study. Here, the functional value of solar panels is lost when discarded earlier than their technical end-of-life. Despite previous research in Industrial Ecology showing such CE interventions have promise to benefit environmental and economic dimensions, coupling these material studies with the social context is missing. Therefore, this risks the implementation of CE interventions without a fully accounting for their associated values of actors which create this new system, the costs incurred and the distribution of benefits. In this study, we ask the question: How are actors' values in a product chain mobilised translated into coordinated action towards scaling up higher tier circular economy interventions? We use the Product Chain Organisation (PCO) approach, to connect the material and social layers and as a framework to scope the study and investigate cross-organisational interactions. It enables the identification of the key actors, their roles, values and concerns throughout the product system of solar reuse. We interviewed 13 key actors,

analysed documents and press releases and did field visits. Coding was conducted inductively, allowing values and concerns to emerge from the data. We then analysed how these values align or conflict with each other and how they translate towards the retention of functional value and what values are mobilised to influence collaboration and the distribution of benefits and burdens. We identified social values such as sufficiency, energy poverty, and social labour inclusion which helped to initiate and sustain the reuse product chain. However, they are fighting against a system which was not designed to fully accommodate them. There are misaligned expectations, governance bottlenecks, and high running costs creating structural incompatibility with the incumbent system. This study contributes to advancing a socio-material understanding of circularity and by highlighting how just and equitable outcomes depend on the alignment of social values across the chain.

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3.11.T03 Avoiding a Compliance-based LCA Culture Under Legislative Pressure: Evidence From a Longitudinal Study of Four Building Companies

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In recent years, many sectors have seen an increase in LCA applications mandated by legislation. Although justified by a general sense of environmental urgency, it remains unclear how affected organisations respond to the institutional pressure exerted by LCA-oriented legislation. It is suggested that LCA-oriented legislation carries a hidden cost by contributing to a compliance culture that limits existing market-oriented LCA practices. At the same time, understanding the influence of LCA-oriented legislation on affected organisations is limited due to a shortage of empirically informed studies.

To better understand the effects of LCA-oriented legislation on existing LCA practices, a longitudinal study was carried out at four Swedish building companies between 2017 and 2025. During this period, the companies saw the development and implementation of a law mandating LCA-based climate declarations in new buildings projects. The research followed a nested-case study design zooming in on LCA-based practices in nine building projects. Empirical data were collected from interviews (34), LCA and climate calculation reports in the studied building projects (9) and additional documentation about the projects and companies (>50).

The results showed that both the volume and variety of LCA-based practices grew between 2017 and 2025. Where LCA was initially a relatively novel method without tangible uses in building projects, it had developed into a routine practice used for (1) building permits, (2) climate optimisation, (3) certification schemes, (4) procurement, (5) purchasing, (6) research and development, and (7) company strategy. Despite the institutional pressure exerted by building climate declarations, organisations were able to avoid a compliance-based LCA culture by carrying multiple LCA-based practices simultaneously in the studied projects. In several instances, LCA-based practices reduced building environmental impacts by deviating from the methodological standard prescribed by the legislation.

The study concludes that LCA-oriented legislation can stimulate LCA-based practices by creating organisational resources and a clear mandate for LCA in projects. To avoid a compliance-based culture, it is important not to stifle the capacity of organisations to carry multiple LCA-based practices simultaneously. This becomes especially relevant where LCA-based legislation targets small and medium-sized enterprises with fewer organisational resources.

3.11.T04 Understanding Decision Situations for More Actionable and Influential Life Cycle Assessment

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Life Cycle Assessment (LCA) is often being presented as a decision-support tool informing development of more

sustainable systems and practices. The decision support is often described as providing accurate “scientific” information in form of the detailed analysis aimed at facilitating rational choices of the decision makers (users of the LCA information). Thus, the emphasis is currently placed on producing detailed and methodologically robust LCA studies, which take significant time and effort. However, decision-makers frequently find LCA results interesting but difficult to interpret and apply in their decisions, critiquing the method as overly complex and unfitting for, or inapplicable for real-world decision-making. This highlights a contradiction between the ambition of LCA as a decision-support tool and its limited influence on actual decisions. That means that there is need to better understand actual decision-making situation and procedure, i.e., the context of the LCA work for LCA to become more usable, relevant, and actionable in practice.
The present work aims to explore if and how Activity Theory and Sensemaking perspectives borrowed from social sciences can be combined to identify key aspects of the decision situation and ways of making LCA more relevant to the specific context. The Activity Theory is used as a framework for structuring and analyzing the decision situation, while sensemaking is used to develop a more detailed understanding of how actors interpret and construct meaning. The study also investigates if the concepts of "contradictions" from Activity Theory and "cues" from sensemaking can be useful in detecting the key points in the decision situation where LCA may have highest potential to influence decisions.
The empirical material consists of semi-structured interviews with LCA practitioners and decision-makers, complemented by case studies in which the authors participated as LCA practitioners.
The outcome of this work is to gain insights on how LCA practitioners could better understand the context and enhance the potential impact of LCA in real-world decision-making.

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3.11.T05 Exploring and understanding the practise of LCA in innovation processes

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LCA provides a framework for assessment of environmental impact that increasingly finds applications. Arguably, part of its success can be attributed to LCA as a fact-based, objective, and quantitative approach. However, this largely ignores the practise: how LCA becomes adopted by practitioners in industry, during innovation and product design. We explore this from different angles.

- Several review studies report difficulty to compare LCA studies. This is due to methodological differences and different datasets, but also differences in considered goals, scope, and alternatives (value-based choices), and due to uncertainties.
- Transformative sustainability assessments do not only require to address knowledge gaps, but also consider normativity and consensus building, and incorporate reflexivity – in line with the distinction between hard, soft, and complex systems. The related field of Multi Criteria Decision Making offers insight and inspiration on how to handle this, by specific participatory approaches.
- The combination of LCA with Responsible Research and Innovation has been suggested to bridge LCA with stakeholder goals and values. RRI focusses on anticipation (foresight), reflexivity (reflecting on assumptions), inclusion (stakeholder engagement), and responsiveness (adapting to new information). Combining the approaches enriches the goal setting stage, as well as critical reflection on outcomes. However, the practical feasibility and effectiveness remains to be proven.
- Studies that focus on the application of LCA in manufacturing firms show that it is depending on industry type and firm size, as well as company goals and skills, and data and time available. Application of LCA shows to be a gradual process of take up, and does not guarantee a full transformation of business processes.
- And finally, studies on sustainable innovation processes in companies show that LCA plays a role, but a variety of simplified assessment approaches gained traction, including indicators and process-based assessments that

evolve over time.

Insights show that understanding the practice of LCA requires considering context, goals, stakeholders, and (inherent) uncertainties, due to the different nature of problems. Academic approaches suggest combining complex frameworks. While innovation practices at firms show a more pragmatic approach, with a preference for simplified assessments, that are context depending and evolving over time.

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3.11.P - Qualitative Life Cycle Studies: Exploring and Analysing the Practical Meaning of LCA

3.11.P-Tu027 Life Cycle Assessment theory and practice: Observations and discussion based on the composite sector

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Life Cycle Assessment (LCA) is increasingly applied to quantify environmental impacts of materials and products, such as fiber-reinforced polymer composites. However, practitioners can select among a multitude of methodological choices that need to consider and reflect technical and economic parameters in order to provide qualitative and meaningful results. This study aims to analyze and critically discuss the application of LCA methodology to composites regarding transparency and consistency of LCA methodological choices, while also investigating coherence with technical and market aspects with a special focus on technological maturity. The composite sector serves as an exemplary field of applying LCA as these materials are used in many applications, traded on global markets with complex supply chains, involve a diversity of academic, industrial and political stakeholders and are subject to chances and challenges of the bio- and circular economy.

Through systematic literature review, 130 original peer-reviewed articles on LCA of composites were identified and analyzed regarding system model (and database) selection, functional unit description, system boundary selection, inventory modelling. A lack of transparency, namely not specifying technical and methodological parameters, and inconsistencies within these choices, especially concerning system model, functional unit and system boundaries, are major issues in multiple studies, which evoke questions of ISO compliance and usefulness of results. On the other hand, multiple positive examples have been identified, e.g. to consider functionality also in LCA studies of composites as intermediary materials. Furthermore, more than half of the reviewed studies does not explicitly state or reflect on technological maturity of materials and processes, while the options to do so vary from quantitative to qualitative elements. Prospects and challenges of emerging methodological refinements within LCA, such as prospective LCA, are discussed regarding their potential to improve the quality of LCA results in the light of these shortcomings. Despite multiple limitations, especially regarding the scope and focus on a particular type of material, this analysis aims to contribute to the broader discussion on divergences between LCA theory and practice, and the outline of potential solutions and future pathways.

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3.11.P-Tu028 Learning Within Life Cycle Assessment Processes: A Deep-seated Assumption Worthy of

(Re)investigation

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Learning is fundamental to how life cycle assessments are envisioned to drive environmental innovation in individual organizations and broader society. Since the early days of the field, learning has been a central motivation for, and outcome of, life cycle assessments. Traditionally, this has been conceptualized as generation of knowledge about the environmental impact of the study object's life cycle, knowledge that is supposed to be transferred to, and internalized by, the relevant stakeholders in specific assessment contexts. However, learning also extends to other areas, such as knowledge about environmental issues, pollutants, and toxins, as well as related to the skills and methodology of planning, conducting, and interpreting life cycle assessments and their results. Moreover, recent studies have shown that the knowledge and skills generated from life cycle assessment studies are often used beyond the decision context of the assessment, leading to indirect effects and the accumulation of life cycle-related knowledge within organizations. Although recent research has begun to touch upon this topic, findings are largely limited to a small number of case studies, mainly involving organizations with extensive experience in conducting and utilizing life cycle assessments. Furthermore, learning is typically examined as just one of several processes and outcomes, rather than as a primary focus. Hence, considerable work remains to create a systematic understanding of learning within life cycle assessment processes. For example; what type of knowledge and skills are generated and learnt; what activities induce learning; what activities are effective for transferring knowledge to relevant stakeholders; and how this knowledge spreads throughout organizations are some questions that remain mostly unanswered. Based on this, the contribution seeks to stimulate discussions toward establishing a research agenda for studying learning in life cycle assessment. This includes presenting and discussing how different theories of learning apply to life cycle assessments, what methods and approaches could be used to capture and evaluate learning, and which promising research set-ups could be exploited for performing such research.

3.11.P-Tu029 Supporting Net-Zero Policy Under Uncertainty: A Scenario-Based Life Cycle Assessment of the London Residential Stock

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With the UK committed to net-zero greenhouse gas emissions by 2050, new initiatives are creating more consistent frameworks for assessing building carbon performance. In this context, life cycle assessment (LCA) is becoming a key policy tool, helping decision-makers evaluate building emissions over the long term in a standardised way. Most policy applications of LCA, however, still rely on static assumptions about future energy systems, climate conditions, and technology adoption, which can substantially affect whole-life carbon outcomes and policy effectiveness.

This study presents a framework that quantifies uncertainties in future LCA scenarios for the London housing stock and assesses the implications for building decarbonisation policy. A semi-detached house in London is used as a representative case study. A range of drivers of uncertainty is screened using local sensitivity analysis, and then the most influential variables are incorporated into a Monte Carlo simulation to generate probabilistic whole-life carbon outcomes. The analysis compares different refurbishment packages, ranging from basic fabric and service upgrades to deeper retrofits that include energy generation and storage techniques such as solar PV and batteries. These packages are assessed under different future scenarios shaped by climate change and grid decarbonisation. The study considers both 2030s and 2050s conditions, using best- and worst-case climate projections from UKCP18 and varying electricity emission factors to reflect different grid futures.

This study addresses the limitations of deterministic LCA in policy applications and supports a more comprehensive decarbonisation decision-making under uncertainty. The probabilistic distribution of LCA results can be used to assess policy risk by estimating the likelihood of exceeding carbon budgets. By comparing alternative future conditions, the analysis identifies which retrofit pathways remain most robust and how sensitive policy outcomes are to future assumptions. In doing so, the framework can help policymakers refine carbon targets and design policies that remain

effective across a broader range of future conditions.

3.11.P-Tu030 Application of Weighting Method in Life Cycle Assessment: A Case Study of Wastewater Reclamation Systems

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An increasing amount of attention has been given to the use of life cycle assessment (LCA) as a tool for evaluating environmental impacts. LCA results typically encompass multiple impact categories, which can make interpretation and decision-making complex. To address this challenge, weighting methods are often applied to aggregate multiple indicators into a single score. Conventional approaches, however, frequently rely on expert judgment or policy priorities, which may introduce subjectivity. To provide a science-based foundation for weighting, this study adopts a framework that integrates Planetary Boundaries (PB) with the Distance to Target (DTT) approach for impact assessment and interpretation. Three global PB-based sets were derived from different reference years, and one downscaled PBs was also made for Taiwan-specific set. The proposed framework was applied to two full-scale wastewater reclamation plants in Taiwan to examine how different PB-DTT weighting contexts influence impact interpretation. Compared with unweighted results, the overall weighted impact scores increased by 7–11% for Plant A and 6–8% for Plant B. Under the Taiwan-specific weighting set, the increases were more pronounced, reaching 25% for Plant A and 15% for Plant B. These findings indicate that PB-DTT-based weighting is strongly influenced by the underlying inventory structure. In particular, Plant A is more sensitive to regional weighting methods because its impacts are dominated by electricity use, whereas Plant B is less affected due to its impacts being primarily driven by chemical inputs. Overall, the results demonstrate that PB-DTT-based weighting can shift the identification of impact hotspots and improve the contextual relevance of LCA results, thereby supporting more regionally sensitive environmental decision-making.

3.11.P-Tu031 Assessing Sustainability Strategic Alignment in Product Development Decision-Making at Volvo Cars Using Analytic Network Process

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The integration of environmental considerations into product development has been discussed in literature with particular attention to approaches related to Life Cycle Assessment (LCA). While these tools aim to inform more sustainable products and business, a particular gap is the alignment between corporate sustainability strategies and operational decision-making.

This study investigates how sustainability goals are operationalized in practice by assessing the strategic alignment between corporate targets and decision-maker priorities, exemplified by a Volvo Cars case study.

This study applies the Analytic Network Process (ANP), a Multi-Criteria Decision Analysis (MCDA) method, to two decision cases involving polymeric automotive parts. Six criteria were evaluated: cradle-to-gate carbon footprint, end-of-life circularity, recycled content, biobased content, weight and cost. Data from 79 decision-makers in product development were used to quantify priorities, enabling assessment of strategic alignment between and within different groups of decision-makers.

Initial findings show variations in criteria prioritization among all defined groups of decision-makers, suggesting misalignment between decision-makers with similar roles. Particularly, large variations were observed related to the carbon footprint, biobased content and end-of-life circularity criteria, while weight and cost criteria consistently dominate decision-maker priorities. This occurs despite target information provided to decision-makers emphasizing environmental performance, raising questions of how effective the current sustainability target steering is.

Ongoing work complements these findings through interviews with company experts responsible for deciding the corporate sustainability target steering and further decision-maker interviews. This enables triangulation between strategic intent, operational practices, and policy directives, which are complemented with green product development literature, to synthesize improvement actions addressing the misalignment areas.

This study is a relevant example of current challenges present in environmental work and green product development, with a particular focus in the automotive industry. It also demonstrates how a quantitative method like ANP can be combined with qualitative analysis and an extended scope of respondents to assess misalignment between sustainability strategy and decision-making practices in complex industrial contexts

3.11.P-Tu032 Stakeholder Perspectives on Automated LCA and Decision-Making

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Recent regulatory developments have increased the use of Life Cycle Assessment (LCA) in industry and policymaking. However, implementing LCA in industry is often constrained by time-intensive data collection, methodological complexity, and the reliance on static models that poorly reflect dynamic production systems. In response, automated LCA approaches have been developed to increase efficiency.
Despite this, there is limited empirical evidence that LCA automation improves the use of environmental information in decision making. Automation often appears to be driven by compliance needs, such as the growing demand for standardized outputs like Environmental Product Declarations (EPDs). While automation enables faster LCA results, this might not necessarily lead into improved environmental performance or better decisions and might even risk becoming a “number generation” exercise without supporting sense-making or learning within the organization.
A further challenge is that LCA automation is usually easier to implement for mature technologies, where processes are well defined and data is available, but design flexibility is limited. In contrast, early design stages offer greater opportunities to influence environmental impact, but incomplete information makes automation difficult. This raises the question of what purpose automated LCA serves if it is mainly applied where the potential for change is already constrained.
This study investigates to what extent automated LCA results contribute to learnings from environmental information in decision-making processes in industry through the lens of organizational learning theory. A mixed-methods research design is applied, combining semi-structured interviews with key stakeholders across industry, research and consultancy, and survey-based data collection targeting a broader group of practitioners.
Preliminary findings will be presented at the conference, providing initial insights into how automated LCA tools are currently applied and perceived by stakeholders and how they contribute to organizational learning. The findings of this study are expected to contribute to the literature on decision-support provided by LCA, and be useful for researchers, tool developers and LCA practitioners by identifying key factors that enhance or hinder organizational learning from automated LCA practices.

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3.11.P-Tu033 Exploring LCA Practice of Goal Definition and Scoping in Studies of Carbon Capture and Utilization

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In the development of carbon capture, utilization and storage (CCUS) and other emerging decarbonization technologies, life cycle assessment (LCA) is often used to assess potential carbon reduction, yet performing LCA in early development stages is challenging. Such contexts involve long time horizons, multiple actors and different knowledge needs, creating several uses of LCA, such as informing, supporting or learning. These needs cannot be

addressed by a “one size fits all” LCA. Consequently, LCA studies need to be tailored for their specific purposes. However, existing guidance on goal and scope definition is limited when it comes to translating an intended use of LCA into contextually meaningful methodological decisions aligned with the decision-making situation. In an earlier review study of LCAs of CCU, it became clear that most studies have unclearly described goal definitions. This prompted us to examine the alignment between stated goals and scopes by comparing studies with similar goals (e.g., “identify hotspots”). Despite similar technologies and goals, these studies were found to have considerably different scopes, revealing no systematic or transparent connection between goal and scope. For example, studies of CCU fuels and chemicals with the goal to identify hotspots were found to have different functional units (based on energy content, mass, duration of operation or distance travelled), system boundaries (cradle-to-gate, cradle-to-grave, well-to-wheel or gate-to-gate) and different types of comparisons (product, process or system level). This is contradicting to the ISO standard stating that method choices depend on the goal definition. These findings highlight the need for better understanding of how the intended use of an LCA can be translated into goal-consistent scope choices. More explicit and context-sensitive formulation of the purpose of an assessment would support LCA practitioners in making the most suited method choices in line with the goal of the study. A stronger utilization-focused approach in the goal and scope phase is needed to improve the relevance of LCAs in technology development contexts. This suggests a need for further methodological development and empirical study on how different LCA purposes relate to specific scoping choices in practice.

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3.11.P-Tu034 Policy-guided and Market-driven Message-LCA: Distinguishing Different Forms of Virtuality in Environmental Accounting

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Recent years have seen a resurgence of “policy-guided” and “market-driven” message life cycle assessments (LCA). This represents situations where environmental accounting is used to communicate political visions or specific environmental features rather than neutrally analyzing physical systems.This study addresses this development by introducing a typology of message-LCA that clarifies how normative methodological choices shape practice. The purpose is to provide conceptual clarity to ongoing debates about how descriptive, prescriptive, and communicative functions interact.

The study employs a conceptual analytical approach. It synthesizes insights from recent debates on message-LCA to develop a typology of modelling choices shaped by normative and communicative intentions. This typology is then used to re-examine a recently proposed “dynamic allocation” method for waste-to-energy.

The message-LCA typology distinguishes between i) the degree of physical versus virtual representation and ii) whether modelling choices are shaped predominantly by policy goals or market-driven positioning. The framework helps unravel how different forms of virtuality enter environmental accounting.

The re-examination of the recently proposed “dynamic allocation” approach shows how policy-guided modelling can introduce “temporal virtual coupling”. This creates an explicit link between present-day environmental burdens and envisioned future systems. Such modelling choices reflect an epistemic drift towards message-LCA, where political aspirations can become embedded in modelling rather than being assessed by it. Thereby prescribing comparative outcomes in line with transformative policy agendas.
Taken together, these insights illustrate how different forms of message-LCA can blur descriptive and prescriptive roles, underscoring the need for clearer conceptual distinctions.

The work underscores the need for conceptual clarity as message-LCA gains influence. Distinguishing different forms

of virtuality, and their policy-guided or market-driven origins, is essential for preserving transparency and scientific credibility when environmental accounting is used for decision making.

3.11.P-Tu035 Recommend Combining LCA and DEA socio-eco-efficiency approaches for European Cereal Production evaluation and predictive optimisation

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Sustainable development has been the interest of multiple researchers and scholars worldwide for centuries. A modelling approach to orient the world for evaluation from the socio-eco-efficiency perspective is vital to empower the collaborative efforts and innovative approaches aiming to build a resilient and inclusive agricultural system meeting current demands, preserving ecosystems and supporting future generations. In this context, this study aims to evaluate the European Cereal Production socio-eco-efficiency and to predict scenarios for Economic, Environmental and Social optimisation through a combination of three phases follow-up: the Life Cycle Assessment (LCA), Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) methods, the first phase aims to define the model variables to use based on the main impact categories clustering and selection, the second phase seeks to quantify the socio-eco-efficiency score, while the third step examines the input variables effects and optimising solutions for performance evaluation. Results of this study have shown that all investigated countries were able to achieve a high value of the "Sustainability index" indicator in the period between 2004 and 2022. Moreover, evaluating the variables, identified in this study as the inputs of the developed model on the productivity value, concluded that the investigated countries were able to gradually achieve relatively high values of socio-eco-efficiency and sustainability scores from 2004 to 2022. However, an analysis carried out comparing all the input variables has concluded the necessity to act on the main variables related to Climate Change, Ozone, Photochemical Oxidation, Abiotic Depletion, and Toxicity to attain the ideal scores equal to 1,00. As result, the developed model could help users, policymakers, scientists, scholars, governments, and communities not only in Europe, but also worldwide to frame their knowledge for achieving the sustainability goals and to orient them per aspect, per family, and per category for better categorisation and multi-dimensional speciality to find a suitable strategy and to establish the right rule in the micro, and macro environment, from the operational level to the strategic one.

3.12 - Quantifying What We Avoid: LCA for Evaluating Waste Prevention and Reuse

3.12.T01 What Should We Do With Our Textile Waste?

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The textile sector is a major environmental impact hotspot, responsible for 8–10 % of global greenhouse gas emissions, high freshwater consumption, and substantial waste generation under linear production systems and fast fashion business models. Enhancing textile circularity is therefore critical to reducing cradle to grave environmental burdens. The introduction of mandatory separate textile waste collection in the EU from January 2025 has dramatically increased the availability of textile waste, as well as the need for appropriate treatment options.

In response, research and development efforts towards increased textile circularity have intensified in recent years, resulting in a wide array of technologies and pathways to make textile products more circular. Beyond the inherent complexities of LCA, the diversity of textile products in terms of fibers, production processes, technology readiness levels and garment types make analysing and comparing these pathways particularly challenging.

The goal of this research is to study how LCA can support stakeholders in choosing circular pathways, including re-use, remanufacturing and recycling, for textile waste management. The study focuses on utilizing different methodological approaches to quantify environmental impact reductions of circular pathways and compares alternative circular pathways. As a baseline, we evaluate the environmental impact reduction potential of garments produced from circular fibres, compared with virgin fibres. Subsequently, we develop scenarios to represent different options of waste

textile management and assess their potential environmental impacts i.e. a “basket of functions” comparing two systems providing waste treatment and new fibers simultaneously. In addition, the Product Environmental Footprint with the Circular Footprint Formula is applied to understand the relevance of different choices.

The results illustrate how the approach used for comparisons can affect the outcome of this study, and how different ways to model the alternative scenarios can lead to different conclusions. The significance of this choice of approach across pathways with different fibers, environmental impact categories and technology maturity are also examined. The study highlights the importance of a systematic perspective when assessing the environmental sustainability of circular textile systems and potential limitations of conventional practice of LCA based decision support.

3.12.T02 Assessing the System-Wide Environmental Impacts of Food Losses in Primary Production: A Consequential Life-Cycle Framework

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Food losses (FL) represent a key sustainability challenge in global food systems, with particularly significant losses occurring at the primary production stage. Yet, the assessment of their environmental impacts remains limited by inconsistent definitions, diverse agricultural systems and complex causal mechanisms, constraining the development of effective mitigation strategies.

The objective of this research is to assess the system-wide environmental impacts of FL in primary production and evaluate potential trade-offs associated with reduction interventions. To this end, a Consequential Life Cycle Assessment of FL is applied. This approach goes beyond conventional attributional methods by accounting for indirect effects, market-mediated responses, and system-level dynamics associated with changes in FL levels and management practices.

The assessment focuses on five commodity groups: grains and pulses, fruits and vegetables, roots and oil crops, aquaculture and fisheries, and dairy and meat. Primary FL quantification data and FL management strategies are obtained from specific case studies for each commodity within FOLOU HE project. System boundaries include ready-to-harvest, harvest, and post-harvest stages, while excluding pre-harvest losses and downstream processing.

The impacts of current food loss management are assessed per product, and a system-expansion approach is adopted to model marginal supply responses and substitution effects resulting from FL. Scenarios are designed to capture FL pathways and their consequences. For example, when vegetable products are lost and left in the field and incorporated into the soil, system expansion is applied to account for the avoided production and use of fertilizers due to nutrient substitution effects. Additionally, the assessment evaluates the effects of FL mitigation strategies, including both direct impacts on resource use and emissions, and indirect effects resulting from changes in marginal suppliers.

Reducing FL can generate both environmental benefits and trade-offs, depending on commodity-specific dynamics and market adjustments. This underscores the importance of accounting for unintended consequences when designing and evaluating mitigation strategies. Overall, the research supports a more comprehensive evaluation of environmental trade-offs, and the proposed framework advances methodological consistency, strengthening the evidence base for decision-making in sustainable food systems.

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3.12.T03 Reduced climate impact from policies to prevent and valorise bread waste in Sweden

Food waste represents a major sustainability challenge, as discarded food implies unnecessary use of resources across the supply chain. Reducing this waste requires policy interventions that steer markets toward more efficient and sustainable practices. However, evaluating such policies in real systems is difficult, particularly as food waste measures often combine prevention with improved handling of unavoidable surplus. This creates challenges in consistently comparing different types of interventions.

This study addresses how policy instruments can reduce food waste and associated climate impacts by modelling their effects using life cycle assessment. The Swedish bread supply chain is used as a case study, characterised by a small number of large-scale producers distributing nationally and operating take-back systems for unsold products. Four policy scenarios were developed based on literature, stakeholder input, and international examples: prohibiting unfair trading practices, advancing redistribution of surplus, enforcing best available technology, and implementing legally binding reduction targets.

A consequential life cycle assessment was applied to quantify changes in waste generation and climate impact across the full supply chain, from production to consumption. This approach enables a consistent comparison of policies targeting both prevention and improved waste management.

Results show that all scenarios reduce both surplus and climate impact compared to the current system. Waste reductions range from approximately 6% to 50%, with corresponding climate reductions of up to 18%. The largest effects are observed for policies addressing multiple stages of the supply chain, particularly when including reductions at the household level. Measures focusing solely on redistribution or retail practices show more limited improvements. The findings also highlight that no single intervention can eliminate food waste entirely, underscoring the need to combine prevention with effective valorisation of remaining surplus.

The study demonstrates how policy design influences outcomes and provides a structured approach to comparing different interventions. The results are relevant for policymakers seeking to design effective food waste strategies and illustrate how regulatory and market-based instruments can contribute to more sustainable food systems, both in Sweden and in similar contexts internationally.

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3.12.T04 From Gross to Net Benefits: Rebound Effects in Life Cycle Assessment of Food Waste Interventions

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Food waste prevention is widely promoted as an essential climate mitigation strategy, where life cycle assessment is commonly used to quantify its environmental benefits. In applied studies, these benefits are typically estimated by crediting avoided upstream production through system expansion or avoided-burden approaches. However, behavioural and economic responses, such as household re-spending of monetary savings, may offset expected gains, leading to differences between gross and net impacts. This study examines how such rebound effects influence the assessment of food waste interventions, combining empirical case evidence with practitioner insights. Two surplus food redistribution systems in Sweden were analysed within a life cycle assessment framework: a food donation system and social supermarkets. Rebound effects arising from household re-spending of monetary savings was found to offset approximately 50% of potential climate savings in the donation system and up to 90% in social supermarkets, reflecting differences in how redistributed food substitutes regular purchases and generate monetary savings. Although both interventions remained environmentally beneficial overall, net impacts were substantially reduced. To understand how such effects are addressed in practice, an international survey of food system life cycle assessment practitioners (n = 79) was conducted. Respondents generally considered rebound effects relevant but rarely included them in

quantitative modelling. Reported barriers included a lack of standardised methods (61%), limited behavioural and economic data (51%), alongside high uncertainty and insufficient interdisciplinary capacity. In contrast, substitution assumptions linking reduced consumption to avoided production are widely applied in life cycle assessment, despite relying on similarly uncertain causal relationships. The findings reveal an inconsistency in how conceptually related effects are treated in the life cycle assessment of food waste interventions, where avoided production is routinely quantified, while rebound effects are rarely included. As a result, assessments may report gross avoided impacts more readily than net outcomes. Addressing this gap requires clearer methodological guidance on when and how rebound effects should be considered, particularly when life cycle assessment is used to inform mitigation targets and policy decisions.

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3.12.T05 Circular and Electrified Freight Futures: A Business Model Life Cycle Assessment Approach

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The European Union aims to achieve climate neutrality by 2050. Reaching this target requires substantial emission reductions from the heavy-duty sector. Electrification of freight fleets will play an important role, but it is unlikely to be sufficient on its own. Increasing the circularity of vehicles and materials is also necessary to reduce life cycle emissions. However, transitioning to a circular freight transportation system is challenging, as vehicle manufacturers must rethink their products life cycle and associated environmental impacts by employing circular business model strategies. While many types of sustainable business models have been proposed, few studies assess whether these models actually improved the environmental performance.

This study aims to identify opportunities and barriers for developing a future electric and circular freight system with minimal environmental impact. The conventional business model, in which a truck is sold and fully owned by the customer, is compared to two future models where the truck is sold as product-as-a-service, as well as a case with shared ownership. Life cycle assessment is used to quantify the environmental impact of the different business models by coupling the economic flows of each business models to the corresponding physical flows. Future-oriented assumptions are incorporated, including developments in battery technologies, energy supply, and low-carbon materials.

The study evaluates how variations in ownership, utilization, and lifetime influence life cycle emissions of electric freight systems and identifies conditions under which circular and service-based business models provide environmental benefits compared to conventional ownership. Sensitivity analysis is used to assess key uncertainties and determine the most influential parameters for reducing environmental impacts. As such, we aim to provide guidance to policy developers and business owners on how to reduce the environmental impact of future freight system.

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3.12.P - Quantifying What We Avoid: LCA for Evaluating Waste Prevention and Reuse

3.12.P-Tu036 Addressing the gap of natural aggregate accounting in LCIA methods for the proper evaluation of

its substitution by recycled aggregate from construction and demolition waste

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Construction sector on the one hand is responsible for around 30% to 40% of total natural resources consumption, but on the other hand Construction and Demolition Waste (CDW) corresponds for about 1/3 of the total volume of waste generated. So, prevention and reuse of CDW have a high potential for overall circularity improvements. LCA assessments have already accurately shown significant reductions in GHG with CDW prevention and reuse. However, the main direct benefit of avoid CDW, i.e. reduce the demand for natural resources, is currently not considered in that analysis because mainstream LCIA methodologies completely neglects these benefits, as they do not have characterization factors for natural aggregates.

Indeed, sand, gravel and clay, are basically not considered in the LCIA methodologies available. This phenomenon hereafter called “aggregates blindness” in the existing LCIA methods hinders the potential benefits from circular practices because the substitution of virgin resources by reused or recycled aggregates from CDW is overlooked, undermining the LCA conclusions.

In this context, this study aims to investigate potential approaches to properly evaluate the benefits of CDW prevention and reuse with a focus on developing a methodology to consider substitution of natural aggregates (NA) by recycled aggregates (RA), by incorporating regionalized characterization factors for NA when applying LCA to assess the benefits of circular practices in the construction sector. This study was organized in the following steps: review of local scarcity and circularity assessment methods, mineral stock estimates; regional discretization of aggregates availability; formulation of theoretical framework for natural aggregates; and proposed approach for estimation of benefits using recycled aggregate in circular construction cases.

We hypothesize that incorporating regionalized aggregate scarcity will provide a more robust way to proper account CDW prevention and reuse evaluation when using LCA studies, and once the model is finalized and validated it can be used in complementarity to other impact categories as a quantitative argument for scaling circular practices in construction.

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3.12.P-Tu037 Environmental and Economic Hotspot Analysis of Supercritical CO2 Extraction of Marine Collagen

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White fish processing generates substantial side-streams, yielding approximately 54 kg of side-streams per ton of fish processed. Seabream skin, a key side-stream, contains up to 48% of protein that could be valorized for high-value applications such as collagen production. However, extraction processes can generate environmental burdens through energy consumption and chemical reagents use. Supercritical carbon dioxide (scCO2) extraction is considered a greener alternative because it eliminates the need for organic solvents, yet its sustainability performance remains insufficiently studied.
This study presents a life cycle analysis (LCA) and life cycle costing (LCC) of scCO2 extraction of collagen from seabream (Sparus aurata) skin. A gate-to-gate LCA was conducted following the ISO 14040 and 14044, using the econinvent database and the Environmental Footprint method. The system boundary covered the receipt of fish skin to the production of one kg of extracted collagen (functional unit) at a processing facility in Turkiye. Five midpoint impact categories were assessed: climate change (CC), acidification (A), freshwater eutrophication (EutF), marine water eutrophication (EutM), and water use (WU). Life Cycle Costing was performed to reflect the economic impacts. Across the five midpoint categories assessed, extraction stage is the dominant contributor to environmental impact,

followed by drying. For CC, extraction accounts for approximately 62% and drying for 35% of the impact. Electricity is the main contributor for both stages. For WU, extraction and drying together contributes approximately 90%, while cleaning accounts for 9% due to disinfection reagents. LCC results indicate that extraction incurs the highest operation costs, followed by hydrolyzation and drying. The carbon dioxide, labor, and equipment maintenance were the main drivers of operation costs at extraction stage.
The findings highlight key hotspots for improving process sustainability, particularly through energy optimization in extraction and drying, and improved cleaning efficiency. The environmental and economic assessments presented here can serve as the basis for an integrated life cycle sustainability assessment. Future research should compare this approach with conventional collagen extraction methods and evaluate the environmental, economic, and social trade-offs between marine and land-based collagen sources.

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3.12.P-Tu038 If Less Is More, What Is Less? A Typology of Sufficiency Measures for Life Cycle Assessment

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Environmental sustainability cannot be reached by solely focusing on efficiency and consistency: sufficiency measures are equally important. Sufficiency measures reduce environmental impact by reducing and/or qualitatively changing consumption or production. Life Cycle Assessment (LCA) is a widely used tool for evaluating environmental impacts of products and services. However, LCA conventionally requires strict functional equivalence between compared alternatives, which makes it poorly suited to evaluate sufficiency measures and quantifying what is avoided through them.

Recent work has proposed the theoretical foundations of Sufficiency-LCA, an adaptation that accommodates non-equivalent functional outputs. A key challenge in operationalising this framework is the absence of a systematic understanding of what types of sufficiency measures exist and how they differ in terms of their effects on functional output.
This study addresses this gap through a semi-systematic literature review of sufficiency measures across sustainability literature. Using a structured search string applied to Scopus and Web of Science, complemented by forward citation searches on key anchor papers, over 1,000 unique records were identified. Following title and abstract screening, a final set of papers will be included for full-text analysis and data extraction.

It is hypothesized that existing categorizations, most notably Sandberg's four-type framework of consumption changes, can be expanded upon and operationalised for LCA by explicitly connecting each measure type to the dimension of functional output it affects: what function is provided, how much, for how long, and how well. Further, it is hypothesized that different measures require different behavioural shifts and therefore relate differently to human well-being. This could provide another layer to how sufficiency differs from efficiency and consistency.

The resulting typology would offer support for decision makers and provide LCA practitioners with a conceptual foundation for categorizing and differentiating sufficiency measures from each other and from other measures, contributing to a more holistic approach to environmental sustainability assessment.

3.12.P-Tu039 From Linear to Circular Product Development in Construction: A DRASTIC Approach Involving

LCA Screening

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The European construction sector faces a dual challenge: rapidly reducing whole-life greenhouse gas emissions while moving away from linear material use. Today, most building components are designed for a single service life, hence difficult to disassemble, and are ultimately downcycled or landfilled as waste. Extending the lifecycle of construction products through design for multiple use cycles is widely recognized as a key strategy to prevent waste and reduce environmental impacts. However, current Life Cycle Assessment (LCA) practices remain insufficiently aligned with circular product development. LCA is predominantly applied ex post, limiting its value for early design decisions. Moreover, existing approaches provide inadequate guidance for identifying, comparing, and consistently defining system boundaries for multiple waste-reduction strategies (R-strategies) for complex and modular construction elements. Consequently, product developers lack robust decision-support tools to evaluate and optimize circular design options across multiple lifecycle iterations. To address this gap, a circular DRASTIC design process is proposed and validated through five case studies, integrating data-driven decision-making via the ex-ante application of LCA, starting from the EN 15804 standard. The approach consists of three iterative stages: (1) assessment of Business-as-Usual (BAU), (2) intermediate screening of circular design alternatives, and (3) validation of final product design. This process enables optimization and enhances circular potential from the early design stage onward. A key contribution is the intermediate screening stage, rarely applied in practice, which identifies environmental hotspots and evaluates the effectiveness of alternative R-strategies across design scenarios. Results show a clear shift from linear practices towards circular solutions prioritizing higher-value R-strategies and multi-cycle use to avoid waste. Across the 5 case studies quantified, which cover façade/structural solutions up to interior finishings, BAU impacts are mainly concentrated in the product stage (A1–A3) and waste-processing stage (C3). The DRASTIC approach mitigates these impacts by avoiding repeated production across life cycles, particularly where whole-element reuse or remanufacture is feasible. Overall, the findings demonstrate the effectiveness of combining circular design strategies with ex-ante LCA while highlighting key considerations for implementation.

