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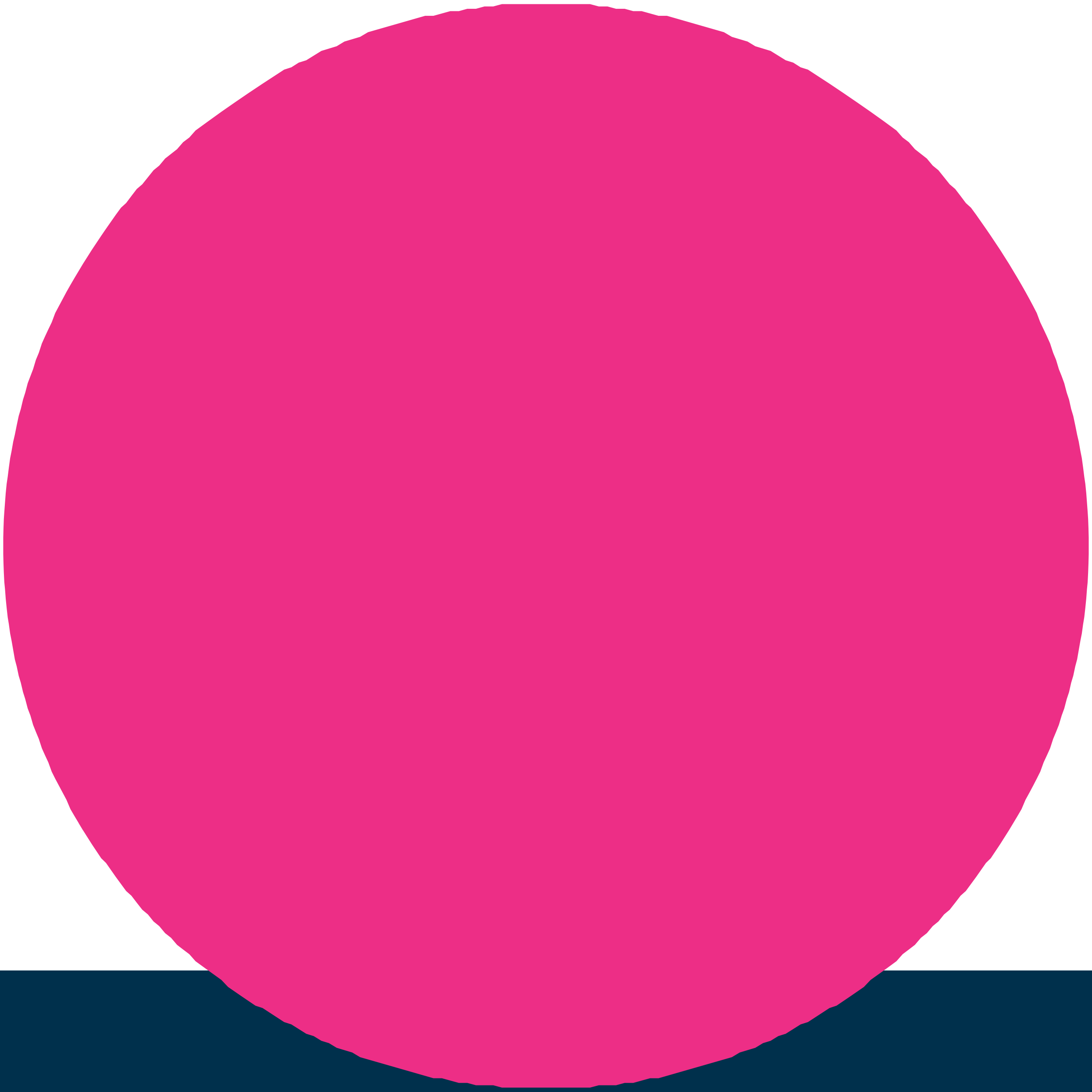

# Extended Abstracts SETAC Europe 26th LCA Symposium

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Editors' note:

This is a compilation of extended abstracts from the SETAC Europe 26th Life Cycle Assessment Symposium jointly organised by the Swedish Life Cycle Center, which was held in Gothenburg from the 21st to 23rd of October 2024. While the short abstracts were published on the conference website by SETAC, authors who had also submitted extended abstracts were emailed regarding the possibility to have those extended abstracts published here. Authors who had chosen this option by the start of the Symposium are listed in the table of contents along with the title of their contribution.

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# Green Hydrogen Production in Uruguay: Integrating Life Cycle Assessment and Energy System Optimisation using Impuls-urbs Framework

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## 1. Introduction

Green hydrogen is a crucial energy vector for decarbonising energy systems, especially in sectors where electrification is challenging. The global push for green hydrogen underscores a collective commitment to decarbonising energy systems worldwide. While advanced economies have made strides in leveraging renewable energy, regions like Latin America, including Uruguay, possess untapped potential for green hydrogen production. Uruguay's "Green Hydrogen Roadmap" [1] reflects the nation's ambition to leverage its renewable energy potential and establish a robust market for green hydrogen, with the aim to export up to 1 million tons annually by 2040. It is estimated that it would require an additional installation of approximately 18 GW in renewable capacity.

Such climate policies and development pathways to address the growing energy demand are made with the help of sophisticated analytical tools like energy system models (ESM). However, most of the existing ESM frameworks focus only on the operational phase of power plants and neglect the indirect emissions. This leads to policy-making with limited insights. Life cycle assessment (LCA) techniques [2] provide holistic thinking including the indirect emissions but are often done as a post-analysis of the optimisation result of ESM. This study addresses this gap by applying a novel model framework that integrates LCA insights into the optimisation of Uruguay's energy system.

The primary aim of this study is to show how policymaking would be affected when the production of key materials required for the related technologies and corresponding supply chain greenhouse gas emissions are taken into account in ESM. This comprehensive approach provides insights into economic, environmental, and technical challenges and opportunities by evaluating the interconnected development of the material sector, the electricity system, and the hydrogen sector.

Ultimately, by integrating LCA insights into Uruguay's energy system model, this study aims to reveal the interdependencies between hydrogen economics and energy infrastructure development. This will deepen the understanding of Uruguay's transition toward green hydrogen and its broader implications for the energy landscape.

## 2. Materials and Methods

The Uruguayan electricity and hydrogen sector is modelled by encompassing the existing Uruguayan electrical system alongside planned expansions, optimising electricity generation, distribution, hydrogen production, transport, and selling. The analysis spans multiple reference years (2021, 2025, 2030, 2040, and 2050), offering a comprehensive outlook on Uruguay's energy landscape evolution. To assess renewable energy potential and incorporate temporal dynamics, the pyGRETA tool [3] is utilised, facilitating accurate calculations and time-series analyses.

The model is optimized using two frameworks comparatively, first in a typical energy system model called urbs [4], [5] and second in a new open-source optimisation framework encompassing an energy model integrated with life cycle assessment called Impuls-urbs [6]. Both frameworks enable the minimisation of an energy system's total costs or emissions and include an intertemporal mode for multi-year optimisation with perfect foresight. In Impuls-urbs, the model constraints are adjusted to identify and incorporate additional energy demand for manufacturing new power plants and materials, with energy needs and emissions derived from the Ecoinvent database [7]. The updated model framework ensures that new power plants become operational only after their construction in previous years. This new framework has already been described using a generic example in [6] but is now applied to a real case of the Uruguayan energy system in this study.

## 3. Results and Discussion

Initially, the model is optimised with the urbs framework to investigate investment planning and energy system evolution. Findings from urbs revealed a significant need for future expansion within Uruguay's electricity sector, driven by heightened demand for hydrogen production, as estimated by Uruguay's green hydrogen roadmap. This expansion often necessitates substantial curtailment of electricity from inexpensive renewable sources to avoid additional investment in costly storage solutions.

Integrating upstream processes in Impuls-urbs provided a more comprehensive evaluation of Uruguay's energy transition prospects, unveiling shifts in the optimal energy mix. Notably, material production phases influenced the prioritisation of power plant expansions due to emissions and energy requirements associated with manufacturing technologies. Capturing indirect emissions during material production phases provided nuanced insights into transitioning to green hydrogen. The shift in the optimal energy mix is prominent with rapid decarbonisation goals and the utilisation rate of the generated electricity is higher.

## 4. Conclusions

This study underscores Impuls-urbs' transformative impact on Uruguay's energy system. The inclusion of material production phases prompted a re-evaluation of power plant expansions and revealed notable shifts in the optimal energy mix, particularly in prioritizing renewable energy sources.

Impuls-urbs facilitated a comprehensive assessment of the economic and environmental implications of Uruguay's green hydrogen ambitions, offering insights into the trade-offs and synergies between different energy pathways. It provides a valuable tool for guiding strategic decision-making and policy formulation towards a sustainable energy transition.

In conclusion, adopting Impuls-urbs represents a significant advancement in understanding Uruguay's energy landscape. Impuls-urbs paves the way for a more resilient, efficient, and environmentally conscious energy future for Uruguay by shedding light on previously overlooked factors and capturing the holistic impact of energy system transitions.

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# Life Cycle Inventories for Aviation: Background Data, Shortcomings, and Improvements

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## 1. Introduction

Despite the Covid-19 crisis, air transportation is expected to grow steadily and faster than efficiency improvements, with emissions likely to double by 2050 [1]. Although the greatest share of aviation emissions occur during flight operations, life cycle stages such as manufacturing and maintenance are also relevant when conducting holistic evaluations [2, 3]. The environmental impacts can be addressed by a standardized tool called Life Cycle Assessment (LCA), in which the Life Cycle Inventory (LCI) phase is especially data-intensive and requires a high amount of both foreground (study-specific) and background (aggregated) information. In aviation, data representativeness and completeness are usually hindered by confidentiality posed by aircraft manufacturers, maintenance providers or operators, leading to significant gaps. Aiming to improve life cycle data coverage, a use-case on aircraft Maintenance, Repair, and Overhaul (MRO) foreground inventory integration into background databases is presented. Aircraft maintenance is based on processes such as repair, inspection, and components replacement with distinct intervals. MRO activities ensure airworthiness and potential for reducing ecological impacts (e.g. increased fuel efficiency achieved by engine washes).

## 2. Methods

This analysis seeks to establish a foundation for integrating MRO in-depth inventories into LCI databases with higher aggregation levels. The different types of maintenance tasks and their frequency were modelled based on recent maintenance LCA studies [4]. General maintenance parameters over the aircraft's entire life cycle are calculated by a top-down approach, which aggregate MRO activities packages that vary in level of detail, maintenance duration, and execution intervals (e.g. daily, weekly, A, C, and D checks, and various shops visits). These parameters can entail the total duration an aircraft spends in maintenance during its life or the service life of specific equipment. The inventory covers both airframe and engine maintenance, including upstream activities such as energy, materials, and resources usage, and is to be connected to existing datasets for aircraft production, airport infrastructure, and kerosene production through a common functional unit. The aircraft's life cycle is simulated using DLR's framework Life Cycle Cash Flow Environment (LYFE) for discrete-event simulation [5], based on flight schedules and maintenance intervals. Maintenance checks are usually dependent on multiple thresholds (such as flight hours (FH), flight cycles (FC), or components service period) and are triggered by the "whatever occurs first" principle [6]. The results for Global Warming Potential (GWP) in kgCO2eq. are given in Figure 1 per passenger-kilometre (PKM), FH, and FC, considering a 25-year lifespan. The obtained LCA results for each maintenance check type (e.g. line, base or shop) are then aggregated and distributed according to its occurrence for different flight distances, ranging from 500 km (very short haul) to 7000 km (very long haul).

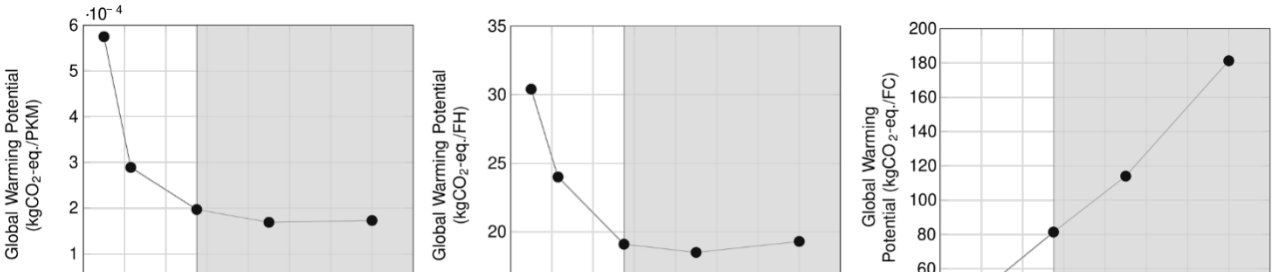

*Figure 1: Global Warming Potential [kgCO2-eq.] per PKM, FH and FC.*

## 3. Results

Aircraft and engine are two highly complex systems with distinct operational lifetimes and maintenance requirements and are not necessarily coupled for their entire life span, i.e. the same aircraft might not operated over its life cycle with the same engine [7]. During its operational life, engines undergo wear, stress, and fatigue, leading to lower efficiency and reliability, and critical components such as the fan, compressor and turbine (referred to as Life Limited Parts (LLPs)) have to be replaced at fixed intervals to ensure safety. Hence, the maintenance activities are divided into two types: airframe (structure and components) maintenance and engine maintenance. Airframe maintenance includes line maintenance (daily, weekly and A-checks), base maintenance (C- and D-checks), and shop maintenance (Auxiliary Power Unit and Landing Gear), whereas engine maintenance is comprised of engine shop visit and LLPs exchanges. In addition, materials and resources used in each activity are distinct for airframe and engine MRO. For instance, composite materials are extensively used for maintaining the aircraft airframe through its life cycle, while engine parts and LLPs are generally comprised of special aviation alloys (e.g. titanium, nickel and steel).

Additionally, the occurrence of maintenance activities for each flight distance changes, e.g. aircraft operating in very short- or short-range networks exhibit higher FCs due to shorter distances and more frequent flights, whereas long- and very long-range routes present higher FHs due to longer flights per cycle. Depending on the inteded use and target audience, the necessary level of data aggregation may change. For MRO and aviation-specific applications, the differentiation between different flight distances is relevant due to presented variability of FCs and FHs. On the other hand, LCI background databases typically represent average technology, requiring a balance between providing sufficient detail and avoiding unnecessary complexity in data aggregation, e.g. a maintenance dataset for aircraft operating medium-range networks. For both ends, splitting MRO into airframe and engine is recommended.

## 4. Conclusions

Translating extensive and detailed foreground data into background data requires comprehensive interpretation, assumptions, and hypotheses consistent with the system boundaries. The results presented in the previous section indicate that the environmental impacts of aircraft maintenance activities vary depending on flight distances. Additionally, it is necessary to categorize MRO tasks into airframe and engine maintenance owing to their distinct complexities and characteristics. The level of data aggregation depends on the intended purpose of the study and the target audience. MRO and industry experts may require more detailed inventories, whereas the aggregation level is higher for LCI background databases.

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# Accuracy and Sector Consistency in Automotive LCAs: A Balancing Act

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## 1. Introduction

Life Cycle Assessment (LCA) methodology is deeply engrained into the sustainability strategy toolbox of environmental conscious enterprises. Companies, including Scania, perform LCAs for four principle reasons: (a) to communicate environmental performance of products with their customers (through externally verified LCA reports or environmental product declarations (EPDs) and enable them to make sustainably wise decisions; (b) fulfil regulatory requirements (e.g., Product Environmental Footprint declarations, Corporate Sustainability Reporting Directive); (c) generate data to facilitate the process of informed decision making on internal research projects like eco and circular design of products; and (d) provide input to Science Based Targets projects initiated by companies.

Sometimes, the outcome of studies is arguable due to multipronged ambiguity (influencing factors include choice of impact assessment method, selection of LCI datasets, etc) associated with current LCA practices. Although unintended, the subjective nature of LCA can affect the credibility of results and can potentially lead to misinterpreted conclusions.[1, 2]

Amidst the growing importance of LCA studies, lack of consistency[1, 2] and/or accuracy[3] in evaluating the environmental performance of products is a cause of a major concern especially for OEMs of automotive industry. The complexity of automotive products with a highly diverse material composition, and difficulties in building use stage modelling scenarios representative of real world conditions, makes it challenging to always conduct LCAs without compromising on consistency or accuracy.

To address this issue, on one hand entire automotive sector is rigorously working to achieve the consistency required by streamlining methodological aspects of vehicle LCAs and on other hand, individual OEMs are constantly striving to improve accuracy of their life cycle inventory (LCI) modelling procedures.

In today's talk, we will discuss on two aspects: (a) Scania's approach (OEM perspective) of developing LCI models with high accuracy through increased representativeness, and systematically reduce margin of error while performing vehicle LCAs; and (b) highlights from some ongoing initiatives of automotive sector of tackling the LCA consistency problem. We conclude our presentation by shedding light on future direction where the industry is headed for conducting vehicle LCAs and also highlight potential risks of such transition.

## 2. Transition Towards Conducting Unambigous Automotive LCAs:

With an ambition to reduce the encircled ambiguity of existing LCA practices in automotive industry, focusing on accuracy and sector consistency is important as shown in Figure 1.

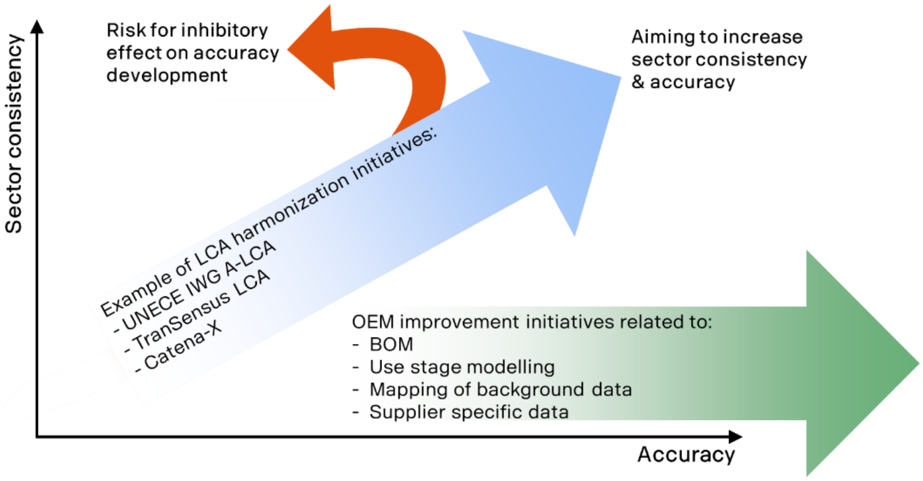

Figure 1: Initiatives of OEM to Improve Accuracy of LCI Data Vs Intiatives to Increase Consistency of LCA Modelling Methodologies of Automotive Industry

Automotive OEMs give paramount importance to accuracy of LCI models while performing vehicular LCAs. Particularly, Scania progressed in improving the accuracy of LCI data. Major LCI modelling improvement efforts of Scania include: (a) development of material translation tool that empowers us to select most representative LCI datasets (reflecting precise composition of material used e.g., using LCI data specific to a aluminium alloy Vs generic aluminium dataset) for modelling cradle to gate life cycle stages of trucks and buses; and (b) utilize Scania's access to vehicle data from customer operations, e.g., energy consumption, driven distance, drive cycles and payload etc.

On the other hand, entire industry is aiming for achieving higher sector consistency of LCA results by aligning on (methodological issues such as: (a) adapting a common life cycle impact assessment (LCIA) method and impact assessment categories to be reported externally; (b) recommendations for modelling of electricity; and (c) use of common end of life approach (e.g., simple cutoff, substitution or circular footprint formula approaches etc).[4-6] Although the transition of automotive industry towards achieving higher sector wide consistency by streamlining LCA modelling methodologies is an essential aspect, the caveat is that some of these initiatives can be a major roadblock for OEMs continuous journey of building precision LCI models. An appropriate example for this kind of situation is lack of accurate representation of datasets in prescribed LCI databases (e.g., EF3.1.) supposed to be used for quantifying the carbon footprint of electric vehicle batteries (according to PEF battery regulation).

## 3. Conclusions

Sector wide consistency of LCA methods increases transparency but can compromise accuracy of LCI data and a serious effort is needed to mitigate such situations. The learnings from this study serve as a guiding principles for non industry LCA practitioners, policy makers and academicians with vested interests in LCA harmonization in automotive industry.