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3.12.P-Tu040 Environmental and Economic Assessment of On-Site Surplus Bread Upcycling Versus Bioethanol Recovery

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Surplus bread is one of the most wasted food products globally, yet most valorisation pathways divert it from the food system. Retaining its material value through on-site upcycling could offer both environmental and economic advantages over conventional recovery routes, but comparative evidence remains scarce.
This study evaluates two on-site upcycling pathways that convert surplus industrial bread into reusable baking ingredients and benchmarks them against off-site bioethanol production. The first pathway reuses enzymatically treated bread slurry directly in new dough formulations. The second separates the slurry into distinct ingredient streams, including a syrup fraction substituting sugar and reducing yeast usage, and a solid fraction replacing soy-based animal feed.
Environmental impacts were quantified using life cycle assessment (LCA) supplemented with system expansion, covering global warming, freshwater and marine eutrophication, land use, and water consumption. Economic feasibility was assessed through net present value (NPV) analysis over a 25-year horizon.
Both upcycling pathways outperformed the bioethanol baseline in most impact categories. The separation-based pathway achieved the strongest climate performance, with net savings of 186-267 kg CO2 equivalents per tonne of surplus bread, driven by avoided production of yeast, sugar, and soy-based feed. The slurry-reuse pathway delivered

the largest land use and water consumption reductions through flour substitution. Freshwater eutrophication was the only category where upcycling did not improve on the baseline. Economically, the slurry-reuse pathway was not viable at a single-bakery scale, whereas the separation-based pathway approached break-even with a modest carbon tax deduction.
These findings demonstrate that retaining surplus bread within the food system through on-site upcycling is environmentally preferable to energy recovery and can approach economic feasibility with targeted policy support while offering a promising circular strategy for reducing the environmental footprint of industrial bakery operations.

3.12.P-Tu041 How Can the Material Footprint of Clothing Consumption Be Reduced? A Bottom-Up Analysis of Reduction Pathways

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Household clothing consumption is characterised by largely linear production and consumption patterns and is associated with substantial resource use. This resource use can be quantified through material footprint accounting, yet, most assessments rely on top-down approaches that can provide limited insight into how reductions can be achieved within the system itself. As a result, they offer little guidance on which interventions within the system should be targeted to effectively reduce the material footprint.

This study applies a bottom-up modelling approach to evaluate material footprint reduction pathways for household clothing consumption in Flanders, Belgium. The approach builds on life cycle thinking and consists of two steps. First, a material flow analysis (MFA) model is constructed for the studied system to quantify textile material flows across production, use, and end-of-life stages. Second, these flows, together with relevant background processes such as electricity use, are converted into material footprints using raw material equivalent conversion factors relying on the ecoinvent database.

Using this method, the material footprint of household clothing consumption in Flanders is first quantified for the 2022 baseline. Subsequently, a range of circular strategies is modelled to assess their effects on the system. The MFA results estimate that first-hand household clothing consumption in Flanders amounted to 9.62 kg per capita in 2022. This corresponds to a total material footprint of 250.6 kg raw material equivalents per capita. The analysis shows that measures reducing the demand for new clothing production, such as lower consumption levels, increased product lifetimes, and higher reuse, are associated with the largest reduction potentials, as they effectively avoid upstream material production. In contrast, interventions at the end-of-life stage contribute comparatively less.

Overall, the results highlight the dominant role of upstream production processes in driving the material footprint of clothing consumption. The study demonstrates that bottom-up material footprint modelling enables the consistent quantification of a broad range of circular strategies, including waste prevention and reuse. By linking physical flows to material footprints at the process level, the approach provides a transparent basis for comparing interventions and identifying where reductions most effectively occur.

3.12.P-Tu042 Waste as a Climate Service : Context-Dependent Climate Performance of rMSW Valorisation Pathways

Alex Newman[1], Stuart Walker[1] and Rachael Rothman[1] (1)University of Sheffield

Residual municipal solid waste (rMSW) is often treated as an inevitable output of consumption systems, with policy attention focused on downstream management rather than upstream prevention. This study examines how life cycle assessment (LCA) can support decision-making within this constraint by quantifying the avoided impacts associated with alternative rMSW utilisation pathways.

A consequential LCA is applied to compare two counterfactual uses of rMSW: energy-from-waste with carbon capture and storage (EfW+CCS) and waste-derived sustainable aviation fuel (MSW-to-SAF). The analysis adopts a harmonised framework aligned with ISO 14040/44, with a functional unit of 1 tonne of rMSW at the facility gate. A cradle-to-gate boundary is used, with system expansion to quantify avoided burdens from displaced electricity, heat, fossil Jet-A, and primary materials.

By holding foreground configurations constant and varying regional context (UK and Saudi Arabia), the study isolates how electricity system carbon intensity and waste composition influence the magnitude and distribution of avoided impacts. Results show that avoided electricity generation dominates system performance under high-carbon grid conditions, leading to substantially greater benefits for EfW+CCS. In lower-carbon systems, the relative advantage diminishes, and MSW-to-SAF becomes more competitive due to a more diverse basket of avoided production credits.

The findings highlight that avoided burdens are highly sensitive to background system assumptions, particularly grid intensity and the biogenic and fossil carbon composition of waste. This introduces significant variability in comparative outcomes and challenges the transferability of results across regions.

From a policy perspective, the analysis demonstrates that downstream LCA of waste treatment options provides only a partial view of mitigation potential. While both pathways deliver net greenhouse gas reductions, their benefits are contingent on the prior generation of waste and the counterfactual systems they displace. This reinforces the need to integrate prevention-oriented scenarios into LCA frameworks, where the avoided production of materials and energy carriers may yield substantially greater benefits than reducing or optimising end-of-life pathways.

3.12.P-Tu043 Clothing Consumption Uncovered – a Quantitative Assessment of Climate Impact

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Textiles account for around 5% of the environmental footprint of EU and is driven by the rising levels of consumption. This shows that measures to influence households purchasing and usage rather than focusing on technical developments in the production phase are necessary to decrease the environmental burdens of clothing consumption. However, the environmental impacts of the different phases of clothing consumption, such as purchase, use, and disposal, are currently understudied, where assessments many times are restricted to only assess clothing production (i.e. cradle-to-gate). In this study, we assess the climate impact of European households clothing consumption using life cycle assessment (LCA). As such, this study aims to inform households and policy makers on how to decrease the environmental impact from clothing consumption, as well as to provide guidance to LCA practitioners on how to assess the environmental impact of household activities.

The goal of the LCA is to assess the climate impact of clothing consumption and use (including wearing, washing, and drying) in Europe. The functional unit of this study is “the acquisition, use and disposal of clothes over one year”. The system boundaries of the study are cradle-to-grave, meaning that all processes from raw material extraction to end-of-life treatment of the clothing are included. Primary data on clothing consumption, laundry habits, and disposal are collected through questionnaires sent to European households in Germany, Estonia, Finland, Norway, and Sweden, with around eighty responses. When considering reuse of clothing (for example second-hand) an allocation issue occurs, where impacts from manufacturing and benefits from avoided clothing production needs to be allocated between the life cycles. In this study we apply the cut-off approach where all manufacturing impacts are allocated to the life cycle where they occur, meaning that reused clothes are only attributed impacts such as transportation to the second-hand shop.

Preliminary results show that, unsurprisingly, the acquisition of clothing is the main hotspot, where most of the household purchase new garments rather than second-hand. A notable share of the climate impact is also related to

transportation associated with purchasing garments. Approximately a quarter of the households travelled by public transportation, while another quarter travelled by car to specifically for this purpose.

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3.12.P-Tu044 Quantifying the Environmental Impacts of Food Losses in European Primary Production

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The mitigation of food losses (FL) in primary production is recognised as a sustainability challenge and is reflected in Sustainable Development Goal Target 12.3, which calls for a reduction of FL across supply chains. However, the Commission Decision (EU) 2019/1597 excludes FL in primary production from the common methodology and minimum quality requirements for the uniform measurement of levels of food waste. Consequently, quantifying FL in European primary production and its associated impacts is challenging due to inconsistent definitions, fragmented data, and the lack of a harmonized methodology.

This work addresses these challenges by developing a stepwise approach to quantify FL and assess their environmental impact using an attributional Life Cycle Assessment (LCA) to understand their magnitude and influence in the primary sector. Considering the FL definition developed within the FOLOU HE project, Product Category Rules were developed to quantify and evaluate the environmental impacts of FL for five major food commodities (vegetables and fruits, grain and pulses, roots, tubers and oil crops, aquaculture and fisheries, and meat and dairy) with specific assessment criteria respecting the particularities of each one of them.

The magnitude of FL was estimated using FL ratios from a metadata evaluation of quantitative and qualitative data on Europe. These ratios were applied to statistical food production data at the product level for 32 countries (EU27+ Iceland, Liechtenstein, Norway, Switzerland and United Kingdom) over five years. Environmental impacts were assessed using an attributional LCA of the impacts related to the resources consumed by the fraction of food that ended up lost and the impacts of FL management. Additionally, sensitivity analyses were conducted to evaluate the influence of key parameters (e.g., FL system boundary definitions per commodity and data quality of FL ratio estimates).

The findings show the relative contribution of the five commodity groups to total FL potential environmental impacts and identify potential hotspots at product level in the 32 countries. Overall, this study facilitates the prioritisation of mitigation strategies and policies with the highest prevention potential and environmental benefits. Moreover, the proposed framework provides a scalable method that enables improvement in FL quantification and assessment as larger, more robust primary data on FL become available across regions and commodities.

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3.12.P-Tu045 Where Tradition Meets Sustainability: A Combined LCA and LCC of Fermented Fish Paste (Bagoong) in Philippine Coastal Communities

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Fermented fish or shrimp paste (bagoong) is a culturally important seafood product traditionally produced across the Philippine islands, providing critical livelihoods for coastal communities, particularly women. Despite facing

environmental, economic, and regulatory challenges, no sustainability assessment of bagoong has been documented. This study evaluates the environmental and economic impacts of bagoong through Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) as core pillars of a Life Cycle Sustainability Assessment (LCSA) framework.
Two production facilities were assessed: fish bagoong (bagoong isda) in Batangas and shrimp bagoong in Iloilo. A cradle-to-gate approach following ISO 14040/14044 was adopted with 1 kg of packaged bagoong as functional unit. The system boundary spans raw material receipt through packaging, excluding the use phase but including packaging end-of-life (sanitary landfill). Environmental impacts were quantified using the Environmental Footprint method with ecoinvent database, focusing on climate change (CC), acidification, freshwater eutrophication (EutF), marine eutrophication (EutM), and water use (WU). LCC assessed economic viability through CAPEX, OPEX, net present value (NPV), and internal rate of return (IRR) over a 10-year horizon at a 7.6% nominal discount rate derived from Philippine macroeconomic indicators.
Packaging dominates environmental impact across most categories, except WU where salting leads. For CC, PET bottles account for 64%, followed by carton boxes (14%). Grinding ranks second for EutF (39%), driven by electricity. Landed anchovy is the second EutM contributor (29%), while salt drives 54% of WU. LCC revealed minimal capital needs (CAPEX: ₱37,387[€ 517.85]) against operating costs of ₱56,156 (€ 777.83)/batch (196,560 bottles/year). Raw materials dominate OPEX at 87.9%, with anchovies alone at 84.1%. At ₱84.05 (€ 1.16)/bottle versus ₱59.42 (€ 0.82) unit cost, the operation yields 29.3% gross margin, a positive 10-year NPV of ₱36.35 million (€ 503,490.00), and an IRR far exceeding the discount rate, confirming high economic viability with payback under one year.
Given bagoong's artisanal nature, energy-related impacts are minimal, shifting the burden to packaging. Alternative packaging and end-of-life scenarios will be explored. S-LCA will be integrated in future work to complete the LCSA framework.

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3.12.P-Tu046 Is Circularity Worthwhile for Blended Textile Waste? The Case of Elastane Blended with Polyester

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The fast fashion industry has grown at a much faster rate than the human population, generating massive resource demands, greenhouse emissions and solid waste streams. Recycling is supposed to be an important tool in the industry’s response to such sustainability problems, but blended textiles challenge recycling system design. Elastane is inherently problematic on account of its relatively complicated polymeric structure and its frequent use as a minority fibre in sportswear and other garments. This challenging material has attracted recent scientific attention and been the focus of experimental work to improve recycling methods. We set out to examine new data on monomer recycling of polyester/elastane blends and used prospective approaches to scale up empirical laboratory results.

We performed a grave-to-gate life cycle assessment on alternative systems for recovering monomers from blended postconsumer textile fibre waste, and compared these systems with business-as-usual in Sweden - incineration with energy recovery. We were able to foresee considerable efficiency gains associated with progressing from laboratory to industrial scale. Nevertheless, these prospective life cycle assessment results suggest that the effort associated with recycling this material cannot yet be justified on climate grounds alone. The solvent demands for the separation processes and for the purification of the recovered monomers are significant, as are the environmental burdens of waste management associated with unrecoverable solvents and materials. Solvent selection plays a major role in the

outcomes of this and allied research which is important context for this conference contribution. Considering this and related work in the field of sustainable fashion, we hypothesize that technical, regulatory and behavioural interventions to prevent the generation of mixed textile waste should be prioritized. Situations where this might not be the case will also be discussed.

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Track 4: Sustainability steering in bio-based and circular economies

4.01.A - Advancing and Aligning Life Cycle Approaches for Emerging Bio-Based Systems: Lessons from Algae and Beyond

4.01.A.T01 Environmental impact of high-value compounds from kelp (Ecklonia maxima)

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The blue bioeconomy offers a pathway toward sustainability by substituting fossil-based systems with renewable biological resources. However, its full potential depends on the implementation of circular, biorefinery-based production models. In algae-based systems, the valorisation of residual biomass and process streams is critical to improving resource efficiency, reducing environmental burdens, and enhancing overall economic viability.
This study presents a Life Cycle Assessment (LCA) of the brown seaweed Ecklonia maxima, wild-harvested in South Africa and processed in to commercial biostimulants, generating residual biomass containing unexploited high-value compounds. The environmental impacts of the existing industrial-scale production chain are quantified, and alternative valorisation pathways for the residual biomass are assessed. Two scenarios are compared: (1) anaerobic digestion producing biomethane, biofertiliser, and compost, modelled using the LCAD 2.0 framework; and (2) extraction, fractionation, and purification of high-value compounds for potential pharmaceutical applications, supported by laboratory characterisation of biomass composition.
We expect that solvent use, energy demand, and solvent recovery efficiency may represent key environmental hotspots in the extraction-based scenario, highlighting a possible trade-off between product value maximisation and process sustainability. Moreover, due to the high energy requirements associated with biomass drying, fractionation, and purification, the pharmaceutical extraction pathway may exhibit higher environmental impacts allocated to the functional unit of 1 kg of biostimulant, compared with the anaerobic digestion pathway, despite its comparatively higher economic value. This study contributes to the growing evidence base on the environmental performance of cascading bio-based valorisation pathways, with examples of bioenergy and high-value bioproducts within the blue bioeconomy. Moreover, it adds knowledge on less-studied wild-harvested kelp systems.

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4.01.A.T02 Seaweed Side-Streams as Textile Dyes: Insights from Prospective LCA

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Since the transition toward sustainable bio-based products is gaining a lot of attention, the textile sector is becoming one of the important research areas due to its high environmental impacts and strong reliance on fossil-based materials, such as polyester. However, most existing studies in this sector focus primarily on textile fibres, rather than dyes, even though dyes can be environmentally harmful, since they contribute to a large amount of coloured wastewater, reduce light penetration, and many of them can be toxic and carcinogenic. Bio-based dyes derived from seaweed already exist and are a promising alternative to synthetic dyes due to the lower environmental impact of biomass, with low land use and no requirement for freshwater or fertilisers. A novel development in this context is the use of the seaweed sourced from the side-streams of other industrial processes, such as alginate production. However, value chains of the side-stream seaweed are at the early stage of development, and their future sustainability performance is unknown. These emerging dyes should therefore be studied.

This study conducts a prospective life cycle assessment (LCA) to evaluate the future potential environmental performance of seaweed-based dyes. A baseline LCA model is first developed using primary data provided by industry, analysing two alternative production routes: liquid and powder dyes. Then the data is upscaled from the lab/pilot data to the industrial scale to analyse the future production performance. Some of the challenges include

accounting for data uncertainty and making sound scale-up assumptions.

The prospective LCA results compare the environmental performance of liquid and powder seaweed-based dyes against conventional synthetic dyes. Hotspots across the cultivation/harvesting and processing of the seaweed and the production stages are identified, highlighting the main areas that influence sustainability outcomes.

By focusing on the seaweed-based dyes as a case study, this work illustrates how prospective LCA can support early-stage assessment of algae-based value chains and how LCA can be used as a tool for guiding innovation in sustainable textile applications.

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4.01.A.T03 Life cycle assessment as optimization tool: Case study for protein-rich microalgae (Chlorella vulgaris) production

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Limited agricultural land and excessive greenhouse gas emissions from food systems are major concerns for the future of global food security. Phototrophic microalgae (Chlorella vulgaris) show strong potential as a protein-rich biomass source due to their high productivity and relatively short cultivation period. However, algae cultivation using cascade photobioreactors remains a relatively underexplored field.
With the objective of minimizing environmental impacts, we performed continuous attributional life cycle assessments (LCA) of multiple cultivation trials of MA in a 250 L photobioreactor system. These assessments go beyond conventional environmental analysis by positioning sustainability as a core parameter at laboratory-scale itself alongside other technical performance indicators. This was achieved by integrating mitigation strategies for identified hotspots and establishing LCA as an optimization tool. For optimization, we applied a four-layered approach. First, process improvements were introduced by shifting from batch to semi-continuous operation, incorporating CO_2 fixation, and evaluating the trade-off between centrifugation time and biomass recovery rate. Second, energy optimization was performed by replacing the Singapore grid electricity mix with renewable energy sources. Third, a prospective assessment (p-LCA) was conducted using 2050 impact assessment scenarios. Finally, process intensification strategies were developed through absorption column modelling to improve algae cultivation efficiency and minimize CO_2 leakage.
These continuous assessments reduced environmental impacts by 5.97 kg CO_2 eq per kg of algae biomass, corresponding to approximately a 430-fold reduction. This was further reduced to 4.2 kg CO_2 eq per kg of biomass when CO_2 fixation was included. Additionally, absorption column modelling improved the efficiency of CO_2 fixation, further enhancing the sustainability of the cultivation system.

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4.01.A.T04 Fair Comparison of the Environmental Performance of Biosurfactants and Fossil-Based Surfactants Using Life Cycle Assessment

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In order for the UK to shift towards a bioeconomy, defossilisation of the chemicals industry is required. The chemicals industry is the second-largest emitter of greenhouse gases after steel in the UK, accounting for 19% of industrial

emissions (Carbon for Chemicals report). Commodity chemicals with widespread industrial applications, such as surfactants, cannot be decarbonised, however can be produced from renewable feedstocks. Biosurfactants are one such example that are derived from microbial fermentation and have comparable performance in terms of functional properties to their fossil counterparts. Although being bio-based does not automatically grant biosurfactants an overall sustainable label, as emerging technologies bring high costs, lower yields and inefficient processes. In order to provide an evidence basis of the environmental sustainability of biosurfactants, the life cycle assessment (LCA) environmental management tool can be utilised. LCA is internationally regulated by several standards, such as ISO 14044, and the recent European standard EN 18027 provides detailed and transparent guidance to compare fossil and bio-based products on an equivalent basis. Recommendations for environmentally sustainable surfactants can therefore be realised. Existing studies that apply LCA to biosurfactants are not directly comparable due to differing functional units, system boundaries, data availability, LCIA methods and lack equivalent comparison to fossil-based surfactants.
This work aims to compare the environmental performance of sophorolipid biosurfactants to sodium lauryl sulphate (SLS), a fossil-based counterpart that is functionally similar and applied namely in personal care and home care products. The chosen functional unit accounts for the functional properties of surfactants and is defined as 1 L of aqueous surfactant at the critical micelle concentration (CMC), assuming cradle-to-gate system boundaries. A mixture of primary lab data and secondary sources including the Ecoinvent database and literature were used for data collection. When considering the functional unit, sophorolipids demonstrate a greater environmental performance than SLS. This work will form the basis of comparison to other surfactants to help guide the industry towards future environmentally sustainable production. This in turn provides a basis for fair comparison of bio-based and fossil-based products.

4.01.A.T05 An LCA Comparison of Liquid and Dry Bonecake-Based Protein Products: Identifying the Transport Tipping Point

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Background and Purpose
Valorising bonecake from the meat industry offers opportunities to produce high-quality protein ingredients for feed, aquaculture and petfood. Conventional dry protein products require energy-intensive steam injection and drying, while downstream processors often rehydrate the product. A liquid protein alternative has been developed to avoid these steps. This study evaluates the environmental sustainability of producing and transporting a liquid protein product as opposed to a dry protein product, with 50% and 90% protein content as lower and upper bounds in a sensitivity analysis.

Materials and Methods
A comparative life cycle assessment was performed from cradle-to-gate, including upstream resource extraction and transport to a hypothetical customer at 20, 200 or 2000 km. Downstream processing, storage and end-of-life were excluded. Impacts were expressed per ton of protein on a fresh-matter basis. Economic allocation was used to distribute impacts among co-products such as fats, electricity recovery and bone material.

Results and Discussion
The sensitivity analysis shows that the liquid product generally performs better than the lower-bound dry product (50% protein) for most impact categories, except resource use (mineral and metals) and water use. The former is driven mainly by the anitoxidant preservative (AOX), packaging and upstream transport; the latter excludes water use at the customer, which would be higher for the dry product. When compared with the upper-bound dry product (90% protein), the liquid product becomes more impactful in most categories, although it performs better for ionising radiation, climate change, resource use (fossils) photochemical ozone formation and human toxicity (cancer).

Including transport introduces a distance-dependent tipping point. For the lower-bound comparison, this ranges from 700 km to 3692 km for the most relevant impact category; for the upper-bound comparison, from 68 km to 488 km.

Transport is therefore a decisive factor for the liquid product's sustainability.

Conclusions
The liquid protein product is environmentally favourable within the lower-bound scenario but less favourable within the upper-bound scenario. Hotspots include steam, electricity and gas use for the dry product, and steam, packaging and AOX for the liquid product. The liquid product is most sustainable when transported within Western Europe, while dry products become preferable for long-distance transport.

4.01.B - Advancing and Aligning Life Cycle Approaches for Emerging Bio-Based Systems: Lessons from Algae and Beyond

4.01.B.T01 Capturing Spatial Variability in the Life Cycle Assessment of European Seaweed Cultivation

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European seaweed production is growing, driven by increasing demand for bio-based resources in various sectors. While most European seaweed is harvested from wild stocks, a shift toward aquaculture is ongoing due to concerns about the environmental impacts of wild harvest.
Seaweed cultivation is highly heterogenous, differing in, e.g., location, infrastructure design, and growth period. These factors influence environmental conditions such as light, nutrients, or currents, affecting seaweed yield but also material and logistical requirements. Consequently, environmental impacts per unit of seaweed may vary substantially. In addition, data on large scale cultivation are scarce. Existing life cycle assessments (LCA) are based on case studies and pilot systems, limiting their ability to capture heterogeneity and scaling. Lastly, consideration of biogenic carbon and nutrient flows remains a methodological challenge.
This study aims to assess how cultivation system design and location influence the environmental performance of seaweed production in the North Sea using the example of the brown seaweed S. latissima. A LCA following ISO 14044 and applying EF3.1 for impact assessment is conducted across ten scenarios, supported by seaweed growth model data. The model provides spatially explicit estimates of biomass yield as well as carbon and nutrient uptake. Using spatial analysis, potential cultivation sites are selected according to yield and additional suitability criteria (e.g., depth, distance from shore, temperature, wave exposure, current speed). For these sites, cultivation system designs are defined based on environmental conditions (e.g. depth and current), and corresponding life cycle inventories are developed.
The study hypothesises that environmental impacts per unit of seaweed biomass are location-dependent. Offshore systems, for example, may require more robust infrastructure than nearshore systems, due to greater depths and hydrodynamic forces, increasing material demand and impacts. At the same time, offshore locations may enable larger-scale operations, reducing impacts through economies of scale.
The findings will provide insights into trade-offs between location, system design, and environmental performance, supporting decision-making in the European seaweed sector. Results can guide site selection and design, while contributing to methodological advances in life cycle assessment through improved representation of carbon and nutrient flows.

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4.01.B.T02 Social Life Cycle Assessment of Circular Bioeconomy Business Models: Cross-Case Insights from the C4B Project

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The development of a circular bioeconomy increasingly depends on biomass valorisation pathways that are

environmentally sound, economically viable, as well as socially acceptable. While social impacts are widely recognised as critical for the uptake and legitimacy of bio-based solutions, they are still rarely assessed in a systematic and comparable manner across different technologies, scales, and business model configurations.

This contribution presents consolidated results from social impact assessment work conducted within the C4B project, embedded in a holistic sustainability framework that also considers environmental, economic, technical, and fairness related dimensions. The analysis covers nine bioeconomy business models based on agricultural, forestry, food processing, and wetland biomass, assessed at different scales and contextual settings across Europe. Most of the assessed business models are conceptual or pre implementation cases, with the objective of exploring potential sustainability implications rather than performing direct performance comparisons.

Social Life Cycle Assessment was applied at the business model level using PSILCA as the primary database, complemented by targeted literature analysis and qualitative comparison with earlier case specific findings derived from surveys, SDG contribution analysis, and the Social Hotspot Database screening.Results point to a consistent set of socially relevant issues along biomass based value chains, particularly related to occupational health and safety, fair wages, employment stability, working hours, and local economic effects. Upstream biomass supply stages emerge as socially relevant where they are directly linked to economic value creation, while in cases using residual biomass their contribution is limited to transport and logistics. Conversion and downstream stages show more technology and scale dependent social profiles.

Overall, the study illustrates how Social Life Cycle Assessment can inform broader sustainability considerations in the design and assessment of bio based business models. By highlighting key social indicators and structural drivers of social performance across diverse valorisation pathways, the findings provide decision relevant insights for researchers and practitioners seeking to support the development and implementation of more robust and socially responsible bio-based systems.

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4.01.B.T03 Early Stage Life Cycle Sustainability Assessment of Fuel Production from a Flexible Feedstock System

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Algae-based and waste-derived biomass systems are gaining traction as contributors to Europe's advanced biofuel sector. The FLEXBY project is developing a conversion pathway based on microwave-assisted pyrolysis and hydrogen-free hydrodeoxygenation (HDO) to produce advanced biofuel, electricity, and biochar from two waste feedstocks: microalgae cultivated in municipal wastewater (with partial wastewater treatment) and dairy-derived oily sludge. This study presents the early stage Life Cycle Sustainability Assessment (LCSA), including environmental LCA (eLCA),life cycle costing (LCC) and social LCA (sLCA), built on a combination of expert estimates, process simulation data, literature research, as well as primary data concerning the algae biomass.

The eLCA follows ISO 14040/44 standards and applies a cradle-to-gate scope. The sLCA follows the UNEP-SETAC 2020 guidelines and applies a hotspot screening approach covering some relevant stakeholder groups. Social LCA databases to fill data gaps. A life cycle costing (LCC) was conducted in parallel, capturing capital and operational expenditures.

eLCA results for the cradle-to-gate process using microalgae show key environmental hotspots are energy required for algae production and drying, pyrolysis, and HDO and for dairy sludge the impacts are focused on pyrolsis and HDO.

The sLCA hotspot screening identifies the pyrolysis and upgrading stages as the poetntial contributors to social risk, with upstream supply chain processes also flagging relevant indicators depending on machinery origins. LCC results confirm that pyrolysis, particularly its energy requirements and capital cost, and HDO raw materials (primarily catalysts) are the main economic hotspots, with feedstock costs varying significantly depending on whether dairy sludge or microalgae is applied as a feedstock)with or without wastewater treatment)

These findings identify some optimization areas for higher TRL levels, such as energy recovery integration, use of renewable electricity supply, improving the microalgae growth, and water reuse within the HDO stage. Conducting and aligning the LCSA from early project stages proves valuable for guiding technology development proactively. The FLEXBY LCSA case study illustrates the methodological challenges and practical approaches involved in performing an LCSA for multifunctional, data-scarce bio-based systems, offering transferable insights for the wider algae and bio-based LCA community.

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4.01.B.T04 Towards Integrated Life Cycle Sustainability and Circularity Assessment for Emerging Aquaculture Systems: Insights from INNOAQUA

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Life cycle assessment (LCA) is a key tool for evaluating the environmental performance of bio-based systems, yet important challenges remain in emerging aquaculture systems characterised by early-stage technologies, multifunctionality, and complex valorisation pathways. In parallel, circularity assessment is gaining relevance, but its integration within life cycle–based sustainability frameworks is not well established.

This work presents the methodological framework developed in the INNOAQUA project to advance the integration of circularity into Life Cycle Sustainability Assessment (LCSA) for aquaculture systems. The approach supports consistent and decision-relevant sustainability evaluation across multiple innovations, including algae-based ingredients, fish by-product valorisation routes, and bio-based products.

The methodology is structured around a dual-level assessment. At ingredient and product level, a four-step framework is applied: system structuring through harmonised Value Stream Maps, circularity assessment based on water recirculation, waste minimisation, waste valorisation and material circularity indicators, environmental assessment using LCA, and integration of sustainability and circularity dimensions. At project level, environmental impacts are assessed through scenario-based aggregation of life cycle results, while circularity is evaluated through a portfolio-based interpretation, reflecting its non-additive nature.

The framework highlights key methodological challenges in aligning circularity with life cycle–based sustainability assessment. Circularity indicators describe intrinsic system properties that do not scale linearly and cannot be directly aggregated, limiting their integration into conventional LCSA approaches. In addition, trade-offs between circularity strategies and environmental performance may arise, particularly in processes requiring increased energy or processing intensity.

These findings support positioning circularity as a complementary dimension within LCSA rather than a directly aggregable metric. The INNOAQUA framework contributes to efforts to harmonise life cycle approaches for emerging bio-based systems by providing a structured and scalable methodology. The insights generated are transferable to other aquatic and bio-based value chains, supporting more robust and decision-relevant sustainability evaluations.

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4.01.B.T05 LCA of Novel Microalgal Production and Biorefinery Technologies: Insights from a Multi-EU-Project Workshop

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This work presents the outcomes of a multi-project workshop on the Life Cycle Assessment (LCA) of microalgae cultivation and biorefineries. The workshop will be held in early October 2026 as part of the Clustering activities of the CBE-JU EU funded research projects MULTIPLY, CleanAlgae2Value, and ALLIANCE.
The goal of this joint initiative is to enable the project participants to gain more awareness of the challenges in conducting LCA of microalgae-derived products. Additionally, the workshop will allow to better understand the differences in LCA approaches applied in the three projects and thus facilitate the comparison between their respective results. The workshop is not directly aimed at LCA harmonization, intended as defining a set of common procedures and methods for the LCA application in the different projects. However, the workshop might indirectly lead to some degree of LCA harmonization as the insights gained in the workshop might be reflected in how the LCA is carried out in the three projects.
The workshop will focus on the following topics:
(1) carbon accounting and system boundary definitions in bio based production systems, with a specific focus on microalgae production; (2) modelling of multifunctional biorefinery systems, in particular microalgae based biorefineries; (3) modelling upscaled versions of currently pilot scale microalgae production and biorefinery processes; (4) Benchmarking of microalgae-derived biobased products with incumbent products on the market that have equivalent functionality.
The workshop will combine presentations by LCA experts with structured discussions on these topics. At the SETAC conference, the main outcomes form the workshop will be presented, including the key highlights from the discussions, the joint recommendations, and the specific decisions and follow-up actions taken by the participants. The expectation is that the findings of the workshop will be useful for LCA practitioners working with algal biomass, bio-based products, and emerging technologies for the bioeconomy in a broader sense.

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4.01.P - Advancing and Aligning Life Cycle Approaches for Emerging Bio-Based Systems: Lessons from Algae and Beyond

4.01.P-Tu047 Advancing Algae LCAs through Harmonization: Insights from a Community of Practice on

Challenges, Needs, and Future Directions

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The blue bioeconomy is growing rapidly, with algae promoted as a resource delivering products with lower environmental impacts than existing ones while providing ecosystem services. To fulfill this promise, innovations in algae cultivation and processing must be assessed in ways both comprehensive and comparable. LCA has become the main tool, especially within EU-funded projects and frameworks such as the Green Claims Directive and European Green Deal. Yet algae LCAs face familiar challenges: results are difficult to compare because studies fix functional units, allocation methods, or impact categories in ways that limit reinterpretation across cases. No single functional unit serves all contexts: per hectare for marine spatial planning, per kg product or per MJ energy for industrial assessments, and per nutrient removed for ecosystem service evaluations. We therefore emphasize providing results in relational terms, enabling functional units to be interchanged according to stakeholder needs.

This paper brings together insights from a community of algae LCA practitioners meeting through roundtable discussions. We identify pressing methodological challenges, from data and inventory gaps to uncertainty in handling biogenic carbon, nutrient fluxes, and scaling effects for technologies at low TRL. At the same time, we highlight key practitioner needs: agreement on core methodological principles, alignment with the PEF approach, and gradual integration of marine-specific impact categories.

Building on these discussions, we propose a methodological blueprint, not as a rigid standard but as a practical guide for current algae LCAs. We recommend structuring datasets to enable interchangeable functional units (per ha, per kg, per nutrient removed), alongside pragmatic allocation hierarchies, common reference datasets, and systematic sensitivity analysis. This relational approach enhances transparency while making LCAs more useful for diverse stakeholders, and supports gradual integration of marine-specific impact categories, from fate-based eutrophication midpoints to endpoint indicators such as biodiversity and ecosystem services. Looking ahead, future work should address the dynamic nature of marine systems, reflect the multifunctionality of algae across value chains, and account for trade-offs between ecosystem use and protection. These perspectives are essential to capture algae's potential in climate mitigation and food security.

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4.01.P-Tu048 Defining Baseline Scenarios for Agro-Industrial Side-Streams: A Life Cycle Assessment of Potato Processing Residues

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The valorisation of agro-industrial side streams is widely promoted within circular bioeconomy strategies; however, its sustainability is often assessed without a consistent definition of baseline scenarios. This can lead to biased conclusions regarding the environmental benefits of alternative valorisation pathways.
This study aims to establish a robust baseline for the life cycle assessment (LCA) of potato processing residues, based on realistic management practices identified in the literature. The analysis focuses on representative end-of-life scenarios for potato side streams: landfill disposal and use as animal feed. These baselines will be used in a posterior analysis. These baseline figures will be used in a subsequent analysis that incorporates the recovery of this waste into the biorefinery concept
A cradle-to-grave LCA approach is applied following ISO 14040/44 standards. The system includes upstream agricultural production, processing stages, and the final management of side streams. Inventory data for the baseline scenarios are derived from literature sources, and data obtained from the case study of a potato industry, ensuring

representativeness and comparability across different management options.
The results highlight significant differences in environmental performance depending on the selected baseline scenario. Landfill disposal is associated with higher environmental burdens, particularly in terms of greenhouse gas emissions, while animal feed pathways show potential benefits through energy recovery and substitution effects. However, these benefits are highly dependent on system assumptions, allocation choices, and local conditions.
The study demonstrates that the definition of baseline scenarios plays a critical role in the assessment of circular strategies and can significantly influence the perceived sustainability of valorisation pathways. Establishing transparent and consistent baselines is therefore essential to support robust decision-making in agro-industrial systems and to avoid misleading conclusions in circular bioeconomy assessments.

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4.01.P-Tu049 Environmental Assessment of Natural Pigment Production: A PRISMA Review of Technological Hotspots and LCA Gaps Across Biological Systems

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Growing regulatory and sustainability pressures are accelerating the shift from synthetic dyes to bio-based pigments. However, their environmental performance remains difficult to assess due to fragmented evidence and inconsistent methodological choices. This study identifies technological hotspots and key methodological gaps affecting environmental sustainability assessments of natural pigments across biological systems.
A systematic review following PRISMA guidelines analysis was conducted on 59 peer-reviewed studies published between 2005 and 2025. The dataset covers pigments from plant-based, microalgae, fungi and bacteria, including technological mapping and Life Cycle Assessment (LCA) or LCA-relevant inventory data.
Technological mapping shows that pigment localization drives downstream processing intensity. Solvent extraction remains dominant but is associated with high solvent use, long extraction times, and energy demand. Emerging techniques such as ultrasound-assisted extraction and pulsed electric fields show potential but lack consistent environmental evaluation. Microalgal systems often require energy-intensive cell disruption, whereas most fungal and bacterial systems remain at laboratory scale, reflecting lower technological maturity.
Only 11% of reviewed studies applied LCA or reported usable inventory data, exhibiting substantial variability in functional units, system boundaries, and data sources. Half of all LCA studies (45.45%) focus on microalgae, particularly Haematococcus pluvialis, while bacteria and fungi represent 9.09%. Plant-based pigments account for 18.18% and synthetic pigments for 27.27%. Across the broader literature, carotenoids dominate applications in food and feed.
The LCA analysis highlights inconsistent boundaries, allocation rules, and frequent omission of upstream processes such as cultivation energy, solvent recovery, and co-product handling. For microalgal astaxanthin, reported lab-scale GWP values range from 81 to 87 g CO_2 eq per g pigment, with cultivation and electricity driving more than half of total impacts. Residual biomass valorization is rarely considered despite its relevance for circularity.
Overall, current studies are difficult to compare and risk leading to misleading conclusions. Harmonized methodological choices, improved reporting, and integration of biological characteristics into LCA are essential to strengthen the robustness and comparability of environmental assessments of natural pigments.

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4.01.P-Tu050 Integrating Life Cycle Assessment into Eco-Design: A Real World Case Study on Bio-Based Composites

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Bio-based composites are increasingly promoted as sustainable alternatives to technical composites derived from non-renewable resources. However, increasing bio-based content does not automatically guarantee environmental benefits, since these must often be actively achieved through informed design choices. Applying life cycle assessment (LCA) during the early design stages is therefore critical to steer innovation towards genuine reductions in environmental impacts.
This contribution presents a real-world case study of integrating LCA into eco-design practice within the Horizon SSUCHY-Next project, which aims to develop sustainable and circular high-performance bio-based composites. Rather than applying LCA as a retrospective evaluation tool, the methodology was explicitly adapted to support designers across the supply chain, enabling informed design decision-making.
An iterative LCA framework was developed, inspired by the Safe and Sustainable by Design (SSbD) approach, to align assessment goals, methodological choices, and interpretation methods with the needs of different actors along the value chain. These include resin developers at laboratory scale and composite designers for wind turbine blade applications. Particular attention was given to tailoring assessment goals and interpretation analyses to the maturity of the technology and the specific decision context, thereby enabling actionable eco-design recommendations and prioritisation of redesign efforts.
Results from the first iteration of the assessment are presented, including the identification of environmental hotspots in fossil-based benchmark products and the evaluation of the sustainability potential of new bio-based designs. These results are actively used to guide subsequent material development and will serve as a reference for tracking sustainability improvements as the project progresses.
By demonstrating how LCA can be adapted and embedded into innovation workflows, this work provides practical insights for LCA practitioners seeking to apply the method in the context of materials design and to promote meaningful sustainable design changes.

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4.01.P-Tu051 Prospective Life Cycle Assessment of Bio-Based Products at Early Development Stages: Methodological Framework and Application

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Biobased products are thought to be environmentally friendly, but this must be supported by environmental quantification method such as life cycle assessment (LCA). LCA helps in quantifying environmental impacts across the life cycle of the product and its major drivers.
Identifying environmental hotspots in the early stages (lower Technology Readiness Levels, TRL) of product development can help select alternatives with lower impacts. As developers have more freedom to change different products and processes to more sustainable alternatives, at this stage.
Conducting a prospective LCA of low-TRL products faces challenges due to data gaps, as production processes for many bio-based materials are still under development and evolve over time. Moreover, identifying the environmental impacts of a product to be manufactured in the future presents challenges, including uncertainty regarding technology adoption and development, future transport and energy mixes, and policy mandates.
Previous works in LCA focus on data upscaling and generic guidelines for emerging technologies. This work aims to

introduce a methodology specific for conducting a prospective LCA of low TRL biobased products. That incorporates data upscaling and scenario analysis using future climate background inventories derived from Integrated Assessment Models (IAMs). Sensitivity and uncertainty analyses are employed to identify drivers of environmental impacts and assess the quality of the results.
The methodology is applied to a low TRL mycelium-based insulation panel. Preliminary results show that the methodology enables identification of environmental hotspots at lab scale are predominately in electricity use and packaging used. Which can be improved in the industrial-scale production through efficient continuous production and economies of scale. Furthermore, methodological insights and challenges encountered in implementing the framework in the case study will be shared and discussed.

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4.01.P-Tu052 Early-stage life cycle assessment of cellulose modification with itaconic acid: decision support for process design

Brener Gomes[1], Rickard Arvidsson[1] and Magdalena Svanström[1] (1)Chalmers University of Technology

Bio-based products are often assumed to be environmentally preferable, although renewable origin alone does not guarantee lower impacts. For emerging bio-based technologies, life cycle assessment (LCA) can therefore play an important role in identifying hotspots early and supporting process design before scale-up. One highly relevant field in this context is the chemical modification of kraft pulp fibers for tailored applications. Kraft pulp is a commercially available and widely used source of cellulose that can be modified to obtain desired properties for a broad range of applications, such as tissues, packaging, and high-quality or specialty papers. Among emerging bio-based modification agents, itaconic acid (IA) has been identified by the US Department of Energy as a promising sugar-based platform chemical with high potential for conversion into value-added products. In this study, LCA is applied as a decision-support tool to compare two laboratory-scale methods for kraft pulp modification with IA, namely gas-phase and kneading routes, and to assess whether IA represents a lower-impact alternative to the commercially available benchmark modifier citric acid. The goals are to identify environmental hotspots, reveal route-specific trade-offs, and assess which option shows greater potential for further process development. A cradle-to-gate approach is adopted, using 10 g of modified pulp as the functional unit. The assessment covers the main process steps required for cellulose modification at laboratory scale. Environmental impacts are evaluated using selected ReCiPe midpoint indicators, including climate change, acidification, eutrophication, and photochemical ozone formation, complemented by the AWARE method for water scarcity. The inventory is based on primary process data provided by experimental researchers, combined with background datasets from Ecoinvent. The results are expected to clarify the environmental trade-offs between the two modification routes and indicate whether IA is an environmentally preferable alternative to citric acid for cellulose modification, discussing also how the material properties that can be achieved and intended application might influence the decision. By comparing modification agents and processing routes, the study aims to support environmentally informed technology development, provide feedback for process optimization, and demonstrate how LCA can guide integrated R&D for emerging cellulose modification processes.

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4.01.P-Tu053 How important is catalyst stability for the environmental performance of bio-derived ethanol-to-

1,3-butadiene conversion?

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The use of bio-derived ethanol as a renewable feedstock for producing platform chemicals offers a compelling pathway to reduce emissions in the chemical sector. One example of a bio-based platform chemical with the potential to contribute to this transition is bio-derived 1,3-butadiene (BD), as it could displace its fossil-derived counterpart in the production of styrene–butadiene rubber (SBR) - an industrially important polymer with applications across a diverse range of products, including automotive tyres.

However, although the technical feasibility of bio-derived BD production via bioethanol-to-BD conversion has been extensively demonstrated, there have been limited studies assessing the environmental footprint of this process. In particular, no life cycle assessment (LCA) studies have systematically accounted for the impact of catalyst deactivation - a critical factor influencing process efficiency, resource use, and emissions.

This poster presentation showcases key findings from three cradle-to-gate life cycle assessment models investigating the impact of Au/MgO–SiO_2 catalyst stability on the environmental footprint of bio-derived BD. The models were developed using ecoinvent 3.11 in openLCA, and impacts were quantified using the ReCiPe Midpoint (H) methodology. This work presents a critical and quantitative comparison between the common assumption of no catalyst deactivation and more realistic scenarios in which catalyst activity decay is considered, alongside the impacts of catalyst recycling via regeneration or replacement. The poster also highlights the need for further research to improve the environmental modelling of this system.

4.01.P-Tu054 Prospective life cycle assessment of agro-industrial waste-based panels

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Agro-industrial waste-based panels have emerged as a promising alternative to conventional wood-based panels. Rice husk (RH) has shown promise as a secondary material, and previous studies have investigated its physical and mechanical properties; however, no studies have assessed its potential environmental benefits, given its low Technology Readiness Level (TRL). A prospective cradle-to-grave life cycle assessment (pLCA) of the RH panel is conducted at an early development stage to estimate its potential environmental impacts at an industrial scale and is compared with conventional wood-based panels produced in Portugal.

To perform this study, first, laboratory-scale data are scaled up to the industrial scale. At the industrial scale, a scenario analysis is performed considering alternative binders (Methylene diphenyl diisocyanate, Maize starch, and Urea-formaldehyde) and energy sources (biomass, natural gas, LPG, and electricity) for the RH panel production stage, assuming manufacturing occurs in 2030. A 20-year lifespan was considered, along with various end-of-life scenarios, including landfill disposal, incineration with energy recovery, and reuse. The Activity Browser software is used to conduct the pLCA, which allows the use of prospective life cycle inventory databases. Future background data for the life cycle inventory were generated using the premise's Integrated Assessment Model (IAM), IMAGE (Integrated Model to Assess the Global Environment), for the SSP2-M future climate scenario.

The prospective assessment is expected to show reduced environmental impacts for the RH panel during the manufacturing phase because the panel's production involves fewer stages than the wood panel (e.g., the digestion process), but trade-offs may arise from alternative binders and energy sources. The study supports not just quantifying impacts but also providing forward-looking insights into how a novel product might perform under future conditions and where its main advantages or limitations lie.

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4.01.P-Tu055 Bridging the Scale Gap: A Regional Life Cycle Assessment of Industrial Seaweed Production in China to Inform Global Upscaling Strategies

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'Seaweed is increasingly recognised as a key component of sustainable food systems and a potential blue carbon sink. China accounts for approximately 65% of global seaweed production, with highly mature systems spanning hatchery, farming, and diversified processing pathways. However, robust understanding of the environmental performance of industrial-scale seaweed systems—spanning hundreds to millions of tonnes of biomass—remains limited. These large-scale operations represent a critical but underexplored case for informing international upscaling efforts.

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This study addresses this gap through a cradle-to-gate attributional LCA of seaweed production in Putian, Fujian Province—one of China's largest producing regions. Adopting a system-level perspective, the study covers hatchery operations, offshore cultivation, and multiple processing routes. The analysis is supported by extensive field engagement, providing both quantitative inventory data and qualitative insights into operational practices and decision-making.

Preliminary results show that environmental impacts are shaped not only by processing technologies but also by system-level dynamics. Drying generally has higher energy demand than salting, while freezing emissions are highly sensitive to storage duration, driven by market demand. Direct transfer to downstream processing, avoiding prolonged storage, can significantly reduce energy use. Supply–demand imbalances further influence processing choices and resource use.

These findings suggest that environmental performance in large-scale seaweed systems cannot be understood through technical parameters alone, but must also consider market conditions, logistics, and temporal variability. This study provides a real-world case of industrial-scale production, advancing LCA approaches for emerging bio-based systems and offering actionable insights for global seaweed upscaling.

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4.01.P-Tu056 Life cycle assessment of a biorefinery based on waste biomass derived from piggery wastewater

treatment photobioreactors.

Bárbara Muñoz Madariaga[1], Rubén Irusta Mata[1], Raquel Lebrero Fernández[1] and Silvia Bolado Rodríguez[1] (1)University of Valladolid

In recent years, the expansion of the pig industry has led to a significant increase in wastewater generation, characterised by high nitrogen concentrations that may cause environmental impacts such as soil acidification and eutrophication. This challenge can be reframed as an opportunity by using this waste stream as a feedstock in a biorefinery approach to produce high value bioproducts.

This study evaluates the environmental impact of a biorefinery based on the microalgae-bacteria biomass generated in piggery wastewater treatment systems. Three products were assessed: peptides, polyhydroxyalkanoates, specifically polyhydroxybutyrate (PHB), and biochar as by-product of PHB production. The main process lines were biomass conditioning, and production, purification and drying stages for each product. The assessment was performed utilising SimaPro and the ReCiPe 2016 Midpoint (H) method.

Results indicate that biomass conditioning contributes with a 70% to the category of marine eutrophication, which is related to the centrifugation for the concentration of the biomass[SB1.1]. Among the bioproducts, the peptide production pathway shows the lowest environmental impact, largely due to internal reuse of process stream. Despite its efficiency in nutrient recovery, acid hydrolysis contributes significantly to environmental consequences due to the utilisation of hydrochloric acid and the necessity for a subsequent neutralisation of the stream. The highest impact of the proposed biorefinery is for the PHB production, making it the main hotspot reaching up to 80% in most of the impact categories, because of the use of chemicals for the neutralisation of the culture medium and the energy required for bioreactor heating.

Although the proposed biorefinery is technically feasible, the results highlight important environmental challenges. Optimisation of chemical use and energy demand, particularly in PHB production, is required to improve the sustainability of waste biomass valorisation pathways.

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4.01.P-Tu057 Life Cycle Assessment (LCA) of Micro and Macroalgae Productions: Approaches and Challenges at LOCALITY Project

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LOCALITY (HORIZON-MISS-2022-OCEAN-01 – ID: 101112884) pioneers sustainable industrial wastewater

management by integrating nutrient recirculation into a carbon-neutral circular economy. By implementing local algae value chains, utilising microalgae in photobioreactors (PBRs) and offshore seaweed in the North and Baltic Seas, the project bridges the gap between waste-producing industries (food, agriculture, aquaculture, and textiles) and sustainable biomass production. To evaluate the environmental viability of these ecosystems, this project employs Life Cycle Assessment (LCA) in accordance with ISO 14040/44 standards.
Although LCA is a recognised methodology, its application in the blue economy, especially in the algae sector, faces unique hurdles. The variability in cultivation and processing techniques, emerging technologies, and regional differences are some examples. There is also the complexity of open-ocean interactions in the offshore cases. Furthermore, the scarcity of representative algae-specific data in databases and literature limits the development of reliable inventory datasets.
This work evaluates the methodological approaches and challenges of applying LCA within the LOCALITY framework by assessing two distinct cultivation routes (PBR-based microalgae and offshore seaweed) and their subsequent product applications, such as biorefinery extractions and agricultural biostimulants. The assessment was performed using OpenLCA and Ecoinvent 3.11. Technical challenges remain concerning characterisation factors and impact assessment methodologies, as they are not always tailored to the specificities of the bio-based sector, particularly regarding biogenic carbon accounting and the integration of natural credits.
Preliminary results emphasise the necessity of alignment among LCA practitioners to harmonise data collection and enhance transparency, consistency, and comparability. This is essential to translate environmental assessments into actionable insights for decision-makers in the evolving algae sector.

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4.01.P-Tu058 Environmental Assessment of an Industrial Scale Spirulina Cultivation and Biorefinery Process

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Microalgae biomass holds a great potential to become the reference source of sustainable ingredients for a broad range of bio-based industries. However, the sustainability of microalgae cultivation and processing at industrial scale still needs to be further demonstrated. At the same time, the methodological approaches for assessing sustainability performance in bio-based systems still need to be improved and harmonized.
In this study, the environmental impact of an industrial microalgae cultivation and biorefinery unit, aiming at the production of phycocyanin and at the valorization of the spent biomass, both for food applications, is assessed. The environmental performance of the derived algal products is evaluated using a life cycle assessment (LCA) approach. This work builds upon a previously developed modelling framework, wich is based on detailed process data, including energy and material requirements across the entire production process. A range of methods and tools are applied, including prospective background modelling and biogenic carbon accounting.
The insights obtained are intended to support investment and operational decision-making through the identification and implementation of lower-impact alternatives in both cultivation and downstream processing. For such, a baseline scenario is compared with alternative ones, aiming at evaluating potential performance improvements. The preliminary finding highlight Spirulina biomass as a sustainable alternative for an industrial scale production, and further biorefinery processing operations. A full macro-level assessment of substitution effects is ongoing.

4.01.P-Tu059 Climate Change Impacts of Biochar Production from Macrocystis pyrifera: A Life Cycle Assessment in Chile

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Biochar production from marine biomass has emerged as a promising strategy for climate change mitigation due to its potential for long-term carbon sequestration in soils. In this context, this study assesses the climate change impacts of biochar production from Macrocystis pyrifera using a life cycle assessment (LCA) approach, with the aim of evaluating its potential as a long-term carbon storage strategy.
The assessment was conducted in accordance with ISO 14040 and ISO 14044. The functional unit was defined as 1 kg of biochar produced, considering a cradle-to-soil system boundary that included sporophyll collection, sporulation, macroalgae cultivation, biochar production via pyrolysis, and soil application. Two cultivation systems located in Bahía Inglesa (Atacama Region) and Faro Corona (Los Lagos Region), Chile, were analysed. Modelling was performed using SimaPro 9.6.0.1 with Ecoinvent v3 and the IPCC 2021 GWP100 V1.03 method. In addition, alternative scenarios were evaluated, including different biomass drying technologies, energy sources, and the use of recycled materials in cultivation infrastructure.
The results show significant differences between cultivation systems and technological scenarios. In the baseline scenario, the production and application of 1 kg of biochar resulted in emissions of 2.22 kg CO_2-eq in Bahía Inglesa and 0.17 kg CO_2-eq in Faro Corona. Key environmental hotspots include energy consumption during biomass drying and material use in cultivation infrastructure, particularly polypropylene ropes. The use of renewable energy for drying, especially wind energy, and the incorporation of recycled materials significantly reduced impacts, achieving net-negative emissions of up to -1.52 kg CO_2-eq per kg of biochar in Faro Corona.
In conclusion, biochar production from Macrocystis pyrifera has the potential to become an effective carbon sequestration strategy. However, its environmental performance strongly depends on the optimisation of key system parameters, particularly drying processes, energy sources, and material use in cultivation systems.

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4.01.P-Tu060 Enhancing the Circular Bioeconomy: Life Cycle Assessment of Industrial Microalgae Production in a Closed-Loop Recycling Culture Medium System

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The versatility of microalgae as a feedstock for different valuable bioproducts, together with their ability to grow on a wide variety of cultivation conditions, offers a promising pathway for the transition toward a circular bioeconomy. However, scaling up these biological processes to an industrial level demands a rigorous evaluation of their environmental performance to ensure that commercial viability aligns with ecological sustainability. This study presents a comprehensive Life Cycle Assessment (LCA) based on primary data collected from the demonstration scale land-based cultivation facility of the Instituto Tecnológico de Canarias (ITC) in Pozo Izquierdo, Gran Canaria. The research was conducted within the framework of the EU-funded project ATL.A.HUB (Atlantic Hubs to boost Marine Algae Land-based Aquaculture and Biotechnology). Hubs aim to promote best practices for minimizing resource use and emissions in algae production. In this context, a key strategy fostered by the hubs is the closed-loop recycling of the culture medium after biomass harvesting, which significantly enhances the resource efficiency of the process. The production of dry biomass powder of two different microalgae, Limnospira platensis (Spirulina) and Tetraselmis striata, was analyzed. The analysis of environmental impacts was carried out using SimaPro software and Ecoinvent database. The functional unit was defined as 1 kg of dry biomass, adopting a cradle-to-gate system boundary. In addition to the environmental assessment, a Life Cycle Costing (LCC) was performed to evaluate economic feasibility of the process under realistic operational conditions and to provide a more comprehensive sustainability perspective.

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(EMFAF).

4.01.P-Tu061 From Biomass to Products: A Gate-to-Gate Life Cycle Assessment of Seaweed Processing Pathways for Industrial Decision-Making

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Seaweed is increasingly recognised as a sustainable biomass for food and bio-based applications. While life cycle assessment (LCA) studies have primarily focused on cradle-to-gate or cradle-to-grave systems, the environmental impacts of downstream processing remain difficult to isolate due to variability in cultivation conditions. This limits the ability of industry stakeholders to make informed decisions regarding processing strategies.

This study presents an exploratory gate-to-gate LCA of brown seaweed (Saccharina latissima) processing, focusing exclusively on post-harvest stabilization pathways. To our knowledge, this is among the first studies to systematically assess and compare multiple seaweed processing techniques within a consistent system boundary, providing a process-level perspective independent of upstream variability. The goal is to offer an industry-relevant framework linking processing choices to environmental performance, resource use, and product outcomes.

The assessment uses a functional unit of 1 kg fresh biomass and evaluates a range of conventional and emerging processing methods, including drying, freeze-drying, blanching, pulsed electric field (PEF), brining, fermentation, ensiling, and dry salting. Life cycle inventory data were collected from laboratory experiment, aided with literature. Environmental impacts are analysed alongside key resource inputs such as energy, water, and material use.

Results indicate that processing choices lead to substantial variation in environmental performance. Dewatering methods, particularly drying, show high energy demand due to moisture removal, while processes involving high water and salt inputs exhibit elevated impacts related to wastewater treatment and eutrophication. Equipment capacity and operational scale significantly influence results, highlighting the importance of technological configuration. Furthermore, different processing pathways produce biomass with distinct quality characteristics, suggesting trade-offs between environmental performance and product functionality.

By isolating processing stages, this study provides a comparative “technology map” for seaweed stabilization, supporting industry stakeholders in selecting processing pathways based on both environmental and product considerations. The findings contribute to advancing LCA applications in emerging bio-based systems and offer a practical foundation for optimizing seaweed value chains.

4.01.P-Tu062 Life Cycle Assessment of Waste Biomass Derived Extracts in Photo-Fenton Wastewater Treatment: Dominance of Operational Energy over Material Synthesis

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Background and Purpose:

Waste biomass derived extracts are used as functional materials in Photo-Fenton processes for wastewater treatment, as their organic components can enhance Fe(III)/Fe(II) redox cycling and promote reactive species generation. This study applies Life Cycle Assessment (LCA) to quantify environmental impacts with emphasis on the relative contribution of extract synthesis and process application, focusing on materials derived from seagrass, grape bagasse and onion peel.

Methods:

The LCA was conducted following ISO 14040/44 standards. Primary experimental data were used to construct a Life Cycle Inventory covering extraction and application stages, with background processes modelled using the Ecoinvent database. Modelling was performed in SimaPro software. Extracts were produced via alkaline treatment and applied in Photo-Fenton degradation of a mixture of emerging contaminants under simulated solar irradiation. The functional unit was defined as the treatment of 1 litre of wastewater. Environmental impacts were assessed using the Environmental Footprint 3.1 impact assessment method, focusing on climate change and energy demand. Contribution and sensitivity analyses were performed to quantify the relative importance of synthesis and operational stages.

Results:
High removal efficiencies were achieved under the tested conditions. Electricity consumption during the Photo-Fenton process was the dominant contributor to environmental impacts, accounting for more than 90–95% of climate change impacts, while synthesis of the extracts contributed a minor share. Differences between extract types were limited relative to the influence of operational conditions. The carbon intensity of electricity was identified as a key parameter influencing results with consistent trends observed across sensitivity scenarios and electricity mixes.

Conclusions:
Environmental impacts of the assessed system are driven by operational energy demand, while extract synthesis has limited contribution. These findings indicate that improving process energy efficiency is more relevant than modifying synthesis pathways for reducing environmental burdens.

Relevance:
The study provides quantitative evidence to support prioritization of operational optimization in Photo-Fenton systems and demonstrates the role of LCA in distinguishing between synthesis and application driven impacts in wastewater treatment technologies.

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4.01.P-Tu063 Assessing Circular Economy Strategies in Bio-Based Protein Products Through Prospective Life Cycle Assessment (LCA)

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As the transition toward a circular bio-economy accelerates, the sustainability of novel protein sources must be rigorously evaluated beyond conventional metrics. While bio-based alternatives often outperform animal proteins in resource use, their true potential lies in integrating waste streams into production cycles. The system under study relies on two main advantages against traditional protein production: production through microalgae, and the possibility of using atmospheric CO2 as feedstock for microalgae. This study addresses the environmental performance of microalgae utilization compared to conventional protein production, considering the capture of atmospheric CO2.
A prospective cradle-to-gate Life Cycle Assessment (LCA) has been conducted for a theoretical industrial-scale microalgae protein production facility designed to utilize captured CO2 as a primary feedstock. The environmental performance of this system has been compared against pea-based (vegetal) and cow milk-based (animal) proteins. The functional unit of the study has been defined as the production of 1 ton of Microalgae Protein, considering an average of 40% protein content, targeting an annual capacity of 2,290 tons with a co-benefit of capturing 10,000 tons of CO2. Two scenarios have been analyzed: a "linear scheme" excluding CO2 capture and a "circular scheme" including it. Impact categories include climate change, land use, and water consumption.
In the linear scheme, the microalgae protein demonstrates superior performance in land and water use compared to animal protein, driven by the elimination of agricultural grazing and crop cultivation, while climate change impacts

remain comparable to vegetal protein. The inclusion of CO2 capture in the circular scheme scenario modifies the sustainability profile, resulting in a net-negative carbon balance effectively offsetting operational emissions and transforming the system into a carbon sink.
These findings demonstrate that bio-based protein technologies can deliver immediate environmental benefits over traditional sources even at early technology readiness levels. Crucially, the integration of CO2 capture shifts the paradigm from simple substitution to active circularity, where waste carbon becomes a resource, drastically reducing the global warming potential.

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4.01.P-Tu064 Circular Fertiliser Pathways From Biodigested Sugarcane Vinasse: A Nutrient-Equivalent Life Cycle Assessment

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Circular economy approaches are increasingly used to transform agro-industrial side streams into circular value propositions for bio-based systems, linking waste valorisation with resource-efficiency goals. In fertiliser systems, nutrient recovery may reduce dependence on mineral inputs and help manage pressures associated with nitrogen and phosphorus flows; however, circularity alone does not guarantee lower environmental impacts. The objective of this study is to evaluate biodigested sugarcane vinasse as a real-world residue-to-fertiliser pathway and to examine how nutrient-equivalent life cycle framing can support sustainability steering in circular bio-based fertiliser systems.
An attributional cradle-to-gate life cycle assessment (LCA) framework is used to structure the evaluation of a circular fertiliser service. The proposed framing compares plant-available nutrient functions rather than product mass and distinguishes nitrogen-, phosphorus-, and potassium-equivalent services. It also considers how multifunctionality is represented when anaerobic digestion provides both a nutrient carrier and recoverable biogas, and how avoided-burden accounting can affect interpretation. Key issues include functional unit definition, nutrient-substitution modelling, energy recovery, and dilution-driven scaling when evaluating low-concentration nutrient streams.
The assessment highlights that biogas valorisation can strongly influence impact profiles, especially for climate change, non-renewable energy demand, and acidification, while nutrient-related categories such as freshwater eutrophication require separate assessment. These findings underline that circular economy claims for bio-based fertilisers should not rely solely on circularity indicators. Transparent life cycle modelling is needed to connect nutrient functions, co-product management, and environmental trade-offs. This contribution supports proactive sustainability management by demonstrating how life cycle approaches can guide side-stream valorisation, circular agricultural practices, and resource-efficiency decisions in bio-based systems.

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4.01.P-Tu065 Life Cycle Assessment of Urban Tomato Production: Comparison of Conventional, Organic, and Regenerative Systems in Santiago, Chile

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Urban agriculture has emerged as a strategy to enhance food security and reduce the environmental impacts associated with conventional agricultural production. However, quantitative evidence comparing production systems under real urban conditions remains limited. In this context, this study assesses the life-cycle environmental impacts of tomato

production under three urban agriculture systems in Santiago, Chile: conventional, organic, and regenerative.
The assessment was conducted using life cycle assessment in accordance with ISO 14040/44. A cradle-to-gate boundary was applied, including input production, infrastructure, irrigation, crop management, and fruit production. The functional unit was 1 kg of fresh tomatoes. Impact assessment was performed using SimaPro v9.6.0.1 and the ReCiPe 2016 Midpoint (H) method, considering global warming, terrestrial acidification, freshwater and marine eutrophication, ecotoxicity, fossil resource scarcity, and land use. The inventory was based on pilot-scale trials, including six experimental beds under greenhouse and open-field conditions, using the same substrate and potable water irrigation system.
Results indicate that the conventional system had the highest environmental impacts across all categories, whereas organic and regenerative systems achieved reductions of 74% to 98%. For global warming, the conventional system reached 0.55 kg CO_2 eq per kg of tomatoes under greenhouse conditions, while organic and regenerative systems reduced these impacts by 84% to 89%. These reductions are mainly explained by the avoidance of synthetic fertilizers and pesticides, the valorization of organic residues, and higher yields.
Across systems, key hotspots included potable water use, landfill disposal, and agricultural inputs. In the conventional system, synthetic fertilizers and pesticides were the main contributors to global warming, ecotoxicity, and eutrophication. In contrast, organic and regenerative systems showed lower impacts overall, although organic fertilizers and biopreparations contributed to some categories.
In conclusion, organic and regenerative systems demonstrated superior environmental and productive performance compared with conventional agriculture, highlighting their potential to support more sustainable and resilient urban food systems.

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4.01.P-Tu066 Towards an Integrated Life Cycle Sustainability Assessment Framework for Circular Valorisation of Bovine and Ovine Co-products

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Large volumes of bovine and ovine co-products generated by the red meat sector remain underutilised, representing low-value streams that incur management costs. These materials, however, offer significant potential for circular bioeconomy valorisation. Emerging biorefinery technologies can convert non-meat fractions and associated wastewaters into high-value bio-based products, yet their environmental, economic, and social implications are often insufficiently characterised from a life-cycle perspective.
This study systematically reviews existing life cycle assessments (LCA) of livestock co-product valorisation to (1) characterise current sustainability evaluation approaches, (2) identify methodological gaps and inconsistencies, and (3) inform the development of an integrated life cycle sustainability assessment (LCSA) framework. A comprehensive search across major databases (March 2010–December 2025) retrieved 1,206 records; following duplicate removal (n = 308) and multi-stage screening, 28 studies met the inclusion criteria. Results show a strong environmental focus: 71% of studies applied environmental LCA, 17% included life cycle costing (LCC), and only 7% conducted full LCSA. Explicit social assessments were scarce, accounting for just 3%. Considerable heterogeneity in functional units, system boundaries, and co-product allocation methods was observed, with limited methodological transparency. Environmental impact assessment was dominated by global warming potential, promoting a “carbon tunnel vision” that obscures broader sustainability dimensions.
In response, a unified LCSA framework is being developed under the CirCoVal project. The framework introduces standardised goal and scope definitions, recommended environmental indicators, harmonised LCC templates, and a hierarchical set of social indicators aligned with technology readiness levels. This integrated approach supports early scoping and progressive refinement of sustainability analyses, enabling evidence-based design, scaling, and policy decisions to advance the circular red meat bioeconomy.
Keywords: life cycle sustainability assessment; bovine and ovine co-products; circular bioeconomy; valorisation

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4.01.P-Tu067 Additive Manufacturing with Chitin/Chitosan Biopolymers for Biomedical Applications: an LCA Approach

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The application of additive manufacturing (AM) in the production of customised medical devices and advanced tissue-engineering structures significantly increased in the last decade. Bio-based polymer alternatives have been explored also for these applications, with the aim of reducing the environmental burdens associated with conventional fossil-based alternatives. However, the life cycle implications of these emerging solutions remain insufficiently studied, particularly when novel bio-based feedstocks are integrated into established AM processes.
This work presents the preliminary LCA results of biomedical devices (e.g. orthotic thumb immobilizer), produced by binder jetting (BJT) with a bio-based chitin/chitosan binder, and compared to the same device obtained through a conventional Multi Jet Fusion (MJF) approach with polyamide powder. Similarly, life cycle engineering was applied to tissue-engineered scaffolds for organoid culture, obtained through two-photon polymerization (2PP) with chitosan-based biopolymer, and compared to similar AM route with established alternative (e.g. laminin/collagen). Both studies were carried out using the ReCiPe 2016 method and SimaPro Craft software, following a cradle-to-grave approach. Preliminary results point out that chitin-based binder jetting outperforms the polyamide MJF benchmark in climate change, toxicity and fossil resource indicators, although the magnitude of the benefit will depend on process efficiency and post-processing requirements. The chitosan-based 2PP case raises more uncertainties, since the high precision and low throughput of 2PP may shift the environmental burden toward electricity use and process time, making the result highly sensitive to the functional unit and foreground inventory assumptions.

Keywords: Additive manufacturing; Binder jetting; Two-photon polymerization; Chitin; Chitosan; Bio-medical; Life cycle assessment

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4.01.P-Tu068 From Food Waste to Chitosan-Based Films for Sensor Applications: A Scenario-Based Life Cycle Assessment of Upscaled Green Chitosan Extraction Compared to Conventional Routes

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Chitosan is a bio-based polymer obtained from chitin, one of the most abundant renewable resources, widely available in crustacean shell waste. Thanks to its biocompatibility and antimicrobial properties, it is increasingly used in various industrial sectors, contributing to circular economy strategies. However, conventional production relies on energy-intensive processes and harsh chemical treatments (e.g., NaOH and HCl), resulting in significant environmental impacts. In recent years, several alternative extraction approaches have been explored, including fermentation, enzymatic treatments, deep eutectic solvents, and ionic liquid-based processes, often combined with enabling technologies such as microwave-assisted processing. However, these methods remain largely at laboratory scale, and their environmental performance at higher scales is still poorly understood.
This study addresses this gap by assessing the upscaling of a green chitosan extraction process and comparing it with the conventional chemical route through a cradle-to-gate Life Cycle Assessment (LCA). The analysis is performed using the Environmental Footprint 3.1 method, combining secondary data from Ecoinvent with primary experimental

data. The study is framed within a food waste valorization approach, considering the invasive blue crab (Callinectes sapidus) as one of the potential feedstocks, thereby linking resource recovery with ecosystem management in the Mediterranean region.
In a second phase, the extracted chitosan is processed into thin films and evaluated in a real-world application, namely Radio Frequency Identification (RFID) tags, as a bio-based alternative to conventional petrochemical substrates. Such devices are widely used, including in environmental monitoring, where biocompatibility and potential biodegradability are key advantages. The system is benchmarked against traditional materials and configurations, considering different substrate types, antenna designs, and manufacturing processes.
The study aims to identify key environmental trade-offs between the conventional process and an upscaled green chitosan extraction route through scenario analysis, as well as to assess the potential environmental benefits of chitosan-based films compared to petrochemical-based substrates when applied in RFID-based sensors. The findings provide insights to support the transition towards Safe and Sustainable by Design (SSbD) innovations.

4.01.P-Tu069 Urban Leaf Waste Valorisation: LCA of Bio-based Material Pathways

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Fallen leaves, a costly and seasonally important urban green waste, represents an underutilised bio-based side stream with a potential for circular valorisation. Currently, only a minor share of fallen leaves is composted locally, while large volumes are collected and transported to central facilities at a financial cost for communities. Due to contamination with sand and anthropogenic waste, leaves are often unsuitable for composting and are instead dried and used for energy recovery.
In our study based in Rhineland-Palatinate (Germany), we explore the valorisation of this side stream, where urban leaves are transformed into bio-based products that can substitute fossil-based alternatives. Different product alternatives are considered, for which leaves are combined and processed with a bio-based adhesive.
A key challenge lies in the heterogeneous quality of the material, including variations in moisture content and contamination levels. These factors make adaptive processing strategies necessary to ensure a consistent product. Additional challenges are the seasonal availability of the material and the limited availability of suitable processing facilities, which introduces logistical requirements that lead to transport-related emissions.
Life cycle assessment will be used to understand the environmental impacts from cradle to gate. We combine primary and secondary data collection. The analysis will focus on evaluating the environmental impacts of different processing and logistics scenarios.
Our hypothesis is that localised production systems are essential to realise environmental benefits, as transportation impacts may otherwise outweigh gains from material substitution. By quantifying these effects, the study aims to provide insights into the environmental impacts of the side-stream valorisation of urban biomass.
Our research will identify key trade-offs related to material variability and transport, supporting evidence-based decisions. The findings contribute to reducing fossil resource use and strengthening local, resilient value chains. They will offer practical guidance for municipalities and industry stakeholders seeking to implement circular solutions that reduce reliance on fossil-based material.

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4.01.P-Tu070 Sustainability Steering of Bio-Based PFAS-Free Water-Repellent Textiles: LCA Modelling Challenges

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Durable water repellency is essential for many textile applications, yet conventional finishes often rely on per- and polyfluoroalkyl substances (PFAS), raising concerns related to persistence and toxicity. Fluorine-free alternatives are increasingly proposed, but their environmental performance depends strongly on formulation choices, durability, and

end-of-life compatibility.

This study was conducted within the PFAS-FREE project (August 2024–May 2026), which aims to develop innovative PFAS-free water-repellent textiles combining bio-based polymer coatings and surface structuring. The project integrates a Safe and Sustainable by Design (SSbD) approach to guide material and process selection from the earliest development stages.

Within this framework, a comparative cradle-to-grave LCA was performed for a PFAS-based reference and PFAS-free alternatives. Special attention was dedicated to methodological challenges such as (i) inventory modelling of PFAS-based finishes under limited transparency of supply chains, (ii) inventory modelling of intermediates and specialty additives not available in life cycle databases, (iii) PFAS emissions modelling under limited availability of characterization factors in toxicity-related impact categories, and (iv) end-of-life scenarios modelling, where halogen-free formulations may facilitate improved waste treatment and enable future recycling pathways.

Results indicate that PFAS-free PUD-based systems can significantly reduce impacts related to climate change, fossil resource use, and ozone depletion, mainly driven by the avoidance of fluorinated chemistry. However, trade-offs are observed, notably increased land use linked to bio-based feedstock production. Hotspot analysis further highlights the selection of crosslinkers and finishing boosters as key drivers of ecotoxicity-related impacts, while the energy demand of drying and curing operations emerges as a major lever for improving the overall environmental performance of PFAS-free textile finishing.

Overall, this study demonstrates how early-stage LCA can support Safe and Sustainable by Design decision-making by identifying the most influential modelling parameters and eco-design levers for PFAS-free textile finishing technologies, while improving robustness and transparency in comparative assessments.

Disclaimer/Disclosure: This study was conducted within the PFAS-FREE project (August 2024–May 2026), part of the Belgium Builds Back Circular (BBBC) national initiative, funded by the European Union under the NextGenerationEU programme and managed by the Belgian Federal Public Service (FPS) Economy.