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# Using multi-regional input-output models for absolute environmental sustainability assessments of industries

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## 1. Introduction

There is an urgent need to limit the environmental impacts of products and services to stay within the environmental carrying capacities [1]. Environmental carrying capacities refer to the maximum level of impact that the environment can handle without experiencing significant damage to the functional integrity of its natural systems [2]. It has also been referred to as safe operating space (SOS), environmental budget, and impact budget, among other terms. Several concepts have aimed to dilenate these limits such as the planetary boundaries (PBs), IPCC carbon budgets, and the science-based targets (SBTs) [3]. Collectively, these boundaries define a safe operating space for humanity. These boundaries tend to be defined on a global scale, and they need to be downscaled to products and services using sharing principles. Several sharing principles have been proposed in the literature [2]. The most commonly used metrics for sharing principles are based on environmental emissions (grandfathering) and monetary terms [2].

Recent studies have developed methods to downscale the environmental carrying capacities of specific products using sharing principles and subsequently assess if the products' impacts are higher or lower than their assigned share of safe operating space (aSoSOS) [4]. However, there is a lack of consistent sources for the emission (grandfathering) and monetary data for deriving the aSoSOS for products and services. To solve such limitations, Oosterhoff et al. have proposed a framework for the assignment of safe operating space to specific industries using the environmentally extended multi-regional input-output (EE-MRIO) models, such as Exiobase 3 [5,6]. Even though the framework can provide aSoSOS for industries, these assigned shares need to be compared with the environmental impacts of such industries to prioritise mitigation efforts. In this study, we derive assigned shares of safe operating space for the industries and products in Exiobase 3 and use the derived shares to determine specific budgets for the different environmental carrying capacities such as climate change. We then compare the environmental impacts of the industries to their aSoSOS to identify industries requiring urgent mitigation actions. Our results also indicate countries performing well in specific industries and vice-versa. Finally, we discuss the challenges and limitations of extending this approach to companies and products within considered industries and derive future research needs.

## 2. Materials and Methods

We operationalise the framework proposed by Oosterhoff et al. to derive aSoSOS for 163 industries and 200 products in 44 countries and 5 regions as shown in Equation 1 [5]. Stranddorf et al. simplify the framework and provide Equation 1 [7]. The combination of sharing principles considered in deriving the aSoSOS in Equation 1 are egalitarian (population) and utilitarian (final consumption expenditure and economic output). Equation 1 assigns a share ($aS_{\text{int},c}$) of the safe operating space to specific intermediate industry sector (int) in country (c) based on its population (Pop). Furthermore, the final consumption expenditure ($\text{FCE}_{\text{sec},c}$) of a given industry sector (sec) is used to further downscale from country to industry sector. Finally, the economic output ($\text{EO}_{\text{int},c}$) of the intermediate products in the industry sector (int) as a fraction of the economic output of the considered industries ($\text{EO}_{\text{sec},c}$) in a country are used to derive the final assigned shares. These assigned shares are multiplied with the environmental SOS to derive the $aSoSOS_{int,c}$ as shown in Equation 2. The environmental impacts of the considered industry sector ($EI_{i,int,c}$) are then divided by the $aSoSOS_{int,c}$ to arrive at the environmental sustainability ratios ($ESR_{int,c,i}$). The ESR values, representative of an absolute environmental sustainability assessment, are used to identify industries' requiring urgent mitigation actions (ratio greater than 1) and to indicate countries performing well in specific industries' (ratio less than 1) and vice-versa. The values for the population are based on the UN World Population Prospects for the year 2019. The values for FCE and EO are based on consumption-based accounts of Exiobase 3 for the year 2019.

$$aS_{\mathrm{int,c}} = \sum_{c}\sum_{\mathrm{sec}} \frac{\mathrm{Pop}_c}{\mathrm{Pop}_{\mathrm{World}}} \cdot \frac{\mathrm{FCE}_{\mathrm{sec,c}}}{\mathrm{FCE}_C} \cdot \frac{\mathrm{EO}_{\mathrm{int},c}}{\mathrm{EO}_{\mathrm{sec},c}} \tag{1}$$

$$aSoSOS_{int,c} = aS_{\mathrm{int},c} \times SOS_i \tag{2}$$

$$ESR_{int,c,i} = \frac{EI_{i,int,c}}{aSoSOS_{int,c}} \tag{3}$$

## 3. Results and Discussion

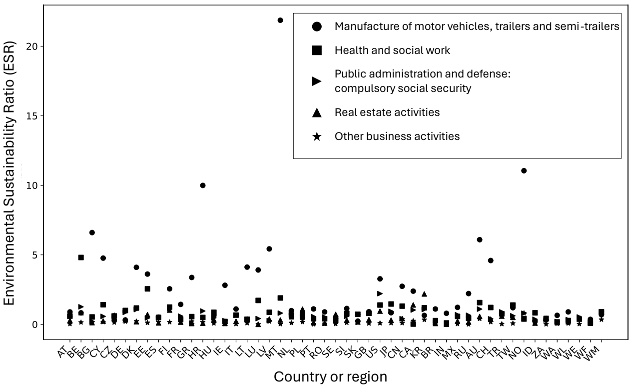

***Figure 1 Environmental sustainability ratio of select industries in forty-four countries and five regions in Exiobase 3***

Figure 1 illustrates the ESR values for select industries. The country codes are shown in the footnote[1]. For instance, in the "Manufacture of motor vehicles, trailers, and semi-trailers" industry, the highest ratio value of 21.9 is in Malta and the lowest value of 0.2 is in Slovakia. Countries with large automobile industries, such as Germany, the United States, Japan, and China have ESR values of 0.3, 3.3, 0.8, and 2.7 respectively. These ratio values indicate the countries performing well within their aSoSOS in a particular industry. In this industry, 26 of the 49 countries and regions have ratio values higher than one. For comparison, in the “Real estate activities” industry, only 4 of the 49 countries and regions have ratio values higher than one.

The assigned shares could vary if based on emission grandfathering, which uses environmental impacts instead of economic output as metrics for implementing sharing principles. Operational challenges remain despite deriving industry-level assigned shares for several countries. These shares vary with the year of the Exiobase model, and selecting a particular baseline year can disproportionately affect certain industries’ mitigation efforts. For instance, industries that have already implemented mitigation measures may see their assigned shares reduced in emission grandfathering. Additionally, translating these shares to specific companies and products poses difficulties. Simplified metrics like company revenue within an industry require mapping all existing companies to industries classified within available EE-MRIO models. Further research is needed to address these challenges.

## 4. Conclusions

The study used the data available in Exiobase 3 to derive aSoSOS for 163 industries and 200 products in 44 countries and 5 regions. The environmental impacts of the considered industries were derived based on extensions provided in Exiobase 3. The environmental impacts were then compared to the aSoSOS of the industries to identify countries performing well and vice-versa. The results aid in prioritising mitigation needs for industries and countries having high ratio values. Challenges in using the EE-MRIO models for absolute environmental sustainability assessments of industries were discussed.

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# Life Cycle Assessment of Innovations in Water Treatment for PFAS Removal: What Do We Know?

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## 1. Introduction

Per- and polyfluorinated alkyl substances (PFAS) are fluorinated anthropogenic compounds comprising approximately 6500 chemical isomers [1]. These persistent substances, often referred to as "forever chemicals", exhibit extreme resistance to degradation. Emissions during PFAS and PFAS-containing product manufacturing, as well as the discharge of wastewater effluents and leachate from landfills, contribute to extensive contamination. The widespread use of PFAS as key components in aqueous film-forming foams (AFFF), frequently used for firefighting and training activities, especially in airports and military bases, further exacerbates the issue, contaminating various sites and affecting both groundwater and surface waters globally [2, 3].

Contaminated drinking waters from these sources often serve as a significant contributor to human PFAS exposure all around the globe since conventional drinking water treatment methods often prove inadequate for PFAS removal [4]. Studies have shown that human exposure to PFAS, mainly through drinking water and food, can lead to cancer risks, fetus malformation and interference with the endocrine system. As more is understood regarding the toxicological impacts of PFAS, interest in removing these substances from drinking water sources is increasing. Legally enforceable standards for PFAS concentrations in drinking water are constantly revised in different countries to lower levels over time. Therefore, numerous studies are underway to implement advanced water treatment, such as granular activated carbon (GAC) filters, ion (IX or IEX) and anion (AIX) exchange columns, nanofiltration (NF) and reverse osmosis (RO) membranes and electrochemical oxidation (EO). These innovative treatments aim to significantly decrease PFAS concentrations in water to achieve lower levels and to enhance the management of waste, such as spent GAC and IX resin, generated during treatment.

When assessing advanced treatment options, it is crucial to consider factors like removal efficiency, cost-effectiveness, process sustainability, and potential treatment waste. Consequently, there is a necessity to evaluate the effectiveness and feasibility of PFAS removal technologies on a larger scale [4]. In this matter, Life Cycle Assessment (LCA) can be performed to assess the environmental impacts, from raw material extraction to disposal, of novel treatment options for removing PFAS from water sources, such as contaminated groundwater or surface water and wastewaters. Engaging in LCA offers several advantages, including identifying the main sources of environmental and human health impacts of a process, areas of high energy consumption within systems, and provision of a foundation for making policy recommendations [5]. The purpose of this review is to help prioritize LCA research activities by mapping current LCA coverage of PFAS treatment technologies and identifying gaps in relevant knowledge.

## 2. Materials and Methods

A scoping review [6] was developed to gather information about the use of LCA in sustainability analysis on novel technologies to remove PFAS from aqueous sources. To accomplish this, a search was performed across Scopus, Science Direct, and Web of Science using title, abstract and keywords as a filter. Relevant publications from any timeframe were sought, without applying any publication year filter. The search was conducted in English. The keywords used were: LCA or life cycle analysis or life cycle assessment or sustainability assessment; and PFAS or per and polyfluoroalkyl; and treatment or removal or technologies. The eligibility criteria used to select articles for this review were based on PECOTS [7].

## 3. Results and Discussion

In total, eight papers matched the eligibility criteria set for this literature review. These studies were published between 2019 and 2023 and they were conducted with the purpose of comparing potential impacts originating from the use of novel technologies to treat water and wastewater contaminated with PFAS. However, when performing LCA, it is imperative to clearly state the intended application of the study and the reason for carrying it out, in other words, the goal of the study. The LCA goal was not evidently stated in all of the reviewed articles, making them difficult to analyse and making it difficult to understand if the results found were aligned with the goal and scope of the study. Additionally, in seven studies, the LCAs were conducted in SimaPro software, and in one study was done in GaBi software. Both are commercial tools. GaBi comes with a database, however, access to the Ecoinvent database requires an additional fee. SimaPro has the Ecoinvent database included in the basic price and lacks the GaBi database.The wide adoption of the Ecoinvent database via these or other software packages has practical benefits beyond accelerating the work of individual analysts. When life cycle inventory models are described at the level of database process elements, a consequence is that analysts have greater potential to compare results across studies, facilitating the verification of published results and promoting transparency in the LCA community.

The aqueous sources analyzed by the eight studies comprehend groundwater, wastewater and waste of water treatment. Moreover, the technologies evaluated through LCA were used to separate PFAS from the aqueous sources (GAC, NF, RO, IX, AIX, and the use of precipitation agents) and, in some cases, to destroy them (EO and incineration). However, the assumption of complete PFAS destruction leads to an underestimation of PFAS emissions in the life cycle inventory analysis, as it fails to account for the volatilization or breakdown of PFAS into other compounds.

A significant limitation identified across the articles is the incorporation of PFAS into LCA studies without verifying the availability of PFAS-related characterization factors in the life cycle impact assessment method. USEtox is the methodology predominantly utilized for evaluating toxicity effects. This omission results in data gaps and underestimation of toxicity-related impacts, as the absence of PFAS characterization factors means their impact cannot be accurately reflected in LCA calculations.

Another constraint identified arises from the LCA scope based on the nature of the treatment processes: if the process involves wastewater treatment, the treated water is generally discharged into natural water bodies. On the other hand, if the water undergoes treatment for drinking purposes, it is then used for human consumption, including drinking, cooking, and other residential uses, leading to direct exposure. The narrow focus of the LCA studies on just the treatment processes and not the application of the treated water results in an underestimation of the presence of PFAS in the treated water and wastewater, their potential ecotoxicity and human toxicity impacts.

## 4. Conclusions

Research on this topic is relatively recent, encompassing the last five years. Most of the studies analyzed the use of IX and GAC to treat water sources contaminated with PFAS. Other technologies were also assessed, however most of the data gathered represent pilot scale. In light of that, there are many gaps that still need to be addressed when conducting LCA on novel technologies to treat PFAS, especially the development of PFAS characterization factors so their impact can be correctly reflected in the environmental and human health impacts calculated through LCA, and the need of full scale data for the results to better represent the life cycle impacts of these technologies.

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# Making chemical footprints practical: user needs and drivers

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## 1. Introduction

Hazardous chemicals and pollutants are continuously released throughout the life cycle of products and services, harming humans and the environment. The monitoring of a chemical footprint can empower industry actors to take actions to reduce potential impacts from hazardous chemicals related to their product portfolio. We define "chemical footprint" as an aggregated indicator of chemical pollution that enables the assessment of potential human toxicological and ecotoxicological impacts of the entire life cycle of a product or service. Herein we provide an overview of tools for chemical footprint calculation currently available and their strengths and limitations in relation to their useability by industry actors.

## 2. Materials and Methods

Our mapping covered existing tools that without further adaptations can be used to calculate chemical footprints and was based on available summary literature such as the ILCD handbook and previous experience by the authors. Special interest was given to interrelationships between the tools.

The tools are currently being tested in a number of case studies with industry partners. Through this work, user requirements for chemical footprint tools are investigated and related to the user and the decision context.

## 3. Results and Discussion

### 3.1. Tools to calculate chemical footprints

A chemical footprint impact score can only be calculated if both life cycle inventory (LCI) and life cycle impact assessment (LCIA) characterization factors are in place. Hence, our inventory was divided into LCI and LCIA tools.

We identified 12 LCI data repositories, of which some were unique databases while others were nodes, re-routing the user to such databases. The majority of globally relevant databases (in contrast to regional databases) were available upon paying a license fee. All LCI databases contained flows relevant for chemical footprinting but no database had this explicit scope, and hence we concluded that all are likely to contain data gaps in relation to direct emissions from industrial activities.

We identified 15 LCIA models in current use, of which several contained multiple model versions, such as USEtox in version 2 (far field) and 3 (near field/far field). [1] All LCIA models covered toxicity indicators but with different scopes. Some included ecotoxicity and human toxicity with several impact pathways covered, e.g. USEtox, ReCiPe, Impact World+ and Environmental Footprint (EF3.1), while others had more restricted scopes, e.g. CDV covering pelagic ecotoxicity and ProScale [2], currently covering human direct exposures. No model was identified to alone cover all possible impact pathways for ecotoxicity and human toxicity pressure from products and services. Furthermore, for several tools the applicability domain is limited to organic compounds and metals, and coverage for other inorganic chemicals is limited. Not all models allow for calculation of new characterization factors, which is potentially a key property when chemical footprinting is used for decision support in the innovation context. Other characteristics of the tools that can be relevant in decision making are the possibilities to use monetary valuation, weighting, and normalisation.

Clear interrelationships were observed between the LCIA models, where both model structures and databases with input data on substance properties have been cross fertilizing the development. The USEtox development has been an important factor also for the advancement of several of the other methods.

### 3.2. Drivers to calculate chemical footprints

There are several policies under the European Green Deal providing incentives to calculate chemical footprints. A clear example of this is the use of Product Environmental Footprints (PEF) (and Organisational Environmental Footprint, OEF), e.g. under the Green Claims directive, to protect consumers from misleading claims regarding so called “green products”. Another example is the EU Zero Pollution Ambition and the Chemicals Strategy for Sustainability (CSS) where one action is the recommendation of a Safe and Sustainable by Design (SSbD) framework.[3] Tools for chemical footprints such as USEtox, ProScale, and PEF are currently discussed or suggested for several steps of the integrated SSbD assessment (going from hazard assessment to workplace and user risks, and finally environmental performance). While not legislating the use of a chemical footprinting tool, the SSbD assessment generates the need for one (or several tools).

### 3.3. Practical user requirements

Though our work to understand industry actor requirements on tools for chemical footprinting is ongoing, we can share some insights already. We see that the calculation of a chemical footprint requires:

- Multiple skillsets, e.g. on (eco)toxicity assessment and system modelling on energy and mass balances, and hence a modular tool, allowing division of tasks between several people.
- Data that are already tabulated for other purposes, or data generated by separate *in silico* models, and hence efficient and easy-to-apply data transfer systems.
- Comprehensive quality control and hence detailed guidance for data collection and operation, the possibility of penalty system and the propagation of uncertainties.
- Considerations of the decision context, as early design decision relies of different data and communication compared to mature systems.
- Tools that reflect the character of existing decision-making sequences and support systems.
- As the result from the tool is to be used by both experts and decisionmakers with less detailed knowledge, the outcome needs to be easily translatable and understood.

For chemical producers, it is tempting to integrate chemical footprinting with the existing regulatory framework to facilitate data supply. This may not work for downstream users without modifications to the regulatory framework or communication systems, for example manufacturers of complex products, who may need to consider a wide range of inputs and currently lack access to the detailed regulatory dialogue.

## 4. Conclusions

We conclude that while several tools for chemical footprinting are available, there is still need for tool development to make possible the practical implementation to calculate complete footprints, covering all relevant exposure pathways. Policy drivers are already in place, for example under the CSS, and are expected to keep building requirements on the inclusion of a life cycle perspective also for chemical safety issues. Whether the future of chemical footprinting lies within the current chemical safety sphere as regulated under e.g. the Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), within the sustainable product sphere, as regulated under e.g. Ecodesign for Sustainable Products Regulation, or both, is not yet clear.

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# Environmental impact of integrating decentralised urine treatment in the urban wastewater management system: A comparative life cycle assessment

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## 1. Introduction

Decentralised treatment of source-separated streams (e.g urine) integrated into the urban wastewater management system, leading to so-called “hybrid solutions”, could maximise resource recovery while minimising environmental impacts at the centralized wastewater treatment plant (WWTP) [1]. This has led to calls for replacing conventional WWTPs with hybrid WWTPs in new settlements.

While previous studies have compared urine separation systems to conventional WWTPs, none has considered an integrative approach encompassing operation, infrastructure (treatment system and building pipes for urine transport), different treatment options (nitrification and distillation of urine and partial nitritation/anammox), state-of-the-art WWTP and process modelling using real plant data. Additionally, a potential replacement of conventional WWTPs with hybrid models will lead to direct and indirect environmental consequences which need to be assessed forward in time through a consequential LCA modelling.

Therefore, this study aims to conduct a consequential LCA to compare hybrid urine treatment technologies (partial nitrification/distillation, partial nitritation/anammox and struvite precipitation with stripping/scrubbing) to evaluate which is the most sustainable option for city block-level treatment compared to a centralised wastewater treatment with low energy consumption and $N_2O$ emissions.

## 2. Materials and Methods

Three hybrid systems (nitrification and distillation, struvite precipitation & stripping/scrubbing and partial nitritation/anammox) were compared to one state-of-the-art centralised WWTP (reference scenario). A fictitious city resembling Zurich, Switzerland, was designed with high population density. A city consisting of seven-story buildings (residential only) was designed with each building housing 400 inhabitants resulting in an average of 2.2 people per apartment. It is assumed that this type of building is implemented homogeneously across the fictitious city, in which all the population have their urine source separated via no-mix toilets and separate piping systems. Urine is separated at the source with an 80% separation efficiency and treated onsite in the basement of a building connected by the other two buildings resulting in a 1200 population equivalent (PE) scale of decentralised urine treatment. The grey water, blackwater and remaining treated urine are transported via gravity sewers to the WWTP. The reference WWTP has a capacity of 189000 PE of wastewater per day. There are 158 decentralised systems connected to the central WWTP in the hybrid scenarios.

One population equivalent (PE) of wastewater treatment per day was chosen as the functional unit for this study. The system boundary encompasses urine collection, treatment, transportation of produced fertiliser, and centralised WWTP. Infrastructure and operational stages are considered for urine treatment scenarios, while only operational stages are accounted for in centralised WWTP scenarios because no change in infrastructure is foreseen between scenarios. Primary data from a Swiss WWTP were used to model the baseline scenario using SUMO software. Operational parameters were adjusted to calibrate the baseline WWTP based on effluent quality and energy use. The LCA was modelled using Activity Browser LCA software and Ecoinvent consequential database 3.9.1. The impacts were assessed using ReCiPe 2016 (H) midpoint LCIA method.

## 3. Results and Discussion

The results show that urine source separation improves the environmental performance in state-of-the-art WWTPs, except for its impact on global warming, making it especially beneficial in facilities with high nitrous oxide emissions and electricity use. For this abstract, global warming impact is only assessed in more detail. The results (Figure 1) show that the hybrid treatment scenarios lead to a higher global warming impact than the reference scenario in all the studied cases. The fact that the centralised treatment plant performs better differs from previous studies that concluded that urine source separation has a lower global warming impact than municipal wastewater treatment. The $N_2O$ emission factors for the activated sludge systems in these previous studies were relatively high, e.g. 1.6% of influent nitrogen (N) [2] compared to 0.3% of influent nitrogen in this study. Additionally, the central WWTP has a relatively low energy consumption (0.17kWh/m$^3$) compared to previous studies with values above 0.3 kWh/m$^3$ [2].