4.01.P-Tu071 Life Cycle Assessment of Bio Based PFAS Free Water Repellent Finishes: Polyurethane vs. Non Isocyanate Polyurethane Dispersions

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Per- and polyfluoroalkyl substances (PFAS) possess unique physicochemical properties that have led to their widespread use in numerous applications. In the textile sector, PFAS-based finishing agents have long been considered essential to achieve durable water repellency. However, growing concerns related to their persistence, bioaccumulation, and toxicity have driven strong regulatory pressure and the development of fluorine-free alternatives.

Among fluorine free durable water repellent finishes, polyurethane dispersions (PUDs) are currently among the most widely adopted industrial solutions for textile applications. While PUDs reduce several environmental and health concerns associated with PFAS, their synthesis still relies on isocyanates, which are classified as hazardous substances. To address this remaining concern, non-isocyanate polyurethane dispersions (NIPUs) have emerged as a promising alternative, aiming to deliver comparable performance while avoiding isocyanate toxicity. However, the environmental benefits of NIPUs cannot be assumed a priori and have to be evaluated.

Within the PFAS-free project (Belgium Builds Back Circular national initiative, 2024–2026), bio-based PFAS-free water-repellent formulations based on both PUD and NIPU chemistries were developed for outdoor textile applications. This study presents a comparative life cycle assessment of PUD and NIPU formulations, with a focus on

identifying potential trade-offs across environmental impact categories in an eco-conception perspective.

The results indicate that the NIPU-based formulation considered in this study exhibit higher overall environmental impacts than the PUD-based one, especially for climate change, ozone depletion, and mineral and fossil resource use. Freshwater ecotoxicity impacts are lower for NIPU; however, the differences are not considered significant given the high uncertainties associated with toxicity-related impact categories. This study also highlights the critical influence of biomass-derived feedstocks on overall results, as well as the substantial contribution of carbamate in NIPU formulations. These findings underline that the elimination of hazardous substances at the molecular level does not necessarily translate into a lower global environmental impact.

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4.01.P-Tu072 Climate Impacts of Wood Fibre as Peat Replacement in Growing Media in Forest Tree Nurseries

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Peat has been energy source and main component of substrates in Europe. Due to concern related to climate change and biodiversity the extraction of energy peat has been reduced. As the infrastructure for energy peat harvesting has reduced it has also reduced availability and profitability of horticultural peat. Due to these environmental and economic concerns there has been pressure to find alternative for peat substrates.

Wood fibre produced from forest industry side flows has been proposed as more climate friendly alternative for peat substrate and some products are already at the market. Still, the scientific literature about wood fibre substrates and their impacts on the substrate users seems to be lacking. This research aims to fill that gap by comparing climate impacts of wood fibre and peat used in tree nurseries.

Cradle-to-grave life cycle assessment is used to recognise the differences in life cycles of the different substrates.

According to preliminary results the climate impacts of wood fibre are 118 kgCO2/m3 whereas peat substrate impacts are slightly higher, 134 kgCO2/m3, when biogenic emissions are considered in both life cycles. However, due to non-renewable nature of peat and carbon of wood belonging to a faster cycle the climate impacts of wood fibre drop to 7.8 kgCO2/m3 when the emissions from the decomposition are not considered.

Results show that climate impacts of the nurseries can be reduced by the adoption of wood fibre even though usage of wood fibres might increase the fertiliser need. Also, wood fibre might be better option in the terms of land use and biodiversity as no dedicated land is needed if the raw material for wood fibre is a side flow.

Thus, changing the substrate can yield some reductions of climate impacts for tree nurseries as substrates cause large share of the climate impacts of tree nurseries. However, additional alternatives are still needed to achieve desired specifications for tree nursery substrates as wood fibre is not perfect replacement for peat.

The results of the studies can also be applicable for other substrate users such as horticulture or greenhouses and help them to reduce their climate impacts. Further research is required to assess climate impacts of other available substrates to replace peat entirely. Still, wood fibre substrate could offer substrate component with less climate, and biodiversity impacts and increase circularity within forest sector.

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4.01.P-Tu073 Up-scaling the cultivation of Macauba palm, an alternative oil crop in Brazil, investigating different land-use scenarios through consequential LCA

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Background_ Macauba (Acrocomia aculeata) is a multipurpose palm native to Latin America and a promising oil crop due to its ability to grow in diverse environments, including dry and marginal lands, unlike African oil palm. Its emerging cultivation in Brazil offers opportunities to diversify vegetable oil supply chains. However, scaling up production requires assessing sustainability beyond the field level, accounting for interactions with global oil markets and potential indirect land-use change.
Aim_ This study evaluates the potential of macauba to support more environmentally sustainable vegetable oil production in Brazil using consequential life cycle assessment (LCA). It addresses three key gaps: representing macauba within global vegetable oil markets, treating it as part of a broader biomass value web rather than a single product chain, and exploring alternative land-use change scenarios.
Methods_ The model integrates substitution elasticities, functional equivalence with existing vegetable oils, marginal displacement in global markets, and coproduct allocation through system expansion. Three management scenarios are compared: pasture-dominated systems (without macauba cultivation), silvopastoral systems, and monoculture systems.
Results (hypothesis)_ The hypothesis is that environmental performance depends critically on land-use context, value-chain configuration and market integration. Silvopastoral systems are expected to deliver the lowest environmental impacts, as they capitalize on system multifunctionality and enable productive land use from early stages. In contrast, monoculture systems face an initial non-productive period of up to five years and are likely to perform less robustly once indirect effects and displaced production are accounted for.
Relevance
This study provides scenario-based environmental information to support the development of Macauba as a sustainable oil crop. By identifying the conditions under which environmental benefits may emerge, it supports land-use planning, value chain and production system design and policy decisions on the introduction of novel oil crops in Brazil and Latin America.

4.01.P-Tu074 Assessing the Environmental Dynamics of Emerging Bio-Based Agricultural Systems: A Life Cycle Approach to P3HB-Coated Fertilizers

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Controlled-release fertilizers can significantly reduce nutrient losses in agriculture. This study evaluates a novel bio-based system in which conventional fertilizers, specifically urea and ammonium nitrate with dolomite (LAD), are coated with the biopolymer poly(3-hydroxybutyrate) (P3HB). The aim is to improve Nutrient Use Efficiency (NUE) while ensuring safe biodegradation of the coating in soil.
The environmental performance of this emerging technology is assessed using a life cycle approach based on the Product Environmental Footprint (PEF) methodology. The system boundary covers the full value chain, including raw material extraction, polymer production, the coating process using the green solvent dioxolane, field application, and biodegradation. Primary agronomic data are directly integrated into the model to quantify the environmental effects of the coated fertilizers against conventional, uncoated alternatives.
Due to limited data availability for emerging bio-based materials, the environmental profile of P3HB is modelled using alternative data sources. Sensitivity analyses of key parameters are performed, and multiple scenarios (including best-case and worst-case conditions) are evaluated to assess uncertainties associated with the technology, such as the efficiency of the dioxolane recovery during the coating process.
The results quantify the trade-offs between the additional impacts of biopolymer production and coating processes and the reductions in emissions achieved through improved fertilizer efficiency, specifically focusing on the mitigation of ammonia volatilization and nitrate leaching. The study provides methodological insights into the integration of empirical agronomic data into life cycle models and supports the development of more consistent approaches for assessing emerging bio-based agricultural systems.

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4.01.P-Tu075 Environmental and Economic Sustainability of Lignocellulosic Feedstocks for Fermentation-Derived Textile Fibres: A Comparison with First-Generation Benchmarks

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Contemporary textile systems rely predominantly on virgin, fossil-based synthetic fibres, associated with significant environmental burdens. Alternatives such as biobased feedstocks are gaining attention and show promising potential for integration into fermentation-based production routes for high-performance protein fibres with engineerable properties (e.g., hydrophobicity) in Belgium. As an initial step, this study analyses the environmental and economic performance of the upstream supply chain. Nineteen second-generation (2G) lignocellulosic feedstocks, including agricultural residues (e.g., cereal straw), dedicated energy crops (miscanthus), forestry residues (wood chips, sawdust), and waste streams (paperboard), were assessed against first-generation (1G) benchmarks.
Life Cycle Assessment (Environmental Footprint v3.1) and Life Cycle Costing were applied from cradle to pretreatment gate. The functional unit was the supply of 1 kg of purified fermentable glucose (C6)-rich syrup for non-food/feed applications. Four contributors are evaluated: (i) feedstock acquisition; (ii) logistics (lorry transport within Europe to Belgium); (iii) feedstock pretreatment; and (iv) management of side streams from pretreatment (C5- and lignin-rich streams) via anaerobic digestion and incineration with energy recovery. Feedstock origins were selected based on market availability, proximity to Belgium, and data availability in ecoinvent v3.9 and Agrifootprint v5. Inventory data was sourced from these databases and the literature.
Results show that ≥80% of the aggregated environmental single score is driven by acidification, climate change, freshwater ecotoxicity, particulate matter, eutrophication (marine and terrestrial), land use, photochemical ozone formation, fossil resource use, and water use. Across pathways, pretreatment, raw feedstock production, and logistics dominate. Pretreatment is the largest contributor for most cases, while feedstock origin strongly influences the relative importance of its acquisition and logistics. Side-streams management plays a minor role.
Compared with 1G benchmarks from a similar origin, most 2G feedstocks show lower environmental and economic performance than 1G starch-rich feedstock (wheat grain), where cultivation burdens dominate, but higher impacts than 1G sugar-rich feedstock (sugar beet), which requires rather simple pretreatment. Future research will address fibre production and downstream life cycle stages.

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4.01.P-Tu076 Life Cycle Assessment Of Innovative Plant Extracts For Biobased Cosmetics

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1. Background and Purpose

The growing use of cosmetics has encouraged companies to seek innovations and demonstrate the evidence-based functionality of their products. The industry has also embraced the consumers' increasing demand for environmentally beneficial and naturally sourced ingredients. This LCA study assesses and provides insight into the environmental impact of biobased cosmetic extracts through different biomass production (BM) platforms and downstream processing (DSP).

2. Materials and Methods

The cradle-to-gate LCA examines the overall environmental impact of an open-field cultivation, aeroponic cultivation and a PCC production system, followed by either a cascade of supercritical CO2 (sCO2E) and ultrasound assisted extraction (UAE), cold maceration or single UAE to obtain hydrophilic and/or lipophilic wet or dry extracts of

bioactive compounds from the biomass for cosmetic applications. Infrastructure, equipment, resource use, energy consumption, emissions, and waste treatment are accounted for.

3. Results and Discussion

Regarding BM production, the largest environmental impacts were traced back to fertiliser application and induced field emissions on the one hand and to energy demand on the other hand. Regarding downstream processing, the environmental impact mainly stems from energy consumption, particularly in the case of sCO2E, and from the solvent used due to the impact from agricultural practices during the production of the crop feedstock used for renewable solvent production. The areas for improvement involve optimisation of the nutrient to yield ratio, and overall, a high dry matter biomass yield and renewable energy efficiency regarding biomass production, as well as the use of more sustainably produced solvents for DSP, which should be recovered through further processing, in combination with renewable energy and higher energy efficiency to prevent problem shifting. Another potential measure is the cascade extraction of both lipophilic and ethanolic extracts from the same biomass source.

4. Conclusions

The transition towards alternative practices requires system-analytic evaluations to prevent environmental problem shifting. Besides yield optimisation, energy savings and energy efficiency measures must go hand in hand with choices for renewable energy to maximally reduce fossil resource dependency and associated impacts. Finally, greater circularity in further processing shows benefits from the recovery of consumables.

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4.01.P-Tu077 Life cycle assessment of an industrial Black Soldier Fly system using agri-food by-products

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Black Soldier Fly (BSF) industrial production has surged as a novel circular solution for obtaining protein and lipids for livestock and aquaculture feed, and frass (the excrement and unconsumed substrate) as an organic fertiliser to replace mineral fertilisers in agricultural systems. As interest in BSF-derived products grows, comprehensive environmental assessments are essential to support robust and informed decision-making.

This study presents a cradle-to-gate life cycle assessment (LCA) of an industrial BSF facility located in Portugal. The system boundary includes agri-food by-products as feedstock (olive pomace and wheat bran), breeding (maternity), larval bioconversion, and larval processing into BSF protein meal, oil, and frass.

Larvae are reared on a substrate primarily composed of locally olive pomace and wheat bran, supporting circular bioeconomy principles and local valorisation of waste streams. Primary data were collected from the BSF production facility.

The functional unit is the combined output of 0.10 t of protein meal, 0.02 t of oil, and 1.0 t of frass at the factory gate, expressed on a dry matter basis. Background processes (electricity generation and natural gas processing), transport and waste management treatment impacts) were modelled using Ecoinvent and Agribalyse databases. Direct biological emissions (carbon dioxide - CO2, and water vapour) associated with BSF respiration and digestion were estimated using a stoichiometric mass-balance model based on published empirical data.

Environmental impacts were assessed using the Environmental Footprint (EF) method. Hotspot analysis identified feedstock production and bioconversion electricity consumption as key contributors to the eutrophication impact category, and natural gas used for thermal drying as a contributor to climate change impacts.

Overall, the results provide quantitative evidence supporting the environmental performance of BSF-derived products and contribute to the development of more sustainable protein production systems based on edible insects.

4.02 - Advancing Ecosystem Services Assessment and Biodiversity Footprinting in Bio-Based and Circular

Systems

4.02.T01 Integrating Biodiversity and Ecosystem assessment in LCA: Lessons Learnt from Early Testing of A-Track´s Harmonized Approach in the wine sector

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The European Green Deal has framed the call for businesses to measure, monitor, and restore their impacts on biodiversity and ecosystem services across value chains. However, companies seeking to assess life cycle impacts on biodiversity and ecosystem services report significant challenges. In particular, the lack of harmonised, ready-to-use methods makes it difficult to navigate and select among existing approaches and guidance, such as the Task Force on Nature-related Financial Disclosures.

This research aims to address some of these challenges by applying the Biodiversity and Ecosystem Footprint framework being developed in the A-Track project (2023–2027) to calculate the life cycle impacts of producing a bottle of wine in Spain.

The framework builds on Life Cycle Assessment (LCA) principles and recommended Environmental Footprint methods to assess impacts on biodiversity and ecosystem services, while integrating concepts and data from natural capital approaches. The proposed impact assessment structure includes two single-score indicators. The Biodiversity Footprint covers, at minimum, habitat destruction (land use, land use change, and water use), pollution (acidification, eutrophication, and ecotoxicity), and climate change (global warming potential). The Ecosystem Footprint addresses impacts on regulating services (soil and water condition) and provisioning services (resource condition). The framework provides relevant impact category indicators, methods, and models. Each indicator can be further disaggregated into footprint (pressure) and handprint (positive contribution).

The case study focuses on land-use-related impacts on habitat destruction using the BioMaps 2023 method for the Biodiversity Footprint, and on erosion resistance and soil organic carbon using the LANCA 3.0 method to assess soil condition as a regulating ecosystem service within the Ecosystem Footprint.

Results will also inform aggregation methods for deriving Biodiversity and Ecosystem Footprint indicators. Additionally, by leveraging existing life cycle inventory data, the study will evaluate whether current datasets are sufficient or if further data collection is needed. Overall, the study supports further development of the framework and contributes to ongoing discussions on LCA method harmonisation and consensus building amongst EU initiatives and projects.

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4.02.T02 Regionalizing Biodiversity Impacts in Life Cycle Assessment: How Is It Implemented in Practice?

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Biodiversity impacts in Life Cycle Assessment (LCA) vary across regions due to differences in species richness, ecosystem vulnerability, land-use intensity, and baseline ecological conditions. As a result, environmental pressures can lead to different outcomes depending on location, making regionalization important for assessing biodiversity.

However, approaches to regionalizing biodiversity in LCA differ widely, and the integration of spatially explicit data into existing methods is not always transparent. This study examines how regionalization is implemented in biodiversity-related LCA case studies, with a focus on the integration of spatially explicit Life Cycle Inventory (LCI)

and Life Cycle Impact Assessment (LCIA) methods.

Relevant studies were identified through a structured literature search using predefined criteria. The selected publications were analyzed in terms of methodological choices, spatial resolution, inventory data, LCI modeling approaches, and biodiversity indicators, including which types of inventory datasets are used to represent different environmental dimensions (e.g., land use, climate, and biodiversity) and how these are linked to impact assessment.

Across the reviewed studies, regionalization is implemented at different levels of detail. Some studies use spatially explicit, site-specific data, while others rely on more aggregated representations, often reflecting data constraints or study scope. Differences are also evident in the choice of biodiversity indicators and in how biodiversity is defined.

The review shows patterns that are relevant for practical application. In many case studies, the level of spatial detail is driven by data availability rather than methodological choice. This suggests that regionalization strategies should be aligned with the decision context and the required level of spatial detail, while accounting for differences in data availability and modeling approaches. It also highlights how inventory data are applied across environmental components in different sectors, indicating which approaches are used in practice and can guide practitioners in selecting suitable data for regionalized biodiversity assessment.

Overall, this review provides a structured overview of how regionalization is currently applied in biodiversity-related LCA case studies and highlights key considerations for practitioners when selecting and implementing regionalized approaches in their own assessments.

4.02.T03 Biodiversity Indicators in the Boreal Forestry Sector: Mapping the Biodiversity Indicators for LCA Study

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Biodiversity impact assessment is gaining increasing attention as biological diversity is exposed to growing risks from multiple pressures, including land use change, natural resource exploitation, and climate change. For the forestry sector, which directly manages and depends on natural forest ecosystems, understanding and assessing the biodiversity impacts of management activities is particularly critical. Beyond mitigating negative impacts, forestry companies are increasingly expected to demonstrate measurable improvements in biodiversity outcomes. A central prerequisite for robust biodiversity assessment is the selection of harmonized, operational and policy-driven indicators that can capture both impacts and positive management interventions over time.

This study reviews and compares biodiversity related indicators from key frameworks relevant to boreal forest in Sweden, including Forest Europe, FSC Sweden, the EU Nature Restoration Regulation, and PEFC. Through a mapping exercise, biodiversity indicators across these frameworks are compared and correlated based on shared ecological dimensions such as forest composition and naturalness, structural attributes, deadwood availability, species status, and ecosystem functions. The analysis highlights differences between regulatory, monitoring oriented, and certification based indicator systems, as well as areas of substantial overlap.

The selected indicators are subsequently compared with biodiversity indicators used in life cycle assessment (LCA), focusing on the Biodiversity Value Increment (BVI) methodology. This comparison identifies areas of convergence and mismatch between forestry based biodiversity indicators and LCA oriented quantification approaches. Based on these findings, the paper discusses implications for further methodological development in LCA biodiversity assessment and provides guidance for forestry companies on improving biodiversity monitoring systems and selecting indicator sets that are consistent, measurable, and fit for integration into environmental assessment and align with the considered frameworks

4.02.T04 Bridging Global and Local Environmental Impact Evaluation of Offshore Wind Farms Through Integration of Life Cycle Assessment and Ecosystem Services Assessment.

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Life cycle assessment (LCA) is among the most widely adopted methodologies for evaluating global environmental impacts across product value chains. Applied to offshore wind farms (OWF), LCA methods quantify global impact categories but inherently lack the capacity to capture site-specific impacts on the local environment. In contrast, ecosystem modelling based ecosystem services assessment (EM-ESA) enables the evaluation of local, context-dependent impacts, including both positive and negative contributions to ecosystems while considering the cumulative impact including the synergistic and antagonistic effects. There are some advancements ongoing trying to include these local, site-specific impacts into the global assessments by developing characterisation factors or including specific ecosystem services (ES). However, a systematic integration of LCA and EM-ESA for OWFs remains underdeveloped. This study proposes a conceptual framework that combines LCA and EM-ESA to enable a holistic assessment of OWFs' environmental impacts on sustainability, encompassing both footprints and handprints across global and local scales. The framework is structured around a shared qualitative cause-effect chain initiated by the presence and life cycle stages of OWFs. Building on earlier more fragmented integration efforts, it systematically incorporates thirteen relevant ES. Within the LCA pathway, elementary flows are linked to midpoint impact categories following established characterisation models. Within the EM-ESA pathway, ecosystem modelling, including tools such as food web models (e.g. Ecopath with Ecosim), connects the ecological impacts, starting from the OWF life stages to food webs into ES indicators as midpoints and into provisioning, regulating, and cultural ES at endpoint level. These parallel pathways are harmonised at mid- and endpoint levels, enabling consistent aggregation into three areas of protection: human health and well-being, ecosystem quality, and natural resources.
The framework advances current practice by bridging methodological gaps between lifecycle- and ecosystem-based assessments, thereby providing a more holistic basis for decision-making in offshore renewable energy development. This is one of the first attempts to include ES into LCA in marine environments enabling applications beyond OWF. It is the basis to integrate all environmental impacts in sustainability assessments and supports more informed, site-sensitive policy and planning.

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4.02.T05 Title: A systemic view of impacts on biodiversity using LCA and NCA- Case study perspective

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Biodiversity loss is a critical risk to humanity, driven by unsustainable production and consumption that depletes natural capital, leading to species loss, ecosystem degradation, and reduced genetic diversity. There is an increasing call for the private sector to develop nature transition plans for reducing pressures on nature and for contributing to global goals for nature restoration. Given this, there is also the need for guidance for the private sector on how to track reduction of pressures and contributions to improving the state of nature at sites and across value chains.

To support action, several diverse concepts, methods, and tools have been developed and used. However, there is often little alignment and few synergies between these. There is a need to improve harmonization and alignment of the available methods and tools, and to provide comprehensive ways to utilize these efficiently. To address this need, while also effectively measuring changes in biodiversity loss and ecosystem degradation, we developed a holistic methodological approach through integration of two concepts: Life Cycle Assessment (LCA) and Natural Capital Accounting (NCA). While LCA can capture potential impacts across a value chain, NCA is well suited to capture changes in the state of nature in one or more specific locations. We apply LCA to measure impacts from specific activities, and NCA to translate these into concrete changes in the state of nature.

We illustrate the application of the method through a case study in Costa Rica. We highlight the role of natural capital and how the pressures and impacts on biodiversity and ecosystems can be captured comprehensively through an integrated LCA-NCA approach. NCA and LCA can work together and complement each other to provide a comprehensive understanding on measuring impacts on biodiversity.

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4.02.P - Advancing Ecosystem Services Assessment and Biodiversity Footprinting in Bio-Based and Circular Systems

4.02.P-Tu078 Biodiversity Impacts at Organisational Level: Lessons from the National Trust, UK

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Biodiversity loss is an increasingly material issue for organisations, yet practical methods for assessing impacts across complex operations remain limited. This study presents a screening-level organisational life cycle assessment of biodiversity impacts for the National Trust, a large UK conservation charity with diverse landholdings, tenanted farms, visitor operations and supply-chain activities. Using the Trust's carbon accounting data as the core foreground life cycle inventory, we modelled direct, upstream and downstream activities over 2020–2022 and quantified ecosystem damage with ReCiPe2016 endpoint indicators, expressed as potentially disappeared fraction of species (PDF/yr). IMPACT World+ was also applied to test robustness in overall patterns. Results show a stable biodiversity impact profile across the three years assessed. Land use was the dominant driver, accounting for around 68–69% of total impacts, followed by global warming impacts on terrestrial ecosystems (15–16%) and terrestrial acidification (8–9%). Agriculture was identified as the principal hotspot, responsible for approximately 84% of total impacts in the 2022 reference year, mainly through livestock grazing, feed production and associated land occupation and transformation. Purchased goods and services, especially construction-related activities, also generated substantial upstream impacts. By contrast, several operational categories made only minor contributions. The study demonstrates that an LCA-based organisational assessment can provide a transparent and consistent way to identify biodiversity hotspots and prioritise intervention areas, even where data are limited and/or imperfect. At the same time, it highlights important methodological constraints, including limited spatial resolution, uncertainty in supply-chain data, and the difficulty in capturing positive biodiversity outcomes from restoration and stewardship. Organisational LCA can therefore serve as a practical entry point for biodiversity footprinting and support strategy development, target setting and disclosure aligned with emerging nature-related frameworks.

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4.02.P-Tu079 A Framework To Include Marine Biodiversity Impact in Fisheries Life Cycle Assessment

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Seafood production through fisheries provides essential nutrients (proteins, vitamins, or fatty acids) globally, while serving as a vital economic activity for coastal populations. Their sustainable production is essential to meet current and future food needs. This requires methods to assess full environmental impacts, such as Life Cycle Assessment

(LCA). However, current LCA methods overlook key drivers of biodiversity loss, especially in marine ecosystems. Therefore, new methodologies have been developed to integrate the effects on biodiversity in Life Cycle Impact Assessments (LCIA), but few have already been added to impact assessment methods. Moreover, the methodologies to take into account the various impacts on biodiversity (e.g. fish harvesting, seafloor damage, or pollution) describe impacts at different levels (regional or global) and thus are not always compatible. This makes their conjoint use harder in assessment at the level of the area of protection ecosystem quality.
This work proposes a novel LCIA framework based on literature to include major marine biodiversity drivers at both midpoint and endpoint levels. Selected categories include: biomass harvesting, seabed disturbance, plastic waste, climate change, ocean acidification, and marine ecotoxicity. The proposed framework is tested through a case study to validate its usability and to explore the consequences of the inclusion of new impact categories on the results.
We hypothesize that at the endpoint level the area of protection ecosystem quality will be strongly impacted by the new categories or the extension of existing categories. This would confirm the need to continue the work to include these impact categories in LCA methods.

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4.02.P-Tu080 Adapting Life Cycle Impact Assessment Models for use in Ecosystem Restoration

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Adapting Life Cycle Impact Assessment Models for use in Ecosystem Restoration

Background and Purpose

Biodiversity recovery is a critical component of ecosystem restoration, yet life cycle impact assessment (LCIA) models often lack the ability to represent recovery dynamics accurately. As restoration activities become more widespread, improving how LCIA captures positive ecosystem changes is increasingly important. This study aims to adapt existing LCIA land use models to better characterize biodiversity recovery during ecosystem restoration and to evaluate how such adaptations influence impact results.

Methods
We developed a set of conceptual recovery scenarios that adjust recovery mode to distinguish passive relaxation from active restoration. The scenarios were implemented for both positive and negative land transformations and tested using project-specific data from the remediation of a contaminated site. We further evaluated how alternative recovery metrics and regional recovery data influence impact results, assessing interactions between recovery mode, metric choice, and regionalization.

Results
Results show that the adjusted models are most informative for production systems or activities where the foreground system dominates impacts or where land use impacts are most noticeable. Recovery mode was found to be a critical parameter, but its interaction with recovery metric and regional recovery data further amplified result variability. The results stress the need for temporal characterization adjustment in addition to selecting models that can characterize positive land transformations.

Conclusions
This work demonstrates that existing LCIA datasets can be systematically adapted to enable more decision-relevant assessments of ecosystem restoration. While recovery time adjustment is necessary to reflect active restoration, it

introduces additional uncertainty and should therefore be applied with caution. Incorporating explicit recovery dynamics represents an important step toward aligning LCIA with contemporary restoration practice and supports more accurate biodiversity assessments in land-use-intensive decision contexts.

4.02.P-Tu081 Integrating Ecosystem Services into Life Cycle Assessment of Bio-Based Aviation Fuels from Perennial Grasses on European Abandoned Land

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The expansion of bio-based value chains requires improved life cycle assessment (LCA) approaches that capture not only climate mitigation but also impacts on ecosystem services (ES). Sustainable aviation fuels (SAF) derived from perennial grasses such as miscanthus and switchgrass offer a pathway to utilise abandoned agricultural land in Europe while potentially enhancing regulating ES, including carbon sequestration, water regulation, and biodiversity support. However, these benefits and trade-offs remain insufficiently represented in conventional LCA frameworks.
This study evaluates SAF production from perennial grasses cultivated on European abandoned cropland using a comparative LCA of Fischer–Tropsch (FT) and alcohol-to-jet (ATJ) pathways, including scenarios with and without carbon capture and storage (CCS). Building on spatially explicit yield and inventory data, the assessment integrates multiple ES-relevant impact pathways, including climate change, water scarcity, land use, and biodiversity loss. In addition, soil organic carbon (SOC) dynamics associated with perennial grass systems are considered as a key regulating ES.
A key methodological contribution is the integration of regionalised indicators within the LCA. These include country-specific characterization factors for water scarcity, land-use biodiversity impacts, and spatially differentiated climate metrics for near-term climate forcers. Regionalisation allows the assessment to capture spatial heterogeneity in environmental sensitivities, such as water stress, ecosystem vulnerability, and region-dependent climate impacts of emissions, which are critical for evaluating ES trade-offs across Europe.
Results show that ecosystem service outcomes are highly sensitive to technology choice land and water management. FT pathways combined with CCS can achieve net-negative climate impacts, while ATJ pathways show higher emissions due to process energy requirements. Biodiversity impacts are dominated by climate-related pressures, particularly affecting marine species, whereas land-use impacts increase under lower-yield rainfed systems. Irrigation reduces land pressure but introduces trade-offs through increased water scarcity and associated ecosystem impacts.
Overall, this study shows that integrating ecosystem services into LCA through spatial differentiation and regionalised indicators can improve the comprehensiveness of sustainability assessments for SAF systems.

4.02.P-Tu082 A Co-Simulation Framework for Evaluating Whole-Life Carbon, Biodiversity, and Health Across Urban Morphology and Residential Archetypes

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The EU Nature Restoration Regulation and CSRD/ESRS E4 have accelerated the demand for spatially explicit, decision-ready biodiversity metrics within circular value chains. Yet, operationalising these mandates requires a shift from isolated indicators toward integrated frameworks that can navigate multi-domain trade-offs:

Decisions about residential density and built form carry simultaneous implications for whole-life carbon, ecological performance, and human health, yet no established simulation workflow addresses these domains together. Each is typically modelled in isolation using discipline-specific tools and incompatible output structures, making cross-domain trade-off analysis impossible without significant manual intervention.

This study presents a simulation framework that integrates three parallel domain models from a shared parametric input layer, prioritising data interoperability to enable systematic, reproducible comparison across a structured set of

residential morphology archetypes. Each archetype, defined by density, built form (e.g., suburban detached, Victorian terrace, residential tower), and urban setting (e.g., city centre, suburban, new town), is instantiated as a standardised synthetic district with consistent geometric and land-cover inputs passed simultaneously to all three domain models.

Whole-life carbon is assessed following EN 15978 and RICS guidance, integrating dynamic thermal simulation for operational energy, embodied carbon accounting, and transport demand modelling alongside infrastructure carbon for roads and utilities. Biodiversity is assessed using the statutory Biodiversity Net Gain (BNG) metric, mandatory under UK legislation, alongside conductance modelling for functional habitat connectivity. Health assessment addresses indoor air quality as a physics-based proxy for morphology-driven environmental burden. Domain outputs are normalised into a shared structure, enabling direct evaluation of inter-domain dependencies.

Application of the framework demonstrates its capacity to surface systemic interactions between carbon, biodiversity, and health that single-domain simulation cannot detect. Results reveal that optimising for one domain does not reliably predict performance in others, with significant divergence observed across archetypes. The framework further enables identification of performance windows, specific morphological configurations where carbon, biodiversity, and health outcomes converge favourably.

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4.02.P-Tu083 From field monitoring to LCIA: advancing biodiversity and climate indicators for ocean restoration in Life Cycle Assessment

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Background:
Life cycle assessment (LCA) is commonly used to support environmental sustainability decision-making within the industry. LCA is also applied to assess positive environmental outcomes of mitigation and restoration initiatives addressing climate change and nature loss, making possible to track the environmental performance of a company.
Challenge:
However, in the context of ocean restoration projects, capturing environmental benefits (e.g., climate change regulation and biodiversity enhancement) still remains challenging. This is due to relevant life cycle impact categories are still limited, or not formally recognized within corporate frameworks. This makes difficult the robust estimation and reporting of climate and biodiversity benefits.
At the same time, industry-led ocean restoration initiatives generate valuable site-specific monitoring data on climate and biodiversity, which currently have a weak link to existing life cycle impact assessment (LCIA) models.
Purpose of the work:
This work presents the methodology to be able to leverage and translate monitoring site-specific data (e.g., biodiversity and carbon sequestration) from an industry ocean restoration project into results that are meaningful, consistent, and usable within climate and nature LCA and corporate frameworks.
Methods / Approach
This contribution uses operational ocean restoration projects as testbeds to explore how measured biodiversity and climate change (e.g., carbon sequestration) outcomes can inform and calibrate LCIA modelling approaches. On site, field monitoring plans generate data on carbon sequestration, fish richness, fish abundance, fish diversity, invasive species, microbiology, and nutrient (nitrogen and phosphorous) management. These indicators are collected using several monitoring techniques such as multi-beam, visual, mother reef cage, sediment and eDNA. The resulting datasets are subsequently used to inform and parameterize modelling approaches that are integrated into the LCA framework.
Main Conclusions
This study demonstrates that industry led applied research can actively contribute to methodological innovation in

biodiversity and climate change LCIA by strengthening the empirical evidence linking field observations to impact modelling. Using ocean restoration projects as real world laboratories supports more robust, transparent, and comparable LCAs, helping to connect the gap between academic method development and practical implementation.

4.03.A - Advancing LCI for the Bioeconomy: Land Use Change and Biogenic Carbon Accounting

4.03.A.T01 Biogenic carbon in the absolute environmental sustainability assessment of the EU forest sector

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The EU forest sector provides feedstock and products to replace fossil products with wood-based alternatives. The sustainability of its products is often studied with life cycle assessment (LCA) and compared to fossil-based products. However, these LCAs often lack comparison to the environmental thresholds, such as planetary boundaries, and exclude biogenic carbon from the climate impacts. Thus, the analysis does not tell if these products are compatible with societies aligned with the planetary boundaries and often underestimate climate impacts over short time horizons.

This study took the approach of absolute environmental sustainability assessment (AESA) to compare the environmental impacts of the EU forest sector to its share of the global planetary boundaries. First, the absolute environmental sustainability of the EU forest sector was assessed with the LCIA-based carrying capacity method and allocation principles of economic value and employment. Second, biogenic carbon was included in the climate change impact category with the standardized -1/+1 method and a time-explicit approach.

The results indicate that the EU forest sector is not operating within its environmental carrying capacity in several impact categories. For example, the climate change impacts transgressed the carrying capacity 4 times and the particulate matter impacts 8 times with the economic value allocation. For the employment allocation, these exceedances were five times greater. As expected, the standardized -1/+1 method for biogenic carbon did not change the climate impacts. In contrast, adding biogenic carbon with time-explicit modelling increased substantially the climate impacts over short time horizons, whereas the impacts were only merely reduced over long time horizons while still transgressing the carrying capacity.

This study reveals that the EU forest sector is not operating within its carrying capacity. The sector needs to take action to attain sustainability, for instance by phasing out fossil fuels, reducing harvest levels, and directing more wood to long-lived products instead of incineration. Additionally, this study highlights that the exclusion of biogenic carbon can underestimate the climate impacts of forest-based products in AESA studies over short time horizons. Thus, more method development is needed to accurately include biogenic carbon with time-explicit modelling into the attributional AESA.

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4.03.A.T02 Temporal and Spatial Choices in Biogenic Carbon Accounting for the wood-based fibre Lyocell

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Static LCA assumes that biogenic carbon sequestration, storage, and release occur simultaneously, ignoring temporal carbon dynamics. As a result, climate assessments of bio-based products (BBPs) may be incomplete or misleading. Dynamic biogenic carbon accounting offers a way to address this limitation. While many dynamic LCA (DLCA) studies consider delayed emissions, the gradual sequestration of carbon in woody biomass is often overlooked. In addition, dynamic approaches introduce methodological complexity. Key choices remain insufficiently explored, including spatial boundaries (stand or landscape), the timing of carbon uptake (before or after harvest), and assumptions about carbon storage duration.

Building on dynamic accounting, this study develops an approach that integrates temporally differentiated carbon accounting into the life-cycle inventory of a BBP. This includes biogenic flows from carbon growth dynamics, taking into account the timing of carbon uptake and emissions, the duration of carbon storage in products, and delayed carbon emissions at end of life. The approach is demonstrated through a case study for Lyocell fibre, a wood-based fibre made from cellulose. Two pulp types are analysed using two perspectives for forest carbon flows: 1) a stand- and landscape-level perspective for eucalyptus plantation from Brazil, and 2) a landscape perspective for a long-term managed beech from Austria. Dynamic characterisation factors are applied to represent time-explicit carbon flows and multiple dynamic scenarios are tested to assess the influence of methodological choices.

Preliminary results indicate that methodological choices related to temporal and spatial system boundaries can substantially influence results and their interpretation. From a stand-level perspective, the result is sensitive to uptake timing and carbon storage duration. Shifting carbon uptake to occur before or after harvest alters its position along the time horizon, while (extended) storage delays subsequent emissions. At the landscape level, results indicate that a −1/+1 approach can be applied to represent biogenic carbon flows under equilibrium conditions. Compared to static LCA, the study highlights the importance of explicitly capturing temporal and spatial carbon dynamics for wood-based products.
This work contributes to methodological discussions in spatial and temporal life-cycle modelling of carbon balances and supports a critical evaluation of the added value of DLCA.

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4.03.A.T03 Biogenic Carbon in Wood Construction Products and Structures: A Critical Overview from Static to Dynamic Life Cycle Assessment.