In the hybrid treatment scenarios, a reduction of urine loads to the WWTP saw a reduction in global warming impact at the WWTP. Despite this reduction, the impacts from the urine treatment caused the overall impacts to be higher than the reference scenario. With nitrification & distillation being the worst-performing scenario, the decentralised urine treatment contributed to 53% of the total impacts. This is attributed to high $N_2O$ emissions (25%, from a 1.5% $N_2O$ emission factor of influent N) and electricity consumption (26%; dominated by distillation) in the urine treatment process. The partial nitritation/anammox with an $N_2O$ emission of 0.85% of influent N in the decentralised urine treatment had the second-best performance. A break-even analysis of $N_2O$ emissions in the activated sludge shows that partial nitration/ anammox, struvite precipitation & stripping/scrubbing and the nitrification & distillation scenarios have a lower global warming impact relative to the reference scenario at emission factors above 0.8%, 1.1% and 1.5% of influent N respectively.

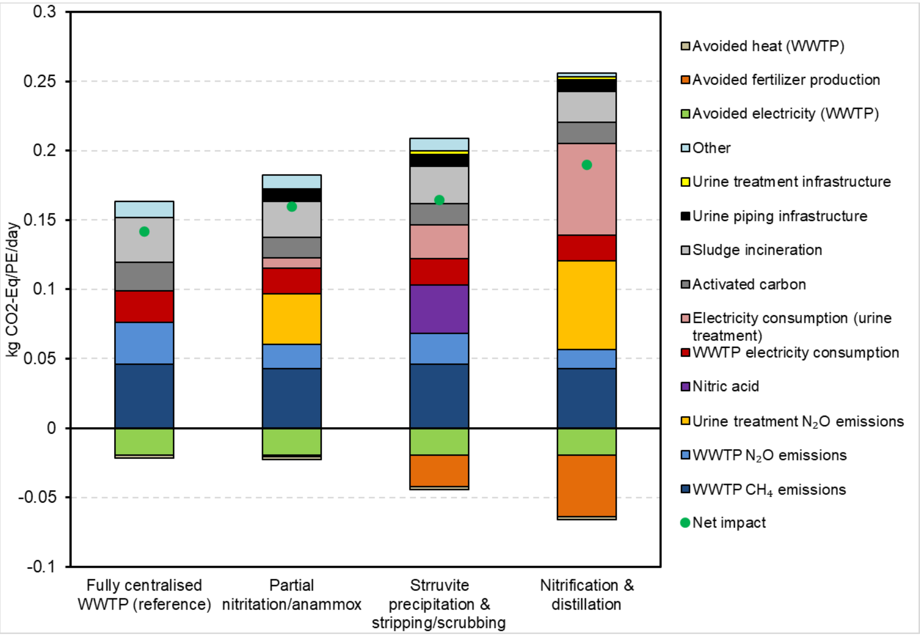

***Figure 1: Global warming impact of the studied scenarios, in kg $CO_2$ equivalents per person equivalent (PE) per day***

## 4. Conclusions

This study investigated the comparative environmental impact of three urine source separations (hybrid WWTP) and a state-of-the-art WWTP through consequential LCA. The results show that urine source separation improves the environmental performance in state-of-the-art WWTPs, except for its impact on global warming, making it especially beneficial in facilities with high nitrous oxide emissions and electricity use. This study suggests that hybrid wastewater treatment systems could be used as a strategy for improving the environmental impacts of WWTPs with high $N_2O$ emissions and electricity consumption.

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# Biogenic carbon accounting: an open framework towards ALIGNED practices for a diversity of bioeconomy stakeholders

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## 1. Introduction

Achieving carbon/climate neutrality has become central to both national and international agendas, which include the substitution of fossil resources with bio-based products [1], the so-called bioeconomy. The potential climate benefits of bioeconomy strategies arise from the concept that atmospheric $CO_2$ is captured during biomass production and is either emitted back as $CO_2$ at the end-of-life of the bio-based products (resulting in carbon neutrality) or embodied within long-lived bio-based products (resulting in net carbon storage). As a result, many LCA studies have disregarded the accounting of biogenic carbon flows [2], which were presumed climate neutral. Yet, it is now established that 'carbon neutrality' does not necessarily imply 'climate neutrality' [3], because the temporal distribution of GHGs flows strongly influences target-based metrics such as the maximum temperature peak [4] – set to '2°C above pre-industrial levels' in the Paris agreement [5].

Bio-based production systems (see examples in [1], [2], [3], [6], [7]) are characterized by numerous factors influencing the temporality of GHG emissions profile (magnitude, time-distribution, etc.), such as growth characteristics of selected biomass feedstocks, land management practices, lifetime of the bio-based products in the technosphere, to mention a few [6]. Consequently, even when biogenic carbon flows are accounted, static LCA studies – i.e. discarding the temporal dimension of a 'life cycle' – are not able to fully assess the actual impacts of bio-based products on climate change [8]. Similarly, national and international guidelines show divergences on biogenic carbon accounting [7], leaving industries with confusing guidance for environmental labelling and unclear results for decision making. This study sheds clarity on best practices for this accounting and supplies support of different complexity levels to this end.

## 2. Materials and methods

The EU-funded ALIGNED project [9] gathers researchers and selected companies with the aim of unveiling best LCA practices for the bio-based industries. To unravel the gaps between current practices (in industries and elsewhere) and the latest available scientific methods with regards to biogenic carbon accounting, a literature review was performed and coupled with insights from recurrent workshops with the project partners. These gaps were regrouped into four key challenges (Figure 1) which should be simultaneously addressed when it comes to climate change impact assessments of bio-based products. Moreover, the solutions to these challenges should also be aligned for both short-term environmental reporting/labelling and long-term decision-making. To this end, recent works (e.g. [7], [10]) scrutinizing LCA and LCA-related standards and guidelines in place (including e.g. PEF, GHG Protocol, EPD) were reviewed. This enabled (i) unravelling the similarities and discrepancies when it comes to biogenic carbon flows accounting in LCAs and (ii) discriminating the strengths and weaknesses of these guidelines and standards between decision-making and reporting activities. In addition, existing and emerging climate change midpoint metrics, with their strengths and limitations, were retrieved from the latest literature (e.g. [4], [8]). Results were mobilized to derive recommendations to assess the climate change impacts of bio-based production systems, targeting users with different levels of expertise and time availability.

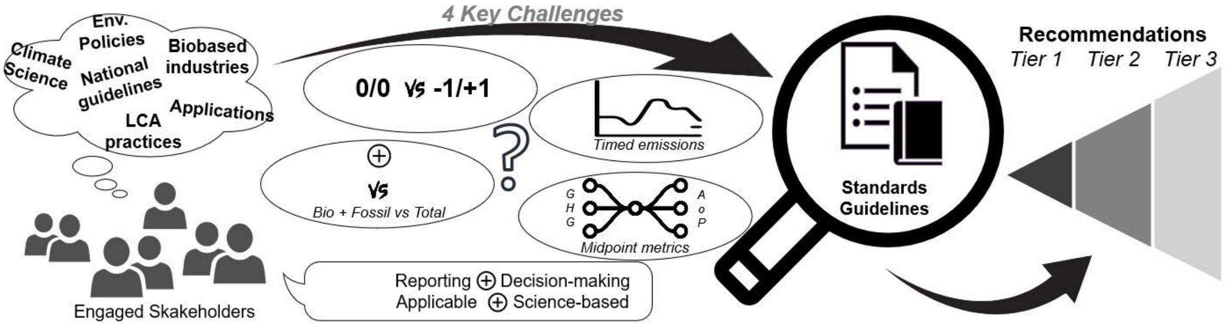

*Figure 1: From stakeholders in bio-based industries to recommendations for biogenic carbon accounting*

## 3. Results and Discussion

We proposed a set of baseline recommendations [9] for consistent, transparent, applicable and comparable accounting of the climate change impact for LCAs of bio-based products. A tiered approach enabling operational implementation of the recommendations is provided, with tier-1 being formulated as the minimum requirements and modelling efforts, and tier-3 targeting users already familiarized with LCA modelling and interpretation. Notably, these recommendations are compatible with most reporting standards and best practices for LCAs supporting long-term decision-making. These were synthesized into a decision tree, designed to guide bioeconomy stakeholders and practitioners for biogenic carbon accounting in LCA studies. Overall, we stressed the relevance of including time-dependent emission profiles in LCA studies and we clarified specific cases where time-dependencies are not strictly required. The tiered approach includes tutorials to facilitate and guide the use of period-specific climate change midpoint characterisation factors for GWP. It also describes various midpoint indicators and their implications during the interpretation phase, illustrated with a simplified example. The limitations of the recommendations were highlighted, and mostly roots in the lack of specialized tools for modelling biogenic carbon flows and the complexity of establishing a consensual climate impact midpoint indicator.

## 4. Conclusion

Carbon footprint is now an unmissable component in the agenda of economic actors. These require both consistent environmental reporting standards for their products, and a robust methodological framework for reliable decision making. Ambiguous reporting rules and repeated criticism from the scientific community regarding commonly used indicators, alongside the rapid emergence of rather new concepts, namely the bioeconomy and circular economy, have led to frequent misuse of carbon accounting, resulting in unclear communications for consumers and producers. Despite seemingly divergent positions among various stakeholders, this work presents a harmonized set of recommendations for biogenic carbon accounting in LCAs, tailored for users with varying levels of expertise. This represents an additional stepping stone towards integrating the latest scientific advances into business practices.

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# A Framework to Estimate Consumption-based Life-Cycle Environmental Impacts of Regions and Cities

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## 1. Introduction

The increasing concentration of population in cities has been associated with significant environmental challenges related to urban resource consumption and climate change. While policies and strategies to improve environmental sustainability in cities and regions have often focused on a single or on a limited number of sectors and/or subsystems, sectoral-based action may offer limited potential to reduce the overall impacts associated with a geographic area [1], and it may be associated with unintended burden shifts. Integrated environmental impact assessment frameworks at regional and urban level that can capture the complexity of cities and their inter-linked sub-systems are needed to identify environmental hotspots and/or significant improvement potential, and to support effective decision-making toward environmentally sustainable urban and regional development [2]. Such frameworks should be holistic, consider a wide range of environmental impacts, have a life-cycle perspective, be comparable and replicable [3,4].

This paper presents a novel assessment framework to calculate the consumption-driven life-cycle environmental impacts associated with a city or region, in a holistic and systematic manner, including all its inter-linked subsystems and sectors. Specifically oriented to support decision-making, the framework can provide valuable insight on: (i) the overall environmental impacts of a city or region, with a consumption-based perspective, and the relative contributions of different consumption areas, sectors and systems; and (ii) potential environmental hotspots, e.g., consumption areas or product types associated with particularly high environmental impacts. This paper applies the framework to calculate potential environmental impacts associated with urban consumption in the Province of Trento (Italy) and its capital city Trento for 2019, and it compares the cradle-to-grave results with those using a cradle-to-gate model. It analyses the importance of including additional life-cycle phases, particularly the use phase for buildings and transportation, which can account for a large share of the overall impacts associated with regional and urban areas.

## 2. Materials and Methods

The paper builds on the framework proposed by Lavers Westin et al. [2] coupling urban metabolism (UM), namely a material flow accounting (MFA) model, with life-cycle assessment (LCA), and advances it by extending the life-cycle perspective from cradle-to-gate to a cradle-to-grave. In brief, the MFA model estimates annual domestic material consumption (DMC) in a region and/or city, for thousands of product types, organized into combined nomenclature (CN) product categories; then, representative product types are selected, and a life-cycle model is developed for the overall regional and urban annual consumption (based on the representative product selection) and its potential environmental impacts are calculated.

The life-cycle model is developed for three consumption areas (i) food, (ii) mobility, and (iii) buildings (incl. energy for building installations & appliances). For each area, a process-based LCA model is developed using a selection of representative products and LCIs, structured in a modular manner by LC phases or processes. While aiming at building a common and consistent assessment framework for the overall consumption, the three consumption areas need specific modelling considerations. For example, annual consumption includes products with a typically short lifetime (up to a year) such as food and some household goods, and products that have a relatively long lifetime and are considered “additions to stock”, such as buildings, infrastructure and vehicles. For products with short lifetime the “apparent consumption” is considered, in line with the consumer footprint approach [5]. Products added to stock, however, have LC stages (e.g., use and end-of-life) and associated emissions occurring well beyond the year under analysis.

The annual DMC builds on the MFA-based model developed for the Autonomous Province of Trento and its capital city Trento [6]. First, a selection of representative products in the DMC was performed, drawing on

Lavers et al. [7]. Our selection was based on the consumption share in terms of mass, complemented with potentially relevant products identified in previous literature, to ensure a reasonable amount and variety of product types to be representative of that consumption area. Then, we developed the LC model using ecoinvent data, complemented with other LC data as needed. We calculated potential environmental impacts for midpoint impact categories using characterization models and factors recommended from the Environmental Footprint package 3.1 [8].

## 3. Results and Discussion

In this paper we present results for Climate change, Climate change – fossil, Ozone depletion, Respiratory inorganics, Ionizing radiation - human health, photochemical ozone formation, acidification, eutrophication - terrestrial, marine, and freshwater. Among the three consumption areas, mobility has the highest environmental impacts in most impact categories, including climate change. Since the model estimates environmental impacts of the products *added to stock* in 2019, over their service life, and the annual renovation rate of the building stock is very low (about 0.5%), the results show larger impacts associated with vehicles added to the fleet in 2019. If the impacts of current stock were considered however, buildings would be associated with higher environmental impacts across most categories The results demonstrate the importance of a cradle-to-grave perspective in mobility and buildings sectors, where the use phase dominates impacts in most environmental impact categories. Despite the lower relative share of the use phase, a cradle-to-grave perspective remains relevant in the food consumption area as well. Such results highlight the need to account for and tackle scope 3 emissions and environmental impacts associated with cities and regions.

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# Material-Energy efficiency through Input-Output Analysis: Italian case study in wood furniture sector

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## 1. Introduction

The European Union has promoted methodologies for measuring and communicating environmental performance from a life cycle perspective of products and organizations such as PEF and OEF (European Commission , 2021). The Organizational Life Cycle Assessment method is slowly spreading: one of the possible obstacles to overcome is the input-output analysis (Mattila, 2018). In fact, collecting reliable data and applying rigorous allocation choices discourage companies.

## 2. Materials and Methods

The research is based on the Life Cycle Assessment methodology to describe the environmental impacts associated with the organization chosen as a case study. The reference is the ISO/TS 14072:2014 standard which concerns organizational life cycle assessment. The methodology traces the four phases of an LCA study: goal and scope deinition; inventory analysis: impact assessment and interpretation of results. The inventory phase is based on the quantification of inputs and outputs for each phase of the process and is inspired by the Material Flow Cost Accounting (MFCA) described by ISO 14051:2011. The analysis is based on the Deming cycle as described in Fig.1.

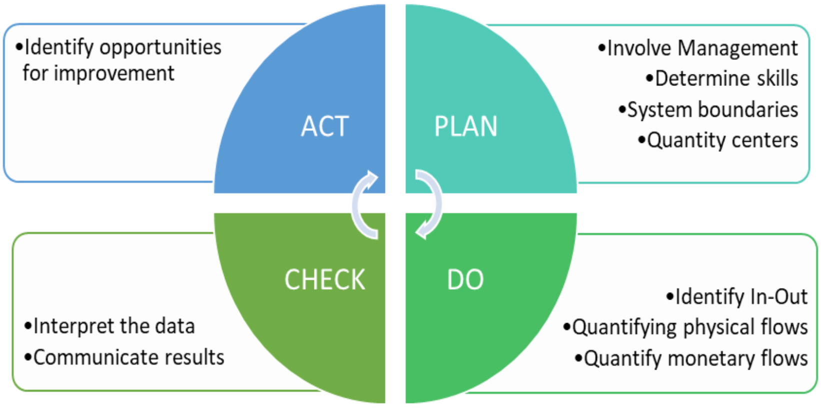

***Figure 1: Steps of Material flows analysis model: Input-Output quantification.***

The study refers to a manufacturing company in the wood-furniture sector in northern Italy and the time horizon describes production in the year 2022. The system boundaries include all the processes that are carried out within the plant without considering the upstream and downstream phases. In the Inventory phase the data sources used were only primary.

## 3. Results and Discussion

### 3.1. Input-Output identification

Through the information present in the company management system, it was possible to quantify the total volume of 368,358 total pieces produced in the plant considering the output of the production lines of bases, wall units, columns and hardware in 2022. The analysis began with the identification of a total of 10 departments and processes to pay attention to. For each of these, the inputs and outputs are identified, divided into natural resources, energy consumption, emissions, waste, workforce, finished products, substandard products, etc. The use of natural resources, energy and workforce are also identified.

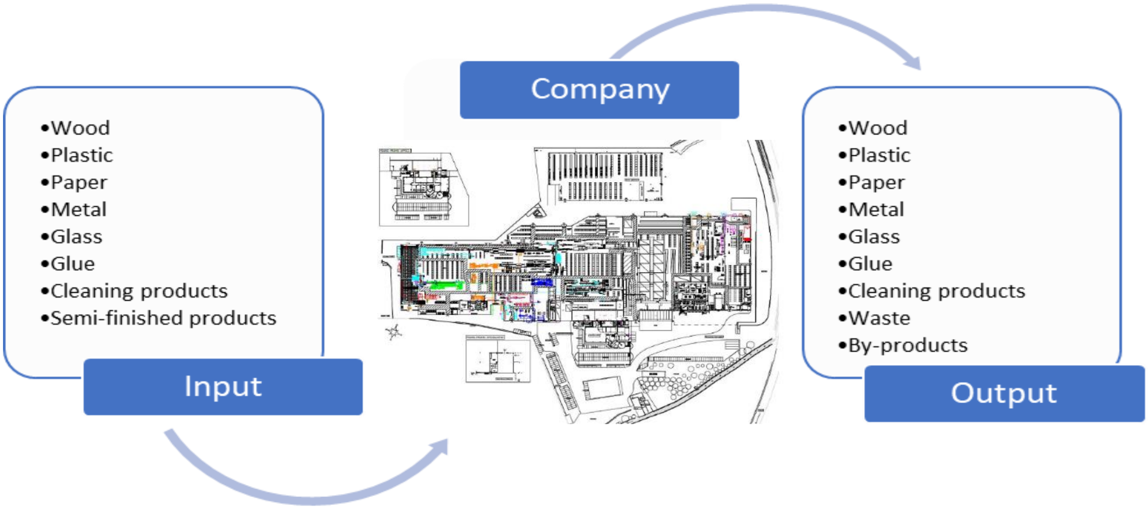

*Figure 2: Input-Output identification and layout.*

## 3.2. Input-Output quantification

Once the identification phase is concluded, the quantification of each highlighted item begins. The results are collected in calculation tables and validated by the managers of each sector as in Table 1.

| Process: FRAMED DOORS | | | |
|---|---|---|---|
| INPUT | | OUTPUT | |
| MATERIALS (semi-finished products, substances, products) | Semi-finished wooden product | WASTE | Stoneware processing sludge |
| | Stoneware | | Cutout PVC |
| | Glass | | Cardboard packaging |
| | Aluminum | | Nylon packaging |
| | Water for machinery | | Label residue |
| | Screws | | Broken glass |
| | Labels | | Non-compliant aluminium |
| | Glue | | Broken stoneware |
| | Cleaning material | | Wood |
| | Nylon | | Milk |
| | Lubricating oil | | Cleaning waste |
| | Seals | FINISHED PRODUCTS | Complete doors ready for assembly |
| WORKFORCE: (staff, hours) | 4 people for 8 hours | REDUCED PRODUCTS (defective product) | Non-compliant products<br>Products with imperfections |
| ENERGY (electricity, heating) | Electrical energy to power machines glue distribution, Cold presses Presses a hot, Conveyor belts | EMISSIONS | Noise |
| | Handling forklifts | | Glue fumes |
| | Energy to heat the department | | Solvent vapours |
| NATURAL RESOURCES | Water | WASTE OF NATURAL RESOURCES | Wastewater |

Table 1: Input-Output quantification.

## 4. Conclusions

Input output analysis was applied in a case study in order to optimize resources and energy from both an environmental and economic point of view. The approach of the work allows the company to replicate this analysis every year and observe the effectiveness of the measures adopted with a view to sustainability. However, data collection takes a long time and it was not possible to scale the information for each step of the process. The implementation of a management system would allow for effective management of information and control over the source of the data also in favor of an LCA analysis of the organisation.

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ISO/TS 14072:2014 Environmental management — Life cycle assessment — Requirements and guidelines for organizational life cycle assessment
ISO 14051:2011 Environmental management — Material flow cost accounting — General framework

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# LCAs role in defining the sustainability of aluminium

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## 1. Introduction

In response to increasing market demand for environmental information, the past five years or so has seen a concerted collaboration between Hydro Aluminium and NORSUS for the development of LCA / EPD studies. Driven both by regulatory and by market factors, the intervening years have seen an explosion of interest in calculating, reporting and reducing environmental impacts. Such interest has largely focused on climate change or carbon footprint as widely termed. However, both metrics of environmental performance in the aluminium industry and how they are calculated are heavily influenced by arguably non-objective, non-scientific decisions developed and negotiated between science, industry, business, the political realm, and the public. Through illustrative examples of recycling issues, climate change metrics, and the broader environmental impacts of aluminium, we discuss what environmental sustainability might encompass and how it is defined for the industrial sector.

## 2. Materials and Methods

The study is a meta analysis of several LCA and EPD projects performed for production of primary and secondary aluminium. Throughout the process, we (the LCA practitioners) have extensively discussed sustainability issues with the industry experts to find the ways of rightfully expressing the sustainability impacts of aluminium production. This paper discusses what ‘rightfully’ means and how LCA plays an important role in defining efforts to market products but also to make real differences in value chains and life cycles. We have chosen three examples to show the importance of LCA method choices in defining sustainable practices.

## 3. Results and Discussion

This section presents three examples before discussing how they are involved in judging the sustainability of aluminium systems.

### 3.1. Recycling of aluminium

One of the merits of aluminium is its high recyclability. Primary production of aluminium is very energy demanding but it is often stated that recycling aluminium only requires 5% of the original energy use of primary aluminium [1]. The exact basis for these assertions, specifically the system boundaries for the calculations, are difficult to find in literature. Nonetheless our analyses show that large savings can indeed be induced by recycling instead of producing virgin material.

Along the value chain from primary production to finished products, there are several activities which consume scrap aluminium from other sources. There are huge discussions whether such pre-consumer scrap should be considered a waste and allocated zero burden, and different standards and even different product category rules (PCRs) in EPD programmes treat this flow of aluminium material differently. Treating process scrap as zero burden raw material enhances the possibilities for green washing and elements of GHG emissions for which no actor takes responsibility. However, treating the process scrap as virgin material enhances the possibilities for double counting of emissions and higher impacts than appropriate. A common method framework is necessary to ensure that everything is counted and only once.

### 3.2. The climate change impacts of aluminium

In the 1990s and early 2000s, reported GHG emissions for the global production of aluminium were rapidly decreasing and several sources were projecting declining emissions well into the future [2]. However, the picture was clouded in mystery - a lack of transparency from the producers meant that specific information for climate change impacts from individual producers was not in the public domain. As China expanded its production capacity in the new millennium, the global GHG emissions from aluminium production shifted upwards. This also had the effect of forcing greater transparency on the producers, and particularly those exploiting hydropower started marketing their products as more climate friendly. In recent years a de facto threshold for low-carbon aluminium has been established at 4.0 kg $CO_2$-eq./kg aluminium [3]. However, this threshold – for all its prominence across the sector – appears suspiciously unclear and uncertain at best, and outright arbitrary at worst. Much as in the case for recycled aluminium, the background data, methodological choices and system boundary identification for analyses are far from clear, consistent and unequivocal – this puts the use of an absolute standard threshold in serious jeopardy. Our analyses have seen shifts in calculated background data – for feedstock materials wholly outside the control of aluminium producers – proving instrumental in shifting calculated emission levels above 4.0 from below.

### 3.3. Broader environmental impacts of aluminium

Before its current image as a lightweight, recyclable metal was firmly established, and before the widespread prominence of climate change in the general consciousness, aluminium was connected to environmental scrutiny in different areas. The issue of fluorosis in livestock was a precursor to the establishment of environmental authorities in Norway [4] and the issue of red mud was also heavily debated some decades ago [5]. More recently, other environmental impacts have been obscured in the shadows of climate change considerations. We have long calculated impacts other than climate change in our work but more recently we have begun to scrutinise these more closely. In the latest updates, we attempt to apply the planetary boundaries concept [6] as a means of weighting different environmental impacts. We will see if other impacts than climate change might be significant for aluminium value chains.

### 3.4. Discussing the sustainability of aluminium

These examples show how evaluating, even defining, sustainable aluminium production depends on non-objective, non-scientific factors relating to assumptions, data sources, methodological choices and the framing of problems and enquiries. These choices are not grounded in hard science but are instead emergent features of negotiation and consensus between industrial practices, analytical frameworks, and political visions. Widespread consensus, for example in the 4.0 de facto standard for low carbon aluminium, is no sure indicator of robustness or meaningfulness.

The three examples only encompass the aluminium sector itself. In practice, aluminium is competing with other materials for fulfilling functions and the (relative) sustainability of aluminium is also heavily dependent on the analogous non-scientific issues in other material sectors. Moreover, to judge whether a function should be performed to be aligned with sustainable development would require quite different frameworks than just environmental LCA itself. There is nonetheless an obvious temptation for non-specialist actors to draw simplistic, maybe inaccurate, conclusions from LCA studies that are as nuanced and as uncertain as the examples show. LCA practitioners must be aware of their power and how their choices and the results thereof may be taken as absolute truths.

## 4. Conclusions

These projects and examples have highlighted the entanglement of LCA methodological discussions with the strategic directions and imperatives of the aluminium producer. Furthermore, a focus on single companies or sectors does not give an indication of a sustainable level of production. The pathway towards more sustainable practices will need projects that investigate multiple sectors and functions in conjunction.

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# Approaching circularity in power electronics

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## 1. Introduction

Nowadays, power electronic components can be found in a wide range of applications. These range from the small, as in consumer electronics, to the large, as in power grids. The recycling of consumer electronics is already implemented in the European Directive on Waste Electronic and Electric Equipment (WEEE) with its first version from 2002 and revision from 2012 [1]. Among others, the directive does not cover power electronic equipment installed in "large fixed installations" [1] or vehicles used for the transportation of persons or goods [1]. For the majority of power electronics, this results in data gaps for their material composition and recycling technologies. However, both data are crucial for the holistic life cycle assessment (LCA) of power electronics. This work maps the first steps for the modelling of circularity of power electronics by carrying out material analyses and elaborating initial recycling paths.

## 2. Materials and Methods

In order to determine which recycling routes and technologies can be used for the treatment of power electronics, their material composition is required. This study analyses a traction inverter for e-mobility (150 kW) and a photovoltaics (PV) inverter (250 kW) in order to map both the varying power range and the field of application. The devices are dismantled manually and the obtained materials are weighed. The classification of the materials is based on data sheets and literature.

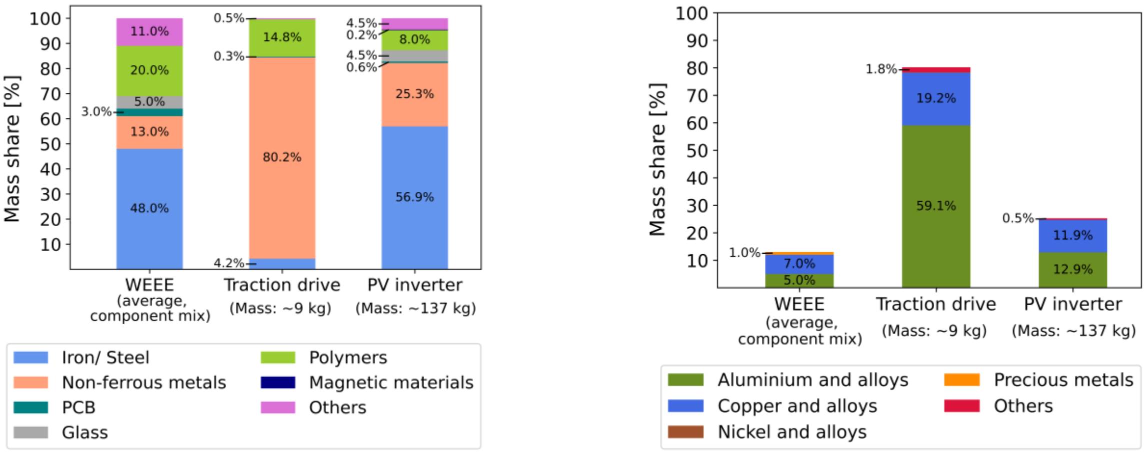
The recycling routes are selected according to the determined material compositions. In addition, the current state of the art of WEEE recycling is elaborated in order to determine applicable technologies for recycling.

## 3. Results and Discussion

Due to the fact that applications such as vehicles are not covered by the WEEE directive, research gaps arise in their material composition. This knowledge however is critical in order to subsequently determine recycling routes and thus close the product life cycle for devices not covered by the directive. For this reason, a discussion of the materials employed in power electronics and the subsequently derivation of the recycling routes follows.

### 3.1. Material analysis

The identified materials are categorised according to the primarily obtained secondary materials from WEEE [2]. Figure 1(a) shows the comparison of the grouped materials of the traction inverter and PV inverter with an average WEEE component mix. In this component mix, electronic equipment from all categories specified in the WEEE directive that was collected and recycled in the EU27 in 2005 was considered [2]. Figure 1(b) provides a more detailed breakdown of the non-ferrous metals category and shows the main components.



(a) Comparison of the mass fractions.

(b) Elements in non-ferrous metal fraction

***Figure 1: Comparison of the mass fractions of the respective materials in WEEE [3], a traction drive and a PV inverter.***

Figure 1(a) shows that the material categories of WEEE and traction inverters or PV inverters are comparable. The shares of the respective categories in total fluctuate depending on the area of application. In short, the composition of the PV inverter is quite close to the WEEE average, dominated by iron/steel (~50%). In contrast the traction drive is dominated by non-ferrous metals (~80%).

Figure 1(b) shows that the non-ferrous metals are primarily aluminium or copper based. In contrast to the WEEE, the analysed power electronic devices do not contain representable quantities of precious metals such as gold or silver.

### 3.2. Recycling routes

The findings of the material analysis show that the WEEE recycling routes can also be applied to power electronics that are not covered by the WEEE directive. The employed recycling processes comprise communition as well as direct and sensor-based sorting processes [4]. The recycling of power electronics consists of a multi-stage concept in which communition processes and sorting processes follow one another [3]. This multi-stage structure and the large number of processes result in a decision tree as to how recycling can be structured. These decision trees must be defined in order to be able to map the circular economy of power electronics.

## 4. Conclusions

This work has laid the first foundation for mapping a circular economy for power electronics that are not covered by the WEEE directive. For this purpose, material analyses of a traction inverter and a PV inverter were carried out and reflected with average values for WEEE. The processes generally applicable to power electronics were then differentiated from the existing process routes for recycling WEEE. Furthermore, this analysis serves as a basis for closing the knowledge gap in the raw material balance in the LCA for power electronics. Through the knowledge of the technologies already available for the recycling of consumer electronics, this work also creates a basis for the end-of-life consideration in LCA of power electronics.

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# Prospective Life Cycle Assessment of Hydrogen production with next-generation low-iridium PEM Electrolysers

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## 1. Introduction

The increasing demand for sustainable and practical solutions in industries that cannot fully transition to electrification has led to the rise of the hydrogen economy. This has driven significant progress in proton exchange membrane (PEM) electrolysers for hydrogen production. According to the International Energy Agency[1], investments in electrolysers for low carbon hydrogen production and its by-products have surged from around 0.7 billion USD in 2022 to projected figures of 4.7 and 41 billion USD by 2030 for the "Stated Policies" scenario and "Net Zero emissions by 2050" scenario, respectively. This substantial increase in investment and the resulting need for expanded electrolyser manufacturing capacity are closely linked to the use of precious metals and critical raw materials such as iridium and platinum in catalysts and other components [2]. The availability of these materials will constrain the expansion of capacity. Therefore, initiatives such as Project Kopernikus P2X and its continuation under Project IRIDIOS, led by the flagship project H2Giga, are aimed at reducing iridium content in PEM Water electrolysers and improving overall efficiency to enable the growth in potential yearly installation capacity to be able to supply this expected growth. However, using PEM electrolysers is only beneficial in a decarbonised energy system. Therefore, it is essential to analyse the future of electricity and how the decarbonisation of the entire economy will impact hydrogen production.

This paper presents a comprehensive prospective life cycle assessment (pLCA) on the fabrication and use of a next-generation PEM electrolyser, which incorporates novel approaches to reduce iridium content [3] without compromising its efficiency and its ecological footprint. The analysis evaluates the environmental impact of these design modifications and future electricity systems prospectively, starting with a benchmark electrolyser and current electricity and going up to 2050 with a “Net zero” electricity.

## 2. Materials and Methods

The functional unit is standardised to 1 kilogram of hydrogen at 30 bar. The chosen impact assessment method is ReCiPe 2016 (H), focusing on key categories, including global warming, stratospheric ozone depletion, land use, fossil resource scarcity, water use, and mineral resource scarcity. Notably, these categories reveal significant trade-offs when compared to steam methane reforming, the prevalent method for hydrogen production [4]. The environmental indicators are meticulously quantified to provide insights into the system’s sustainability performance.

To conduct a prospective life cycle assessment (pLCA), the "premise" tool [5] is utilised to update the background Ecoinvent database [6]. This involves aligning background data on electricity systems and the energy industry with projections from Integrated Assessment Models. Through this process, the anticipated impacts of the system on future scenarios can be accurately estimated. A comprehensive pLCA is then conducted to evaluate the environmental impact of the PEM electrolyser throughout its entire life cycle, with a cradle-to-grave scope.

The research begins with the LCA of the fabrication of the low-iridium PEM electrolyser, incorporating state-of-the-art development in the materials, components, and design considerations to optimise its performance and resource usage. The development of electrolyser technology is represented in an evolving life cycle inventory (LCI) and operational parameters.

For the use phase, the electricity scenarios derived from the optimised energy scenario for Germany and Europe in the Kopernikus P2X project [4] are considered. Under this framework, the electrolyser is assumed to operate nearly continuously for 8000 hours.

For the end of life, an economical allocation of the effects caused by dismantling the system, disposing of waste and the energy required for recycling materials was considered.

## 3. Results and Discussion

The PEM stack and the electrolyser plant play no significant role, with their share of the specific greenhouse gas emissions of the produced hydrogen being less than 0.5% for the 2020 scenario and less than 2% for the 2050 scenario. Most emissions are attributable to electricity generation. The significant reduction in impacts from electricity is not only due to a reduction in the impacts of electricity itself but also to an increase in the efficiency of the electrolysis stack.

The "today's scenario" comparison demonstrates that the production of electricity-based hydrogen is not yet viable from a climate perspective compared to conventional grey hydrogen due to the indirect emissions caused by the required electricity. However, this changes with an increase in the share of renewable energy in electricity generation. In the "2050 scenario," a reduction of 90% in greenhouse gas emissions can be achieved for hydrogen produced using PEM electrolysis.

In addition to the discussed reduction in greenhouse gas emissions, future hydrogen production with PEM electrolysis can reduce the Stratospheric ozone depletion, land use, and fossil resource scarcity categories compared to the benchmark scenario. In the case of mineral resource scarcity, future development leads to a deterioration, which is attributable to the electricity mix; for the water consumption case, there is a reduction for 2030 but then a minor increase in 2050. The pLCA allows to identify not only direct trade-offs from the electrolyser fabrication, performance, and use, including the consumed electricity but also the whole supply chain and background processes, which gives a more comprehensive understanding of the system.

## 4. Conclusions

In summary, this study offers a comprehensive examination of the fabrication process and use for a next-generation PEM electrolyser. Our findings underscore the critical importance of updating background data, which serves as a primary driver influencing the environmental impacts of hydrogen production. While infrastructure development for the electrolyser plays a subordinate role in comparison, the efficiency of the system and its consequent electricity consumption emerge as pivotal factors.

Through prospective life cycle assessment (LCA), enhancements in background processes related to electricity production yield further improvements in environmental outcomes for future scenarios, particularly in $CO_2$ reduction. Simultaneously, we observe similar trends across other impact categories, whereby improvements in background processes have the potential to amplify effects, potentially exacerbating inevitable trade-offs. However, it is essential to note that these effects are primarily attributable to electricity production.

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# The Reuse of Goods: a Model to Quantify the Environmental Benefits

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## 1. Introduction

The current dominant economic model follows a linear approach, assuming unlimited resources and following a "take-make-dispose" process. This leads to continuous raw material demand and waste generation. To address these issues, a transition to a circular economy is necessary, aiming to decouple economic growth from resource depletion and environmental degradation. The "Waste Framework Directive" (Directive 2008/98/EC) provides a legal framework for waste management and treatment in Europe, prioritizing prevention and reuse, followed by recycling, other types of recovery, and disposal. This work aims to define a methodology to examine whether and to what extent the reuse of goods can actually bring environmental benefits. The assessment is performed through the development of an ad-hoc model based on the Life Cycle Assessment (LCA) methodology. To examine its effectiveness, the model has been applied to a case study i.e. the “Panta Rei” reuse centre in Italy, a structure where the collection and subsequent sale of reusable used goods are carried out.

## 2. Materials and Methods

### 2.1. LCA of a used good and the environmental impact of a reuse centre

To quantify the environmental impacts associated with a used good, the model considers the additional impacts (which cause environmental burden) due to the phases necessary to reuse the good (transport from the first user to the reuse centre, transport to the second user, reuse) and attributes the benefit of having avoided the life cycle of the same new good (i.e. the phases of production, transport to the first user, use, waste collection, end-of-life). The used good had a first life before, but it is assumed that all the phases related to that are entirely allocated to its first use. In the quantification of the net environmental impact associated with the used good, two parameters have been integrated in the model, which represent the innovative integration of this work with respect to the existing literature on this topic. The first parameter considers whether the purchase of the used good actually replaces the equivalent purchase of a new one, rather than being an additional purchase not really necessary. This is accounted for by introducing a coefficient, called *substitution rate,* acknowledging that the purchase choice might be driven by the attraction to the affordable price of a used good, in the absence of which the same new good would never have been purchased. The second parameter, represented by two coefficients, called *quality rate* and *energy performance rate*, considers the potential lower quality of a used good with respect to a new one, both in terms of potential material worn-out and -in case of electronic equipment- electrical inefficiency. All three coefficients range from 0 to 1. For the substitution rate, 0 means a not necessary purchase of the used good and 1 means a necessary purchase. Regarding the quality and energy performance rates, 0 indicates full inefficiency/worn-out of the used goods, while 1 indicates that the quality/efficiency of the used good is the same of the equivalent new good. To define the introduced *rates,* different instruments can be used, such as questionnaire submitted directly to the users at the reuse center, or updated datasets (e.g. containing statistics on trends or data about energy efficiency of electrical equipment). Regarding the inventory data necessary to conduct the LCA of the different products, accordingly to the LCA framework (ISO 14040 and ISO 14044), primary data should be used if available, otherwise secondary data derived from the scientific literature and LCA databases (e.g. ecoinvent) can be considered.

A reuse centre generally enables the marketing of a variety of used goods, which could be clustered in N different product categories. One or more representative product can be chosen for each product category (e.g. a computer and a bed for respectively the electronic equipments and bulky goods categories) and subjected to impact analysis using the proposed model. The quantification of the total environmental impact associated with the reuse practice offered by that centre is to be carried out by integrating the impact computed for those representative products with the information on the weight and number of goods sold in a certain timeframe (e.g. 9.6 kg/unit and 5 units for bulky goods and 2.98kg/unit and 24 units for electronic equipments).

## 2.2. Sensitivity and breakeven analysis

In order to investigate the effects of data and assumptions on the final results of the analysis, it is paramount to carry out sensitivity analyses: data and assumptions are changed to analyse how the results will change. Besides the newly introduced factors (substitution rate, quality rate, and energy performance rate), also other key parameters (already mentioned in the literature) can be varied, such as the transport distance of used goods and the product utilisation time. It is also recommended to carry out breakeven analyses: the values of the aforementioned rates are varied in their domains of existence (i.e. 0-1) with the aim of identifying the minimum value in correspondence of and above which the net environmental impact associated with each product switches from a positive sign value to a negative sign value, i.e. the practice of reuse actually brings an environmental benefit.