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Wood products are increasingly recognised for their role in climate change mitigation; however, existing methodologies fail to accurately capture biogenic carbon flows. This study presents a critical review of life cycle assessment (LCA) of timber structures and wood products, to assess how state-of-the-art studies address biogenic carbon. Thirty peer-reviewed LCA articles were critically reviewed, and relevant insights were obtained by further creating five key analytical areas.
The key analytical framework focused on the applied LCA methodologies to analyse biogenic carbon flows in building elements. The frame involved a systematic examination of goal and scope definition, selection of metrics and environmental impact categories, and the identification of dynamic parameters, where applicable.
The analysis identifies a trend toward accounting for biogenic carbon in the literature. However, the -1/+1 approach, which is commonly applied in these studies, appears insufficient for capturing the temporal dynamics of biogenic carbon. Consequently, the application of Dynamic Life Cycle Assessment (DLCA) is encouraged, as it enables the calculation of the impacts of pulse emissions using time-dependent parameters. This temporal dimension facilitates comprehensive assessments, from forest management dynamics to the end-of-life of wood products. This analysis shows that the dynamic parameters in LCA are evolving, however, standardised framework is still lacking. Methodological gaps were identified in allocation methods, which can become challenging when assessing synergies between the forest and building industries. Furthermore, methodological inconsistencies were identified in defining conceptual framework for dynamic parameters and sensitivity analyses in various scenarios within several DLCA studies. The review suggests that further development is required in the treatment of biogenic carbon and end-of-life

emissions to achieve a more comprehensive understanding of the role of timber products as carbon sinks. The study highlights the necessity of a well-defined DLCA framework to support practitioners, including the development of dynamic functional units, establishment of consistent system boundaries, and inclusion of additional environmental impact categories. Standardising dynamic parameters within DLCA methodologies will ensure methodological robustness and improve decision-making, particularly regarding biogenic carbon sequestration.

4.03.A.T04 Comparing Static and Dynamic Biogenic Carbon Accounting of Bio-Based Plastics under Alternative Carbon Release Profiles

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Bio-based plastics are often promoted as climate-friendly alternatives because they contain renewable carbon. However, their climate impact depends not only on how much carbon is absorbed and released, but also on when these flows occur. Conventional static life cycle assessment (LCA) typically assumes instantaneous emissions, whereas dynamic LCA (DLCA) accounts for the temporal evolution of biogenic carbon flows using time-dependent inventories and characterization factors. While prior DLCA studies have examined carbon uptake, biomass regrowth, and storage, less attention has been given to how end-of-life emission timing influences climate impacts relative to static accounting.

This study addresses that gap through a systematic comparison of alternative end-of-life emission profiles for bio-based plastics. Given limited empirical data, we model emission patterns to explore how emission timing influences results, including fast-release (exponential, first-order), delayed or peaked (Gaussian, log-normal), and gradual or multi-phase emissions (sigmoidal, linear-ramp, bi-exponential). Results are evaluated using time-dependent inventories and dynamic characterization factors, considering both instantaneous radiative forcing and global warming potential over 100 years (GWP100).

When 50% of biogenic carbon is released within 20 years, the dynamic GWP100 remains close to the static reference (within 15%), indicating that static LCA provides a reasonable approximation under rapid emission conditions. When emissions are delayed beyond this 20-year threshold, divergence increases substantially, with the largest deviations observed for delayed and gradual release profiles. These differences arise because earlier emissions contribute more strongly to near-term radiative forcing, whereas delayed emissions are temporally discounted in integrated metrics. Delayed profiles shift peak radiative forcing to later decades (up to year 100), while more distributed release profiles can reduce peak magnitude by 40–52%.

These findings demonstrate that the timing and shape of end-of-life carbon release are key determinants of climate impact and provide guidance on method selection: static LCA and DLCA may similarly approximate GWP100 for systems dominated by rapid emissions, but static LCA could misrepresent systems with delayed or distributed release, such as those involving extended product lifetimes, temporary storage, or multi-stage treatment, where DLCA becomes necessary.

4.03.A.T05 The Climate Impact of Biogenic Carbon in Life Cycle Assessment: A new Framework and Application

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The utilization of biomass for energy and products plays an important role in the path towards a sustainable future for many stakeholders. But renewable and biobased products do not necessarily result in environmental beneficial impacts and the critical assessment of biomass use and circularity is needed to ensure sustainable development. A key part of such an assessment is to deal with the impact of biogenic CO2 emissions. Having historically been treated as climate

neutral, the impact assessment of biogenic CO2 is now a topic of increasing interest. As shown by recent developments such as the Biogenic Carbon Project or discussions on the new GHG Protocol Standard.
This work presents the newly developed Green Carbon Cycle (GCC) approach and demonstrates its application with several cases. These include the calculation of generic GWPbio emission factors for wood from fast growing plantations in South America and sustainable managed forests in Germany divided in wood from final harvest, thinning, and forest residues. The LCA application of the GCC approach is demonstrated to several case examples for material and energy use to demonstrate the easy use of the approach for practitioners.
For the generic GWPbio factors related to German forests, five typical forest stand types are the basis for the analysis with data from the German federal forest inventory. Final felling is considered for mature forest stands with different harvest intensities. For thinning, forests stands between 20 and 80 years age are considered together with different thinning intensities and stand densities. For wood from forest residues the influence of using different calculation methods and decay constants are analyzed. For all cases, both GWPbio20 and GWPbio100 are calculated to show short- and long-term impacts.
The case studies and the generic GWPbio factors showcase how the GCC Approach can greatly improve the assessment of biogenic CO2 in LCA. They highlight the importance of including realistic use and counterfactual scenarios and the flexibility of this new approach resulting in positive or negative impacts on climate depending on different forest management operations, resulting growth dynamics and wood product use-cases. The GCC Approach opens up the possibility for LCA practitioners to assess biogenic carbon in a structured, repeatable and consistent way to support science-based policy decision support and reporting of harvested wood products climate impacts.

4.03.B - Advancing LCI for the Bioeconomy: Land Use Change and Biogenic Carbon Accounting

4.03.B.T01 Integrating Earth Observation and Spatially Differentiated Impact Indicators to Advance Sustainability Assessment of Cocoa Expansion

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Cocoa expansion in the Peruvian Amazon is driving forest conversion, but accurately accounting for the related environmental impacts remains challenging. LCA of bio-based value chains, crop-specific land-use change (LUC) inventories often rely on spatially aggregated estimates of area or carbon-stock changes. This obscures fine-scale spatial heterogeneity and fails to capture broader impacts on biodiversity and regulating ecosystem services. Here, we present an Earth-observation based workflow that converts high-resolution land monitoring into crop-specific direct LUC transition data and spatially differentiated impact indicators for the Ucayali Agroecological Living Landscape, Peruvian Amazon.
We combined Sentinel-1 and Sentinel-2 satellite imagery, field/reference observations and a random forest classifier to produce a 10 m land-use and land-cover map distinguishing cocoa from forest, pasture, oil palm, other agriculture and secondary vegetation. Current cocoa pixels were overlaid with annual forest-cover histories from 2000 to 2020 to identify forest-to-cocoa transitions. This direct LUC inventory was coupled to three spatially differentiated impact indicators: foregone above- and below-ground biogenic carbon stock, biodiversity impact based on species-rarity weighted intactness loss, and increased nitrogen export as a proxy for water-purification loss.
We mapped 25,659 ha of cocoa in 2020, of which 17,452 ha (68%) originated from direct forest conversion since 2000. This deforestation component accounts for 3.0 million Mg C of foregone biogenic carbon stock, reduced regional biodiversity by 0.5%, and increased nitrogen export by 58.2 Mg N per year. Per-hectare losses for biodiversity, carbon and water purification each peaked in different districts. Multi-indicator hotspots were concentrated in parts of the frontier, indicating that deforestation area or carbon stock change alone cannot represent the full environmental impact of cocoa expansion.
We restrict LUC to direct forest-to-cocoa conversion. The contribution is therefore not a complete LUC account, but a transparent procedure for transforming high-resolution land monitoring into crop-specific transition data and spatially differentiated impact indicators to be used in LCA. This can support updating of crop-specific LUC factors in specific

regions and thus companies pursuing EUDR-aligned sourcing.

4.03.B.T02 Emission Footprints of Agriculture in 2050

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Food demand is expected to increase up to 56% by 2050. While previous studies quantify the future land use emissions (including land use change (LUC) and agricultural management) as an aggregated agri-food category, it remains unclear what future emission footprints of specific crops looks like. Such footprints are critical for defining mitigation strategies and agricultural policies that reduce emissions, and are highly relevant for prospective life cycle assessment. This study presents future crop footprints for the period 2025-2050 based on Shared Socioeconomic Pathways (SSPs) 1-3.

Our analysis builds on two coupled components of the IMAGE 3.3 integrated assessment framework: the IMAGE land-use allocation model and the dynamic global vegetation model LPJmL 4.0. IMAGE-Land simulates future land-use dynamics including agricultural expansion under different SSPs, while LPJmL simulates carbon dynamics. By using these two data, we derive carbon stock losses from LUC to agriculture. Agriculture management for future years are also modelled in IMAGE such as manure and synthetic fertilizer application, agricultural waste burning, and wetland rice cultivation considering modelled crop productivity and nutrient management. The total emissions from LUC and agriculture management at grid level are attributed to 16 crops and pastureland. Crop footprint can be derived by combining emissions with crop production.

Future global agricultural production in year 2050 is associated with total LUC emissions of 480, 5280, 8890 MtCO2 under SSP1-3 respectively. For our default scenario, SSP2, 56% of these emissions resulted from conversion of natural land to agriculture, while 23% are from non-forested natural land conversion, and the rest (21%) attributed to biofuel expansion. The LUC emissions are attributed to pasture (30%), woody and non-woody biofuel (28%), tropical cereals (7%), maize (6%), tropical oil crops (4%), rice (2.5%), palm oil (2%), the rest (20.5%).

The resulting footprints can provide insights into how footprint may differs across crop, region, and scenarios. These outcomes can help identify crop-region combinations that remain emission-intensive and where targeted land-use or agricultural mitigation may be needed. Scenario-based crop footprints are useful for a background database for prospective life cycle assessment (pLCA) and can potentially be integrated with foreground life cycle inventory (LCI) for complete pLCA of specific crop commodities.

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4.03.B.T03 Land-Use Change Emissions Limit Climate Benefits of Biobased Chemicals

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The petrochemical industry relies on fossil resources to produce six key carbon-based chemicals: methanol, ethylene, propylene, benzene, toluene, and xylene, which underpin thousands of products. This sector consumes approximately 12% of global crude oil and contributes ~4% of global greenhouse gas (GHG) emissions. While electrification and carbon capture and storage can reduce process-related emissions, achieving net-zero requires addressing carbon embedded in petrochemical products by transitioning away from fossil feedstocks. Biomass is often proposed as an alternative, yet the role of land-use change (LUC) emissions in determining its climate benefits remains uncertain.

Here, we quantify lifecycle GHG emission factors for biobased production of these six base chemicals, explicitly accounting for spatially resolved LUC emissions. We evaluate 30 production pathways using four feedstock types: sugarcane, fast-growing grasses, short-rotation coppicing woody crops, and agricultural residues. The assessment includes emissions from LUC, cultivation, processing, transport, chemicals production, and end-of-life carbon release. To avoid indirect LUC effects, we restrict cultivation to marginal and abandoned agricultural land. Using global production volumes, we estimate the potential climate mitigation from replacing fossil-based production with biobased alternatives.

Among 21 crop-based pathways, only sugarcane-based ethylene shows lower median emissions than its fossil counterpart when LUC is included. In contrast, excluding LUC, as is commonly done, would suggest that 19 of these pathways are beneficial. Agricultural residues-based pathways are assumed not to lead to LUC emissions and perform more favourably, with 8 out of 9 showing emission reductions relative to fossil equivalents. Combining the most favourable routes suggests that emissions from the petrochemical sector could theoretically decline from 5.6% to 1.2% of global emissions.

However, limited availability of marginal land and residues, alongside competing biomass demands, constrains the scalability of fully biobased production. Our results underscore the importance of incorporating LUC emissions in environmental assessments and indicate that while biobased chemicals can contribute to emission reductions, they are not a standalone solution for decarbonising the petrochemical industry.

4.03.B.T04 Carbon in Soil, Impacts Elsewhere: Life Cycle Trade-offs of Soil Carbon Sequestration Strategies

Soil carbon sequestration (SCS) is a promising near-term climate mitigation option, with potential co-benefits for soil health and productivity. However, its performance is context-dependent, and its implementation may induce environmental tradeoffs beyond climate change. This study aimed to (i) identify priority SCS strategies for French croplands and (ii) assess their life-cycle environmental impacts to anticipate unintended consequences.
We reviewed 26 SCS strategies, harmonizing evidence from 264 meta-analyses into eight key performance indicators (KPI), covering sequestration potential, feasibility, co-effects, costs, and carbon permanence. A multicriteria decision analysis highlighted biochar application and hedgerow systems as priorities, with mean sequestration rates of 3.2 and 0.7 tC ha-1 yr-1, respectively, and balanced performance across KPIs. These practices were then assessed using consequential life cycle assessment (LCA), integrating soil organic carbon (SOC) dynamics and global sensitivity analyses. Using EF v3.1, both options were evaluated across six impact categories with practice-specific soil models and functional units. Hedgerows were modelled by introducing black locust hedges into conventional farms (FU: 1 ha over three black locust cycles; SOC from C-TOOL), while biochar was modelled as wood-derived production followed by soil application (FU: 1 t CO_2 sequestered over 100 years; SOC from AMG), explicitly accounting for energy recovery from pyrolysis co-products.
Relative to the conventional baseline, hedgerows reduced climate change and mineral resource depletion by 64–68% and particulate matter by 68%, but increased freshwater and marine eutrophication and water use. Uncertainty analysis revealed overlapping distributions with the conventional baseline, indicating that improvements are not robust across all impact categories. For biochar-to-soil, the full supply chain achieved −1.2 t CO_2-eq for climate change, while other impact categories increased, driven mainly by indirect land-use change and energy recovery from pyrolysis co-products.
Overall, SCS can enhance SOC stocks and mitigate climate change, but may shift burdens to other environmental dimensions. These results highlight that the environmental performance of SCS strategies depends strongly on supply-chain assumptions and cannot be judged using carbon metrics alone.

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4.03.B.T05 Integrating mass balanced biogenic carbon attributes into certified product carbon footprints

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Product carbon footprints based on life cycle assessment are increasingly applied to reflect the climate impact of a product along complex value chains. In systems where fossil- and bio based feedstocks are processed together, established product carbon footprint methodologies often rely on averaged input representations, thereby limiting the ability to reflect differences in the sourcing and origin of biogenic materials, particularly during the initial and transitional phases toward a more bio-circular economy.
This work addresses the challenge of reflecting biogenic origin and associated carbon uptake in product carbon footprints when multiple feedstocks are jointly processed. The purpose of the study is to examine how certification based mass balance principles can be extended to biogenic attributes within product carbon footprints, enabling differentiated, traceable and verifiable product level carbon accounting in systems with co-processed fossil and bio-based feedstocks.
A framework is presented in which biogenic content, together with its carbon uptake, is subject to chain of custody mass balancing. Within shared processing units, fossil and biogenic inputs are treated as virtually segregated streams, each linked to distinct life cycle inventory characteristics. This enables attribution of biogenic attributes to outputs under a certification framework, that ensures consistency with physical throughput and auditing constraints.
From a methodological perspective, the approach accounts explicitly for both the mass balanced attribution of biogenic carbon content and the remaining fossil based product carbon footprints. This ensures overall greenhouse gas consistency, prevents double counting of biogenic carbon, and supports transparent verification of certified and non certified products within the same system boundaries.
The results illustrate that incorporating mass balanced biogenic attributes into product carbon footprints allows a more differentiated and forward looking representation of bio based sourcing options. The proposed framework advances life cycle inventory practices for the bioeconomy by linking certified sourcing choices to product level carbon footprints and supporting sustainability steering in bio based and circular economic systems.

4.03.P - Advancing LCI for the Bioeconomy: Land Use Change and Biogenic Carbon Accounting

4.03.P-Tu084 Life-cycle climate performance of Lepidium campestre (Field Cress) oil for HVO: attributional baseline and consequential scenarios for co-product pathways and Nordic land availability

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Hydrotreated vegetable oil (HVO) is a central component of EU transport decarbonisation, yet new temperate oilseed options require robust evidence on climate performance plus credible co-product routes. This study evaluates Fältkrassing (Lepidium campestre), a newly domesticated Nordic oilseed with potential in short-season regions. An attributional model is first applied to permit comparison with the Renewable Energy Directive (RED) framework. The cradle-to-gate footprint for HVO is 34.1 g CO_2-eq MJ^{-1}, driven mainly by cultivation, giving a 63.7% reduction relative to the RED fossil comparator (94 g CO_2-eq MJ^{-1}) yet remaining slightly above the ≥65% requirement. A consequential model is then used to quantify system responses once co-product markets are introduced. In this framing the full upstream burden is assigned to the oil, yielding 104 g CO_2-eq MJ^{-1} before any substitution. Press-cake routing includes feed substitution, nutrient recovery, biochar, plus anaerobic digestion. Routing press cake to feed drops the footprint to 55.3 g CO_2-eq MJ^{-1} at 50% substitution and to 6.6 g CO_2-eq MJ^{-1} at 100% substitution. This sharp decline is driven by the massive avoided-emissions credit from displaced soybean meal, which outweighs the upstream process burdens. Sequential N–P–K recovery reduces the consequential footprint to 76.6 g CO_2-eq MJ^{-1} at 90% recovery. Reductions are limited by the high energy intensity of ammonia stripping and the low nutrient density of the cake relative to the HVO output. For the AD, the system reaches climate neutrality at full press cake utilization, dropping to -8.6 g CO_2-eq MJ^{-1}. The performance is optimized by combining biomethane displacement with the significant carbon sequestration potential of returned digestate. Additionally, cultivating fältkrassing on fallow land transforms the system carbon

balance. While unmanaged fallow land loses carbon over time—dropping from 27.5 to 16.1 kg C m^{-2} over 100 years—an intercrop rotation of Fältkrassing and spring barley acts as a net carbon sink, increasing SOC to 29.5 kg C m^{-2}. Monte Carlo distributions reinforce this pattern, while Sobol indices confirm limited interaction between the two parameters. The results highlight the climate mitigation potential of Fältkrassing once cultivation emissions are reduced plus viable co-product markets are secured, creating a credible pathway for a novel Nordic oilseed within future renewable-fuel supply chains.

4.03.P-Tu085 Scaling Biochar Application from Farm to National Level in Belgium: Dose-Dependent Soil Effects and Environmental Trade-Offs

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Biochar is increasingly discussed as a way to support climate mitigation in agriculture, yet many assessments focus on a single application rate or a single field-scale case. This limits understanding of how environmental performance changes when biochar use is scaled up across farms, Flanders, and Belgium, and when application rate affects not only carbon storage but also soil processes.
This study examines how different biochar application rates influence the environmental performance of biochar use for an average arable farmer and at wider regional and national scales. The work addresses four application levels: 6.5, 10, 20, and 50 tonnes per hectare. The central question is whether higher application rates improve overall environmental performance once both carbon capture and dose-dependent soil effects are considered.
To address this, a scenario-based environmental assessment is developed using life cycle modelling linked to agricultural soil processes. The analysis includes upstream supply, processing, transport, field application, and changes within the soil-crop system. In addition to carbon storage, the scenarios account for rate-dependent effects on soil emissions and agronomic functions, including changes that may affect nutrient losses, liming demand, and related field burdens. A brief heavy metal leaching evaluation is also included to examine how scaling biochar use may influence potential contaminant-related trade-offs alongside climate and soil benefits.
The study tests the hypothesis that climate benefits increase with application rate, but that broader environmental performance does not improve uniformly across categories. Higher rates are expected to strengthen carbon removal and selected soil benefits, while also increasing burdens linked to biomass demand, pre-treatment or sourcing, transport, and field operations. As a result, environmental gains are likely to be highly dependent on both application level and system configuration. The relevance of the study lies in moving beyond single-rate, field-scale biochar assessments toward a dose-sensitive and scale-aware perspective. The findings will help identify application ranges at which biochar provides meaningful environmental benefits, where trade-offs begin to dominate, and how farm-level choices translate into regional and national implications for agricultural and climate policy.

4.03.P-Tu086 A Consequential Prospective Life Cycle Assessment of a Polylactic Acid-Based Insulation Foam Panel: Comparing Static and Dynamic Approaches with End-of-Life Considerations

Hannah Peeters[1], Ben Moins[1] and Amaryllis Audenaert[1] (1)University of Antwerp

The decarbonization of the construction sector requires insulation materials with substantially lower embodied greenhouse gas emissions while maintaining thermal performance. Biopolymers such as polylactic acid (PLA) offer promising alternatives to fossil-based insulation foams due to their renewable feedstock origin, comparable properties, and potential for carbon storage during long service lives. However, the environmental impact results of bio-based materials are strongly influenced by methodological choices, particularly biogenic carbon accounting and End-of-Life (EoL) scenarios. Conventional life cycle assessment (LCA) assumes temporal and spatial non-variability, aggregating emissions irrespective of timing and location. This is especially problematic for bio-based construction materials, where biogenic carbon flows, temporary carbon storage, and delayed emissions strongly influence climate impacts.

This study presents a cradle-to-grave prospective LCA of a novel PLA-based insulation foam. The functional unit is

defined as 1 m² of insulation with a thickness that provides a thermal resistance of Rd=3 m²K/W over a 60-year building service life. Multiple EoL scenarios are modeled, including mechanical recycling, chemical recycling, incineration with energy recovery, and landfill with varying degradation rates.

In addition, static and dynamic LCA approaches are compared to assess how the timing of carbon sequestration and release influences climate change results. Static biogenic carbon accounting is implemented using the 0/0 and -1/+1 approaches, while dynamic assessment is performed using the Cherubini method, and Levasseur's dynamic LCA. A comparative analysis is conducted, to identify key differences.

The results are expected to show that both biogenic carbon accounting methods and EoL assumptions significantly influence the estimated climate impacts of bio-based materials. This work highlights the importance of consistent biogenic carbon accounting in prospective LCA of bio-based materials, and demonstrates how methodological choices can affect conclusions regarding their climate mitigation potential.

4.03.P-Tu087 Expanding circular fertigation: multi-crop life cycle inventory for hydroponic fertilization with treated human urine

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Synthetic nitrogen fertilizers contribute to environmental impacts of horticultural production, particularly climate change, eutrophication and cumulative energy demand. Nutrient recovery from source-separated human urine can reduce mineral fertilizer use and support circular food production. However, agricultural applications are often modelled with simplified substitution credits rather than crop-level inventories showing how urine-derived nutrients are produced and applied in real fertigation systems. This real case study develops a crop-cycle life cycle inventory (LCI) for 2025 hydroponic production of tomato (var. Gigawak and Montgrí), green bean and lettuce fertilized with nitrified yellow water (YW) produced on site using an activated-sludge nitrification reactor in a rooftop greenhouse in Barcelona, Spain. The study compares mineral-fertilizer control and a treatment combining YW, rainwater and complementary mineral fertilizers. The inventory uses primary data on cultivation dates, area, plants, irrigation, fertilizer additions, YW volumes, nutrient composition and yield. It includes reactor operation: electricity for aeration and pumping, potassium hydroxide for pH control, and electricity for ultraviolet disinfection. The functional unit is 1 kg of edible fresh product. Shared greenhouse infrastructure is allocated by occupied area and cultivation time, while the urine-treatment system and operational inputs are assigned by YW use and fertigation volumes. Preliminary results show that YW supplied 45.1% of crop nitrogen in tomato, 55.8% in lettuce and 47.4% in green beans. Yield responses differed among crops and tomato varieties. Gigawak tomato yielded 5.1 kg plant-1 under the control and 3.7 kg plant-1 under YW, while Montgrí obtained similar yields in both treatments, with 3.6 and 3.5 kg plant-1, respectively. Total lettuce yield was higher under YW than control, with 1.26 versus 1.16 kg. Green bean showed the same trend, with 2.16 kg for YW compared to 1.61 kg for control. These preliminary results show that treated urine can provide a relevant nitrogen share across hydroponic crops without compromising its agronomic performance although its environmental value must be assessed at crop-cycle and variety level. The resulting inventory will support a full life cycle assessment including mineral fertilizer replacement and the energy and chemical inputs required for on-site YW production and help assess options to improve circular fertigation.

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4.03.P-Tu088 Revisiting the Climate Benefits of Wood-based Products Using Future-Oriented Displacement

Factors

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Forests play a dual role in climate change mitigation: as carbon sinks and as sources for raw materials for products that can avoid emissions from concrete, glass or steel. Climate benefits of wood use are estimated with static displacement factors (DFs), despite expected changes in the future supply chains and the fact that production and end-of-life processes occur at different points in time under different technological conditions. This study applied a time-explicit life cycle inventory (LCI) approach, linking each life cycle process to the technology landscape at the time it occurs. We modelled 26 wood product archetypes across construction, energy, furniture, packaging, and chemicals and textiles, represented by 81 product-material combinations and compared against 31 functionally equivalent non-wood alternatives. LCIs were linked to prospective ecoinvent v3.11 databases generated with premise under three scenarios (SSP1-L, SSP2-M, SSP3-H). Production was modelled at 10-year intervals between 2020 and 2070; end-of-life processes were assigned to future years based on product lifetimes. Biogenic CO2 was excluded, following the established practice of reporting displacement effects and forest carbon balances separately.
Wood products generally showed lower emissions than non-wood alternatives, but displacement benefits decline over time. In 2020, the highest average DFs occurred in textiles, followed by construction and packaging. Energy applications showed low positive values, while furniture was near zero. By 2070, DFs decreased across most end-uses, most strongly in climate-ambitious scenarios. This decline was mainly driven by faster decarbonisation of supply chains of the competing products, which reduced the relative advantage of wood-based products. Production-stage impacts dominate most displacement factors. Sensitivity analyses indicate that heat-related assumptions have the largest influence, while lifetime, transport, and production losses have limited effects.
The study provides a consistent product-level understanding of future-oriented DFs for European wood use and demonstrates how time-explicit LCIs can improve the temporal accuracy of bio-based product assessments. The results confirm that wood-based products can contribute to emission reductions, but that the magnitude varies across products, declines over time, and must be considered alongside temporally resolved biogenic carbon balance of forests to draw policy-relevant conclusions.

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4.04 - Conflict between Safety and Circularity: Integrated Approaches to Inform Product and System Design

4.04.T01 End-of-Waste Assessment and Multi-Cycle Life Cycle Assessment (mLCA) Contributions to Circular and Safe Secondary Material Use

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Circular economy strategies are increasingly used to reduce resource use and retain material value. However, putting circularity ambitions into practice requires careful consideration of environmental and human health benefits due to safety and sustainability concerns related to waste-derived material inputs. Recycling pathways may unintentionally recirculate substances of concern. This presentation uses the Dutch Circular Materials Plan as a case example of how circular, societally beneficial recycling routes can be substantiated for the safe use of secondary materials.

A material derived from waste must satisfy end-of-waste criteria under the EU Waste Framework Directive before it can re-enter the market. This requires a structured assessment of hazards and exposure related to regulated substances (such as Substances of Very High Concern), as well as other substances of potential concern, to demonstrate that no residual risk to the environment or human health is expected in the intended application after recycling.

However, demonstrating safety alone is not always sufficient to justify that a circular pathway provides long-term societal benefits. When it is uncertain whether a waste treatment approach performs as well as, or better than, the minimum requirements for handling a waste stream in accordance with the waste hierarchy, the Dutch framework combines end-of-waste assessment with a novel multi-cycle life cycle assessment approach.

The multi-cycle Life Cycle Assessment (mLCA) quantifies environmental impacts across several successive life cycles, allowing the benefits and burdens of secondary material use to be evaluated beyond a single product system. This makes it possible to test whether a recycling pathway delivers environmental gains over conventional waste treatment approaches while accounting for value retention over multiple cycles.

In this presentation, we will describe both approaches and provide a hypothetical case study derived from our work in the field. This combined approach enables the assessment of both safety and sustainability aspects, as promoted by the Safe and Sustainable by Design (SSbD) framework, however, the focus on waste recycling is more suitable to practical, real-life regulatory compliance than the SSbD focus on design iterations.

4.04.T02 A Fully Automated Life Cycle Assessment Model for SSbD-Driven and Circularity-Oriented Lubricant Design

Jonas Hoffmann[1] and Max Frederik Bringmann[1] (1)GreenDelta

Lubricants keep industries in motion, both literally and figuratively. In industrial and transport systems, they reduce friction, wear and oxidation in a wide range of applications. Sustainability assessment approaches promoted by industry associations increasingly focus on “carbon handprints”, highlighting avoided emissions from improved energy efficiency during use. However, these approaches often rely on narrow system boundaries that highlight operational benefits while neglecting downstream environmental burdens. Losses in use, uncollected waste lubricant oil (WLO), and impacts from WLO treatment are typically excluded in Europe. As a result, problematic additive chemistries, such as chlorinated paraffins, benzotriazoles and per- and polyfluoroalkyl substances (PFAS), may pose environmental pressures, influence lubricant fate by limiting re-refinabiltiy of the whole lubricant.
Driven by regulatory pressure and environmental incentives, such as the the Safe and Sustainable by Design (SSbD) framework, producers face challenges in identifying viable alternatives to such substances. This work contributes to addressing this gap by developing a fully automated, parameterised life cycle assessment model to support early-stage evaluation workflows of lubricant formulations over the whole life cycle following the SSbD framework. The model integrates generic, application-specific lubricant fate data with composition-based parameterisation of formulations. Chemical composition is derived from component distributions and linked to downstream fate modelling of collected WLO, incorporating known circularity inhibitors and treatment pathways. The automated workflow enables rapid assessment without labour-intensive specific modelling.
Preliminary results for selected use cases, including PFAS, benzotriazole and chlorinated paraffin formulations, demonstrate the model’s capability to identify environmental risk hotspots along the supply chain. Emissions such as hydrofluoric and hydrochloric acid from combustion, as well as direct toxicological impacts, are quantified based on composition. Additionally, the influence of formulation design on WLO treatment routes and circularity addresses recyclability according to the SSbD framework. The proposed model advances lubricant sustainability assessment by expanding system boundaries and enabling scalable evaluation of alternatives, supporting informed decision-making and practical implementation of SSbD principles.

4.04.T03 From Waste to Value? Navigating Trade-Offs in Apple Side-Stream Valorisation

Sini Valmari[1] (1)Natural Resources Institute Finland

Food loss and waste are increasingly recognised as both an environmental burden and a potential resource within circular bioeconomy systems. In Finland, significant quantities of surplus apples from households, public green areas, retail and processing remain underutilised, despite their content of valuable bioactive compounds.

This study aims to develop and assess a circular model for valorising apple side streams into higher-value applications, including food and health-related products, as well as energy and nutrient recovery. However, the feasibility of such pathways depends on multiple interacting factors, including material quality, logistics, processing requirements, regulatory constraints and economic conditions. International examples, such as apple-pomace-based materials in regions with concentrated apple processing, suggest that high-value valorisation is strongly shaped by local industrial ecosystems.

The approach combines side-stream mapping, pilot-scale collection and logistics modelling, analysis of bioactive compounds, and evaluation of alternative utilisation pathways. A prospective life cycle assessment framework is applied to compare current waste management practices with valorisation scenarios, taking into account substitution effects, logistics-related impacts and potential burden shifting. The study develops a decision-oriented framework linking material quality, logistics constraints and life cycle impacts to allocation choices across competing pathways.

Particular attention is given to trade-offs between environmental performance, economic feasibility and material quality in determining optimal allocation strategies. In some contexts, decentralised valorisation may be constrained by high collection and processing costs, while in others it may provide environmental and regional benefits compared to conventional supply chains.
Rather than treating circularity as an objective in itself, the study examines under which conditions apple side-stream valorisation is justified, including in more dispersed systems where side-stream availability, logistics and scale differ from centralised processing regions. The results are expected to support decision-making for municipalities, producers and industry, and contribute to life cycle approaches for designing viable circular bio-based systems under real-world constraints.

4.04.T04 Towards Safe and Sustainable Bioaromatics: Techno-Economic and Life Cycle Assessment of Lignin-Derived Phenolics.

Laurent Astruc[1] and Albane Bauby[2] (1)Dr, (2)Engineer

The European Green Deal and the Chemicals Strategy for Sustainability aim to accelerate the transition to safer and more sustainable chemicals by promoting the phase-out and substitution of harmful substances, including Substances of Very High Concern (SVHC). Many SVHC used in high-volume applications are phenolic derivatives (alkylphenols, bisphenols, etc.) and substitutes safe across the full life cycle that maintain performance are urgently needed. Bioaromatics derived from biomass have emerged as promising alternatives, with increasing evidence of improved hazard profiles versus fossil-based counterparts. In particular, Lignin-Derived Phenolics (LDPs) are attractive candidates. Lignin is an abundant aromatic biopolymer present in diverse plant-based feedstocks, including agricultural residues and post-consumer paper and cardboard waste, and represents a major renewable source of aromatic building blocks.
Recent advances in catalytic depolymerisation enable efficient conversion of lignin into phenolic monomers. The resulting streams contain functional monomers (e.g. bisguaiacols) that can serve as bioaromatic templates for developing safer and more sustainable alternatives to commercially important phenolic chemicals.
Within the RADAR project (Renewable and safe Aromatic compounds As Replacements for substances of concern), the objective is to design renewable, locally sourced biomass-based substitutes for SVHC used in surfactants, flame retardants, and can-coating applications. RADAR applies a Safe-and-Sustainable-by-Design (SSbD) approach integrating innovative hazard assessment with life cycle-based methods. Targeted SVHC include bisphenols, tetrabromobisphenol A, alkylphenols, and ethoxylated alkylphenols.
As an industrial partner, Syensqo contributes by evaluating LDP production routes through combined techno-economic assessment (TEA) and life cycle assessment (LCA). The LCA focuses on various environmental impacts, while the TEA addresses production costs, scalability, and sensitivity to key process and market parameters. Initial results indicate that, at current laboratory scale, LDP routes exhibit higher environmental impacts and costs than fossil

benchmarks, mainly due to energy intensive demand and waste requiring treatment. These results reflect non-optimised lab-scale operation; significant improvements are expected through scale-up and process optimization, notably via energy integration and reduced waste formation.

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4.04.T05 Ecodesign of Lubricants for Bottle Conveyors – the BBBC CLEANLUBE Project

Angélique Léonard[1] (1)Liège Université

The calls for proposals published under the Belgium Builds Back Circular (BBBC) initiative aim to accelerate Belgium's transition towards a circular economy. They are part of the National Plan for Recovery and Resilience (NPRR). This call is aimed at supporting innovation initiatives to bring to the market alternative chemicals, technologies, and/or products that eliminate the use of substances of concern or their presence in a product (1).
The CLEANLUBE project, led by Sopura, is transforming the way industrial lubrication is approached by developing greener, safer solutions for bottling lines and conveyor belts. Traditional lubricants often contain substances that are harmful to both humans and the environment. CLEANLUBE sets out to replace these with high-performance alternatives that align with modern sustainability goals, such as "no amine" detergents.
A comprehensive life cycle assessment (LCA) model is under construction to compare the environmental impact of legacy formulations against the new green alternatives. This analysis will offer valuable insights into sustainability gains and help guide future product development with measurable impact. (1)
The University of Liège – Chemical Engineering is in charge of evaluating the environmental and social impacts of the common formulations and the innovative proposals developed in the CLEANLUBE project.
One of the main issues was the absence of the chemicals used by Sopura in the available common databases such as ecoinvent or Environmental Footprint. The first step was in consequence to model these chemicals in order to be able to include them in the Life Cycle Assessment of both the commercial formulations but also the updated version developed by partners. Different approaches were implemented, including the RREM proposed by Huber et al. (2022), global bibliographical research, and AI helps (to be used with caution and after verifications).
The results so far are somewhat mixed, in that the new formulations contain a higher concentration of active ingredients than the basic formulations.
Concertation with industry should be done to ensure how the final products can be implemented since they are diluted before use in the conveyors.
For the social assessment, the basis formulas have been analyzed following the UNEP recommendations, and with the risk mapping tool.
(1) https://economie.fgov.be/en/themes/enterprises/calls-projects/belgium-builds-back-circular-3

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Huber, E., Bach, V., Holzapfel, P., Blizniukova, D., & Finkbeiner, M. (2022). An approach to determine missing life cycle inventory data for chemicals (RREM). Sustainability, 14(6), 3161.

4.04.P - Conflict between Safety and Circularity: Integrated Approaches to Inform Product and System Design

4.04.P-Tu089 Environmental Sustainability Assessment of Innovative Fire-retardant Formulations at Pilot Scale

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The transition toward safer and more sustainable fire retardant solutions requires robust environmental assessment frameworks to support eco-design from early development stages. This study presents a comparative environmental sustainability assessment of innovative fire retardant formulations developed at pilot scale. In parallel, alternative life cycle assessment modelling of early-stage fire retardant recipes is applied to evaluate the influence of formulation choices on environmental performance and to support eco-design optimization. The assessment is performed following the life cycle assessment methodology in accordance with ISO 14040 and ISO 14044. A performance-based functional unit is defined to ensure comparability between alternative formulations providing equivalent fire safety performance. Sixteen impact categories are considered to quantify potential impacts across resource use, climate change, ecosystem quality, biodiversity, and pollution. Life cycle inventory is developed to represent pilot-scale production processes. Alternative fire retardant formulations are evaluated relative to a conventional baseline scenario using a consistent functional framework. Contribution and hotspot analyses are conducted to identify key drivers of environmental impacts. In addition, an absolute environmental sustainability evaluation is performed following the Safe and Sustainable by Design framework. The results enable the identification of environmentally preferable formulations and provide quantitative insights into trade-offs environmental impacts under the assumption of equivalent fire safety performance, as defined by the performance-based functional unit. he combined use of pilot-scale data, early-stage modelling, and performance-based comparison demonstrates the potential of life cycle assessment to guide formulation development and support informed decision-making in the design of safer and more sustainable fire retardant systems.

4.05.P - Nature's Feedstocks: LCA of Emerging Bio-Based Products and Processes

4.05.P-Tu091 Insect Frass Fertilizer in Circular Agriculture: A Life Cycle Perspective

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This contribution presents a life cycle–based assessment of insect frass fertilizer within bio-based and circular agricultural systems. The study applies life cycle assessment (LCA) in line with EF 3.1, covering feed production, insect cultivation, processing, transport, and soil application.