# 3. Results and Discussion: case study

To examine its effectiveness, this model has been applied to the case sudy of the “Panta Rei” reuse centre, located in Italy: 10 product categories have been selected as significant among those involved in the activities of the reuse centre during the year 2022 [1] and the analysis investigated 16 environmental impact categories proposed in the Environmental Footprint method (EF 3.1), developed for the European Commission by the Joint Research Centre [2]. The results show that the environmental benefit associated with the reuse centre is not obvious, but depends on numerous factors, foremost among them being the substitution rate, which has been obtained through a survey submitted to 577 users of the Panta Rei reuse centre in April 2023 [1]. The results of the base scenario indicate that the activity of the centre allowed for environmental benefits in only 5 impact categories out of the 16 examined, but the results can vary a lot with the introduced parameters (Figure 1): if, for example, a 100% substitution between new and used goods was considered for all the goods (i.e. substitution rate equal to 1 for all products), there would be environmental benefits in all 16 impact categories.

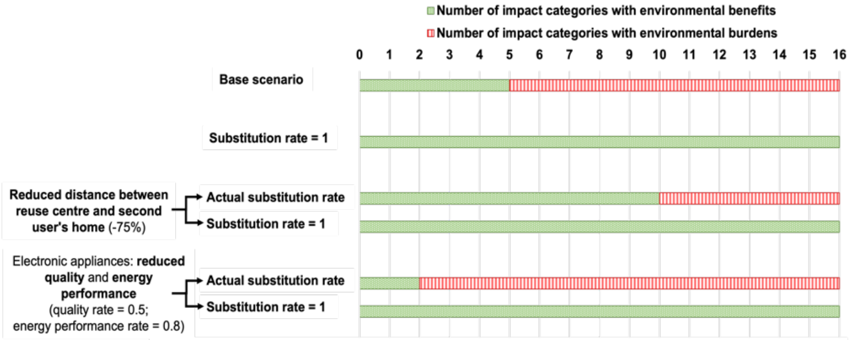

*Figure 1: Summary of the analysis results*

# 4. Conclusions

Reuse allows to extend the useful lifespan of goods, intercepting them before they become waste, so that they can be made available to other users. This could potentially generate environmental, economic and social benefits. This study presents an LCA-based model to assess the environmental impact of reuse, introducing a group of specific parameters like substitution rate and energy performance rate. It emerged that the environmental benefit associated with the reuse of a single good and, consequently, with the entire activity of a reuse centre, significantly depends on those factors, especially substitution rate. This result underlines the importance of conscious purchases and that the integration of this parameter into LCA analyses leads to a more accurate assessment of the benefits. Additionally, it is recommended to improve the proposed methodology by integrating in the model other important aspects such as the number of reuses of the same used good (one ore more) and the potential socioeconomic impacts associated with the practice of reuse.

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# A life cycle analysis model for the circularity of permanent magnet synchronous motor manual disassembly

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## 1. Introduction.

Research was carried out using previous literature and models. Heim M et al shows that it is possible to disassemble Permanent Magnet Synchronous Motors (PMSM) however when disassembling the neodymium magnet care is needed as the high forces acting on the magnets can damage them. In addition, the demand for Electric vehicles has made the EV market the largest contributor to rare earth element demand of Neodymium and dysprosium [1]. Malte Hansjosten and Fleischer J, show that there are alternative machines to autonomise the industry process however their application requires more research especially when considering complex geometries [2]. Finally, Tiwari D et al highlights the lack of literature available on this topic and the need for future research in this area. Furthermore, they revealed in a UK wide survey electric machine companies didn't have repair strategies in place for their products but show a willingness to become more sustainable and with guidance implement processes [3].

## 2. Materials and Methods

The model's functional unit is 1 PMSM motor.

Assumptions assumed in this LCA Model –

- Assumed that all the insulation and resin is negligible/ consumed in the disassembly process.
- The waste once sorted and cleaned is transported to a recycling facility.
- Electrical steel isn't recycled.

The recycled rates were chosen from previous literature for each element present in a motor. For example, copper, aluminium and neodymium magnet. The masses of these materials were calculated based on the masses in the model by Nordelöf A et al. [4]

## 3. Results and Discussion

### 3.1. results of model for 20kW motor

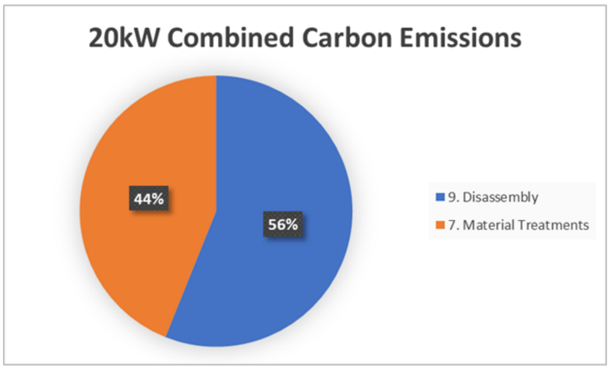

*Figure 1: Combined CO2 Emissions 20kW Motor.*

Figure 1 shows the combined CO2 Emissions the overall total emissions incurred were 1.6kg. These emissions are segregated in the pie chart above. The pie chart shows that 44% of the emissions came from the Material Treatment and 56% of the emissions came from the disassembly process. The overall mass of this motor is 9.6kg.

### 3.2. results of model for 80kW motor

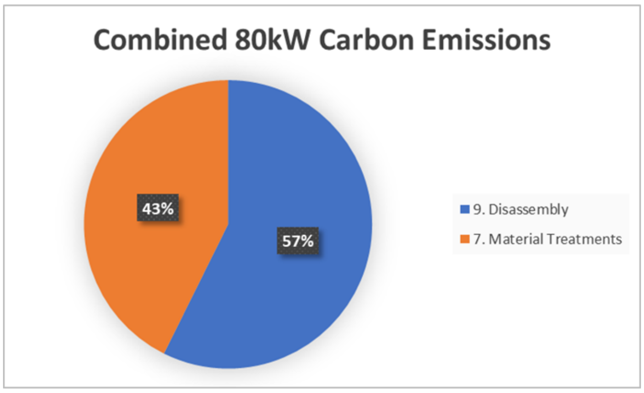

*Figure 2: Combined CO2 Emissions 80kW Motor*

The combined carbon emissions in figure 2 show how the emissions are segregated into material treatment and disassembly. The material treatment contributed 43% of the total emissions whilst the disassembly contributed 57%. The total emissions for the 80kW motor were 2.2kg. The overall mass of this motor is 32kg.

### 3.3. results of model for 200kW motor

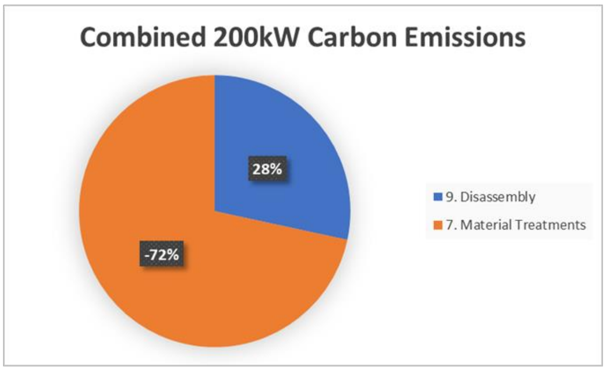

*Figure 3: Combined CO2 Emissions 200kW Motor*

The combined carbon emissions for the 200kW motor can be seen in figure 3.The combined emissions show the negative contribution from the Material Treatments of -72% and the carbon emissions produced from the Disassembly process being 28%. The total emissions for the 200kW motor are -3kg. The overall mass of this motor is 96kg, 10x more than the 20kW motor.

## 4. Conclusions

The conclusions of this project show that it is beneficial to recycle PMSM'S. The emissions involved in the disassembly process for PMSMs are dependent on their size and power output. The 200kW motor had a saving of 3kg emissions whereas the 80kW motor produced 2.2kg and the 60kW motor produced 1.6kg respectively. The results show that the greatest emission saving is with the larger motors due to the mass of material recovered and the marginal electricity difference.

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# Assessing the Environmental Impact of Products: The Role of Data Quality in Ecolabels

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## 1. Introduction

Life cycle assessment (LCA)-based ecolabels that summarise the environmental performance of products in single scores and ratings have developed rapidly in recent years [1, 2]. These environmental rating ecolabels (ERE) aim to facilitate product comparisons, and thus more sustainable consumption choices. Developing a rigorous and consistent approach to data quality, whilst maintaining feasible implementation at scale, is key for successful roll-out of such labels.

Data quality is a complex topic and has been described as ‘an elusive element’ of LCA, specifically due to a lack of clarity around data quality management [3]. In the context of ERE, rules regarding data sources and quality have been found to be inconsistent or lacking across existing schemes [1]. Where data quality is acknowledged, schemes may simply refer to ‘primary’ or ‘secondary’ data (i.e. the provenance of the data) – often also used interchangeably with ‘specific’ and ‘generic’ despite the latter terms referring to the representativeness of the system under study. In practice the picture is much more complex as product LCA studies usually combine data gathered via different methods and from multiple sources – often relying on a mix of company specific as well as third party life cycle inventory (LCI) datasets.

In ERE, specific product information (e.g. Bill of Materials) is an important consideration, helping to facilitate adequate product differentiation. In addition, the use of secondary LCI datasets is relevant to approximate the elementary flows associated with these materials, when supply chain specific data are unavailable. The quality of these secondary datasets can however be heterogeneous and will be context (i.e., product system) dependent. Determining the suitability of secondary datasets for modelling the product system therefore necessitates the evaluation of contextual indicators to assess their ‘representativeness’ level [3].

This study therefore aims to 1. Differentiate secondary LCI datasets efficiently based on context suitability (their ‘representativeness level’) to guide potential data choices in ERE; and 2. Evaluate how LCA results and environmental ratings are impacted by these data choices. We do this by conducting a large-scale sensitivity analysis: varying the LCI datasets used to represent key ingredients in a portfolio of products, characterising their representativeness and evaluating the impact on product level results.

## 2. Materials and Methods

Cradle to grave (excluding use phase) LCA midpoint results were calculated for 100 laundry detergent products currently sold across Europe and Latin America using the EU Environmental Footprint (EF) life cycle impact assessment methodology, version 3.1.

The LCA calculation for these products was carried out via high-throughput modelling (designed in Python using Brightway 2.5) using five distinct data scenarios, in which data chosen to represent 19 key ingredients of the products in this portfolio were varied (Table 1). The representativeness of the mapping between these key ingredients and the various datasets used in scenarios 1 to 4 was assessed against the three dimensions of data representativeness (technology, time, geography) used in pedigree matrices [4, 5]. In scenario 5, each ingredient was mapped randomly to a dataset amongst scenarios 1 to 4. This reflects the various levels of data representativeness that might be included in a product level assessment in real conditions, as a consequence of data availability.

Midpoint results were aggregated using the EF 3.1 normalisation and weighting sets to obtain 500 distinct single scores. Potential performance ratings (A-E) were awarded to products in the different scenarios based on their relative performance to other products in the sample.

| **Scenario number** | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Description** | Most specific dataset chosen (substance specific, e.g. triethanolamine) | Medium specificity dataset chosen based on chemical structure (e.g. monoethanolamine) | Medium specificity dataset chosen based on ingredient function (e.g. alkalinity source: sodium hydroxide) | Most generic dataset chosen (wide chemical class, e.g. chemical, organic) | Randomised selection of datasets across scenarios 1 to 4 |

***Table 1: The five data scenarios explored for ingredients mapping. Ingredients sourcing and production representing a major hotspot of environmental impacts for these products [6], their mapping to secondary LCI datasets has the potential to influence product level LCA results.***

## 3. Results and Discussion

Large-scale implementation of ERE will almost certainly rely on the use of third-party datasets for the calculation of product environmental ratings. Data representativeness will be a critical consideration when evaluating data quality and the robustness of product ratings. Contextual indicators (time, geographical and technological relevance) are particularly important. We found that final product ratings varied based on the level of representativeness of secondary LCI datasets chosen to represent key activities (here ingredients production) in the LCA study. In addition, we demonstrated that including datasets of low representativeness can lead to an under / over estimation of the environmental impacts associated with a product.

The assessment of data quality and the provision of good quality data is resource intensive, thus presenting challenges for the implementation of ERE schemes at scale and ultimately their relevance and impact. Our results suggest that evaluation of data representativeness is likely to strengthen the robustness of product environmental ratings, by enabling explicit selection (and reporting) of higher quality data in the LCA component of ERE. While some expert knowledge is required to evaluate the representativeness of datasets accurately, this can be mitigated through developing sector-level guidance regarding data quality criteria for application in ERE.

## 4. Conclusions

Understanding the impact of varying data quality on potential product ratings awarded by ERE schemes is critical to the development of data quality management strategies which are aligned with environmental labelling objectives. To our knowledge, this is the first study to assess the sensitivity of product environmental ratings to secondary LCI data choices, for a large portfolio of consumer products. The results demonstrate how environmental impacts quantified via LCA may be influenced by data representativeness, and how this propagates to aggregated single scores and relative rankings. The study provides insights and recommendations for improving data quality management and communication in ERE schemes, and for ensuring the credibility, relevance, and impact of the information provided to consumers and stakeholders.

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# Dynamic and prospective LCA combined with energy system modelling to address the temporal impact of energy production and storage

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## 1. Introduction

Transitioning towards renewable energy sources and the ability to cope with their variable nature with effective energy storage strategies will play a key role in mitigating climate change. Mainstream practice in LCA of energy technologies consists of looking at the present state statically, meaning that future evolution of the technological context and temporal specificities of producing and using energy technologies is neglected.

Two up-to-now largely independent fields of LCA, dynamic and prospective LCA tried to deal with time-agnosticism from different angles, the former by capturing explicitly the timing of processes and emissions, and the latter by projecting future changes in production systems. A notable advance in the last years in pLCA brought the use of sector-wide future background LCI databases resulting from integrated assessment models[1]. Despite notable, these advances still only partially address the dynamicity of the highly temporally variable energy system since, typically, a static analysis of future scenarios is performed. This means that future average yearly energy mixes are used instead of hourly marginal mixes, which are highly relevant considering the fluctuating nature of renewables.

This presentation has the main goal of showing how, by combining a fully dynamic and prospective LCA with the results of ESM, it is possible to develop a more realistic scenario to be used in LCA that takes into account the short and long-term temporal dynamics of the electricity system. This will be done by using the results of the ESM TIMES-Be model [2] to perform a fully dynamic and prospective LCA of wind energy production with the innovative software for dynamic and prospective LCA called timex_lca [3].

## 2. Materials and methods

The research conducts a full cradle-to-grave LCA encompassing all stages of the wind turbine life cycle. The functional unit is defined as 1 kWh of electricity delivered by the wind turbine, and its impact on global warming has been assessed. The LCI data has been gathered from various secondary sources, and inputs for the wind turbines have been scaled towards a power capacity of 3 MW.

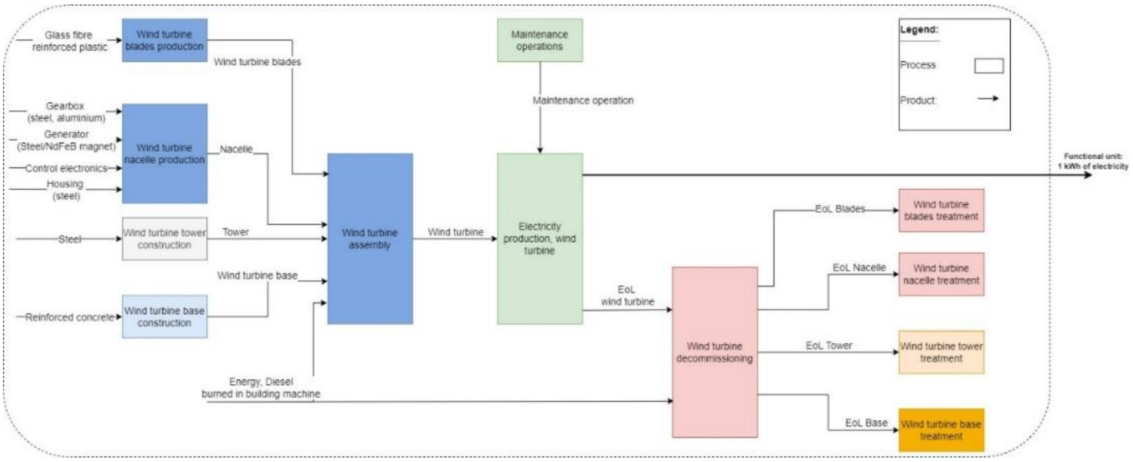

*Figure 2.1: Flowchart for the wind turbine technologies.*

In the next step PATHS 2050 - Scenarios towards a carbon-neutral Belgium by 2050 from the TIMES-Be model are being used to produce bi-hourly resoluted databases of future energy system changes with timex_lca. This results is being used to both produce and use more realistic futurized database and to model the use stage dynamically to assess the actual benefits of producing wind energy depending on the timing of its production.

## 3. Results and Discussion

The preliminary results from the LCA show that among the three types of wind turbines, the direct drive electrically excited synchronous generator wind turbine type has the largest impact on global warming. The direct drive permanent magnet synchronous generator wind turbine and the gearbox double fed induction generator wind turbine roughly have the same impact on global warming.

Most environmental impacts occur during the production phase of the different wind turbine lifecycles. This is a result of the large amount of steel in the nacelle and tower, aluminum in the nacelle, fiberglass reinforced plastic in the wind turbine blades, and the reinforced concrete needed for the foundation of the wind turbine. Conducting a prospective LCA where the complete system is put in a future scenario, the usual practice in prospective LCA, would significanlty and wrongly reduce environmental impacts of the product system, which could be adressed via this combined approach.

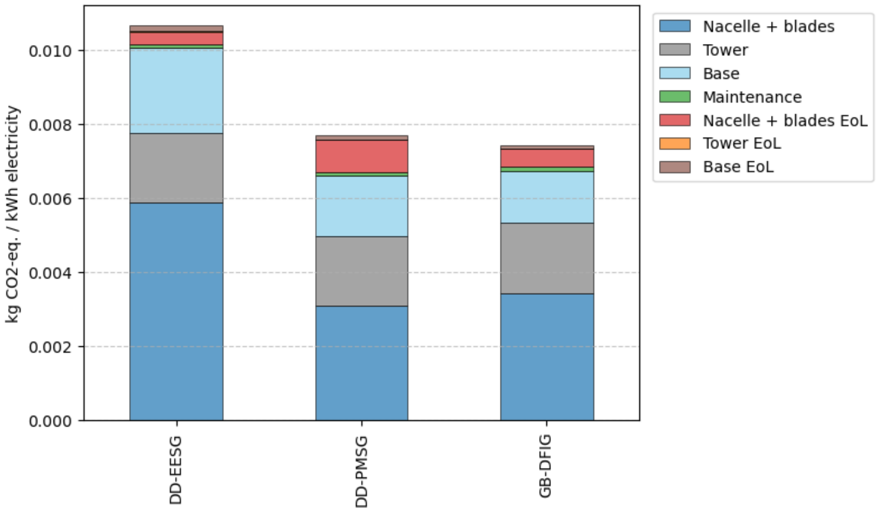

***Figure 3.1: Preliminary contribution analysis for the three different wind turbine technologies. Legend: DD-EESG: Direct Drive Electrically Excited Synchronous Generator, DD-PMSG: Direct Drive Permanent Magnet Synchronous Generator, GB-DFIG: GearBox Doubly Fed Induction Generator.***

Impacts at the use phase and end of life are limited. However, current practices are used when modeling the end-of-life of wind turbines. A noteworty dynamic is that for wind turbines currently being built, the end of life and corresponding circular economy approaches will occur twenty years from now. Therefore, it is paramount to assess how these circular approaches evolve.

## 4. Conclusions

This presentation has the main goal of showing how, by combining a fully dynamic and prospective LCA with the results of ESM is possible to develop a more realistic scenario to evaluate the impact of renewable electricity production from various wind turbine technologies in Belgium. The preliminary results showed that many of the environmental impacts occur at the production stage. Putting the whole system in a prospective future scenario, without temporal distribution, could potentially significantly underestimate the actual environmental impacts of the system. This combined approach tackles this issue and yields more detailed and comprehensive LCA results, which could better inform stakeholders in making informed decisions concerning the sustainability of renewables.

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# Reuse and Recycling Potential for Mass Timber Curtain Walls: A Consequential, Ex-Ante Life Cycle Assessment

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## 1. Introduction

The built environment is a key sector to combat climate change, necessitating strategies to reduce environmental impacts, waste production and address resource consumption. These changes require advanced life cycle assessments (LCAs) that can adapt to evolving technologies, conditions and policies. Mass timber curtain walls, known for their potential environmental benefits but shorter lifespan compared to entire buildings, offer a unique opportunity to develop end-of-life (EoL) methodologies for reuse and recycling [1]. This study employs a consequential LCA framework to evaluate EoL strategies for key components (i.e., aluminium pressure plates, spandrel insulation, and glazing), while integrating emerging technologies (ex-ante) with varying technological readiness levels (TRLs) and projected grid decarbonization. The objective of this research is to investigate the potential environmental benefits of adopting circular economy principles in construction, thereby contributing to sustainable development in the built environment.