The results identify key environmental hotspots related to feedstock selection, energy use during cultivation, and emissions from soil application, highlighting leverage points that are also relevant for soil-related ecosystem services such as nutrient cycling and soil quality. The comparative perspective illustrates that the environmental performance of frass fertilizer is highly context-dependent, emphasizing the need for integrated assessment frameworks that go beyond single impact categories.

Overall, the study positions insect frass fertilizer as a promising component of circular agri-food systems by supporting nutrient recycling and resource recovery, while underlining the importance of incorporating ecosystem services into life cycle–based decision-making for bio-based solutions.

4.05.P-Tu092 Sustainability Assessment of a Cascading Valorization Route for Invasive Crayfish in Austria

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Invasive crayfish species pose a serious threat to biodiversity in Austrian waterbodies, primarily through competition with native species and transmission of the crayfish plague. By combining stock management with innovative economic solutions, benefits can be generated for the environment as well as society. However, robust sustainability assessment is essential to such novel approaches so that unintended trade-offs may be prevented and truly beneficial outcomes ensured.

This study presents the results of a sustainability evaluation for a novel cascading valorization route currently being developed for invasive crayfish in Austria. The route integrates fishing of invasive crayfish, gastronomic use of the meat, fermentation of shells to produce garum, and subsequent chitin extraction for bioplastic production using green

chemistry approaches. Thus, decentralized circular economy strategies are combined with green chemistry approaches and measures to protect biodiversity in regional waterbodies.
The presented sustainability assessment focusses on Life Cycle Assessment (LCA) to evaluate environmental impacts across all stages of the valorization chain using primary data from fishing and fermentation processes and literature data for chitin extraction. Environmental impact assessment is complemented with economic and social evaluations, including price calculations and qualitative insights from structured interviews, in order to reach a holistic evaluation of all sustainability aspects of the valorization route.
The aim of the study is to identify environmental hotspots within the valorization system and derive recommendations to further optimize the route toward an ecologically robust solution that also offers economic and social benefits.

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4.05.P-Tu093 Environmental Performance of Tenebrio molitor Protein Powder

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Insect-based proteins for human consumption are increasingly promoted as a sustainable alternative to livestock-derived proteins, primarily due to their higher feed conversion efficiency and potentially lower resource requirements. Conventional livestock systems typically show feed conversion ratios of 4.5-7.5 for cattle, 2.5-3.5 for pigs, and 1.5–2.0 for poultry, whereas insects have been reported to achieve ratios between 1.5 and 2.2, suggesting a greater potential for efficient conversion of feed into edible protein. This suggests reduced demand for resources such as feed, land, and water. However, such advantages are highly dependent on production conditions and feed substrates. Robust life cycle assessment (LCA) studies are therefore essential to critically evaluate the environmental performance of insect-based protein systems.
This study presents a cradle-to-gate LCA of Tenebrio molitor protein powder intended for human consumption. The system boundaries encompass all processes from raw material production to the facility gate, including breeding (maternity), larval rearing (bioconversion), biomass separation, thermal processing (inactivation and drying), milling, and powder packaging. Primary data were collected directly from an insect-rearing and processing facility operating under commercial conditions in Portugal.
The functional unit is the production of 1 kg of edible T. molitor protein powder on a dry-matter basis. Insect frass was modelled as a co-product valorised as a biofertiliser. Background processes, including wheat bran production (feedstock) and energy supply (electricity and natural gas), were sourced from the Ecoinvent and AGRIBALYSE databases. Environmental impacts were assessed using the Environmental Footprint (EF) method, covering categories such as climate change, eutrophication, acidification, and ecotoxicity.
Results identify wheat bran production and electricity consumption during bioconversion and processing as the main environmental hotspots across most impact categories. Climate change impacts were estimated at 4.17 kg CO_2 eq per kg of edible T. molitor protein powder.
Overall, the study provides quantitative evidence on the environmental performance of T. molitor-based protein powder and highlights key leverage points for impact mitigation, supporting informed decision-making toward more sustainable protein production systems.

4.05.P-Tu094 Assessing the Economic Sustainability of Insect-Based Foods: TEA and LCA of Tenebrio Molitor–Enriched Cereal Bars

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This study provides policy-relevant evidence on the economic and energy performance of insect-based foods, focusing on cereal bars incorporating Tenebrio molitor flour as a partial substitute for wheat flour. Using an integrated Techno-

Economic Assessment (TEA) and Life Cycle Assessment (LCA), the analysis quantifies production costs, energy demand, and scale effects across the full value chain, from mealworm rearing and processing to final cereal bar manufacturing. The results show that the inclusion of Tenebrio molitor flour significantly alters the cost structure of production, with energy consumption—particularly for climate-controlled rearing, drying, and processing—identified as the dominant cost driver. Raw material processing and electricity sourcing emerge as key techno-economic hot spots shaping overall feasibility.

Scenario analysis indicates that economic performance improves substantially under large-scale production configurations, where economies of scale reduce unit costs and improve returns on investment. In addition, scenarios incorporating renewable electricity investments demonstrate lower exposure to energy price volatility and improved long-term cost performance compared with reliance on national grid electricity. These findings highlight the importance of energy efficiency, decarbonized energy supply, and industrial scale-up in enabling the economic sustainability of insect-based food products.

The results are closely aligned with the objectives of the European Green Deal, particularly its focus on decarbonization, energy efficiency, and sustainable industrial transformation. By explicitly linking food production systems with energy infrastructure, the study also supports the goals of EU strategies aimed at improving energy security and resilience. Furthermore, the findings contribute directly to the Farm to Fork Strategy by providing quantitative economic evidence on feasible pathways for protein diversification beyond conventional livestock systems.

Finally, the analysis complements the EU Novel Foods framework by extending the assessment of insect-based foods beyond safety and nutrition to include economic sustainability under realistic industrial conditions. Overall, this study demonstrates the value of integrated TEA–LCA approaches as decision-support tools for designing coherent EU policies that connect sustainable food innovation with the energy transition and long-term industrial competitiveness.

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Track 5: Resource efficiency and critical raw materials management

5.01 - Assessing Emerging Energy Systems to Foster the European Energy Transition

5.01.T01 Prospective Life Cycle Assessment of Defossilized Synthesis gas Production via Co-Electrolysis

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Synthesis gas (syngas), a key precursor for producing synthetic fuels, methanol, and other chemicals, is conventionally produced from fossil-based sources (e.g., natural gas reforming and coal gasification). Co-electrolysis in high-temperature solid oxide electrolysis cells (SOEC) can provide an environmentally friendly alternative for converting CO2 and H2O into syngas using renewable energy sources.
The environmental performance of co-electrolysis depends on the electricity mix, CO2 source, heat supply, stack efficiency, maintenance and material composition. Moreover, SOECs contain nickel, zirconium, yttrium, lanthanum, cobalt and other rare elements. Most of these are listed as critical by the European Union.
This study employs a prospective Life Cycle Assessment to assess the environmental hotspots, benefits, and trade-offs of syngas production via co-electrolysis, using a system to be tested at demonstration scale within the PHOENIX project.
The prospective foreground inventory comprises project-related primary data, assumptions and secondary data from literature and databases. The prospective background system is defined using scenarios for a future electricity mix and energy system, based on up-to-date energy-mix data, as well as integration of the premise data package for the energy system. The models are developed using the Brightway2.5 software package.
Following a bottom-up approach, the assessment identifies the processes and flows that contribute to the environmental performance of syngas production via high-temperature SOEC. Preliminary results provide an initial overview of hotspots, climate benefits, disadvantages, and the conditions under which co-electrolysis may contribute to the de-fossilisation of the chemical industry.
The findings of this study provide support at an early stage of development for decision-makers and involved technology developers working on the employment of high-temperature SOEC and its co-electrolysis application, as well as prospective information for broader efforts to defossilise syngas production.

5.01.T02 Navigating The Valleys Of Death Through Eco-Design: Methodological Principles For Prospective Life Cycle Assessment Of Emerging CO2 Valorization Technologies At Various Development Stages

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Climate change is driven by rising greenhouse gas emissions, particularly CO_2 from fossil fuels and industry. Carbon capture and utilization (CCU) offers a mitigation pathway by converting CO_2 into fuels, chemicals, and materials. However, the environmental and economic performance of CCU technologies depends on Climate change is driven by rising greenhouse gas emissions, particularly CO_2 from fossil fuels and industry. Carbon capture and utilization(CCU) offers a mitigation pathway by converting CO_2 into fuels, chemicals, and materials. However, the environmental and economic performance of CCU technologies depends on technological maturity, energy inputs, and market conditions, making systematic assessment essential. This is particularly critical at transition points, called “valleys of death”, where moving between laboratory, pilot, and demonstration stages involves heightened technical and financial risks. Prospective life cycle assessment(LCA) is widely used to evaluate emerging technologies. Yet, results can vary significantly depending on the assumptions about the technological evolution and the dynamic development of e.g. renewable energy and CO2 markets. This raises a key question: how can future technology performance be estimated across different market contexts to inform “GO/NO-GO” and “WHERE TO GO” decisions at various development stages?
To inform technology design, this research extends the Global CO2 Initiative guidelines for LCA and techno-economic assessment (TEA) for CCU by integrating TEA feedback into LCA, incorporating prospective LCA scenario

modelling, and explicitly accounting for variability across technology readiness levels(TRLs). Using a TRL-6 CO_2 electrolysis prototype as a proof-of-concept, it proposes a novel iterative, tiered approach distinguishing three feasibility domains.
Different modelling principles apply at each tier, informed by technological risk, uncertainties and learning effects. Across all tiers, key criteria apply: demonstrated positive net present value(NPV); NPV accounting for projected carbon prices, i.e. outputs should not exceed the projected value of CO_2; and cradle-to-gate emissions not exceeding those from CO_2 capture. Beyond data accuracy, the main distinction between tiers lies in the definition of the functional unit(s) based on technological design. This TRL-tiered prospective LCA framework supports development decisions and helps emerging technologies navigate the innovation "valleys of death".

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5.01.T03 Integrating Large Language Models and Environmental Learning Theory for Prospective Life Cycle Assessment of e-Formaldehyde Production

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The transition towards climate-neutral societies calls for innovative Power-to-X solutions to reduce environmental impacts. The emerging Power-to-Formaldehyde (PtF) technology offers a promising route to convert renewable electricity and captured CO2 into green e-formaldehyde. However, data scarcity and uncertainty about future technological improvements pose a challenge for assessing environmental feasibility. This study addresses this knowledge gap by integrating environmental learning theory, generative artificial intelligence, and process modelling to construct environmental learning curves and forecast the environmental impacts of the PtF technology, accounting for advancements in both foreground and background systems.

Environmental learning curves are constructed by sequentially developing first-of-a-kind (FOAK) and nth-of-a-kind (NOAK) PtF production plants, which are modelled using the ASPEN Plus V14 software. Environmental learning effects are captured by optimising and scaling up production, combining robust process modelling with Large Language Model (LLM)-guided flowsheeting and creative synthesis. The proposed novel and optimised configurations are validated via ASPEN Plus v14 simulations. The environmental learning curves are used to quantify environmental progress within foreground system processes. Shared Socioeconomic Pathways (SSPs), climate policies, and the premise framework are applied to assess background system dynamism and conduct a comprehensive prospective life cycle assessment (pLCA) between 2030 and 2055.

Subsequent NOAK configurations of PtF plants show superior technological and environmental performance, achieving significant reductions in energy consumption and prospective environmental impacts. Quantified explorative environmental learning rates range from 5.5% to 16.4%, indicating substantial opportunities for further improvement in environmental performance. The findings underscore the potential of LLMs to fill key gaps in inventory data for early-stage technologies, while emphasising the need for thorough and independent validation. By incorporating quantified environmental learning rates into prospective LCAs, this study advances the development of assessment frameworks for emerging technologies, supporting informed decision-making while avoiding prospective temporal inconsistencies between foreground and background system processes.

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5.01.T04 Environmental Impacts of Future International Hydrogen Transport Value Chains: Implementation and Case Study using premise

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Prospective LCA (pLCA) studies of the growing hydrogen sector under Net-Zero targets in Europe typically focus on hydrogen production, while international distribution is modelled in lower quality in background databases. Yet, since the projected quantities of hydrogen and its derivatives cannot fully be produced locally economically, imports from regions with surpluses of renewable energy are likely. New trade routes will emerge, transporting hydrogen and its derivatives across the oceans. Due to its low volumetric energy density, hydrogen will be converted into other energy carriers. Ammonia is one promising option as a hydrogen transport vector, shipping fuel and product itself.
In premise, a widely used python package for pLCA based on scenarios from Integrated Assessment Models (IAMs), international hydrogen transport is currently represented by generic inventories that do not reflect the complexity of emerging hydrogen trade at scale. This includes hydrogen derivatives as alternative fuel technologies for transport and distribution as well as their future developments.
This study fills that gap by consistent implementation of improved hydrogen transport and trade modelling into the premise python package. A case study on hydrogen transport as ammonia that quantifies the differences in environmental impacts between the current generic premise modelling and the improved implementation of trade routes under selected Net-Zero scenarios from IAMs is presented.
The implementation and findings of this study contribute to decision making in developing sustainable technologies for the energy transition. Furthermore, LCA practitioners are provided with the possibility to assess implications of future environmental impacts of hydrogen distribution in greater detail than currently possible.

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5.01.T05 Best Practices in Environmental Life Cycle Assessments of Hydrogen Valleys

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Hydrogen valleys are geographically defined ecosystems that integrate the full hydrogen value chain, from renewable hydrogen production to storage and end-use applications. By clustering these value chain steps, valleys create synergies that accelerate the decarbonization of the energy, industry and transport sectors.

Evaluating their environmental performance holistically, covering all material and energy flows across the valley, is essential as the impacts cover the entire value chain, from the source of electricity to the downstream hydrogen utilization. Quantifying these impacts does not only provide a baseline picture of their environmental performance, but can also identify hotspots across the value chain and inform policymakers and investors, providing actionable insights for strategic decisions. Yet, to date no comprehensive guidance exists on performing a life cycle assessment of such complex systems.

This study addresses the gap by proposing a set of recommendations and best practices, following the Organization Environmental Footprint method of the European Commission. This approach treats the hydrogen valley as a single organizational entity, mapping its boundaries, defining its product portfolio based on the end-use stage and outlining how to construct a comprehensive life cycle inventory for each step of the hydrogen value chain.

A set of recommendations for every life cycle assessment phase is provided, covering the goal and scope definition, inventory analysis, impact assessment and interpretation. The recommended best practices can be adapted to the specific goals of a study, as different objectives may require distinct methodological approaches. By adopting these best practice recommendations, practitioners can produce transparent, comparable and policy-relevant assessments that support the sustainable development of hydrogen valleys across Europe.

5.01.P - Assessing Emerging Energy Systems to Foster the European Energy Transition

5.01.P-Mo059 Prospective Life Cycle Assessment of hydrogen production combined with desalination in Tunisia for advancing national and EU energy transitions

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Hydrogen is expected to be a key component of future decarbonised energy systems. The European Union is increasingly relying on regions with abundant renewable resources to meet its projected hydrogen demand. Tunisia, with its high renewable energy potential, its strong commitment to developing a national hydrogen economy, and its strategic position for supplying hydrogen to Europe, is well positioned to contribute to both its own energy transition and that of the EU. However, producing green hydrogen via water electrolysis can intensify pressures on water scarce regions due to the substantial need for water. In coastal areas, seawater desalination can provide this input, although brine discharges may pose risks to marine ecosystems. A prospective assessment of these implications is therefore essential.

This study examines how environmental impacts of seawater based hydrogen production in water scarce coastal regions could be mitigated by 2050 using a prospective Life Cycle Assessment (pLCA) framework. Two desalination–electrolysis pathways are assessed in combination with proton exchange membrane electrolysis. Pathway 1 considers Reverse Osmosis (RO) desalination process with explicit modelling of cooling demand for electrolysis, while Pathway 2 integrates waste heat from electrolysers into a membrane distillation (MD) desalination process. Future developments are captured through scenario modelling of Tunisia's electricity mix to 2050 and complemented with sensitivity analysis to evaluate the influence of cooling configurations and extreme future scenario frameworks. Results indicate that desalination based hydrogen can significantly reduce greenhouse gas emissions relative to fossil-based options, but increased desalination and cooling requirements elevate marine ecotoxicity risks. These findings highlight a clear trade-off between climate benefits and marine impacts. Pathway 2 shows the lowest climate burden and reduced water demand. Sensitivity analysis shows that the cooling system configuration is a dominant driver of environmental performance.

This study advances methodological developments in pLCA by combining modelling of water treatment, thermal management, and future-oriented environmental modelling. The findings support the design of resource-efficient hydrogen systems and provide decision-relevant insights for planning large-scale Power to X infrastructures in water scarce coastal regions supplying future energy systems.

5.01.P-Mo060 Advancing Life Cycle Assessment of PEM Water Electrolysis: Prospective Time-Resolved Modelling with Closed-Loop Catalyst Recycling

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The construction of proton exchange membrane water electrolysis (PEMWE) plants relies on critical platinum group metals (PGMs) for catalysts. Circular business models like leasing—where manufacturers lease plants to operators—are emerging to enable strategic recovery of catalysts after decommissioning through recycling and reuse in subsequent stack generations. Concurrently, PEMWE technology evolves rapidly with short innovation cycles, allowing multiple stack generations within one plant's lifespan. Accurate environmental impact assessment of this dynamic technology requires time-resolved prospective life cycle assessment (pLCA).

This study presents a first-of-its-kind, time-resolved pLCA of a 5 MW PEMWE plant incorporating closed-loop recycling for catalyst materials using the cut-off end-of-life approach. The functional unit is hydrogen production over a 20-year lifetime starting in 2026.

The model integrates closed-loop recycling and anticipated technological improvements in future PEMWE generations. Electrolyzer stacks are replaced once after 80,000 full-load hours in 2036; other components remain unchanged. Significant advances are expected within this period. The replacement stack (gen 2) offers higher current density, lower cell voltage, and substantially reduced material demand compared to the initial stack (gen 1). Gen 2 has a nominal power of 5 MW—twice gen 1's—so two 2.5 MW gen 1 stacks are replaced by one 5 MW gen 2 stack in 2036. The gen

1 stack, made exclusively from virgin materials, is decommissioned in 2036. The gen 2 stack uses secondary PGMs from recycling gen 1 stacks of a different plant; all other materials are virgin. The gen 2 stack's PGM end-of-life is modelled after final plant decommissioning in 2046 with the cut-off approach.
PGM demand declines across generations. Two gen 1 stacks contain 5,306 g PGMs total, while one gen 2 stack requires 982 g. With a 95% recycling rate, gen 1 stacks supply over 513% of gen 2's PGM needs, creating a multifunctional product system resolved per ISO 14040/44 standard. Product system modelling uses Brightway 2.5 with bw_timex and premise.
This circularity-based, time-resolved prospective model tracks resource demands across multiple technology generations and highlights options for critical resource reduction and future procurement. It also reveals the temporal development of environmental impacts over the plant's life cycle, contextualizable against emission targets and planetary boundaries.

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5.01.P-Mo061 Scaling Green Hydrogen From Renewable Energy Sources as a Natural Gas Substitute for Pharmaceutical Process Heat: an LCA-Based Scenario Analysis

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The pharmaceutical industry depends heavily on natural gas for process heat generation, making it a notable contributor to industrial greenhouse gas emissions. Decarbonizing industrial energy supplies is critical to meet climate policy objectives and corporate sustainability commitments, and to reduce dependence on fossil supply chains.
This attributional life cycle assessment (LCA) estimates the environmental impact of substituting natural gas with green hydrogen to supply process heat to a pharmaceutical facility in Austria. Given the intermittency of renewable sources for green hydrogen, the influence of various storage solutions is addressed as well.
The LCA varies the renewable energy source, storage integration, and the degree of natural gas substitution. It takes a cradle-to-gate approach, encompassing electricity generation, electrolytic hydrogen generation, storage where applicable, and gas combustion. The focus lies on two main pathways for green hydrogen use: First, hydrogen produced via electrolysis powered by surplus electricity from an on-site photovoltaic system, with a share of that electricity temporarily stored in a battery before conversion, and the resulting hydrogen subsequently stored for later use; second, hydrogen produced via electrolysis driven directly by photovoltaic or wind power, without intermediate battery storage. Scenarios are scaled up to a hypothetical replacement of the facility's entire natural gas demand. The scenarios are benchmarked against a reference natural gas-only system, with additional comparisons across different natural gas supply scenarios, including liquefied natural gas (LNG) and pipelined natural gas from various countries of origin, to account for supply-chain variability in the fossil baseline.
Preliminary results indicate that both pathways can significantly reduce greenhouse gas emissions. However, scaling the system introduces trade-offs in other impact categories, particularly those associated with the manufacturing of electrolysers and battery components, and the differences between the two pathways increase at larger scales.
The study illustrates how LCA can provide a robust, scenario-based foundation for decisions involving energy transitions in industry. It offers a transferable methodological framework for optimal decarbonization of process-heat-intensive sectors and can thus inform industry strategies that contribute to European energy independence and align with the EU Green Deal goals.

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Research Association.

5.01.P-Mo062 Advancing the Environmental Assessment of Emerging Power-to-X Technologies: Case of Electrochemical CO2 Reduction

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Emerging technologies are essential to enable the European energy transition while maintaining global competitiveness. Power-to-X (PtX) pathways are promising solutions to convert renewable electricity into synthetic fuels, contributing to decarbonization targets under the Paris Agreement. Among these, electrochemical CO2 reduction (eCO2R) offers a novel route to produce synthetic fuels from carbon dioxide and electricity. This study assess the environmental impacts of e-diesel production via syngas from eCO2R coupled with Fischer–Tropsch (FT) synthesis, using a Life Cycle Assessment (LCA) approach.

An LCA was conducted for an integrated system comprising CO2 capture, electrolyzer manufacturing and operation, downstream gas separation, and FT synthesis in a 1 MW plant. The functional unit is defined as 1 MJ of e-diesel A parametric life cycle inventory (LCI) was developed to represent key system variations, including CO2 source (flue gas vs. direct air capture) and the need for supplementary H2 electrolysis to meet syngas requirements. This approach enables the representation of non-linear effects and interdependencies across process stages, including implications for material demand in electrolyzer manufacturing and operation. The foreground was compiled combining primary data and literature sources while ecoinvent v3.8 was used for background data. Environmental impacts were assessed using the Environmental Footprint (EF) 3.1 method, focusing on climate change.

Electrolyzer operation dominates global warming potential (GWP), contributing approximately 50% of impacts, followed by gas separation (36%) and CO2 capture (8%) when CO2 is sourced from flue gas. Electrolyzer manufacturing contributes <5%. The high energy demand explains this profile, highlighting the importance of electricity supply. The CO2 source also plays a key role, with direct air capture showing potential for net-negative GWP under specific conditions.

The environmental sustainability of eCO2R-based e-diesel is highly sensitive to electricity source, CO2 feedstock, and faradic efficiency. For electrochemical reduction technologies, operational energy inputs outweigh manufacturing related impacts for GWP. Substituting the electricity supply with renewable electricity and the selection of CO2 source is critical to produce synthetic fuels with a positive environmental impact.

5.01.P-Mo063 Resource Efficient Deployment of Sustainable Aviation Fuels Using Integrated Life Cycle Assessment and Techno Economic Analysis

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Sustainable aviation fuels are expected to play a central role in reducing aviation emissions, yet their large scale deployment is constrained by limited availability of sustainable biomass, renewable electricity, hydrogen and carbon sources. Conventional life cycle assessment approaches primarily compare pathways based on carbon intensity, but do not capture how efficiently these constrained resources are used to displace fossil aviation fuel.
This study develops an integrated life cycle assessment and techno economic framework to evaluate the resource efficiency of multiple sustainable aviation fuel pathways under realistic deployment conditions. Ireland and Japan are used as contrasting case studies, reflecting different resource availability and energy system characteristics, with prospective scenarios explored to 2050.

The analysis considers thermochemical and synthetic pathways, including hydrothermal liquefaction of sewage sludge and algae, fast pyrolysis and Fischer Tropsch conversion of forestry residues, and methanol to jet routes using captured carbon dioxide and methane derived carbon. Process modelling is based on harmonised mass and energy balances to

ensure consistency between environmental and economic assessment. Scenario specific assumptions are applied for electricity supply, process heat options including natural gas, biomethane and solid biomass combustion, feedstock availability and transport.

In addition to carbon intensity and production cost, a resource based indicator is introduced, defined as fossil carbon displaced per unit of constrained resource, including feedstock, electricity, hydrogen and carbon dioxide. This enables direct comparison of how effectively pathways utilise limited resources and supports assessment of trade offs between emissions, cost and resource use.

Preliminary results suggest that pathways with similar carbon intensities can differ substantially in their resource efficiency and cost structure, with electricity demand and feedstock availability emerging as key limiting factors. The framework is further used to estimate the potential contribution of each pathway to national sustainable aviation fuel targets and the associated resource requirements.

This work demonstrates how integrated life cycle approaches can support the resource efficient deployment of sustainable aviation fuels, providing decision relevant insights for energy system planning and policy under conditions of resource constraint.

5.01.P-Mo064 Coupling Life Cycle Assessment and Techno-Economic Assessment of Advanced Anion Exchange Membranes: Insights from the AEMELIA European Project

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The transition toward low-carbon hydrogen and circular chemical processes requires the development of high-performance and durable membrane materials. Within this context, the European AEMELIA project aims to advance next-generation anion exchange membranes for green hydrogen production, with a focus on improving efficiency, lifetime, and sustainability.

As an industrial partner, Syensqo is involved in the development and scale-up of innovative membrane materials, contributing its expertise in polymer chemistry and industrialization pathways. To support decision-making from early-stage development to potential commercialization, a combined Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA) has been conducted on the AEMELIA membrane system.

The study evaluates both the environmental impacts and the economic performance of membrane production. The LCA focuses on key impact categories such as climate change, resource use, and human toxicity, while the TEA assesses production costs, scalability, and sensitivity to key parameters (e.g., material composition, lifetime, and manufacturing processes).

Preliminary results highlight the main environmental hotspots associated with membrane production, particularly those related to precursor synthesis and energy consumption during processing. The integration of TEA and LCA enables the identification of trade-offs between cost reduction and environmental performance, thereby guiding material design and process optimization.

This work demonstrates how the early integration of TEA and LCA can support the development of more sustainable membrane technologies and accelerate their deployment in electrochemical systems.

The findings provide actionable insights for both industrial stakeholders and research partners within the AEMELIA project. In addition, this study aims to generate high-quality primary industrial data for membrane production, contributing to more robust and representative LCAs of the overall hydrogen production value chain. This effort supports improved transparency and accuracy in sustainability evaluations of emerging electrochemical technologies.

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5.01.P-Mo065 From LCA to Supplier Dialogue: Environmental and Biodiversity Impacts of Energy Transition Materials

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The transition toward cleaner energy technologies is accompanied by a rapid increase in demand for raw materials. Technologies such as photovoltaic systems, wind turbines and energy storage solutions rely on higher quantities and a wider variety of metals than fossil fuel based systems. The extraction and processing of these materials can lead to significant environmental and biodiversity impacts, including habitat degradation, water pollution and greenhouse gas emissions, especially when mining and refining practices are not carefully managed.
In this context, industrial actors face growing pressure to better understand upstream impacts, anticipate risks and respond to increasing stakeholder and regulatory expectations, often in situations where data availability and supply chain transparency remain limited. This work illustrates, through the ENGIE case, how life cycle approaches can support the energy company by providing an initial, first level pre screening tool of environmental impacts and biodiversity risks associated with materials critical to the energy transition.
The study combines, for materials identified in ENGIE's value chain, life cycle assessment of metal extraction and processing with a complementary biodiversity risk analysis at mine level, using spatial information and biodiversity related indicator. This coupled approach allows the identification of potential hotspots and supports aggregation of results at material and country scales.
Results illustrate how such an approach can help industrial stakeholders structure internal discussions, identify priority materials or sourcing regions, support procurement teams in initiating targeted engagement with suppliers, and manage environmental risks related to the supply chain. Beyond impact identification, the work also highlights current limitations, including gaps in value chain knowledge and methodological challenges in assessment within LCA frameworks.

5.01.P-Mo066 Advanced Biomass Gasification for Decarbonising Light-Industry Sectors Heat supply: A Life Cycle Assessment of the Novel CBE4I Concept

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Decarbonising industrial heat remains a major challenge in the European energy transition, particularly for light-industrial sectors requiring medium- and high-temperature heat that cannot be fully electrified. Biomass gasification is increasingly recognised as a promising alternative to fossil-based heat production, although medium-scale systems still face challenges related to tar formation, electricity demand, catalyst use, and ash management.

This study evaluates the cradle-to-grave environmental performance of the Clean Bioenergy for Industry concept, a novel 5 MWth combined gasification and combustion system for decentralised industrial heat production from low-value forest residues. The system integrates flue gas condensation with a heat pump for low-temperature heat recovery, a three-way catalyst for nitrogen oxide reduction, thermal-catalytic tar reforming for clean product gas generation, and ash valorisation in fertiliser production.

An attributional life cycle assessment was performed using detailed primary data from pilot-scale tests and project partners, including inventories for plant construction, catalyst manufacture, heat pump integration, operation, and end-of-life treatment. The functional unit was 1 MJ of industrial heat produced. Environmental impacts were assessed using

Environmental Footprint 3.1 and compared with heat production from a natural gas industrial boiler.

Both operating modes outperformed natural gas-based heat production in nearly all impact categories. The least favourable configuration still reduced climate change impacts by 92%, fossil resource use by 93%, acidification by 68%, photochemical ozone formation by 60%, and terrestrial eutrophication by 36%. The main hotspots were electricity demand and catalyst manufacture, particularly platinum and rhodium consumption, while ash recycling and catalyst recovery generated substantial environmental credits.

The results show that advanced biomass gasification can support the decarbonisation of light-industrial heat demand in Europe. However, climate-change benefits alone are insufficient to characterise sustainability, since important trade-offs may arise in eutrophication, acidification, particulate matter, and critical raw material use.

5.01.P-Mo067 A data-driven approach for the prospective environmental assessment of ce-mentitious materials in medium-to-high temperature thermal energy storage

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Development of novel construction materials requires tools that support decision-making from an early stage of innovation, particularly within overarching frameworks such as Safe and Sustainable by Design (SSbD). While the SSbD framework provides a referential approach to integrate safety, sustainability, and functionali-ty/performance, its practical implementation remains challenging, especially in early design phases.
Industrial process heat is one of the least decarbonized energy segments. In the EU, industry consumes ~1,800 TWh/year of process heat, about half below 400 °C, a range compatible with Concentrated Solar Power (CSP). However, solar intermittency limits direct supply, making thermal energy storage (TES) essential to ensure sta-ble and dispatchable renewable heat.
Materials research increasingly targets energy storage to support a higher renewable integration. Within TES systems, operating between ~200–500 °C, material options remain however limited, with molten salts domi-nating despite issues such as degradation and corrosion. In this context, cementitious materials are emerging as potential candidates for these applications due to low cost, scalability, and availability, although, their per-formance and footprint is not yet fully characterized, indicating the need for more robust prospective proce-dures.
The present work explores a data-driven approach combining thermo-mechanical simulations of mortar spec-imens, implemented in COMSOL Multiphysics (validated experimentally up to 500 °C), with predictive model-ling. Parametric datasets are generated from thermophysical properties, composition, processing parameters, and microstructural descriptors, producing outputs such as temperature evolution, storage capacity, and sta-bility indicators. These data support predictive models in Python and are therefore combined here with life cy-cle assessment data using the Brightway2 tool in order to estimate related environmental impacts. Our ap-proach is then applied to a CSP plant case study to evaluate how cementitious TES materials may influence plant design and life cycle inventories. The integration of predictive modelling and life cycle assessment is ex-pected to enable the screening of material alternatives under uncertainty and support early-stage develop-ments, particularly within the SSbD framework during the intended innovation and design/redesign phases, as well as in the selection of scenarios coupled with the sustainability dimension.

5.01.P-Mo068 Evaluating Additive versus Conventional Manufacturing for Generation IV Reactor Components: A Comparison of Classical and Prospective Life Cycle Approaches

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The deployment of advanced Generation IV nuclear reactors (e.g., operating with supercritical water or high-

temperature helium) is considered an important pathway for the European energy transition. As these systems require highly complex components capable of withstanding extreme conditions, assessing the environmental performance of their manufacturing processes at early design stages is essential. This study performs classical Life Cycle Assessment (LCA) and Prospective Life Cycle Assessment (pLCA) for selected reactor components, namely micro-heat exchangers and fuel assembly headpieces, manufactured using additive manufacturing (AM) and conventional manufacturing (CM).
The analysis focuses on high-performance materials, including austenitic steel (AISI 310S) and nickel-based alloys (Inconel 617 and Inconel 625), using both Laser Powder Bed Fusion (L-PBF) and Directed Energy Deposition (DED) technologies. As the selected components have not yet been physically manufactured, the study relies on expert estimates and CAD data. This introduces a key methodological challenge: defining a appropriate Functional Unit (FU), given that AM enables topologically optimized geometries and potentially different lifetimes compared to conventional designs. The assessment is conducted using the European Commission's Product Environmental Footprint (PEF) methodology.
The classical LCA relies on current data reflecting low technology readiness and present-day background systems. In contrast, the pLCA models a future scenario corresponding to Technology Readiness Level 6 (TRL 6) for small-series production and accounts for expected changes in energy systems and material supply chains over a 15–20 year time horizon.
Environmental hotspots are identified for both manufacturing routes, including the high energy demand of AM and post-processing steps such as Hot Isostatic Pressing (HIP) and Laser Shock Peening (LSP), as well as significant material losses associated with CM. By comparing classical and prospective results, the study examines how future-oriented assumptions influence eco-design recommendations and supports the development of consistent methodological approaches for emerging energy systems.

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5.01.P-Mo069 Prospective decommissioning of Concentrated Solar Power plants

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Concentrated Solar Power (CSP) is a key renewable technology for dispatchable heat and electricity, with ~7 GW installed globally at more than 120 operational plants. These are mainly based on parabolic trough and power tower technologies, ranging from 50 to over 300 MW, and deployed between 2007 and 2020. With a design lifetime of 25–30 years, many will soon reach end-of-life, yet only two plants have been fully decommissioned to date. While CSP life cycle emissions are relatively low (~50 gCO2-eq/kWh), the decommissioning phase remains poorly characterized.
This work proposes a modular prospective life cycle assessment (LCA) framework to evaluate future decommissioning scenarios of CSP systems on a global scale. Representative datasets of existing plants are constructed, including technology type, capacity, location, and operational parameters. The approach relies on the modular structure of CSP plants, using published life cycle inventories for parabolic trough and tower systems as a baseline, which are then parametrically adapted to reflect plant-specific characteristics. This modularity enables systematic scaling and transferability across technologies.
The modelling is implemented in brightway2, enabling the construction of scenario-based matrices to assess environmental impacts under different end-of-life pathways. The standard decommissioning after 25–30 years design lifetime is considered, as well as extended operations up to 40 years with refurbishment. Future energy mix is included via SSP-compatible background systems, allowing scenario comparisons under different climate mitigation trajectories.
The model includes the treatment and recovery of major components such as steel, concrete, and mirrors with attention to heat transfer and storage materials. For parabolic trough systems, the management of synthetic thermal oils is addressed, considering degradation, potential recycling, and hazardous waste handling. For tower systems, molten salts

are analyzed under reuse, purification, or disposal pathways.
The approach accounts for regional variations in recycling infrastructure and energy systems. By combining modular inventories with prospective modelling, this work enables assessing decommissioning strategies under uncertainty and supports circular economy. The results aim to improve understanding of end-of-life impacts in CSP and contribute to more robust sustainability assessments of optimal operative lifetimes for energy infrastructures.

5.01.P-Mo070 Ecodesign Strategies for Photovoltaic Modules: Reducing Environmental Impact and Critical Raw Material Dependency

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The dependency on critical raw materials for solar photovoltaic (PV) production, together with its associated environmental impacts, is raising increasing concerns about the long-term sustainability of this technology. In this context, this study investigates the application of ecodesign principles to solar heterojunction (SHJ) cells and modules, aiming to reduce both environmental impacts and material criticality. A key focus is the reduction of critical raw materials, particularly in the production of the cell, through the replacement of silver (Ag) in screen-printing with copper (Cu) or silver-coated copper-particles based pastes (Ag-Cu), as well as the use of thinner Indium Tin Oxide (ITO) or its replacement by Aluminum-doped Zinc Oxide (AZO) layers. At the module level, design modifications include substituting conventional aluminum frames with wood and optimizing cell interconnections through copper ribbons and electrically conductive adhesive (ECA) bonding. A comparative Life Cycle Assessment (LCA) is conducted using inventory data provided by a specialized research center (CEA), applying the Environmental Footprint method (EF 3.1). The functional unit is defined as 1 kWh of electricity generated in DC by the PV module over a 25-year lifetime. This approach enables the evaluation of a conventional SHJ production system as a reference case against five alternative ecodesign scenarios. Preliminary results indicate a consistent reduction in climate change impacts across all scenarios compared to the reference system. The optimized configurations achieve reductions of up to approximately 25–30%, mainly driven by decreased silver content and improved material efficiency at both cell and module levels. Thus, these findings suggest that integrating sustainable material alternatives and bio-based components can drastically lower the carbon intensity of solar energy, providing a viable roadmap for the next generation of eco-friendly PV systems.