## 2. Materials and Methods

A detailed 3D model of the mass timber curtain wall assembly, based on manufacturer specifications, formed the basis for the life cycle inventory (LCI) used in this study.The LCI was supplemented with industry reports and ecoinvent v3.8 consequential as the background dataset to conduct this assessment. Life cycle impact assessment (LCIA) was performed using openLCA with the ReCiPe 2016 Midpoint (Hierarchist) method. Reuse and recycling scenarios were developed, as described in Table 1 and compared against a business-as-usual (BAU) scenario based on current EoL practices for aluminium, insulation and glass.

| Scenario ID | End-of-Life Description | Utilized Emerging Technology |
|---|---|---|
| L1/*(L2)* | Current end-of-life practices for the given materials were employed in a consequential, ex-post, contemporary/(prospective) framework [2] | |
| R1/*(R2)* | Reuse was assumed for primary materials utilising current technology in a consequential, ex-post, contemporary/(prospective) framework. | |
| RE1/*(RE2)* | Recycling was assumed for primary materials utilising current technology in a consequential, ex-post, contemporary/(prospective) framework. | |
| RE1A/*(RE2A)* | Recycling was assumed for primary materials utilising immature (TRL=low) technology. A consequential, ex-ante, contemporary/(prospective) approach was used. | Hydrolysis, kiln-casting, polystyrene degradation to aromatics |
| RE1B/*(RE2B)* | Recycling was assumed for primary materials utilising immature (TRL=high) technology. A consequential, ex-ante, contemporary/(prospective) approach was used. | Multi-step friction stir consolidation, hybrid ceramic pavers, chemical depolymerization |

***Table 1: Description of End-of-Life Scenarios for a Mass Timber Curtain Wall***

A review was conducted on each selected emerging technology to ascertain potential carbon reductions or savings. EoL scenarios (L1, R1, RE1, RE1A, RE1B) were adjusted by an emission factor for anticipated grid decarbonization, based on long-run marginal emissions factors for Ontario [3]. This adjustment was applied to the BAU and reuse scenarios to determine if ex-ante methods would compare to recycling methods over time. A consequential life cycle assessment (CLCA) framework evaluated the environmental impact of the BAU case for the primary components, chosen to capture the broader environmental consequences of changes in EoL options, considering market-driven changes and indirect effects [4].

The analysis included life cycle stages A1-A3 (production), A4 (transport to site), A5 (construction and installation), and C1-C4 (EoL processes) as defined by EN 15804 [5]. The curtain wall was modelled following typical supply chains with materials being transported to Toronto, Ontario for construction. Stage C1 assumed deconstruction impacts mirrored construction impacts, with equivalent labor and fuel use. Stages C2-C4 varied depending on the EoL scenario described in Table 1. Benefits and loads beyond the system boundary were modeled as separate processes. A declared unit of one representative square meter of mass timber curtain wall provides a basis for comparison across the EoL scenarios and technologies.

## 3. Results and Discussion

Figure 1 illustrates the life cycle impacts for the different scenarios considered in this analysis. While the results of this study are complex, the following section aims to detail five of the key findings in relation to Global Warming Potential (GWP). First, the benefits beyond the system boundary (D) are primarily due to the recycling potential of aluminum and energy recovery from timber, as shown in L1, and reflect common Canadian practices. Second, R1 shows increased benefits from the reuse of aluminum and energy savings from avoiding the re-smelting process. Third, all three recycling scenarios (RE1, RE1A, RE1B) demonstrate greater benefits compared to L1, underscoring the energy-intensive nature of material production. Fourth, ex-ante methods perform slightly below the basic recycling method (RE1) due to their limited commercial viability and scaling challenges, though upscaling and optimizing by-products could significantly reduce GWP. Finally, grid decarbonization scenarios indicate an average overall change in GWP of 7%, driven by Ontario's reliance on natural gas as a marginal fuel source. Stage C3-C4 produces slightly higher emissions, however, benefits beyond the system are also increased due to the displacement of natural gas as the marginal fuel source.

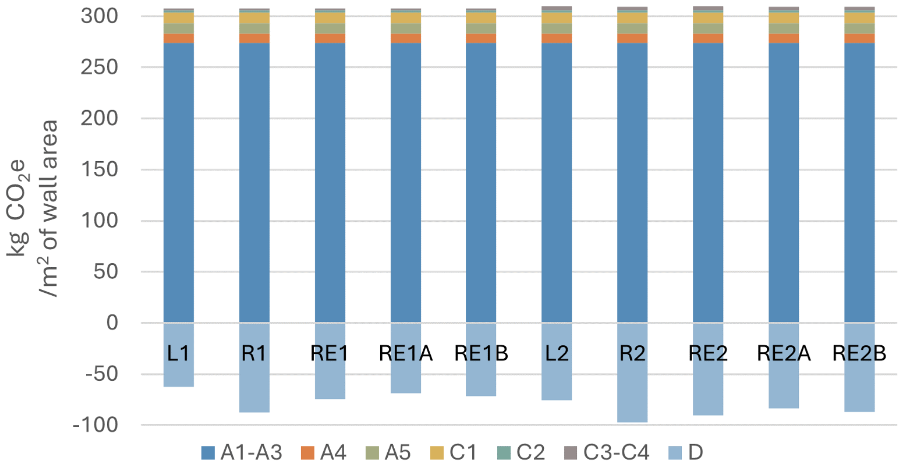

***Figure 1: Global Warming Potential of a Mass Timber Curtain Wall with Varying End-of-Life Methodologies***

## 4. Conclusions

This study uses a consequential LCA framework to evaluate EoL strategies for a mass timber curtain wall system, integrating emerging technologies with varying TRLs and projected grid decarbonization. Based on the assumptions of this assessment, reuse and recycling are anticipated to remain as favourable options compared to landfilling over time. This study highlights the potential for the adoption of reuse and recycling EoL options to be more prominently utilized in building systems and the built environment. Additionally, these findings underscore the importance of continued research and development in the field of recycling technologies. Future investigations will focus on additional ex-ante methods to ascertain further environmental benefits and optimize the life cycle impacts of mass timber curtain walls.

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# Systematic Technology Selection and Data Inventory in Lab-scale LCA: The Case of Perovskite Light-emitting Diodes

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## 1. Introduction

The emergence of new technologies is driving recent advancements in future-oriented LCA, further categorized into prospective, ex-ante, or anticipatory LCA [1]. Several methodological advancements in modelling the future have been proposed, focusing on various aspects such as technology upscaling, scenario development, background data, and impact assessment. However, preceding the aforementioned foci is another critical consideration in terms of technology selection among numerous new technologies at the lab scale (i.e., which technologies are promising for scaling up?) [1].

Perovskite light-emitting diode (PeLED) is an emerging technology that already rivals the conventional organic LED. It is an exponentially growing field owing to its simple and low-cost production, flexible and lightweight device, and exhibits color purity and tunability [2]. Like other new technologies, further research and development branch in multiple directions using various chemical reagents and synthesis routes to improve technical performance. However, improvement in terms of environmental sustainability remains lacking as there is no known LCA study on any PeLED as of the writing of this abstract.

With multiple PeLEDs under development, this study aims to introduce a systematic technology selection process and subsequent data inventory preceding a lab-scale LCA for screening purposes towards identifying technically- and and environmentally-promising PeLEDs.

## 2. Materials and Methods

A series of workshops was conducted among researchers specializing in sustainability assessment and material science at Linköping University. The primary focus of these workshops was to establish a shared understanding of how to select PeLEDs from the literature pool and how to collect corresponding lab-scale data in a format relevant for performing an LCA. The specific objectives were (i) to design a literature search and selection process aimed at achieving comprehensive coverage of technically promising PeLEDs, and (ii) to collect material and energy input-output data, simulating similar laboratory synthesis conditions (Figure 1).

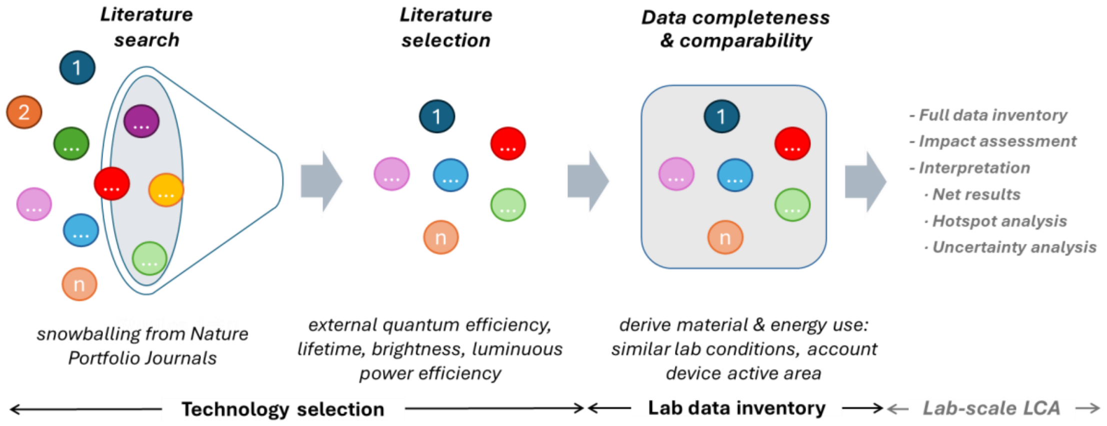

*Figure 1: Framework for systematic technology selection and data inventory applied for lab-scale LCA of PeLEDs.*

## 3. Results and Discussion

### 3.1. Technology selection

Snowballing from Nature Portfolio journals published between 2018 and 2023, 18 PeLED devices (4 red, 4 green, 4 blue, 2 white, 4 near infrared) were identified as technically promising based on four elicited selection criteria such as external quantum efficiency, lifetime, brightness, and luminous power efficiency (LPE). While

LPE required derivation, the first three criteria are explicitly reported as characterization results of the device performance. LPE is an important parameter for performing an LCA as it measures the amount of power used to generate light or simply put, the electricity consumption during the use phase. LPE is reported in commercially-available LEDs.

### 3.2. Data inventory

Inventory of data from the literature demands completeness and comparability—aspects which are not detailed in typical lab-scale LCA. Completeness necessitates deriving the amount of materials from the given concentration of reagents and thickness of different layers of PeLED devices, and the energy consumption from the time of use of every machine. Comparability, on the other hand, requires adjusting effective material use based on stoichiometric relations and resulting device active area, knowing that the reported material proportions are not optimized for material efficiency. Such a manner of collecting amount of materials and energy consumption using similar machines from one lab simulates similar conditions for laboratory synthesis of selected devices.

### 3.3. From narrow to broad lab-scale LCA

While lab-scale LCA has demonstrated its usefulness in providing guidance for technology development [3], it typically focuses on one or a few technologies, which are then subjected to future-oriented LCA (green, Figure 2). From a narrow scope, a broad range of technolgies is necessary to account for, especially for exponentially growing field such as in PeLEDs. A broad lab-scale LCA can assist in screening among promising technologies, not just among alternative materials for one component [4], but covering all components of a device (orange, Figure 2). It is within broad lab-scale LCA that the introduced technology selection and data inventory are most relevant, thereby identifying which technologies are indeed promising for scaling up (red, Figure 2).

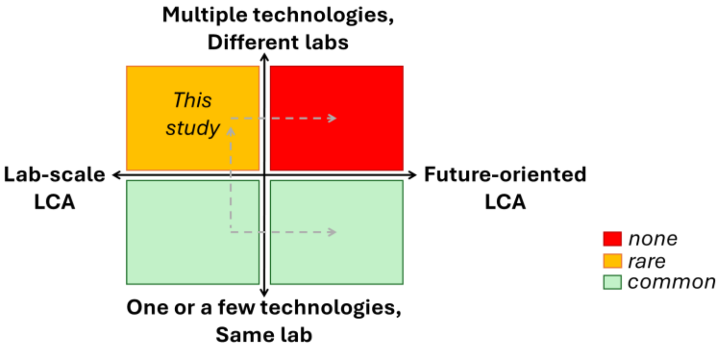

*Figure 2: Positioning the contribution of this study in screening promising technologies for scaling up.*

## 4. Conclusions

Interdisciplinary collaboration is essential for a systematic technology selection and subsequent data inventory. This contribution extends beyond the common narrow lab-scale LCAs, whihch often assess only one or a few new technologies. Instead, this provides a comprehensive selection process aimed at guiding further technological developments by considering promising technologies from a broad pool of options.

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# Circularity metrics and life cycle environmental management of wind turbine blades

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## 1. Introduction

Circularity indicators do not necessarily inform about the products´ environmental hotspots and performance, due to their yet limited scope as some lack the integration of a life cycle perspective and the consideration of all relevant resource inflows and outflows [1]. On the other hand, life cycle environmental impact indicators do not integrate the consideration of technical product qualities [2] and their calculation is usually time consuming, constraining their actual adoption by some companies (e.g. specially small and medium enterprises) [3]. Consequently, multiple authors propose a combined application of circularly and life cycle environmental impact indicators for a more robust decision-support [4]. However, the abundance of diverse circularity indicators coupled with the lack of clarity about their goals and scope can make their selection and comparison for a specific context challenging [1]. Likewise, the relationship between circularity and life cycle environmental impact indicators have not been yet fully explored as it an emerging line of research [5]. Finally, the actual applicability of circularity indicators to assess the resource efficiency and environmental sustainability performance of product systems has been poorly addressed in some sectors, such the wind industry, where the life cycle management of wind turbine blades (WTB) is critical. Considering that the average lifetime of wind turbines (WTs) is 20-25 years, the assets that were implemented over 20 years ago are reaching their end of useful life and it is expected that they will be dismantled and replaced by more modern and efficient turbines or directly dismantled as some wind farms are shut down. From an environmental standpoint, the most critical components of the WTs are the generators (requiring the use of critical raw materials) and the blades (large and heavy composite constructions) [6]. Focusing on the composite WTBs, is estimated that up to 570 Mt of WTB waste will be generated in Europe alone by 2050 [7]. Consequently, there are many research projects and business cases exploring alternative and more circular strategies (e.g. reuse, repurposing, recycling and/or co-processing) than landfilling and incineration [8]. However, there are no studies available that have yet evaluated in an integrated way (from a qualitative and quantitative perspective) the circularity and environmental sustainability of the life cycle management of WTBs to identify opportunities for improvement in the design and end-of-life management of these products, which requires to understand the scope and interlinks between improved circularity and enhanced environmental sustainability [9]. In this conference paper a number of circularity indicators with application to the analysis of the life cycle management of WTBs are analysed. First, the major WTB life cycle management processes are mapped and characterised from a qualitative technical, economic, social and environmental perspective to identify hotspots. Secondly, the maximum possible achievable scores for the selected circularity indicators is qualitatively determined by relying on the information available in the academic and industrial literature. Finally, the potential environmental gains and trade-offs (compared to benchmark systems) as consequence from the maximum possible achievable circularity scores are explored. As a result, guidelines for the effective use of circularity and life cycle environmental approaches and metrics in the assessment of this type of product systems are explored, which can be extrapolated to other sectors using composite products (such as aeronautics, shipping and automobile industries).

## 2. Materials and Methods

On the one hand, WTB reuse, repurposing, recycling (mechanical, thermal and chemical), and co-processing scenarios were defined and characterised by relying on academic and grey literature. Subsequently, a systematic literature review of circularity indicators was performed, leading to the identification and classification of 300 indicators. The scope of the indicators was analysed by relying on three checklists: i) an adaptation of the RACER checklist (Robust, Accepted, Credible, Easy and Relevant), as suggested by the ORIENTING project (Bachmann et al., 2022), ii) checklist has been built that contemplates different elements for the circular design of composite products, including variables such as traceability or product specifications (Joustra et al., 2021), and iii) circular economy frameworks developed for the wind industry contemplating design, end-of-life, recovery, or logistic aspects (Lobregt et al., 2021). The purpose of these checklist was to reduce the sample of indicators in order to consider the most scientifically relevant for the case study. Subsequently, the practical applicability of the metrics was assessed by analysing how well they can support decision-making by considering if the metrics´ variables integrate all the relevenat WTB life cycle management processes and resource in- and outflows. Finally, the maximum achievable score for a selection of the circularity metrics was calculated and the links to improved environmental performance assessed through a simplified life cycle assessment (Hochschorner and Finnveden 2003). As a result, possible future research guidelines for developing more meaningful indicators and case studiesfor the wind energy sector were defined.

## 3. Results and Discussion

Five suitable circularity indicators were selected and cross-checked with the WTB life cycle management stages, processes and resource flows (Figure 1) to determine their actual applicability.

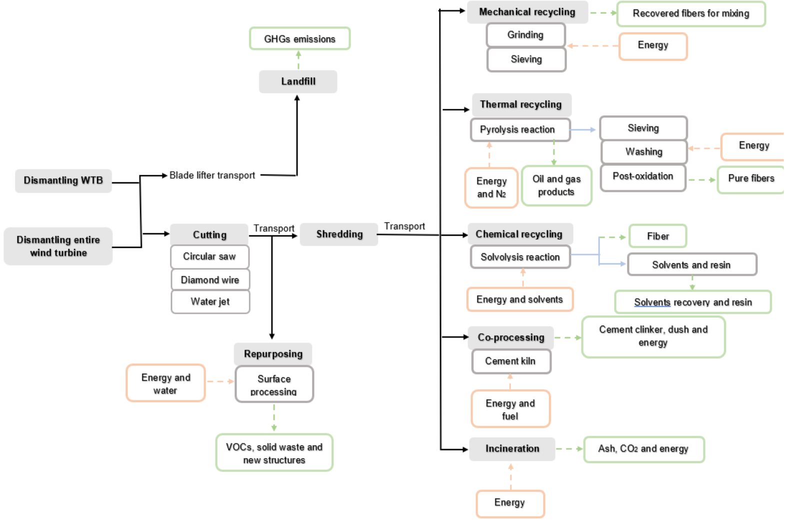
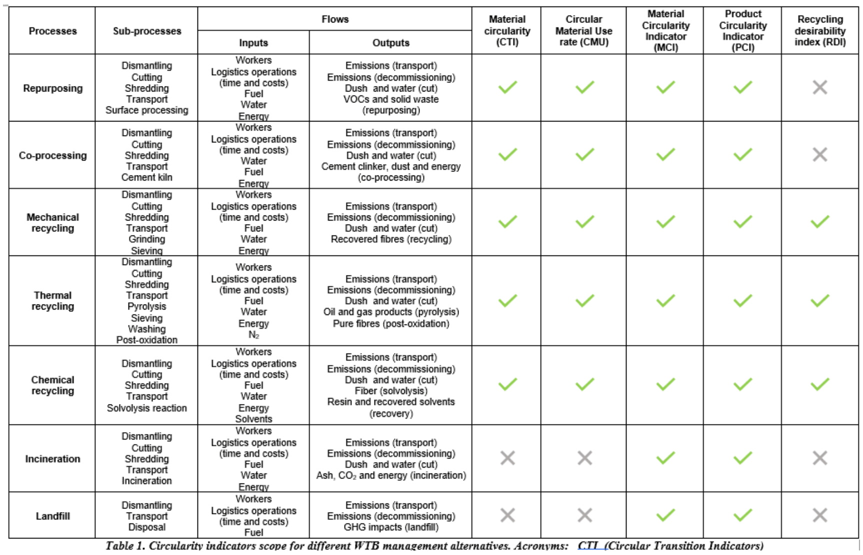


*Figure 1. Flowcharts for each management alternative. Acronyms: VOCs (Volatile organic compounds), GHG (Greenhouse gases).*

Table 1 shows each WTB life cycle management alternative input and output flows, the indicators, and their applicability in each case. Based on the results, it can be concluded that only two indicators seem promising for the assessment of the actual circularity performance of WTB life cycle management systems due to their broader perspective. However, their maximum circularity scores and link to environmental sustainability will be assessed to determine if they are actually robust for the sector.



| Processes | Sub-processes | Flows |  | Material circularity (CTI) | Circular Material Use rate (CMU) | Material Circularity Indicator (MCI) | Product Circularity Indicator (PCI) | Recycling desirability index (RDI) |
|---|---|---|---|---|---|---|---|---|
|  |  | Inputs | Outputs |  |  |  |  |  |
| **Repurposing** | Dismantling<br>Cutting<br>Shredding<br>Transport<br>Surface processing | Workers<br>Logistics operations (time and costs)<br>Fuel<br>Water<br>Energy | Emissions (transport)<br>Emissions (decommissioning)<br>Dush and water (cut)<br>VOCs and solid waste (repurposing) | ✓ | ✓ | ✓ | ✓ | ✗ |
| **Co-processing** | Dismantling<br>Cutting<br>Shredding<br>Transport<br>Cement kiln | Workers<br>Logistics operations (time and costs)<br>Water<br>Fuel<br>Energy | Emissions (transport)<br>Emissions (decommissioning)<br>Dush and water (cut)<br>Cement clinker, dust and energy (co-processing) | ✓ | ✓ | ✓ | ✓ | ✗ |
| **Mechanical recycling** | Dismantling<br>Cutting<br>Shredding<br>Transport<br>Grinding<br>Sieving | Workers<br>Logistics operations (time and costs)<br>Fuel<br>Water<br>Energy | Emissions (transport)<br>Emissions (decommissioning)<br>Dush and water (cut)<br>Recovered fibres (recycling) | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Thermal recycling** | Dismantling<br>Cutting<br>Shredding<br>Transport<br>Pyrolysis<br>Sieving<br>Washing<br>Post-oxidation | Workers<br>Logistics operations (time and costs)<br>Fuel<br>Water<br>Energy<br>$N_2$ | Emissions (transport)<br>Emissions (decommissioning)<br>Dush and water (cut)<br>Oil and gas products (pyrolysis)<br>Pure fibres (post-oxidation) | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Chemical recycling** | Dismantling<br>Cutting<br>Shredding<br>Transport<br>Solvolysis reaction | Workers<br>Logistics operations (time and costs)<br>Fuel<br>Water<br>Energy<br>Solvents | Emissions (transport)<br>Emissions (decommissioning)<br>Dush and water (cut)<br>Fiber (solvolysis)<br>Resin and recovered solvents (recovery) | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Incineration** | Dismantling<br>Cutting<br>Shredding<br>Transport<br>Incineration | Workers<br>Logistics operations (time and costs)<br>Fuel<br>Water<br>Energy | Emissions (transport)<br>Emissions (decommissioning)<br>Dush and water (cut)<br>Ash, $CO_2$ and energy (incineration) | ✗ | ✗ | ✓ | ✓ | ✗ |
| **Landfill** | Dismantling<br>Transport<br>Disposal | Workers<br>Logistics operations (time and costs)<br>Fuel | Emissions (transport)<br>Emissions (decommissioning)<br>GHG impacts (landfill) | ✗ | ✗ | ✓ | ✓ | ✗ |

*Table 1. Circularity indicators scope for different WTB management alternatives. Acronyms: CTI (Circular Transition Indicators)*

## 4. Conclusions

Results demonstrate that there is a scarcity of circularity indicators that can address all the WTB life cycle management stages, processes and criteria. Thus, there is a need to develop specific indicators for the sector. Aspects such as transport and logistics are essential for consideration, as they are very important in managing WTBs. It is also proposed to analyze these indicators from a quantitative point of view to make a comparison.