5.01.P-Mo071 Global Potential and Environmental Footprints of Floating Solar Photovoltaics (FPV)

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Floating solar photovoltaic (FPV) systems are a land-sparing and potentially more energy efficient application of PV energy systems and add to renewable energy capacity to mitigate climate change. In addition to generating electricity, FPV installations have the potential to preserve water resources by preventing evaporation from water bodies. The global trade-offs between FPV’s energy and water-savings potentials and their environmental footprints are not yet clear. We aim to assess spatially explicit greenhouse gas (GHG) and water footprints, trade-offs between these, and FPV's potential GHG mitigation and water savings on a global scale.
Based on existing datasets of the global FPV installation potential on water reservoirs we first estimate the potential FPV electricity generation worldwide. Second, we compute the GHG footprints and other relevant environmental impacts of this global FPV potential in 2030 and 2050 with prospective life cycle impact assessment. Third, we assess the regionalized and water scarcity-based water handprints (water savings) at the potential FPV installation locations. Finally, we compare FPV electricity and its environmental impacts and benefits to other electricity sources to assess FPV’s contribution to global GHG and water scarcity mitigation. Systematic uncertainty and sensitivity assessment quantifies the effect of different FPV support structures, solar panel tilt, and other decision parameters.
We expect that a combination of latitude, degree of forest coverage and remoteness (transportation distance and electricity grid connection) of the FPV installation location drive the potential electricity generation and, consequently, the magnitude of the GHG footprints. Preliminary findings show that the water handprint is generally larger than the

water footprint of FPV installations. Installing FPV would offer significant benefits in water-scarce regions due to the higher weight of water savings. Determining the GHG and water footprints also allows to assess the global GHG mitigation and water savings potentials. Overall, our work identifies hotspots of environmental impacts and benefits of the global FPV installation potential from a life cycle perspective, which is crucial for sustainable FPV implementation and upscaling within the renewable energy transition.

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5.01.P-Mo072 Integrating Critical Raw Materials into Life Cycle Assessment: Evaluating Resource Resilience in Photovoltaic Technologies

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The rapid expansion of renewable energy technologies is increasing demand for critical raw materials (CRMs), raising concerns about supply risks, geopolitical dependence, and long-term resource resilience. Photovoltaic technologies, particularly emerging high-efficiency nanowire solar cells, may require material compositions that increase exposure to criticality risks if these aspects are not assessed alongside environmental impacts.
This study develops an integrated framework combining life cycle assessment (LCA) with material criticality evaluation to assess the resource resilience of conventional and nanowire photovoltaic technologies. The approach introduces a quantitative Critical Raw Material index that links the criticality score of each material with its relative mass contribution within the device architecture. This allows the identification of critical material hotspots and enables comparison between alternative photovoltaic configurations.
The framework integrates criticality indicators with life cycle inventory data, enabling simultaneous evaluation of environmental impacts and supply vulnerability. In addition, the system boundary is extended to include end-of-life scenarios, where different recovery and reintroduction pathways are modelled. These scenarios assess the potential for retaining critical materials in the system while accounting for environmental burdens associated with recovery, transport, and reintegration processes.
Preliminary results indicate that combining criticality and life cycle metrics improves the identification of material hotspots and supports the evaluation of design and circularity strategies. For instance, materials such as aluminium, titanium and tin emerge as relevant contributors to the overall criticality profile due to their combined mass contribution and criticality scores within specific photovoltaic configurations.
By integrating resource criticality considerations within LCA, this work provides a methodological basis for evaluating trade-offs between environmental performance, material supply risks, and circularity strategies in emerging renewable energy systems.

5.01.P-Mo073 A Discussion about Life Cycle Inventory Management: Data collection, Use and Dissemination for Power Electronics

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In an eco-design perspective for power converter systems, more and more researchers are attempting to apply Life Cycle Assessments (LCA) on their systems. This type of analysis is based on Life Cycle Inventories (LCI), describing the flows of a product's lifecycle, from manufacture to end-of-life treatments, including product usage. Data in LCIs varies in nature (primary or secondary) and may come from different sources (e.g. industrial measurement, experiment and dismantling, simulation). In addition, LCI are usually a part of scientific contributions, as a section, or supplementary material of research papers. Multiple diffusion formats for such content co-exist in literature (e.g. table, csv or excel, ecospold, notebook). This variety leads to identification and software interoperability issues preventing

data capitalization practices in engineering. In that regard, some research groups are working on LCI data standardization. However, before a standard emerges, this paper tends to answer the research question “how to help electrical engineers navigate in the existing scientific LCA literature?”. To do so, a literature review was carried out in the electrical engineering sector. In addition, a characterization framework is proposed to sort contributions in terms of LCI, LCA, models, methods or tools and study them regarding FAIR (Findable, Accessible, Interoperable, Reusable) principles. This results in the statement that multiple contributions in the electrical engineering field base their findings on a small number of accessible sources. A discussion is therefore held to question, as a researcher, the lifecycle of our own LCI data (collection phase, daily use and dissemination) to favor interoperability and capitalization for the LCA community. This relies on data format, but also on structured open-access strategy and practices.

5.01.P-Mo074 Designing Sustainable Manufacturing Routes for Solid-State Batteries: A Comparative LCA between Emerging Dry and Wet Processing Technologies

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The increasing demand for electric vehicle batteries is driving the urgent need for next-generation technologies that offer higher energy density, enhanced safety, and extended operational lifetimes. Solid-state batteries have emerged as a frontrunner in this transition. Currently, significant efforts are being directed towards developing advanced SSB cells and efficient manufacturing processes for battery systems within the transport sector. However, to ensure these technologies are truly sustainable, it is essential to integrate environmental criteria into the design of manufacturing processes at the earliest stages of development.
This study presents an attributional Life Cycle Assessment to guide the ecodesign of emerging manufacturing routes for solid-state cells. Two distinct production alternatives are compared: a traditional 'wet-processing' route, reliant on conventional solvent-based techniques, and an innovative 'dry-processing' approach, which utilises solvent-free methods for both the cathode and solid electrolyte. Primary data was collected from laboratory-scale testing to assess and quantify the potential environmental impacts related to the production of a single coin cell. Both production routes are considered to be within early-stage technological readiness levels.
Although the solid-state cells are still under development and lab-level data remains preliminary, the results indicate that using dry processing for the cathode and electrolyte manufacturing can significantly influence the environmental performance of solid-state battery production. The comparison highlights substantial differences between the two processing routes, demonstrating that manufacturing choices play a relevant role in shaping the life-cycle impacts of emerging solid-state manufacturing technologies, enabling the design of cleaner production lines before industrial scale-up. These findings show that the sustainability of the European battery value chain depends not only on the battery chemistry itself but on the strategic decisions of the manufacturing systems of tomorrow.

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5.01.P-Mo075 Innovative Battery Manufacturing Technologies to Minimize VOC Emissions – Life Cycle Assessment of Cell Manufacturing via Dry and Wet Processing

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The ongoing global shift away from fossil fuels is leading to increasing demand for batteries, both for stationary storage and for electric vehicles (EVs). For EV batteries, there is today a large dominance of Asian manufacturers, making the EU push for more European capacity and resilience in the battery value chain as well as in battery manufacturing. One way of gaining advantages is to introduce innovative manufacturing methods, with lower impacts

on environment and human health.
Large scale manufacturing of Li-ion batteries for EV applications is today dependent on use of N-Methyl-2-pyrrolidone (NMP) as a solvent. NMP is very toxic for humans and when it evaporates, it causes emissions of hazardous volatile organic compounds (VOCs). In an ongoing research project, VOC free manufacturing methods are developed and tested in pilot scale for formation of battery cells with Si/C anode and NMC811 cathode. One of the methods uses a water-based slurry, while the other method focuses on producing electrodes with a dry extrusion/calendaring process. New manufacturing methods might lead to other types of environmental impacts, which are difficult to foresee. Therefore, to get better knowledge about potential environmental risks and to avoid sub-optimization, a life cycle assessment (LCA) has been performed, based on data from the pilot scale production set up in the project.
The LCA aim to identify hotspots related to the two different manufacturing methods and function as a support to further development of the methods in order to minimize environmental impacts in potential future full-scale applications. The main functional unit of the study is 1 kWh of manufactured battery capacity, and the system boundaries span from cradle to grave, including raw material acquisition and pre-processing, main product production, distribution and end-of-life and recycling, excluding the use phase, in line with the battery regulation. Primary data for pilot production is used for manufacturing and recycling while raw materials rely on database and literature data. Results show that impact from raw materials is dominating, meaning that innovative manufacturing methods that minimize production scrap is an important step on the road to more sustainable production of EV batteries. Elimination of NMP is important as it will lead to lower toxicity impacts throughout the life cycle.

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5.01.P-Mo076 Life Cycle Assessment of a Battery Pack Combining Cell Level Innovations with Primary Pack Inventory Data

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Transport electrification is widely regarded as a key pathway to decarbonise the transport sector and reduce tailpipe emissions, driving a rapidly growing demand for lithium-ion batteries. Designing battery packs that improve technical performance while reducing life cycle environmental impacts remains a key challenge. Most life cycle assessment (LCA) studies either focus exclusively on cell level or rely on secondary datasets for pack design that do not reflect recent design innovations such as cell-to-pack or cell-to-body integration.

In this study, we combine cell level process innovations aimed for European gigafactories, such as improvements in slurry mixing, electrode cutting, drying, formation and direct recycling of production scrap, with primary, pack level inventory data for from commercially available electric vehicle battery packs using the same chemistries (NMC811 and LFP). The environmental implications of implementing these innovations are quantified and assessed per kWh battery pack capacity against their cradle-to-grave environmental impacts.

The cell-to-pack ratio was found to vary significantly between packs on the market and, on average, being higher for LFP than NMC packs (77% versus 63% on average among 145 studied packs). In addition, rest-of-pack materials has been found to be an important contributor to climate change impact (around 20-30% of a battery's cradle-to-gate impact), highlighting the importance of considering pack-level design and rest-of-pack components alongside cell level optimisations when developing more sustainable batteries.

Finally, the results are compared towards absolute environmental sustainability targets derived for battery production at giga-scale, to evaluate the potential of individual cell level process innovations towards meeting the derived targets.

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5.01.P-Mo077 Prioritising Sustainability Hotspots in Advanced Lithium-Metal Batteries

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Battery technologies are central to the energy transition, but their production depends on complex value chains involving critical raw materials and energy-intensive processing. For emerging battery technologies, sustainability assessment is needed during research and development, when design choices can influence environmental, economic, and social performance.
This study applies Life Cycle Sustainability Assessment to identify priority sustainability issues in advanced lithium-metal battery development and covers four life cycle phases: raw material extraction, material processing, component manufacturing, and cell assembly. A stepwise approach includes literature review, indicator selection, sustainability matrix development, expert workshop, double materiality assessment, and hotspot identification. Indicators cover environmental, economic, and social dimensions. Each indicator is assessed from two perspectives: relevance for external stakeholders and importance for technology development.
The results show that stakeholder relevance is generally rated higher than project importance, suggesting that ethical, regulatory, reputational, and supply-chain concerns may be perceived as more significant by external actors than as immediate priorities for technology development. Key hotspots include human toxicity potential, cumulative energy demand, global warming potential, cost, and occupational exposure to toxics and hazards. Social risks, including child labour, forced labour, fair salary, and corruption, were particularly relevant in raw material extraction and material processing. Component manufacturing showed high importance for human toxicity and occupational health indicators, while cell assembly received lower overall scores, except for occupational hazards and human toxicity risks.
The findings highlight the need to prioritise sustainability assessment in early life cycle stages, where critical raw materials and upstream supply chains dominate potential impacts and risks. The approach supports transparent decision-making by identifying where detailed environmental modelling, economic assessment, and social risk analysis should be focused. Further work will therefore include quantitative life cycle assessment, environmental cost valuation, and social life cycle modelling.

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5.01.P-Mo078 Life-Cycle Assessment of Low-Noise Power Systems

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The transition toward low-noise power systems—encompassing renewable energy technologies, advanced power electronics, and noise optimized infrastructure—has emerged as a critical dimension of sustainable development, particularly in densely populated and environmentally sensitive regions. While conventional assessments of power systems emphasize carbon emissions, energy efficiency, and cost, the noise footprint and its associated social, environmental, and health externalities remain under-evaluated.
This study proposes a comprehensive Life-Cycle Assessment (LCA) framework for low-noise power systems, integrating traditional environmental impact categories with noise behaviour metrics across all life-cycle stages: raw material extraction, manufacturing, transportation, installation, operation, and end-of-life management. The objective is

to quantify the cumulative environmental and noise impacts, and to identify design, technology, and policy interventions that minimize both carbon and noise externalities.
The research introduces a novel Noise Behaviour Index (NBI) and Noise Impact Equivalent (NIE) as measurable indicators within the LCA framework, enabling the monetization and comparison of noise-related impacts alongside conventional metrics such as Global Warming Potential (GWP). The study further explores how low-noise system design—such as optimized inverters, vibration-dampened transformers, and silent renewable generation technologies—can contribute to improved public health outcomes and urban livability.
The findings are expected to inform policy frameworks, sustainable financing instruments (including Noise Behaviour Taxation models), and engineering design standards, thereby aligning technological innovation with broader goals of environmental sustainability, behavioural regulation, and climate-resilient infrastructure development.

5.02.A - Critical Resources, Circular Strategies, and the Future of Sustainable Emerging Technologies – With a Focus on Energy- and Mobility Technologies

5.02.A.T01 Developing and harmonising energy and digital transition narratives for future raw materials demand and supply projections

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The European Union's twin transition combines energy and digital transformations to mitigate climate change while advancing digitalisation, increasing demand for raw materials (RMs) [1–2]. Given the uncertainties surrounding this transition, scenarios are used to structure assumptions on demand, supply risks, and other factors, thereby supporting preparedness and strategic decision-making [3]. Scenarios describe internally consistent futures based on qualitative and/or quantitative assumptions [3–4], while narratives (or storylines) provide qualitative context through socio-economic, technological, and institutional conditions [5]. Existing studies project energy technologies and associated mineral demand for 2030 and 2050 [6–9] and assess supply chains under different scenarios [10]. However, these approaches often lack harmonised narratives and overlook missing drivers for the twin transition, which may hinder defossilisation and complicate resource planning in a fragmented world. Therefore, this work aims to develop and harmonise narratives to inform future RM demand, supply, and environmental impacts for the twin transition in 2030, 2050, and 2070. This presentation introduces both the process used to develop these harmonised narratives and the resulting storylines, supporting EU policy and industry decision-making. Energy transition narratives were developed through a stepwise, consensus-based process involving domain experts to identify key driving forces. Anchor scenarios—SSP1 VLLO, SSP2 Medium, SSP2 Low, and SSP2 Low with geopolitical tensions—were selected from the ScenarioMIP framework under CMIP7, based on Shared Socioeconomic Pathways (SSPs) [11–12]. Synergies and interdependencies among the driving forces of the energy transition were analysed using causal loop diagrams (CLDs). Digital transition narratives were built on anchor scenarios by incorporating driving forces such as greenhouse gas footprint of hardware, software and digital services, usage patterns, regulation, and maintenance. A master CLD was developed to capture system-wide feedbacks and integrate often overlooked aspects of both transitions, including supply constraints, environmental impacts, circular economy strategies, technological developments, market shifts, geopolitical constraints, and competition for critical RMs. This process resulted in storylines as the main outcome, while their further development with qualitative and quantitative outputs is left for future work.

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5.02.A.T02 Future Demand of Raw Materials for the Digital Transition: a Case Study on "Internet of Things" in

a Smart Home

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The global "twin transition" towards low-carbon energy systems and digitalization is driving rapidly growing demand for critical raw materials (CRMs). These are metals such as lithium, cobalt, copper, and rare earth elements that enable everything from semiconductors and data centers to Internet of Things (IoT) devices. In Europe, this is amplified by a fast-expanding smart home sector, which already counted over 72 million smart homes across EU27 countries at the end of 2024 and is projected to exceed 102 million by 2029. Yet quantitative studies on the demand for CRMs specifically from IoT smart home technologies are still rare. Most existing research looks at bigger areas like digital infrastructure or electric vehicles. This study, part of the EU-funded RAWCLIC project, fills that gap by predicting future CRM demand from IoT smart home devices in Europe up to the year 2050.

Accordingly, the work developed aims to achieve three interconnected goals, each producing specific outcomes. First, it provides a detailed characterization of IoT smart home technologies down to the level of electronic components. System boundaries were established through expert consultation and literature review, followed by mapping individual devices, their functional modules, and components across three smart home implementation cases. Second, this device architecture served as the basis for creating an expert-validated material composition dataset. This dataset integrates teardown reports, industry declarations, and scientific literature into a structured and detailed mapping of material intensities from components to devices. Third, three adoption scenarios for 2025–2050, business-as-usual, policy-driven, and high technological innovation, were developed and combined with the quantified material intensities to generate demand projections for 21 CRMs related to smart home deployment across Europe. Key findings show that some devices and components contain many different CRMs, and several important metals are found in almost every type of device. Thus, this highlights the significant dependency of smart homes in CRMs and how this IoT group can impact the twin transition. The detailed framework created in this study can be easily expanded and added to larger models that track how technology spreads and predict material needs.

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5.02.A.T03 Process simulation-based life cycle assessment of cobalt sulfate production for lithium-ion batteries

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The transition to low-carbon technologies has intensified global demand for critical raw materials, including cobalt, which is a key component of lithium-ion batteries used in electric vehicles. LCA studies of cobalt based batteries rely heavily on LCI data for cobalt sulphate heptahydrate; however, existing datasets are often highly aggregated, combine multiple cobalt products within a single dataset, or lack geographic representativeness. For example, the ecoinvent cobalt sulphate dataset, which is largely derived from the inventory data of Dai et al. (2018), reports a global warming potential of approximately 30 kg CO_2-eq, whereas the dataset published by the Cobalt Institute reports a considerably lower value of about 4 kg CO_2-eq. As a result, these datasets leads to inconsistencies in environmental assessments. These limitations are further increased by the limited availability of detailed inventories for specific process routes and restricted access to primary industrial data, which is often confidential. In this context, process simulation has been identified as the most accurate method for generating LCI data for LCA in the absence of plant data.
To address these limitations, this study develops and applies a process simulation-based framework for the generation of high-resolution LCI data. A structured procedural framework is proposed to guide the systematic development of simulation-based LCI. The framework integrates flowsheet definition, selection and development of unit operation models, collection and completion of thermodynamic and process data, linking of interconnected process units, and iterative validation of simulation outputs. Challenges arise in the selection of representative unit models, the definition

of thermodynamic properties for missing species, and the use of incomplete or heterogeneous process data. The multi-output nature of the system, which includes cobalt sulphate heptahydrate, copper cathode, and sulphuric acid, introduces allocation challenges within the LCA framework. These are addressed through a combination of subdivision, system expansion, and economic allocation, consistent with the process structure and functional relationships between outputs. By linking process simulation outputs with LCA modelling, the study increases the granularity of LCI data, improves consistency between process modelling and environmental assessment, and enables traceable attribution of material and energy flows across the value chain.

5.02.A.T04 Mineral Resource Impacts of Future Carbon-Neutral Passenger Vehicles: Influence of Impact Assessment Methods and Allocation Approaches

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Alternative passenger vehicle powertrains such as battery electric and fuel cell electric vehicles are increasingly promoted to reduce greenhouse gas (GHG) emissions and thereby contribute to climate change mitigation. However, these climate-friendly powertrains are generally more mineral-intensive than conventional vehicles. As deployment expands, mineral resource impacts become essential for capturing trade-offs beyond climate change and identifying hotspots relevant to future mobility systems.

Life cycle assessment (LCA) is a suitable method to evaluate trade-offs between environmental impact categories, such as GHG emissions and mineral resources. However, a sound comparison of mineral resource impacts for competing climate-friendly powertrains requires addressing three challenges. First, a common reduction in GHG emissions should be considered as a boundary condition because this is the main motivation of climate-friendly powertrains. Second, large-scale deployment of climate-friendly powertrains may increase mineral resource demand, while some impact assessment methods rely on present-day extraction relationships. Third, mining processes are often multifunctional, and the economic allocation commonly applied in life cycle inventories can distort mineral-specific hotspot interpretation. For example, the abiotic depletion impact attributed to palladium from a platinum group metal concentrate under economic allocation is mainly driven by gold and platinum, while palladium itself contributes only about 6%.

This study addresses these challenges in a prospective LCA of four powertrains: battery electric, plug-in hybrid, fuel cell electric, and e-fuel based internal combustion engines. For all powertrains, mineral resource impacts are compared in a carbon-neutral scenario that reflects the main motivation of climate-friendly powertrains. In parallel, different impact assessment methods for mineral resources are evaluated for their suitability in prospective applications. In addition, multifunctional mining processes are adjusted by reallocating elementary resource flows from economic to physical allocation. The reallocation is implemented through an automated workflow within the Brightway2 framework. Overall, the study supports a more robust comparison of mineral resource impacts, improves mineral hotspot identification in future mobility systems, and provides insights into the suitability of mineral impact assessment methods for prospective applications.

5.02.A.T05 A New Method Combining Statistical Entropy Analysis and Life Cycle Assessment for the Evaluation of Circularity and Sustainability: A Case Study on Li-Ion Battery Recycling Processes

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Lithium-ion batteries (LIBs) are currently the most popular energy storage devices in large grid systems and electrical vehicle applications. The demand for LIBs is increasing because of a global shift in the electrification of various industries, favoring the use of renewable energy systems to reduce the emissions associated with the use of fossil fuels. The criticality of the raw materials needed for their manufacturing is also growing by making the recycling of LIBs

vital. Recycling, as one of the circular economy (CE) strategies, helps alleviate the need for virgin raw materials while reducing the environmental problems associated with their improper disposal. Despite their expected benefits, LIB recycling processes consume resources and have intrinsic limitations. Therefore, it is still essential to evaluate recycling processes considering the circularity of materials and their environmental sustainability. In this work, we evaluated the circularity and sustainability of LIBs recycling scenarios in which various pre-treatment routes are used prior to hydrometallurgical refining. For the evaluation, a newly developed methodology combining statistical entropy analysis (SEA) and life cycle assessment (LCA) was applied. By performing this analysis method, the correlation between circularity of materials and environmental sustainability from a systemic perspective was established. Based on the results, it was seen that the efficient pre-treatment of LIBs makes a significant impact to decrease the environmental impact and improve material recovery even with the additional resources and energy consumed. Furthermore, the correlation between various categories of environmental impacts and battery elements recovery was substantially enhanced by effective pre-treatment. This study delivers new perspectives into LIBs recycling while also contributing to the improved understanding of material circularity and environmental impact.

5.02.B - Critical Resources, Circular Strategies, and the Future of Sustainable Emerging Technologies – With a Focus on Energy- and Mobility Technologies

5.02.B.T01 Sustainable Battery Manufacturing at Gigafactory Scale: Combining Material Flow and Life Cycle Models with Wider Sustainability Metrics

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The rapid scaling of lithium-ion battery gigafactories is central to decarbonising energy and mobility systems, but it intensifies demand for critical resources and raises complex sustainability challenges. While circular strategies are widely proposed, there remains a lack of integrated approaches to assess their implications across environmental, economic, and broader sustainability dimensions.

This study addresses this key question: how can the sustainability implications of circular versus linear manufacturing systems be robustly evaluated in the context of battery manufacturing, and how can this be integrated at a gigafactory scale?

To address these questions, we develop a novel, integrated modelling framework and apply it to a real-world gigafactory site in the West Midlands, UK. The framework combines material flow analysis (MFA) with life cycle assessment (LCA), techno-economic assessment (TEA), and broader indicators (including criticality and risk assessments) within a unified structure. MFA is used to quantify material requirements across multiple battery chemistries and manufacturing scenarios, explicitly incorporating circularity strategies such as scrap recovery, reuse, and recycling. These scenarios form the basis for LCA to evaluate environmental impacts, alongside TEA and qualitative assessment to capture economic feasibility, supply chain vulnerabilities, and broader sustainability considerations.

This work advances the assessment of sustainable emerging energy technologies by providing a practical, scalable approach for evaluating gigafactory systems under different circularity pathways. The framework is directly applicable to industry and policy contexts, supporting more informed decision-making on critical resource management, circular economy strategies, and the design of resilient battery supply chains. Future work will use this framework to assess the holistic sustainability implications of various policy, battery chemistry and recycling scenarios at the real-world gigafactory site in the UK, to assess the full impact of circularity within the context of battery manufacturing.

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5.02.B.T02 Eco-Designed Modular Batteries: Life Cycle Assessment for Environmental and Critical Raw Material Recovery Benefits

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Growing demand for electric vehicles (EVs) has increased the use of critical raw materials (CRMs), primarily due to lithium-ion batteries. Expanded CRM extraction and energy-intensive battery manufacturing can partially offset the environmental benefits of electric mobility. To address these challenges, the EU Battery Regulation sets ambitious recycling goals, including recovery rates of 95% for cobalt, copper, and nickel and 80% for lithium by 2031, to enable a circular battery value chain. Achieving these goals requires the integration of circularity at the battery design stage. This study investigates the environmental benefits of an eco-designed modular, swappable lithium-ion battery for micromobility, focusing on design strategies that enable circularity. The modular architecture enables non-destructive disassembly, facilitating component reuse, secondary applications, and efficient end-of-life processing, thereby reducing manufacturing energy demand and improving material recovery. The Life Cycle Assessment follows ISO 14040/14044 standards and is modelled in SimaPro using primary industrial data, Ecoinvent secondary data, and the Environmental Footprint 3.1 method across 16 impact categories. Three scenarios are evaluated: BASE, OPTIMAL, and business-as-usual (BaU), to quantify the eco-design benefits. Modularity enables extended use phases: cell modules are repurposed for secondary energy storage system (ESS) applications, while non-cell components can be reused up to two additional times. The BASE scenario assumes a single-use lifetime of 2,000 cycles in EV applications. The OPTIMAL scenario includes an additional 500 cycles in ESS applications for cell modules, reuse of non-cell module components for up to 7,500 cycles across EV and ESS applications, and reuse of non-module battery components for up to 6,000 cycles. Hydrometallurgical recycling is applied for end-of-life cell treatment in all scenarios. The OPTIMAL scenario achieves a total single-score impact of 1.08 mPt, representing a reduction of ~55% compared to the BASE scenario (2.38 mPt) and ~70% compared to the BaU (3.54 mPt). The results demonstrate a significant reduction in environmental burdens, driven by component reuse, extended battery lifetime, efficient raw materials recovery enabled by the modular eco-design. These findings highlight the critical role of battery design in enhancing circularity and improving the environmental performance of electric mobility systems.

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5.02.B.T03 Assessing the environmental impacts, circularity and criticality of silicon recovery from PV modules: improving the resilience of the European silicon industry

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The EU currently faces a 60% reliance on imports of silicon metal, a critical raw material and a key feedstock for high-purity silicon production used in applications such as silicon wafers. At the same time, none of the current demand can be met through secondary raw materials. In response, the Horizon 2020 Resilex project is engaged in developing emerging technologies crucial for the transition towards a resilient silicon economy. This case study focuses on innovative recycling of photovoltaic (PV) panels, with the aim of recovering purified silicon to replace metallurgical-grade silicon, as well as recovering various metals and glass. The recycling process covers several stages, including grinding, sorting, and purification of silicon concentrate. The objective is to compare the environmental impacts, criticality and circularity performance of this innovative PV panel recycling process with a literature-based baseline recycling scenario, excluding silicon recovery which reflects current practices. The assessment applies a waste perspective and additive system expansion approach. The life cycle inventory is based on primary data provided by the company Comet, complemented by upscaled laboratory-scale data from the University of Liège. The life cycle assessment follows the guidelines of the Product Environmental Footprint, applying the Environmental Footprint v3.1

method and covering the impact categories climate change, resource use (metals/minerals and energy), freshwater ecotoxicity, water use, and ionising radiation. The criticality assessment uses the CriticS method, which is based on the life cycle inventory while applying a stakeholder perspective to the selection of four applied criticality factors linked to supply risk and economic importance. The circularity assessment follows the ISO 59004 standard. Preliminary results indicate that the innovative scenario shows improved environmental performance compared to the baseline (e.g. up to 52% impact reduction for climate change impacts), primarily due to the efficient recovery of silicon and various metals. A better performance in terms of circularity is also observed. Finally, the innovative scenario results in lower criticality scores compared to the baseline scenario with natural graphite and silica sand identified as main contributors. Further research should be dedicated towards varying composition of the input waste and the recovered metal fraction, and its influence on the comparison.

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5.02.B.T04 Life Cycle Assessment of Rare Earth Metal Recovery from NdFeB Magnets: Impact of Process Scale-Up

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Recycling of rare earth elements (REEs) is becoming increasingly important for permanent magnets used in electric vehicles, wind turbines, and motors. Due to the growing imbalance between supply and demand, REEs have been identified as critical raw materials by the European Union. Therefore, it is essential to develop recovery methods for REEs (La, Pr, Nd, Dy, and Y) that not only achieve high recovery yields at laboratory scale but also demonstrate strong potential for pilot-scale commercialization and sustainability.
In this study, we performed life cycle assessment (LCA) of an REE recovery method based on antisolvent crystallization and evaluated its future applicability by scaling up the process to produce 100 kg of $REE_2(SO_4)_3 \cdot 8H_2O$ per batch using hybrid process modelling. To assess and optimize the process, we applied LCA together with a hybrid process modelling framework based on chemical engineering principles. While LCA was used to identify the environmental hotspots within the existing process flow, hybrid process modelling played a key role in process optimization and intensification by identifying suitable mitigation strategies without compromising overall yield. The main optimization measures included the integration of a steam generation unit to improve energy flexibility, incorporation of an additional solvent recovery unit to enhance circularity, waste heat reutilization, and trade-off analysis of process parameters. Scaling up the process to 100 kg per batch, combined with these mitigation strategies, reduced the global warming potential significantly from 40 kg CO_2 eq to 0.96 kg CO_2 eq per kg of $REE_2(SO_4)_3 \cdot 8H_2O$. This approach highlights the importance of considering environmental impacts as a core parameter at the laboratory scale itself, serving as a pre-assessment before actual industrial scale-up. Such early-stage integration of sustainability can substantially reduce additional efforts and environmental burdens during future commercialization.

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5.02.B.T05 Multi-Criteria Decision Analysis for the Sustainability Assessment of Biochar and Hydrochar Production from Organic Side Streams: Part 1

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The generation of biomass residues is increasing worldwide, and tens of thousands of tonnes of organic side-streams

and waste materials are produced in Finland each year. Sustainable management of biomass residues is crucial to meet circular economy objectives and to contribute to climate neutrality goals. Consequently, organic side-streams emerge as a promising renewable resource and can be valorized into higher-value materials such as biochar (BC) and hydrochar (HC) through pyrolysis (Py) and hydrothermal carbonization (HTC) processes, thereby contributing to the mitigation of the effects of climate change, with potential applications in fields such as water treatment, metallurgy, and agriculture. Although the benefits of biochar have become more evident in recent years, there are still gaps in the sustainability assessment (SA), which integrates technical performance, economic viability, social impacts, and environmental dimensions. An integrated sustainability assessment can demonstrate, from a global perspective, that the manufacturing of carbon products represents a cost-effective and eco-friendly sustainable initiative. A multi-criteria decision analysis (MCDA) framework can support decision-makers in making more informed choices and integrating a diversity of criteria. This work presents an MCDA with the Analytical Hierarchy Process (AHP) technique as a prospective approach to evaluate environmental, social, technical, and economic dimensions for carbon production (pyrolysis and HTC) from the early research stage. For this purpose, four side-stream biomasses were selected: (i) green waste from tomato cultivation, (ii) garden waste, (iii) demolition wood, and (iv) digestate from biogas production. Commercial biochar produced from spruce chips was used as a reference. According to the MCDA results, biochar produced from demolition wood ranks as the preferred option, showing better performance than the reference biochar. Hydrochar produced from all biomasses exhibited better performance in social and economic dimensions compared with biochar; however, technical and environmental dimensions showed lower performance. Sensitivity analysis showed the stability of the ranking among alternatives even when the criteria weighting varies by ±30%. This work can support future innovations, presenting a forward-looking approach to developing sustainable initiatives.

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5.02.P - Critical Resources, Circular Strategies, and the Future of Sustainable Emerging Technologies – With a Focus on Energy- and Mobility Technologies

5.02.P-Mo079 Assessing the Sustainability of Tribolysis for Fluoropolymers: Green Metrics, Criticality, Circularity and LCA of Urban Mining of Critical Raw Materials

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Fluoropolymers pose major environmental and regulatory challenges at end of life. Common disposal routes such as landfilling and incineration do not fully control fluorinated degradation products, may promote formation of per- and polyfluoroalkyl substances (PFAS), and result in the loss of valuable fluorinated materials. This is particularly relevant because fluorine chemistry depends on fluorspar, which the European Commission classifies as a critical raw material. Tribolysis of fluoropolymers may offer a safer and more circular route for fluorine recovery. To evaluate its sustainability, this study combines Green Metrics (GM) with a tailored ex-ante life cycle assessment (LCA) framework for early-stage process and reactor design, explicitly addressing circularity and criticality through recovery of inorganic fluoride and carbon products.

Conventional ex-ante LCA is often retrospective and data-intensive, which limits its application at low technology readiness levels where process data are scarce. To address this, GM was applied using atom economy, E-factor, solvent use, and process energy intensity. These indicators were combined with a gate-to-gate LCA model for treatment of 1 kg of fluoropolymer waste, including electricity, reagents, tribopair materials, and downstream waste treatment, while accounting for credits from recovered products.

The GM analysis shows that eliminating solvent and washing steps, increasing conversion, and reducing energy demand can reduce solvent and water use by more than 90%, lower waste indicators by up to one order of magnitude, and decrease process energy intensity by about 90% compared with baseline conditions. These improvements reflect

higher atom efficiency, improved recovery, reduced solvent demand, and lower waste generation. However, the LCA identifies energy demand as the main climate hotspot: under baseline conditions, electricity accounts for 98% of total impacts, while direct emissions contribute only 0.5%. Under improved conditions, impacts shift toward material inputs, including tribopairs (62%), trapping agents (18%), and reagents (21%), while credits from calcium fluoride production remain limited at about 8%.

Overall, combining process-level metrics with system-level assessment supports early-stage decision-making and advances more circular fluorine recovery from fluorine-rich waste. Criticality and circularity are still under evaluation and may reveal advantages over incineration and landfilling.

5.02.P-Mo081 Life Cycle Assessment of Lithium-Ion Battery Production for Electric Vehicles in a Photovoltaic-Integrated Plant

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The transition to electric vehicles is widely seen as an important step towards reducing greenhouse gas emissions in the transport sector. At the same time, the production of lithium-ion batteries requires large amounts of energy and critical raw materials, raising important environmental concerns. Understanding the environmental impacts associated with battery production is therefore essential for improving the sustainability of electric mobility. In this study, we evaluate the environmental impacts of lithium-ion battery production using detailed data from a photovoltaic-integrated plant located in Antalya, Türkiye. The aim is to identify the main environmental hotspots along the production chain and to better understand the role of energy use in the overall environmental profile of battery production. A cradle-to-gate life cycle assessment is carried out in accordance with the ISO 14040 and ISO 14044 standards. The system boundaries include raw material supply, material processing, and battery cell manufacturing. Primary data obtained directly from the plant are modelled using SimaPro software and combined with background data from the Ecoinvent database. Particular attention is given to electricity consumption during manufacturing, including the contribution of photovoltaic electricity integrated into the plant's energy supply. The main environmental indicators considered include global warming potential, energy demand, and resource depletion. Preliminary results suggest that upstream processes, particularly the extraction and processing of materials such as lithium, nickel, and cobalt, account for a large share of the overall environmental impacts. Electricity use during battery cell manufacturing also plays an important role, whereas the presence of photovoltaic electricity in the plant has the potential to reduce climate-related impacts associated with energy demand. Overall, the study provides insights into the environmental profile of lithium-ion battery production based on real industrial data and highlights opportunities for reducing impacts through improvements in energy sourcing and material efficiency.

5.02.P-Mo082 Life Cycle Assessment of Emerging Battery Material Production Routes under a Safe and Sustainable by Design Framework

Meritxell Rovira Antonell[1] and Pamela Ciacia[1] (1)Leitat Technological Center

Energy storage technologies, particularly batteries, are essential for the decarbonisation of the electricity and transport sectors, however, their large scale deployment raises concerns related to the use of critical raw materials and the environmental impacts of production processes. As a significant share of these impacts is determined during early design stages, Life Cycle Assessment is a key tool to support informed technology selection and sustainable design decisions.

Within the EU-funded RESTORE project, several innovative technologies are being developed for the sustainable production of battery-grade precursors and their respective anode and cathode active materials. These processes are applied to materials from primary and secondary sources, with the aim of supplying pilot scale manufacturing of sustainable battery cells. As the different routes vary in input requirements, efficiencies and recovery potential, comparative assessment is essential to identify the most sustainable options for further development.

This study applies life cycle assessment in an early stage screening approach to evaluate current laboratory and pilot scale configurations across the developed technologies. Using primary foreground process data, the assessment identifies environmental hotspots and opportunities for improved recovery of critical raw materials, supporting evidence based prioritisation and selection of technological options. The assessment is embedded within the Safe and Sustainable by Design framework to guide technology development.

In addition, a prospective Life Cycle Assessment is performed to evaluate the environmental performance of processes under upscaling conditions. The study also combines foreground data with prospective background modelling based on scenarios generated with premise, allowing future changes in energy systems and supply chains to be considered when selected routes converge towards upscaled battery cell production.

In parallel to the environmental assessment, a Social Life Cycle Assessment is also conducted in line with the Safe and Sustainable by Design framework, with particular attention to aspects related to criticality and social risks associated with key raw material supply chains.

Overall, the work demonstrates how early stage life cycle assessment combined with circularity and criticality considerations can support actionable decision making towards more sustainable and resilient battery value chains.