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# Investigating Contradictory Results for the Future Direct Climate Impact of the Global Information and Communication Technology Sector

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## 1. Introduction

Digital technologies are changing core economic sectors and can promote sustainability. At the same time, these technologies are also causing substantial environmental and social impacts [1]. A few studies have applied life cycle assessment (LCA) methodology to assess the direct climate impact of the global information and communication technology (ICT) sector in the future [2,3,7,8]. These studies often arrive at contradictory results for the global ICT sector's future climate impact. So far, only general overviews have been provided of these types of assessments [e.g., 4], while concrete reasons behind contradictory results remain unclear. The aim of this study is to identify reasons behind contradictory future projection results in studies on the global ICT sector's direct climate impact. This is done by investigating calculation approaches and strategies for future scenario construction applied in practice.

## 2. Materials and Methods

This work is based on ongoing research [5] and the selection of studies to be investigated was made based on a previous literature screening [6] and overviews [e.g., 4]. Studies were included in the study if they provided an assessment of direct current and future climate impacts of the global ICT sector and considered all three ICT subdomains (end-user devices, networks and data centres). Only studies that were publicly available and written in English were considered. In total, four studies which commonly are cited both in scientific literature and by media were scrutinized with regard to calculation approaches and strategies for future scenario construction [2,3,7,8]. Two studies showed an increase in the future climate impact of ICT [3, 7] and one showed a decrease [2]. One [8] showed an increase in the climate impact in all their scenarios until 2030 but a slight decrease for their best case until 2020. The studies' results were reconstructed for the year of 2020 since this was the only year for which future projections were shared among the studies. The studies' comparability was investigated in terms of scope to identify comparable parts over all the reviewed studies and to pinpoint differences in terms of model and/or parameter uncertainties.

## 3. Results and Discussion

Future projections for the year 2020 were possible to reconstruct for three studies [3, 7, 8] but not [2] since a detailed description of forecast calculations and data were not presented. Due to differences in study scopes, the total results for the global ICT sector are not directly comparable. However, the parts that are comparable in terms of scope over all studies are responsible for a larger share of the respective studies total scenario results at about 60% [7], 50% [8] and 70% [3]. Some parts are incomparable due to differences in scope (e.g. in terms of end-user devices, life cycle phases and/or different calculation approaches in turn influencing the studies' scopes) or due to a varying level of aggregation in data and results preventing a comparison of some parts with shared scope.

For the comparable parts shown in Figure 1, both model and parameter uncertainties are important. For use phase emissions of end-user devices, only computers, smartphones and tablets were shared over all studies. Other end-user devises, including fast-growing digital technologies such as Internet-of-Things (IoT) or artificial intelligence (AI), are typically not included despite that these are considered to potentially emerge as significant future impact contributors. All studies calculated the use phase emissions of end-user devices based on the installed base of devices, their related annual electricity consumption and the carbon intensity of global electricity generation. However, only one of the studies included the carbon intensity of global electricity generation as a scaling factor [8]. This implies that in the other studies, the current and future electricity system is modelled to have the same climate impacts. The investigation of the comparability of use phase emissions of networks and data centers was only possible on the ICT subdomain level due to limited transparency on scopes making a detailed investigation very challenging. Only one parameter was shared by all calculation approaches and strategies for future scenario construction for use phase emissions of networks; the carbon intensity of global electricity generation. In general, the uncertainty related to this parameter is important. For data centres, the same calculation approach was applied in all studies, considering the total data center use phase electricity consumption and the carbon intensity of global electricity generation. None of the studies included stocks and flows as well as all life cycle phases of the ICT sector and its subdomains. Notably, the strategies for future scenario construction applied in two of the studies suggests that data center emissions are bound to increase in the future. Only one study enabled both an increase and decrease in data centers' use phase emissions depending on the values applied for data traffic growth and electricity efficiency improvements. A comparison of the comparable future climate impact projections parts for 2020 with a recent current estimate for the same year [9] shows that the projections tend to be significantly higher, e.g. about 110-670% higher for the use phase of data centers and highlights the difficulties of making realistic future projections.

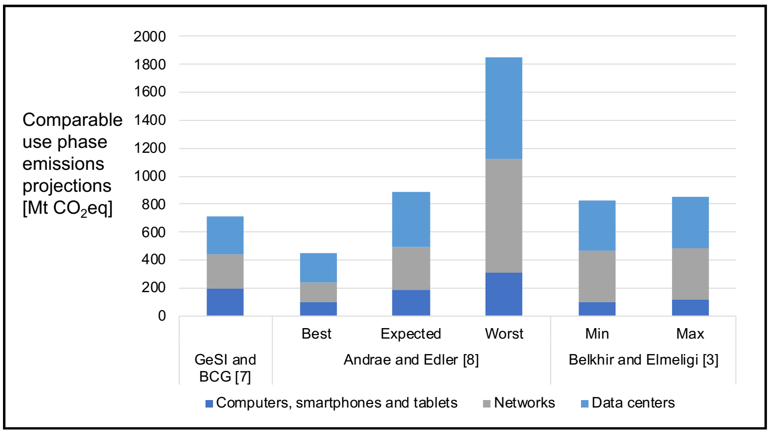

*Figure 1: Reconstructed future projections for use phase emissions in 2020 that are comparable in terms of scope.*

## 4. Conclusions

The reasons behind contradictory results are mainly due to model uncertainties but parameter uncertainties are also important. Notably, some of the reviewed studies used strategies for future scenario construction for specific ICT subdomains and life cycle phases that in practice do not allow emissions to decrease why it is not strange that these studies show increasing climate impact results. LCA practitioners are recommended to consider the critical aspects identified in this study and develop practical guidelines for future studies.

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# Study on the decarbonisation potential of hydrogen implementation in the float glass industry using Life-Cycle Assessment (LCA)

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## 1. Introduction

With a history dating back thousands of years, glass has been crucial to the development of human civilisation and mankind's [1,2]. Like any other industrial activity, glass manufacturing is usually accompanied by energy consumption which has environmental consequences. Glass manufacturing is generally considered one of the highly energy-consuming industrial activities [2-4]. Currently, the principal energy demand is usually related to the heating of raw materials by combusting conventional fossil fuels, such as natural gas, in the glass furnace [2,3,5].Several approaches are being proposed as an effective measure of decarbonisation such as carbon capture, Biofuels, electric melting or hybrid fuels mainly using hydrogen [6]. According to the glass industry stakeholders, hydrogen presented itself as the most preferable and cost-effective candidate due to the unstable supply and disruptions involved with the other alternatives [6-8]. However, the emission of the hydrogen generation process should be considered before the switch to avoid shifting the emissions to the fuel production phase instead of the glass production phase.

There are several methods to assess the environmental impacts such as the Carbon Footprint of a Product (CFP), Environmental Impact Assessment (EIA), Environmental Management System (EMS) and Life-Cycle Assessment (LCA). LCA is the widely used standardised method to assess the environmental impacts of a product through its life cycle as outlined by the ISO 14040 and ISO 14044 [9-11]. The academic literature covering glass production using hydrogen is very scarce, with only [12] examining various scenarios of hydrogen delivery to the production site either by pipelines, delivery trucks or onsite production. However, to the best of the authors' knowledge, no other articles examined the environmental effects of glass manufactured using hydrogen produced by various means and how it compares to conventional fuels.

In the present article, a comparative LCA evaluating the environmental impact of float glass produced using conventional natural gas and hydrogen is presented. The study aims to give an understanding of the environmental impact of hydrogen implementation on float glass production emissions. The gained insights will assess the potential of hydrogen utilisation, by examining the environmental burdens of hydrogen produced using various methods. This LCA study will present a holistic overview of the environmental impact of float glass production using hydrogen to identify the key areas that need tackling to reduce emissions.

## 2. Methodology

The LCA study was done following the guiding principles in ISO14040 [9] which have four phases: “Goal and Scope definition”, “Inventory analysis”, “Life cycle impact assessment” and “ Interpretation of results”. The declared unit chosen for this study was 1 kg of float glass produced. The functional unit term should not be mistaken for the declared unit as there is no quantification of the product function in this research as it is the same glass being produced but with a different fuel/fuel source. The three case studies were for float glass production using Natural gas as the baseline case, using hydrogen produced by renewable wind energy (green hydrogen) and using hydrogen produced by steam methane reformation without a carbon capturing system (grey hydrogen). The system boundary chosen for the studies was cradle-to-gate but without considering the transportation of raw materials or energy sources to the production site. This mainly evaluates the burdens of the raw materials used and input materials/energies (A1) and manufacturing (A3). The environmental impact indicators adopted were some midpoint indicators used by the impact assessment method CML IA baseline V3.08 and they are Global Warming Potential (GWP), Ozone Layer Depletion (ODP) and Abiotic Depletion (AP). The calculations were conducted using SimaPro 9.4. The materials and energy upstream of 1 kg of float were based on the LCA report made by Glass for Europe [13]. The data for the material and energy upstream were obtained from EcoInvent 3.8 and then localised to address the UK market by either changing the inputs to UK inventory or localisation of the Rest of the world (RoW), Global market or European market to have UK inputs in the first level of inputs. The primary data for the production process was obtained from a chemical combustion model using FactStage software which is a thermochemical software applied in fuel firing studies for computing multiphase multi-component at equilibrium status with the relevant fuel composition, atmosphere and temperature settings [14]. Two reaction models were developed in Factstage, one using Natural gas based on UK grid data and another using pure hydrogen to explore the emissions produced by each. This is due to the lack of real-world data from the glass industry on glass produced using hydrogen.

## 3. Results and Discussion

Early results suggested that hydrogen may be a promising candidate for global warming potential due to the reduced amount of carbon dioxide released on combustion, specifically green hydrogen. However, the other impact indicators were not all in favour of hydrogen due to the environmental effects of the hydrogen production plants.

## 4. Conclusions

This research was conducted to assess the potential of hydrogen implementation in the glass industry in the UK as one of the preferred candidates for decarbonisation. This was done via conducting an LCA on 1 kg of float glass produced using natural gas as the conventional way and comparing that to the use of hydrogen sourced by different techniques. Modelling combustion data from FactStage was used to provide the primary data and supplemented by data from EcoInvent. Preliminary results indicated that hydrogen might have some challenges in terms of other impact assessments other than the GWP. Therefore, further analysis in this research will examine the effects of different routes of producing hydrogen on float glass production.

## 5. Acknowledgement

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# Prospective and Life Cycle Assessment in Sustainable Building Practices: the role of sustainable materials

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## 1. Introduction

The urgent need to decrease greenhouse gas emissions in the construction sector presents a significant global challenge, as buildings account for a substantial portion of energy consumption and environmental impact [1]. The PRIN - Italian national research project - CHOISIS, which focuses on characterizing the environmental and thermophysical properties of innovative insulating materials, directly addresses the imperative to improve building sustainability. This study aligns with the European Union's objectives to transition to zero-emission buildings by 2050 [2], emphasizing the use of innovative materials and energy-efficient construction practices. The aim of this research is to incorporate Life Cycle Assessment (LCA) methodologies to anticipate the long-term environmental impacts of these new building materials, ensuring alignment with sustainable development goals. The results provided by the LCA can be conveyed in different forms, including generic reports or eco-labels such as Environmental Product Declarations (EPDs). Manufacturers and suppliers of building materials are encouraged to offer products with EPDs because they can gather a competitive edge in the market [3].

## 2. Materials and Methods

Drawing on insights gained from a thorough analysis of Environmental Product Declarations (EPDs), our methodology critically evaluates the embodied global warming potential (GWP) of key building materials such as concrete, expanded polystyrene, and bricks. Through the utilization of standardized international protocols in alignment with ISO 14025, ISO 21930, and EN 15804, we assess the consistency and comparability of EPDs across various production chains, while also examining the influence of local energy mixes on the GWP of these materials. This analysis plays a pivotal role in forecasting and mitigating long-term environmental impacts, reflecting a forward-thinking perspective that is essential for sustainable construction practices.

Furthermore, our research employs a comprehensive Life Cycle Assessment (LCA) framework to evaluate the environmental footprint of both conventional and innovative building materials throughout their lifecycle, from production to disposal. This includes the evaluation of materials such as glass fiber, aerogel, nanorenders, and those derived from agricultural waste. Our analysis goes beyond immediate environmental impacts to incorporate forward-looking scenarios, which are developed based on anticipated technological advancements and shifts in material supply chains. This forward-looking approach is crucial for precise environmental planning in construction, enabling a more accurate assessment of future sustainability and the selection of materials that align with circular economy principles.

## 3. Results and Discussion

### 3.1. Environmental Impact of Insulation Materials

The findings of our study emphasize the significant impact of incorporating innovative materials such as aerogels and nanorenders in reducing thermal transmittance, thereby decreasing energy consumption in buildings. Additionally, the utilization of materials derived from agricultural waste not only contributes to waste reduction but also diminishes the carbon footprint associated with construction materials. This approach aligns with the principles of the circular economy, which advocate for the reuse and recycling of construction materials to prolong their lifespan and minimize waste.

Furthermore, our analysis uncovered substantial variations in the Global Warming Potential (GWP) of building materials, primarily influenced by standardized production processes and reliance on local energy sources. Materials with established and standardized production chains demonstrate more consistent GWPs, highlighting the importance of consistency in supporting Environmental Product Declarations (EPDs).

Transparent and verified data from EPDs play a crucial role in enhancing environmental performance in construction projects.

Moreover, our prospective Life Cycle Assessment (LCA) integrated the use of EPDs to further align construction practices with circular economy principles. This showcases how sustainable material choices, supported by EPDs, can lead to reduced environmental impacts throughout a building's lifecycle. By strategically leveraging EPDs, construction projects can meet sustainability certifications and green building standards, underscoring the significance of validated environmental information in promoting sustainable building practices.

### 3.2. Broader Implications for Sustainable Building Practices

The findings of our study emphasize the significant impact of incorporating innovative materials such as aerogels and nanorenders in reducing thermal transmittance, thereby decreasing energy consumption in buildings. Additionally, the use of materials derived from agricultural waste not only contributes to waste reduction but also helps lower the carbon footprint associated with construction materials. These practices align with the principles of the circular economy, which advocate for the reuse and recycling of construction materials to extend their lifespan and minimize waste.

Furthermore, our analysis identified substantial variations in the Global Warming Potential (GWP) of building materials, largely influenced by standardized production processes and reliance on local energy sources. Materials with established and standardized production chains demonstrate more consistent GWPs, highlighting the importance of transparency and verified data in enhancing environmental performance in construction projects. Our prospective Life Cycle Assessment (LCA) integrated Environmental Product Declarations (EPDs) to further align construction practices with circular economy principles. This showcases how sustainable material choices, supported by EPDs, can lead to reduced environmental impacts throughout a building's lifecycle.

By strategically utilizing EPDs, construction projects can meet sustainability certifications and green building standards, emphasizing the significance of validated environmental information in promoting sustainable building practices.

## 4. Conclusions

The findings of the PRIN project underscore the significance of innovative and sustainable materials in propelling the construction industry towards a more sustainable future. By employing a prospective LCA approach, this study establishes a framework for predicting the environmental impacts of new materials and construction techniques. The integration of circular economy principles further ensures that the construction sector can achieve its emission reduction targets while fostering economic viability and environmental stewardship. This research not only enhances our comprehension of sustainable building practices but also provides practical insights that can be implemented industry-wide to mitigate the overall environmental impact of construction activities.

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# Circularity Assessment of Reusable Packaging Developed in the BUDDIE-PACK Project

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## Introduction

Over recent years, numerous Life Cycle Assessments analysing reuse systems and comparing them to existing single-use systems have been published. Whilst useful for assessing when and how switching to a reusable system can be a better option to tackle issues such as global warming or resources depletion, it is difficult to draw conclusions from them to make strategic decisions on the regional or national adoption of reuse, as they suffer from a lack of real operational data and methodological reference frames. For the example of reusable packaging, the scientific community has even published a letter warning European politics about the insufficient scientific rigour and transparency of comparative LCAs used to influence decisions for the future Packaging and Packaging Waste Regulation (1). To ensure the LCAs for reuse systems are robustin identifying which use-case reusable systems should be adopted, several methodological points must be addressed.

The BUDDIE-PACK project aims to develop business-driven systemic solutions for sustainable plastic packaging reuse schemes in mass market applications. To assess their sustainability, a two-step (screening study and full assessment) environmental, economical and social Life Cycle Assessment is performed on the five reusable packaging items developped in the project. This paper focuses on the environmental evaluation of a reusable takeaway food container (Vytal), before drawing general conclusions about the LCA screening studies.

## 1. Materials and Methods

The LCA screening studies evaluate the contributions to impacts, along with the assessment of Break-Even Points (BEP) of reusable systems, i.e. the number of times the reusable system must be used to be better than a single-use alternative. They follow the ISO 14044 standard (2), as well as the general PEF guidelines (3). As there is no Category Rule for packaging, the ADEME method for packaging comparative LCA (2) is also used.

Data coming from project partners include weight, material, process of single-use primary/secondary/tertiary packaging or washing consumptions. Assumptions were made for reusable solutions that are not commercialised. Literature was used for plastic recycling process. Other data (material, process, transport, end-of-life) comes from the Ecoinvent 3.9 database. All the impact categories from EF3.0 are evaluated for the hotspots identification. Break-Even Point analyses which are performed for climate change and water consumption give design guidelines.

## 2. Results and Discussion

For the take-away food packaging in the Vytal use-case, a reusable PP container is compared to a single-use laminated cardboard container, for service and on-site washing in a restaurant in Berlin (Germany). The baseline study gives a break-even point of 17 uses for Climate change and 32 uses for Water use. Sensitivity analysis is performed on packaging mass and material, energy mix for washing, end-of-life scenario and consumer transportation as in Figure 1. Analysis on consumer transportation is presented here as it is the parameter that has the most impact on the BEP evolution, when using the worst-case assumption of a trip 100% allocated to the packaging return. This hypothesis will be thoroughly refined, with input from the social study work package partners, for the full assessment.