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5.02.P-Mo083 Sustainability Performance Assessment of Green Hydrogen Production through an Innovative Electrochemical Route Powered by Renewable Energy

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The production of green hydrogen using renewable energy sources has been described as one of the main pillars of energy transition. It closely aligns with the fundamental principles of sustainability and the Sustainable Development Goals, as defined by the United Nations in the 2030 Agenda. Nevertheless, remarkable challenges and bottlenecks remain to be solved regarding the process sustainability performance: high energy demand, consumption of Critical Raw Materials (CRMs), transport of this energy vector over long distances, as well as high CAPEX and OPEX. This study examines the nature of environmental impact analysis when developing photoelectrochemical (PEC) cells for green hydrogen production, considering some alternatives to CRMs, like the recycling or the reduced use of these kinds of materials. The PEC module is more effective than other traditional production ways and it will be addressed to reduce the use of the CRMs and to improve the efficiency utilising new innovative methods.
This preliminary analysis does not seek to examine the entire value chain, but rather to identify key areas with a low Technology Readiness Level. These hotspots will then be used as a starting point for future process enhancement and optimisation. Examples of such hotspots include energy consumption, the selection of more environmentally friendly raw materials, and the identification of substances and CRMs to be minimised. By addressing these performance gaps first, the focus in future steps will shift to other areas until reaching the environmental profile of the value chain as a

whole.
Although impacts assessment methods such as Environmental Footprint (EF) will be applied to determine all impact categories, from the extraction of the raw materials to end-of-life management, particular attention will be given to the CRMs present in the cell, for instance the use of tungsten (W) in the photoanode. The application of new coating methods in novel photoanodes might contribute to reduce this CRM requirement for energy systems. Nevertheless, its environmental performance profile should be complemented by adequate criticality assessments which currents methods like EF do not fully address – regarding, for instance, geopolitical constraints for access to raw materials. In summary, the assessment aims at demonstrating the environmental viability of these new components and improve resource efficiency, whereas also ensuring alignment with regulatory requirements.

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5.02.P-Mo084 Evaluating Circularity: An LCA-Based Indicator to Measure the Environmental Effectiveness of R-Strategies

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The transition towards a circular economy requires effective tools to drive and monitor progress. This underscores the need for suitable circularity indicators and metrics. Existing circularity indicators, however, primarily focus on the material level (e.g. Material Circularity Indicator) and the company or business level (e.g. Circular Transition Indicators). Only limited research has addressed the relationship between circularity indicators and life cycle assessment. Specifically, there is a paucity of approaches that assess the implementation of so-called R-strategies (e.g. Reuse, Repair, Recycle) in terms of their ecological effectiveness.

This topic addresses the missing link between quantitative, robust LCA-based metrics and R-strategies by providing a unified way to measure their effectiveness and demonstrates its application through a case study. The indicator is based on comparative life cycle assessment, in which product life cycle scenarios including at least one R-strategy are compared to a specific baseline scenario (e.g. landfill, incineration). In a first step, the relative reductions of the environmental impact achieved through the implementation of R-strategies are calculated. In a second step, an aggregated performance metric is derived with reference to the baseline scenario on a scale ranging from 0 (indicating no reduction compared to the base scenario) to 1 (indicating 100% reduction compared to the baseline scenario). Subsequently, a circularity-specific factor is applied to the performance metric, which incorporates (i) the components addressed by R-strategies, (ii) the relative contribution of the components to the product's environmental total impact, and (iii) a weighting of the applied R-strategies.

The objective of this work is to provide a thorough and comprehensive insight of the indicator's methodological structure and its derivation. The subsequent discussion focuses on the application of the indicator supported by a case study of a specific product-service system of a light electric vehicle.

In summary, this contribution presents a novel LCA-based indicator that directly measures the environmental effectiveness of specific R-strategies. Beyond its methodological contribution, the indicator enables researchers and practitioners to identify which R-strategies deliver the greatest impact and to guide decision-making in designing more circular product–service systems.

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5.02.P-Mo085 Circular Carbon Fibre Composites: Exploring Opportunities and Constraints Using Life Cycle Assessment

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Carbon fibre reinforced polymers (CFRPs) are characterised by high specific mechanical performance, which enables lightweight structural design. They have been widely adopted in sectors such as aerospace, energy, automotive, and construction. Their low weight enables significant reductions in fuel consumption of vehicles, contributing to lower emissions during their use. However, these benefits are accompanied by certain challenges. Due to the energy intensive carbon fibre production phase, a net environmental benefit is not always reached even if fuel is saved during use. Furthermore, CFRPs are challenging to recycle in terms of recovery of high-quality materials. Considering circularity is therefore essential to not only address the current challenges but also maximizing the sustainability benefits of CFRPs across cradle-to-grave product systems. This work explores circular strategies for carbon fibre composites, focusing on identifying solutions that best balance technical performance, sustainability, and circularity.

To understand system-level opportunities and challenges for the circularity of CFRP, three cases of composite utilization across distinct applications are evaluated. The first case represents an application with low mechanical performance requirements: a car mirror bracket. The second reflects higher demands on mechanical integrity: a hydrogen storage tank for trucks. The third explores a composite with expanded functionality, incorporating also energy storage: a structural battery composite (SBC). Life cycle assessment is used to evaluate the environmental impacts of these solutions and to provide insights into their implications for circularity, including potential for reuse, recycling, and value retention for the three different cases. Thus, the study aims to inform decision-making on the environmentally preferable use of CFRP across applications, helping to avoid its use in low-value contexts that may constrain future circularity pathways and limit environmental performance.

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5.02.P-Mo086 Assessing the role of Sustainability-by-Design in Emerging Circular Value Chains for Repair and Repurposing

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Despite the multiple advantages of product remanufacturing, widely recognised as an effective means for transitioning towards a circular economy, further research is still needed to enhance the sustainability of final products, and impact monitoring.
Sustainability requires integrated approaches capable of modeling complex systems. To support decision-making, life cycle-based approaches provide a framework that allows for the comparison of options and solutions in terms of sustainability. Life cycle thinking can be applied to assess the environmental, social, and economic pillars using Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and the Social Life Cycle Assessment (sLCA). This is particularly important for emerging circular value chains, as in the R3MYDAS project, which focuses on the remanufacturing, repurposing and recycling of energy goods through advanced mechatronic and digital technologies, where it is essential to ensure that end-of-life solutions are also sustainable.
The R3-MYDAS project focuses on three value chains: Oil and gas, electric vehicle (EV) batteries, and wind energy. In the oil and gas industry, the components of engines and pumps are subjected to demanding conditions such as high mechanical loads and aggressive environments, which accelerate the wear process. The proposed repair process uses advanced technology to scan and create a 3D model of the component. Then, laser cladding is used to repair the damaged areas. A similar situation occurs in the wind sector, where rotor components have a shorter lifespan than the rest of the wind turbine. Various combinations of methods for repairing nacelle components have been suggested, such

as recoating, heat treatment, and reworking using additive manufacturing processes. In the case of EV batteries, one of the main bottlenecks is the state of health (SoH) at the end of service. An automatic dismantling system has been developed to enable reuse, repair, and repurposing strategies at cell level, depending on their SoH, instead of the commonly used recycling process.
The Sustainability by Design assessment facilitated the identification of opportunities to enhance performance and develop novel, more advantageous circular scenarios in comparison to the current linear value chains. Furthermore, the identification of potential bottlenecks at an early stage was facilitated, thus enabling the design of strategies for the straightforward adoption of these new business models.

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5.02.P-Mo088 Life Cycle Sustainability Assessment at low Technology Readiness Level for sustainable decision-making – application to Cultural Heritage conservation

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Sustainability assessments of emerging technologies are most valuable when they can inform development choices. At early Technology Readiness Levels (TRL), this requires methods that simultaneously address environmental performance, economic viability, and supply security. This contribution illustrates how a full Life Cycle Sustainability Assessment (LCSA) can serve this role, using the MOXY project (Horizon Europe, 2022–2026) as a case study.

MOXY is developing an Atomic Oxygen (AO) plasma-based device for the contactless surface cleaning of cultural heritage objects, using a helium-oxygen mixture in a low-pressure radiofrequency (RF) plasma. The LCSA integrates an environmental LCA, a Social LCA, a Life Cycle Costing (LCC) study, and a raw material criticality assessment using the IRTC framework (International Round Table on Materials Criticality), linking supply risk indicators to three company-level risks: accessibility, price fluctuations, and reputation damage.

Helium emerges as the dominant hotspot across all three quantitative assessments: as the main environmental impact driver in the LCA, as the dominant cost contributor in the LCC (up to 85% of yearly user expenditure), and as the most significant supply risk by quantity in the criticality assessment. The RF power supply unit is a secondary hotspot across all three methods, driven by the use of a lab-scale generator and critical raw materials in its electronic components. The anticipatory value of this integrated assessment was confirmed in 2026, when Strait of Hormuz supply disruptions produced exactly the accessibility problems and price volatility for helium that the 2025 assessment had identified as risks.

The LCSA results directly feed back into the technology development roadmap: transitioning to multi-point operation reduces helium consumption and cost per minute tenfold, and helium may be substituted in certain AO applications by argon. LCSA at low TRL therefore helps prioritise where development effort is most needed.

The MOXY case illustrates both the feasibility and added value of conducting a full LCSA at early TRL. This contribution also discusses key methodological challenges and pathways for translating this approach into decision support for energy transition technologies facing analogous material dependencies.

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5.02.P-Mo089 Circularity Assessment of Electric Vehicles - A New LCA Approach on the Circularity Potential in IEA EV Task 52

Circular economy is a key challenge for our society. Assessing circularity of a product/service is possible in dynamic LCA calculating resource demand and material recovery over lifetime. In the IEA Technology Collaboration Program (TCP) experts cooperate on LCA since 2010, currently in Task 52 on Circularity. A totally new methodology to assess the Circularity Potential (CPO) between 0 - 100% including primary energy was developed and applied in case studies on transportation services using this definition: “A product/ service is ”100% circular“, if in the whole life cycle the total mass of used materials consists only of reused components, recycled and renewable/bio-based materials and primary renewable energy whereas no waste (incl. GHG emissions) occur. That means no primary material (metal and minerals), no primary fossil energy (oil, gas and coal) and complete recycling or reuse of materials. To assess circularity the Circularity Potential (CPO) is calculated with the lifecycle-based circular and non-circular massflows between 0 - 100%." The CPO assessment framework is based on the Material Circularity Index (MCI), where in Inventory Analysis the new assessment approach is based on the mass flows of the materials and primary energy in lifetime. Using ISO 59020 core circularity indicators the circular and non-circular masses are identified in Impact Assessment. The CPO is the relation of circular mass to total mass and can be increased by minimizing total mass and increasing share of circular mass. The critical masses are calculated by using Sb-equivalent for materials.
In a case study on vehicles using fossil fuels, e-fuels, H2 and electricity, initially circularity was assessed for electricity: PV and nuclear have lowest mass of 7 – 12.5 g/kWhel and fossil fuels have highest mass of 144 – 265 g/kWhel, with CPO is highest for biomass and hydro (45 – 90%) and lowest for fossil fuels (0.5 – 1.5%). The highest non-circular critical mass is in PV and wind (2 – 6 mg Sb-eq/kWhel, CPO of 2 – 10%). Circularity assessment of vehicles shows: fossil fuels have highest mass (85 – 103 g/km) with a CPO of 1.7 – 2.6%; e-fuels: 146 – 300 g/km with CPO 40 – 55%; H2: 68 – 123 g/km with CPO 30 – 35% and electricity has lowest mass: 39 – 53 g/km with CPO 10 – 15%.
The CPO covering also energy is a new impact category not yet covered in Impact Assessment and influenced by energy consumption, amount and types of (critical) materials, and insensitivity of use.

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5.02.P-Mo090 Life Cycle Assessment for the Ecodesign Approach of Electric Traction Motor

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The present study provides insights into how Life Cycle Assessment (LCA) has been applied to support sustainable decision-making in the development of a new Electrical Machine (EM) in the project MAXIMA. The objectives are to develop a modular EM that reduces critical raw material use while improving both the recyclability and recycled content of permanent magnets.
This novel EM is designed to meet the technical requirements while being compared to a reference EM, implemented in current market vehicles, across all relevant criteria. To systematically assess the environmental burdens of the EM

and integrate sustainability considerations into the design process, a structured approach is adopted throughout the project. The LCA indicators are not a single post-design settlement assessment but are considered from the exploration phase, alongside the technical specifications. First, a state-of-the-art review of existing LCA studies on EMs is conducted to pinpoint key environmental hotspots, from both results and methodological aspects. These findings are further reinforced by assessing the reference machine. The second step involved iterative data collection, from approximate data to refined inputs, to compare two initial designs against the reference machine. The selection of the most suitable architecture is based on a multi-criteria evaluation including technical performance, environmental impact, and cost. At the third stage, LCA serves as a monitoring tool, tracking the environmental evolution of successive design iterations and ensuring that impacts remain within acceptable bounds.

The indicators in this study are climate change, mineral resource depletion and dissipation. Two are used for mineral resources due to methodological differences and the lack of characterization factors for certain rare earth materials. The evolution of the designs' impact reveals trade-offs between efficiency losses and the mass of active materials, which must be balanced, underscoring the need for full life cycle assessment. Key challenges include communicating LCA results to non-experts, managing dependencies on other tasks that introduce early-stage data uncertainties, and modelling innovative processes with no established references. A dedicated LCA tool was developed to facilitate exchanges with partners and broaden accessibility of results. This experience confirms that LCA is most impactful when integrated early and supported by strong multidisciplinary collaboration.

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5.02.P-Mo091 Integrating Flood Risk Analysis and Life Cycle Assessment to Evaluate Road Infrastructure Resilience

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Improving road infrastructure construction such as bridges, against floods can require additional concrete and steel, which are known as materials significant environmental burden. In this study, we integrate flood risk assessment with life cycle impact assessment (LCIA) to consider the environmental burden of sustaining the brigde over time, in such a way connecting short-term robustness aspects of the infrastructure object with long-term environmental performance, including contributions to climate change.
An integrated flood risk and LCIA was applied to the Dviete Bridge over the Dviete River, located in Latvia. Two scenarios were investigated: Continued maintenance for damages occurring after floods was compared with full reconstruction based using a functional unit (FU) of 1 m² of bridge deck providing service for 50 years. Inventories covered reconstruction, routine maintenance and flood-damage repairs. Historical data on flood return periods and water levels were used for hazard assessment. LCIA for two scenarios were calculated using ReCiPe 2016 Midpoint (H) and Endpoint (H). Because damage could not be predicted reliably from available hydrological data, repair volumes were varied through sensitivity analysis.
Reconstruction produced higher initial impacts but could reduce cumulative impacts if subsequent repair needs were sufficiently low. With reconstruction-scenario, the endpoint single score was 87.23 ecopoints per FU. Under continued maintenance without reconstruction, scores ranged form 45.43 up to 142.20 points/m² for different flood repairs scenario, including 20% to 80% of the maximum destruction. The results help to identify a break-even flood-repair volume of approximately 46% for continued maintenance. Above this threshold, reconstruction leads to a lower cumulative environmental impact over 50 years than maintenance.
The framework identifies the reductions in future interventions needed to justify the environmental burden of infrastructure resilience measures. It supports decisions that jointly consider flood resistance and lower cumulative environmental impacts, while highlighting the need for improved assessment and empirical data for better decision-making.

5.02.P-Mo092 A Spatially Explicit Life-Cycle Assessment of Wildfire-Induced Infrastructure Loss and Reconstruction

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Wildfire-related carbon accounting emphasizes biogenic emissions from vegetation combustion while underrepresenting the anthropogenic emissions and material demand associated with damage to the built environment, debris removal, and reconstruction. We present a spatially explicit Life-Cycle Assessment (LCA) to quantify this overlooked carbon burden and compare the embodied carbon of reconstruction against the operational carbon of fuel treatments to establish a resilient-oriented metric for the climate return on fire prevention.
The assessment uses representative building archetypes in the Wildland-Urban Interface (WUI) of California to establish a baseline for material intensity, reconstruction demand, and post-fire debris flows. The study quantifies the additional embodied carbon associated with compliance with California's Chapter 7A fire-hardening regulations, referred to here as the 'WUI Code Penalty. Using a model in SimaPro with ecoinvent 3.11, we estimate product-stage emissions and transport to remote WUI sites for fire-resistant assemblies. Furthermore, the model incorporates a "Debris Removal Loop" (life cycle stages C1–C4) that accounts for the carbon-intensive process of scraping toxic ash and hauling it to specialized hazardous-waste landfills.
By synthesizing these LCA results with 30m-resolution fire simulation (FSim) burn probabilities and 2050 hydroclimate projections, this study identifies where forest thinning and prescribed burns are "Carbon Positive". The findings clarify how safety policies, climate risks, and infrastructure sustainability interact, and evaluate whether fire-hardening regulations, while essential for protecting lives, also result in a measurable hidden carbon cost.

5.02.P-Mo093 Integrating Circular Design into Sustainable Mass Management of Excavated Soils

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This study addresses the challenges of reducing land use and minimizing waste generation for construction on unstable soils by developing strategies for sustainable valorization of excavated geomaterials. In Norway, large volumes of excavated soils (particularly from soft and quick clay areas) are currently treated as waste, despite their potential for reuse and recycling. Stabilization methods such as jet grouting and lime–cement columns enable construction in quick and soft clay areas but produce considerable soil wastes that are typically landfilled. The EU Waste Framework Directive (2023) requires 70% reuse or recycling of construction waste, but there is currently a gap towards reaching these targets in Norway. This study explores circular approaches for managing waste materials from soil stabilization. In this study, we apply life cycle assessment (LCA) to evaluate the environmental performance of different valorization options for comparing conventional landfill disposal with circular solutions, emphasizing material recovery, local reuse, adaptability, and recycling. The findings highlight the importance of integrating circular design principles into early-stage planning and infrastructure design to facilitate material traceability, reduce environmental impacts, and optimize land use. Incorporating such strategies can transform excavated masses from waste to valuable resources, advancing both sustainability and circularity in the construction sector.

5.02.P-Mo094 Toward Prospective Assessment Frameworks for the Sustainability, Circularity, and Resilience of Emerging Clean Energy Technologies: Insights from a Literature Review

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Introduction
The rapid deployment of emerging clean energy technologies is essential to achieving European climate neutrality. However, robust and harmonized assessment methodologies remain limited, particularly for early-stage technologies. This study aims to identify key methodological challenges in assessing sustainability (environmental, economic, and

social), circularity, and European Union (EU) resilience for emerging clean energy technologies.

Methodology
A systematic review of 217 peer-reviewed articles and institutional reports was conducted following the Reporting Standards for Systematic Evidence Syntheses (ROSES) guidelines. The review evaluates methodological approaches used across sustainability, circularity, and EU resilience dimensions.

Results
The results indicate that environmental and economic assessments are supported by well-established methods, such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Techno-Economic Analysis (TEA). In contrast, circularity and EU resilience are addressed inconsistently and lack standardized operational frameworks. Social Life Cycle Assessment (S-LCA) is gaining traction but remains fragmented due to the absence of harmonized indicators. Across all dimensions, methodological robustness is strongly linked to technology maturity, with most approaches better suited to higher Technology Readiness Levels (TRLs). Key limitations include insufficient transparency in assumptions, limited disclosure of data quality, and the underuse of uncertainty and sensitivity analyses—critical elements for prospective assessments. Moreover, most methodologies are static and fail to capture technological evolution over time.

Conclusions
These findings highlight the need for TRL-adaptive, prospective assessment frameworks that integrate multiple sustainability dimensions while consistently incorporating circularity and EU resilience. Key recommendations include the development of harmonized indicators, integration of materiality analysis, improved transparency in data and assumptions, and the systematic inclusion of uncertainty analysis. This work advances life cycle thinking by identifying key methodological gaps and outlining pathways to extend conventional approaches toward more comprehensive, forward-looking, and policy-relevant assessments, supporting EU objectives on sustainability, circularity, and strategic autonomy.

5.02.P-Mo095 Comparative life cycle assessment of sodium-ion and lithium-ion batteries for electric vehicles

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Electric vehicles are central to transport decarbonisation, with the battery pack representing one of the most important components determining both vehicle performance and environmental impact. Lithium-ion batteries currently dominate electric vehicle applications, but their rapid growth raises concerns around critical raw material demand, supply chain vulnerability and long-term sustainability.

Sodium-ion batteries have therefore emerged as a promising alternative chemistry, offering potential advantages in material abundance, reduced critical material dependence and lower supply risk. Recent studies indicate that sodium-ion batteries may also offer improved environmental performance, particularly in terms of climate change impacts. With the first commercial electric vehicles incorporating sodium-ion batteries now entering the market, there is a timely need to evaluate their life cycle implications at the vehicle level.

This study addresses the current lack of life cycle assessment studies on sodium-ion battery electric vehicles by comparing their environmental performance with that of conventional lithium-ion battery electric vehicles. A cradle-to-use life cycle assessment is conducted, accounting for vehicle design parameters, driving range, battery cycle life and transport energy consumption. Four electric vehicle configurations are assessed: a sodium-ion battery electric vehicle, a hybrid sodium-ion and lithium iron phosphate (LFP) battery electric vehicle, a nickel manganese cobalt (NMC) battery electric vehicle, and an LFP battery electric vehicle. This comparison enables the environmental implications of sodium-ion battery deployment in electric vehicles to be assessed against established lithium-ion technologies.

The findings contribute to Track 5 by providing a comparative life cycle assessment of sodium-ion and lithium-ion batteries. It directly addresses the sustainability of critical raw materials and potential approaches to mitigate battery supply chain risks.

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5.02.P-Mo096 Battery-Grade Graphite for the EU: Linking Life Cycle Impacts and Supply Risks Across Natural and Synthetic Routes

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Battery-grade graphite is a critical anode material for lithium-ion batteries, but its environmental sustainability and supply security cannot be inferred from graphite markets in general. Producing battery-grade graphite requires additional steps, including purification, shaping, coating, and, in some cases, graphitization, which introduce specific environmental burdens and supply dependencies beyond the extraction of the primary raw material. At the same time, battery-grade synthetic graphite can fulfil the same function as battery-grade natural graphite in batteries while relying on fundamentally different feedstocks, processing routes, and geographical supply structures. This is particularly relevant for the European Union, which seeks to expand domestic battery value chains while reducing greenhouse gas emissions and dependence on concentrated imports.

This study applies an integrated framework combining supply chain analysis, life cycle assessment, and supply risk quantification to compare the environmental impacts and geopolitical supply risk of battery-grade natural and synthetic graphite from an EU perspective. Supply chain analysis is used as a first step to distinguish battery-grade production routes from graphite markets more broadly and to support the development and interpretation of representative life cycle inventory data. Environmental performance is assessed per kilogram of battery-grade graphite, with a particular focus on climate change impacts. The Geopolitical Supply Risk impact of both product systems is evaluated using the GeoPolRisk method along their different stages, including raw materials and intermediate products such as flake graphite and needle coke.

The results highlight a central trade-off for resilient battery production in EU: natural graphite may offer lower climate change impacts, whereas synthetic graphite may present a different risk profile depending on feedstock origin, energy mix, and refining location. The findings indicate why battery-grade graphite should be treated as a distinct assessment object and why combining supply chain analysis, environmental assessment, and criticality assessment is necessary for robust decision-making. By providing an integrated overview of climate and supply-risk trade-offs, the study supports more transparent material choices, scenario development, and policy design for sustainable and resilient battery supply chains in Europe.

5.02.P-Mo097 From Waste to Energy: Assessing the Environmental Consequences of Co-processing Strategies in the Brazilian Cement Industry

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The cement industry is a significant contributor to global greenhouse gas emissions, accounting for approximately 8% of CO_2, especially by producing clinker, the main component of cement. The sector faces the challenge of mitigating the impacts of its production chains. In contrast, the waste management sector faces increasing volumes of industrial and municipal waste, making one option co-processing waste to supply the energy demand in clinker kilns. The primary challenge lies in quantifying the systemic environmental shifts when transitioning from fossil-based energy to

waste-derived fuels. This study aims to evaluate the environmental consequences of substituting petroleum coke with alternative fuels derived from waste, such as biomass, tire-derived fuels (TDF), and refuse-derived fuels (RDF), in a case study in clinker kilns in Brazil. To address this, the research adopts a consequential Life Cycle Assessment (LCA) framework to capture the market effects of adopting the strategy. Using SimaPro 10.3 and the Ecoinvent 3.10 database, scenarios were modeled based on the Brazilian Cement Technology Roadmaps for 2030, 2040, and 2050. Impact assessment was conducted using the ReCiPe midpoint method. Results indicate that waste-to-energy strategies significantly mitigate CO_2 eq. emissions, especially when using biomass waste, resulting in the lowest emissions in each impact category. Otherwise, RDF has presented great environmental potential in the waste-to-energy strategy. On the other hand, TDF resulted in higher impacts, such as petroleum coke. In clinker production, the substitution of fossil fuels by waste alternative fuels can reduce 11.3% of CO_2 eq/ton. This also represents the avoidance of 40% of the use of petroleum coke in the usual thermal matrix. Otherwise, the strategy can avoid not only the emissions of petroleum coke but also the landfilling of that waste, generating a benefit of around 45-65 kg of CO_2 eq. per ton of clinker produced using waste-to-energy systems. The strategy can also improve transport efficiency, substituting long-distance travel for fossil fuels with short internal distances for waste-derived fuels. The study concludes that achieving Brazil's 2050 decarbonization goals is dependent on co-processing strategies. The findings can support policymakers and industry stakeholders in optimizing waste allocation to maximize environmental impact mitigation and align local industrial practices with international sustainability targets.

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5.02.P-Mo098 Recycled Material Quality and Environmental Impacts in Battery Recycling

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Life cycle assessment (LCA) of battery recycling typically define the system boundary as encompassing battery material extraction, manufacturing, and recycling, excluding the usage stage. This approach assumes that recycled material is of equivalent quality to raw material and can be reintroduced into battery production, representing closed-loop recycling. However, achieving this quality standard may require additional resources and energy, potentially making closed-loop recycling less environmentally preferable than open-loop recycling. From an environmental impact perspective, both process impacts and recycling credits are important considerations, regardless of whether recycling is closed-loop or open-loop. Therefore, this study aims to develop a framework to identify environmentally optimal recycling routes. Retired EV batteries are used as a case study. We analyze peer-reviewed articles and industrial reports, focusing on chemical recycling routes and decomposition into elemental species, to explore the relationship between recycled material quality and associated environmental impacts, particularly energy consumption and GHG emissions. This research is expected to produce a visual graph illustrating the relationship between recycled material quality and its associated environmental impacts, along with potential applications for various recycled material qualities. This graph will facilitate strategic planning for battery recycling.

5.02.P-Mo099 Evaluating the Environmental Performance of Technologies for Critical Raw Material Recovery from Lithium-Ion Batteries

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The rapid expansion of electric mobility and renewable energy storage systems intensifies concerns over critical raw materials (CRMs) demand and end-of-life management of lithium-ion batteries (LIBs). In this context, the recovery of

CRMs from waste LIBs has the potential to address both resource demand and lifecycle management challenges contributing to the circular economy. While industrial-scale processes for metal recovery from LIBs already exist, uncertainties remain regarding their environmental performance. Life Cycle Assessment (LCA) enables the evaluation and comparison of emerging technologies. This study conducts a cradle-to-gate attributional LCA to assess the potential environmental impacts of two distinct hydrometallurgical CRMs recovery processes from spent Nickel-Manganese-Cobalt oxide (NMC) LIBs (HM1 and HM2) developed in Brazil. HM1 comprises LIB discharge in FeSO4 and manual disassembly, followed by metal recovery utilizing NaOH and oxalic acid. HM2 uses resistor-based discharge, size reduction, sieving, and leaching the finer fraction with H2SO4, NaOH and glucose. Both processes are in the laboratory scale phase (TRL 4) and produce lithium carbonate and nickel, manganese, and cobalt hydroxides. The functional unit was set as the recycling of 1 kg of spent NMC LIBs, and the ReCiPe 2016 Midpoint (H) impact assessment method was applied. Foreground inventory was retrieved from experimental data and the literature, supplemented by background data from Ecoinvent v.3.8 and Sphera professional databases. Multifunctionality was addressed by the substitution approach, considering open-loop recycling. The intensified mechanical treatment in HM1 is expected to result in higher electricity demand, particulate matter emissions, and the generation of a mixed waste stream. While manual disassembly in HM2 enables the separate recycling of battery components, solution-based discharge may increase material demand and hinder the reuse of LIBs residual energy. These trade-offs highlight the critical role of LIBs pre-treatment in determining the overall environmental performance, suggesting that the processes are likely to yield comparable overall environmental impacts, with different contributions across impact categories. The modular LCA framework enables the attribution of impacts among individual unit processes, facilitating the design of an optimized hydrometallurgical process by interchanging lower-impact unit processes.

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5.02.P-Mo100 Refining Circularity Indicator in an Early-Stage Sustainability Index for Steelmaking Materials

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Early-stage sustainability assessment tools are increasingly needed in sectors such as steelmaking, where material selection decisions must be made under limited data availability and full life cycle inventories are rarely accessible. A Sustainability Index (SI) recently developed by our research group addresses this challenge by integrating environmental, economic, social, criticality, and circularity dimensions into a unified multidimensional framework for comparing scraps, ferroalloys, and pure elements. While the SI provides a solid foundation for multi-criteria material screening, this work focuses specifically on advancing its circularity dimension by introducing a more granular and structurally grounded representation of circular economy principles.

The proposed circularity indicator captures key material flow parameters at both input and output stages while remaining fully compatible with the original SI framework. The result is a bounded, dimensionless metric that increases the resolution with which circularity differences among steelmaking materials can be distinguished, without introducing data requirements beyond those typical of early-stage screening contexts.

The methodology is applied to the original steelmaking material dataset, enabling a direct comparison between the published SI and the refined version. This refinement enhances differentiation among materials and supports clearer interpretation of circularity-related trade-offs within the broader sustainability framework.

The proposed approach strengthens the methodological basis of simplified sustainability indices by moving toward a more continuous and structurally grounded circularity metric. This refinement offers a feasible pathway to more thoroughly integrate circular economy principles into early-stage material selection and supports more robust

sustainability screening for industrial decision-making.

Keywords: Early-stage sustainability assessment; steelmaking materials; circularity indicator; Sustainability Index; material selection; circular economy; multi-criteria decision support

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5.02.P-Mo101 Recycling Metallic Lithium Anodes from Solid-State Batteries: Environmental and Material Recovery Performance

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Solid-state batteries (SSBs) with lithium-metal (Li-M) anodes are gaining traction as a next-generation energy storage technology. However, end-of-life management of Li-M anodes remains largely uncertain, as this technology is yet to enter the market and its recycling process is still under development. Nonetheless, the EU Battery Regulation sets binding targets for Li recovery efficiency, making the development of efficient recycling processes increasingly urgent for SSB sustainability and lithium circularity.
This study conducted a life cycle assessment (LCA) to an emergent hydrometallurgical recycling route for Li-M anodes, composed of four main stages: Li dissolution, filtration, evaporation, and drying. The ReCiPe 2016 (H) method was used to quantify the environmental impacts and characterise the main hotspots across the process.
Results showed a total endpoint impact of 997.87 Pt, with global warming (70%) and fine particulate matter formation (20%) as dominant impact categories in endpoint analysis. Drying and evaporation are the main process contributors (62% and 38%, respectively), driven by high energy consumption. The assessed hydrometallurgical route achieved a recycling efficiency of 81%. When Li (as LiOH) and copper recovery are accounted for as avoided impacts, total endpoint impacts are reduced by 13%, with copper recovery being the primary driver (12.7% reduction). These findings highlighted energy intensity as the key hotspot for process optimisation and improved environmental performance of SSB anode recycling. These results provide an initial viewpoint on how Li-M anode recovery can support the EU Battery Regulation battery material recovery targets.

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5.02.P-Mo102 Trade-offs Between Carbon Footprints and Material Criticality in Circular Battery Strategies for Maritime Electrification

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The decarbonization of maritime transport requires batteries capable of delivering substantial reductions in life-cycle greenhouse gas (GHG) emissions. As battery technologies evolve, Life Cycle Assessment (LCA) plays a key role in evaluating environmental impacts across production and end-of-life (EoL) stages of various battery chemistries. Given the high capacity demands of maritime applications, these systems offer significant potential for second-life use in less demanding applications. However, existing LCA literature largely prioritizes recycling, with limited attention to battery reuse and repurposing, particularly in maritime contexts. In addition, conventional lithium-ion batteries rely on

several critical raw materials. Within the EU, where strategic autonomy and raw material security are key priorities, criticality—capturing geopolitical and supply risks—is not consistently integrated into environmental assessments. To support maritime electrification and compliance with upcoming battery and maritime regulations, a forward-looking perspective is required in this niche market.
The study combines prospective LCA and criticality assessment to support battery system design and EoL management in the shipping sector. Five alternative battery configurations are evaluated for a ferry application: 1) lithium iron phosphate (LFP) with second-life use in grid storage, assuming no recycling due to low content of valuable metals; 2) nickel manganese cobalt (NMC) with second-life use followed by recycling; 3 and 4) oversizing of LFP and NMC systems to extend service life by reducing equivalent cycles; and 5) substitution with sodium-ion batteries, assumed to be discarded after first life. Forward-looking assumptions are applied to foreground (technological innovation, capacity fade) and background (grid decarbonization, socioeconomic pathways) systems, while accounting for ferry-specific operational parameters (charging frequency, depth of discharge). GHG emissions are quantified using Activity Browser with ecoinvent 3.9.1 (cutoff) and premise databases, while the criticality assessment evaluates supply concentration, geopolitical risk, and resource depletion of key battery components.
The integrated approach enables identification of trade-offs between climate mitigation and supply security across technologies and circularity pathways, providing industry-relevant insights for battery system design that are both climate-compatible and supply-chain resilient.

5.02.P-Mo103 Life Cycle Assessment of Electrical and Electronic Equipment: Integrating Critical Raw Materials Assessment and WEEE Recycling Circularity

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The increasing demand for electrical and electronic equipment (EEE) is intensifying pressure on critical raw materials (CRM), calling for robust methodologies to assess resource efficiency beyond conventional metrics. While life cycle assessment (LCA) is widely applied, existing indicators often fail to capture resource degradation and thermodynamic limits to circularity.
This study addresses this gap by analysing the life cycles of three representative EEE products—a refrigerator, a washing machine, and a laptop—across production, distribution, use, and end-of-life stages. The objective is to evaluate how product lifetime extension and end-of-life strategies influence environmental performance, material consumption and resource criticality.
A scenario-based LCA approach is applied, exploring different use-phase durations and multiple end-of-life pathways, including variations in recycling efficiencies. Particular attention is given to trade-offs between lifetime extension, technological obsolescence and material recovery.
The study introduces a novel indicator that measures the accumulation of thermodynamic irreversibilities throughout the life cycle. From a thermoeconomic perspective, irreversibility represents the physical cost associated with exergy degradation and entropy generation, providing a consistent measure of resource consumption and system inefficiency. This approach enables quantification of the “physical loss” accumulated across life cycle stages, and assessment of losses within circular systems relative to their maximum theoretical circularity. The methodology is further benchmarked against existing approaches for material criticality assessment.
Preliminary results suggest that lifetime extension can significantly reduce impacts for certain products, although its effectiveness depends on use-phase energy consumption. End-of-life strategies play a key role in recovering critical materials; however, the intrinsic dispersion of materials within complex products makes recovery increasingly energy-intensive, ultimately limiting achievable circularity.
These findings contribute to advancing life cycle methodologies by integrating thermodynamic principles into sustainability assessment. The approach supports improved decision-making in circular economy strategies and critical raw material management, highlighting the importance of considering physical limits to resource recovery.

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5.02.P-Mo105 Quantifying the Supply-Demand Gap in Closed-Loop Concrete Recycling: Can Denmark Produce Clinker from End-of-Life Concrete at Scale?

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The cement sector accounts for approximately 8% of global CO2 emissions, driven by fossil fuel combustion during clinker production and CO2 release from limestone calcination. Concrete demolition generates substantial volumes of end-of-life (EOL) concrete waste, conventionally downcycled as road filler, recovering little of its value. Closed-loop recycling offers a more ambitious alternative: ultrafine concrete waste particles (UFCWP, 0–0.25 mm fraction) extracted from EOL concrete can theoretically re-enter the clinker raw meal, closing the material loop from demolition back to cement production and reducing dependence on virgin raw materials. Realising this circular economy (CE) strategy at scale, however, is not straightforward. The chemical composition of the clinker raw meal must satisfy strict quality boundaries for successful clinker formation, and whether EOL concrete waste can meet those boundaries and in sufficient volumes, remains an open and critical question.

This study quantifies how much UFCWP recovered from EOL concrete can chemically substitute conventional raw meal in Danish Portland cement clinker production, and whether current EOL concrete volumes are sufficient to meet that demand.

A conceptual stoichiometric mass balance model was, for the first time, combined with material flow analysis (MFA) to quantify the chemical limitations of UFCWP substitution in Danish clinker production, evaluating two scenarios , business-as-usual and closed-loop UFCWP recycling against clinker quality moduli as boundary conditions.

The model demonstrates that a maximum of 11.76% UFCWP can replace conventional raw meal in Danish cement clinker production, yielding a 10% reduction in GWP compared to conventional clinker production. However, meeting this substitution rate would require approximately three times Denmark's current annual EOL CEM I concrete volume around 1.2 million tonnes exposing a fundamental supply demand gap that undermines closed-loop recycling at scale. This work provides a replicable stoichiometric framework for assessing the material and environmental feasibility of concrete closed loop recycling, and underlines that chemical composition constraints must be explicitly modelled before circularity potential can be claimed.

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