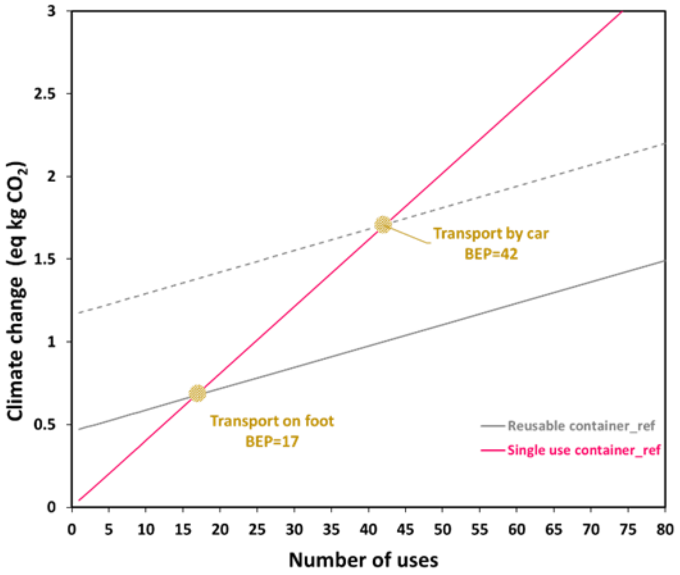

***Figure 1: BEP analysis on Climate change depending on the consumer's mean of transportation (no change for Water use)***

## 3. Conclusions

In conclusion, LCA screening studies enabled the BUDDIE-PACK partners to identify the main hotspots of each use-case, as seen in *Table 1*, as well as any additional data required to perform a full LCA.

| **Use-case** | **Main contributors to Climate Change and Water Use** | **Data gaps** |
|---|---|---|
| Take-away food container | Container production, Consumer transport | PBT production, Consumer transport |
| Refillable system for laundry detergent | BiB and reusable bottle production | Detergent distribution, recycled plastic content, BiB volume |
| Semi-rigid catering tray | Tray production, Transport | PBT production, cost of RPP production, Industrial washing |
| On-the-spot food consumption container | Container production, Washing | PBT production, Industrial washing, Reverse Vending Machine |

***Table 1: Conclusion on LCA screening results***

Future work will collect additional data (real reuse rate, real mass of the packaging, material production, addtionnal compared solutions...) from project partners and external companies to assess the environmental, economic and social relevance of the developed reusable packaging.

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# Life Cycle Assessment of Lithium Recovery Alternatives from Mine Tailings

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## 1. Introduction

Lithium (Li) is a strategic raw material for achieving Europe's Green Deal plan, mainly due to its importance for the production and market penetration of electric vehicles that rely on lithium-ion batteries [1,2]. However, the extraction and processing of primary lithium has led to several environmental implications for the local communities and ecosystems [3,4]. Considering that lithium is also present in other sectors (e.g., ceramics and alloys), there can be an interesting case to be made for the recovery of lithium from Li-rich waste generated from those industries, and its integration as a high-value stream into the battery value chain. This study presents a life cycle assessment (LCA) [5,6] for the comparison of Li recovery processes from mine tailings, obtained in a former mining site of pegmatite. The study analyses several case stud of leaching alternatives. A final comparison between treated and untreated samples leached from different leaching alternatives was made to determine the best environmental performance.

## 2. Materials and Methods

The LCA study followed the standardized methodology [5,6] with the goal to determine the Li recovery scenarios with the best environmental performance. Several scenarios were considered for separating Li from the solid sample into a liquid solution for further processing. Two pre-treatments were considered to potentially increase the Li leaching efficiency: roasting and particle liberation. For the leaching step, the roasted sample was leached with water. The particle liberated and the untreated samples were leached in four different alternatives: deep eutectic solved (DES) leaching, pressurized leaching, microwave leaching and acid-base leaching. Considering laboratorial conditions, the inventory collected from developers was matched with life cycle databases, to obtain background data in Belgium and European conditions. The results were calculated using the functional unit of "1 gram of leached Li into a liquid solution" in the ReCiPe v1.1 Endpoint (H) method [7].

## 3. Results and Discussion

The results showcase that water leaching, pressurized leaching and microwave leaching have the lowest potential environmental impacts. The water leaching with the roasted sample had the highest Li amount recovered with smaller consumption of resources and waste generation, and is the scenario with the best environmental performance.

When assessing the categories of the impacts generated, there is an overall uniformization of the main contribuing categories, reflecting that the hotspots generated are similar in all leaching alternatives. The potential environmental impacts generated from the analysed alternatives come mostly from the global warming (GW) and fine particulate matter formation (FPMF) impact categories, where between 47-52% are GW impacts. These categories are the most relevant due to the high electricity consumption and the incineration of the solid waste generated during leaching, i.e., the remaining solid sample after the leaching process. The electricity impacts are derived from the selected 2018 Belgium energy mix, which has a relevant portion of energy production from natural gas, as well as energy importation coming from the Netherlands (that make use of natural gas and coal to produce electricity). The incineration step generates also impacts for these categories due to the combustion of fuel oil for incinerating the waste.

From the analysed alternatives, it is clear that the particle liberation pre-treatment of the mine tailings did not lower the environmental impacts. This is due to the fact that the particle liberation pre-treatment did not obtain higher yields of Li leaching, which led to higher consumption of materials and energy for less amounts of Li leached, while simultaneoulsy adding more impacts to the alternative scenario. As such, all of the leaching options with the particle liberated sample have more impacts than the untreated sample in each leaching process.

In the overall environmental performance of Li recovery processes with pre-treated samples, the leaching is the most relevant step, with more than 99% of total impacts, except for the water leaching of the roasted sample, where 36% of impacts occur in the roasting pre-treatment. In roasting, the main source of impacts is the energy consumption for roasting the sample.

An assessment of the initial amount of Li present in the samples was conducted to ascertain the leaching efficiency, and the results showed that the mine tailings had a significant variating Li concentration before pre-treatment and leaching. This result led to a sensitivity analysis to understand if the LCA conclusions would vary if the samples had the same Li content for each leaching. The results were adjusted for the smallest and highest Li concentration measured in the samples, and the comparison in both scenarios concluded that water leaching remained the best performing alternative. Regarding the worst alternative, for the minimum amount of Li, DES leaching had the least best performance, whereas in the highest Li concentration scenario, acid-base leaching was again the alternative with more environmental impacts. This indicates that, for mine tailings, the process performance is the main determining factor when selecting the leaching alternative with lowest environmental impacts. On the other hand, the highest environmental impacts can be derived from either DES leaching in low initial Li concentrations, or acid-base leaching in higher Li concentrations.

## 4. Conclusions

The environmental assessment of the mine tailing leaching alternatives allowed to conclude that the water leaching and the pressurized leaching, followed by the microwave leaching, of the untreated samples, had the lowest environmental impacts. This indicates that the mine tailings do not require further pre-treatment, avoiding unnecessary processing steps which can increase the environmental impacts and the associated costs.

The results showed that water leaching had the best environmental performance. Nonetheless, the mine tailing samples that were received for leaching had stark differences in the initial Li concentrations. However, after a sensitivity analysis for levelling the same initial Li amount for all processes, and based on the leaching efficiency of each alternative, the obtained results validated the same conclusions as the initial LCA study, indicating that the process flow impacts are the main factor for determining the best Li recovery alternative. The obtained results were further considered in an assessment combined with economic results for decision making, supporting the further development of these technologies to higher levels of development.

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# Using LCA for evaluating hotspots and circularity strategies in semiconductor manufacturing

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## 1. Introduction

During the last decades, electronic devices have become an essential and non-separateable part of modern societies by enabling advancements in healthcare, information flows and business operations. All these are made possible by the semiconductor industry. However, manufacturing semiconductors causes significant environmental impacts due to precious raw materials that need to be extracted and refined [1]. Additionally, the production facilities, “fabs”, have strict hygiene requirements and therefore, the highly controlled infrastructure processes (e.g. recirculating air, ultrapure water, compressed dry air) consume a lot of energy, water and chemicals [1], [2]. The pace of technological development is not showing signs of slowing down, and more advanced and efficient integrated circuits (ICs) are developed all the time [3]. As ICs get more complex, more refined manufacturing processes are needed which leads to more profound environmental impacts [3].

Due to growing environmental pressures, also the semiconductor industry needs to find ways to minimize their impacts on climate and environment. Several studies have examined e.g. greenhouse gas (GHG) emissions, water use and energy consumption of semiconductor manufacturing (e.g. [1], [3], [4], [5]) but circularity aspect hasn’t received attention yet. In this study the environmental impacts of semiconductor manufacturing are examined, considering if increasing circularity in manufacturing could help to mitigate any of the environmental pressures currently wittnessed. The study contributes to a Finnish roadmap aimed at increasing circularity in the semiconductor industry, identifying hotspots and areas of improvement.

## 2. Materials and Methods

ZeroChip (2024-2025) project strives to develop in-depth understanding of the global semiconductor supply chains’ eco-efficiency and to create competitive circular solutions. The project aims to increase Finnish companies’ understanding of the life cycle environmental impacts, focusing on activites where these companies can make an impact. Together with partner companies a roadmap for achieving circularity in semiconductor fabrication will be generated, buiding upon the learnings gained from the LCA study, and technical process development.

Life Cycle Assessment (LCA) is used to explore potential environmental burdens within the main process phases of the IC manufacturing. Under the spotlight are the most significant raw materials, chemicals and critical raw materials. As semiconductor industry is trying to keep up with Moore’s Law by adding more and more computing power to ICs [3], currently used materials, such as copper as an interconnect, do not perform well enough and must eventually be replaced. In this study, the use of alternative raw materials in wafer processing is evaluated from the perspective of environmental impacts and criticality. Potential environmental impacts, related to the recovery of critical raw materials during the chemical mechanical planarization (CMP) phase of wafer processing, are assessed.

For the LCA, lack of data (or access to data) covering the whole life cycle is acknowledged as one of the challenges. Main data source will be lab-scale experiments conducted at VTT. Literature research was conducted, in order to determine the key processes to be evaluated and fill in the data gaps. For generic processes, such as electricity production and production of raw materials, Ecoinvent 3.9.1 database is used.

## 3. Results and Discussion

As a first step, relevant processes were identified for the LCA. In reality, semicondutor manufacturing might contain hundreds of different process steps. Therefore, a typical manufacturing procedure with most relevant steps was drafted. This process scheme presented in Figure 1 also presents the planned system boundary for the LCA study. Figure will be udpated based on the learnings gained during the study. Final results are expected by the end of 2024.

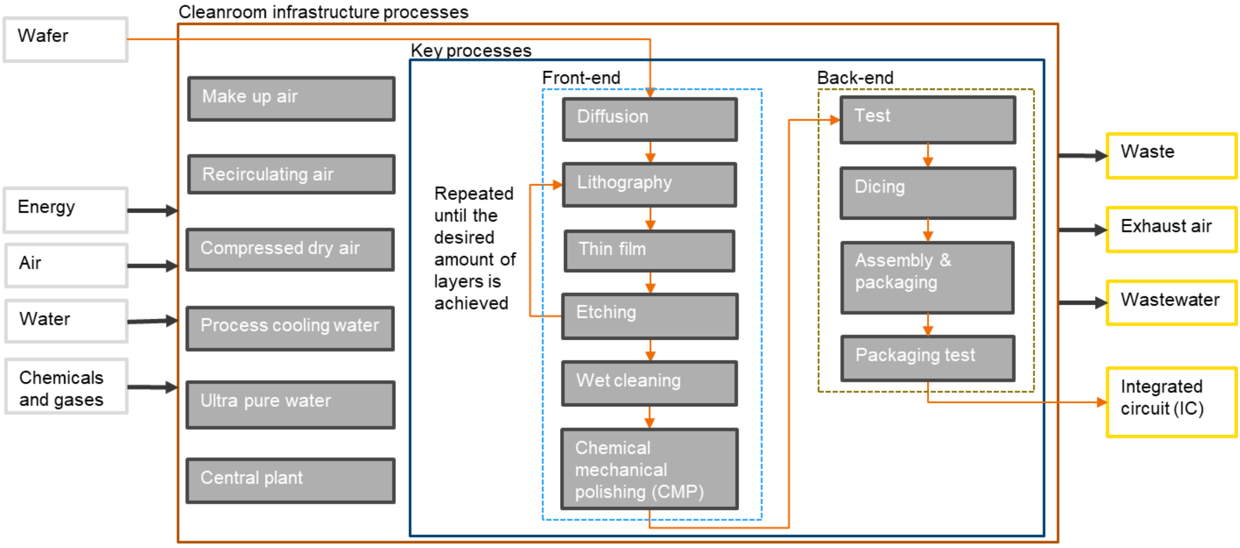

***Figure 1: Draft figure of the system boundary for the LCA [1], [2], [3], [6], [7], [8].***

## 4. Conclusions

The aim of the LCA study is to contribute to life cycle management in the Finnish semiconductor industry with novel information about potential environmental impacts of semiconductor manufacturing, focusing especially on new strategies and solutions for material recovery, recycling and industrial reuse. Based on the identified hotspots, process steps with high potential for improvement are examined and communicated to the actors of Finnish semiconductor ecosystem. This gives them tabgible measures to minimize their environmental impacts, optimize their processes according to circularity principles and support decision-making related to most promising future raw materials.

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# A life cycle based assessment toolbox to assess and improve safety and sustainability of chemicals – half time report

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## 1. Introduction

At the SETAC Europe conference in 2021, we stated that we wanted to address challenges connected to fostering a sustainable chemical industry. We stated that to reach the goal of an environment where exposure to hazardous chemicals is minimized, there is a need for life cycle methodology supporting chemical substitution, identifying unacceptable trade-offs in the chemical's or product's life cycle, including burden shifting among safety, health and environmental related impacts. In 2021 we were at the beginning of a research journey within the Mistra SafeChem programme. Today, halfway through this eight-year programme, we can report the first tangible results.

The vision of Mistra SafeChem "***is to enable and promote the expansion of a safe, sustainable and green chemical industry"***. The programme has to date advanced data and methods, towards this vision, via 86 scientific articles. To extend its availability to a wider audience, this research has been implemented into a conceptual toolbox on www.mistrasafechem.se, containing 37 tools so far. This toolbox covers the areas "Process design and optimization", "Hazard and exposure screening" and "Life cycle based assessments". In the following, we describe the developments of the life cycle based tools, their application, and integrated use with hazard and exposure screening tools. With another four years of research just granted for the programme to continue and further advance science and tool development, we finalize with an outlook on our long-term goals and ambitions.

## 2. Materials and Methods

The starting point for building this toolbox was a step-wise framework for quantitatively assessing exposure (near-field and far-field) and life cycle impacts in chemical alternatives assessment (CAA), where in each step the assessment scope is increased from use-stage risks to worker health and chemical supply chain and finally full product life cycle impacts. We defined the toolbox as having three entry points: CAA and chemical substitution with life cycle considerations, "chemical footprint assessment" (CFA), i.e. focus on (eco)toxicity life cycle assessment (LCA) impact categories, and broader scope LCA, integrating the CFA and additional impact categories. USEtox (www.usetox.org) and ProScale (www.proscale.org), for (eco)toxicity life cycle impact assessment (LCIA), are key tools in the toolbox.

## 3. Results and Discussion

The developments of the life cycle based tools included that *i)* USEtox was advanced into version 3, including a near-field module, incorporating exposure from consumer products in LCIA, [1] and *ii)* ProScale was showcased for its potential use in a Product Environmental Footprint (PEF) context, and user needs and perspectives on an expansion to include ecotoxicity was investigated. [2] In addition, opportunities for digitalizing (eco)toxicity assessment in LCIA was investigated. By mapping the potential of machine learning based approaches, it was demonstrated that currently crucial data gaps can be filled for up to 46% of globally marketed chemicals. [3] We further explored the aligned application of the toolboxes for hazard and exposure screening with the LCIA tools in dedicated case studies.

In six major case studies, the toolbox was applied in diverse application contexts and technological readiness levels, covering process design and substitution assessment (*Figure 1*). For example; toolbox use guided decisions on recirculation of process chemicals, [4] and alternative electrode materials, [5] and a fully digital workflow was employed for high throughput risk screening and ranking. [6] In all case studies, the LCA results provided additional insights to the sole application of green chemistry principles or chemical risk assessment.

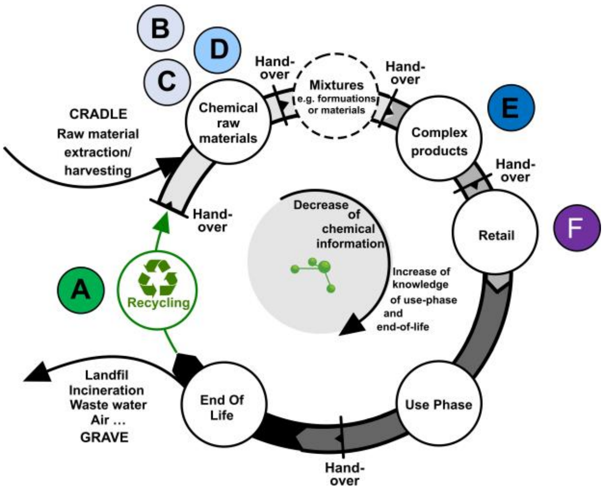

***Figure 1:*** *Example case study topics (A) Textile recycling, (B) A novel hydrogenation reaction process, (C) A biocatalytic pipeline, (D) Production of a low-risk building block chemical for surfactants, (E) Materials inside the car that do not cause health effects, (F) Substitution of cyclosiloxanes and silicones in cosmetics. Each case study covered a full system cradle-to-gate or cradle-to-grave.*

## 4. Conclusions and recommendations

We conclude that a sustainable transition requires system thinking and integration of a full life cycle perspective. Novel tools for rapid screening and integration of hazard and risk information into LCIA are key for relevant decision support in process design and substitution. Tools like USEtox and ProScale, integrated with *in silico* approaches for substance property predictions, make this possible.

There is still room for improvement of the life cycle based tools in the toolbox; hence, for the coming four year period, we look forward to address further challenges, such as:

- Prospective LCA, including life cycle considerations in design stages.
- Operationalisation of assessment according to the Safe and Sustainable by Design framework and to support Ecodesign for Sustainable Products Regulation assessments of chemicals, including integration in PEF methodology.
- Facilitating relevant life cycle inventories for chemical footprint.
- Further integration of high throughput *in silico* tools and LCIA.
- Substance specific challenges, e.g. fate and exposure of metal emissions.

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# EU shipping fleet decarbonization: Well-to-wake assessment model

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## 1. Introduction

Maritime shipping significantly contributes to global $CO_2$, $SO_2$, and NOx emissions as a result of its dependence on fossil fuels. These emissions would continue to increase with the expected increase in transport demand and economic growth. Maritime transport at the EU level accounts for approximately 3 to 4% of the total CO2 emissions, which amounts to over 124 million tonnes of $CO_2$ in 2021 [1]. Shipping is included in the EU's "Fit for 55" package, which aims to contribute to the EU's goal of carbon neutrality. One element in “Fit for 55” is the Fuel EU Maritime regulation which aims to decrease GHG emissions by reducing the yearly average GHG intensity of energy used on board a ship from a 2020 reference value of 91,16 grams of $CO_2$ equivalent per MJ, by 2% in 2025 and achieving the reduction target of 80% by 2050 [1]. In 2023, 40% of the new ships ordered globally can run on alternative fuels and this is a significant rise compared to previous years [2] and this indicates that the shipping sector is bracing for energy transition. However, the transition towards decarbonization in the shipping sector relies heavily on emerging technologies, and it is important to develop climate-friendly energy transition strategies that can capture the political decision impacts, technological development, the transport demand and renewable energy availability.

Energy system models are often used for a better understanding of energy transition strategies. However, the energy system models often consider the possibility of achieving $CO_2$ targets for specific sectors in target and often ignore other emissions and environmental impacts. One way of understanding the trade-offs is to integrate the energy system models with life cycle assessment models. However, the coupling of the LCA models with energy system modeling is challenging as both methods are data-intensive and complex. Another challenge is that the LCA approach provides static snapshots and thus needs to be extended to include prospective scenarios. An integration of life-cycle assessment and integrated energy modeling has been conducted in previous studies for other sectors, specifically focusing on deriving embodied energy use and emissions from prospective LCA modeling [3]. Through the integration of prospective life cycle assessment (LCA) into energy modeling, this study seeks to offer a perspective on the well-to-wake greenhouse gas emissions and energy demand of low-carbon solutions within the framework of the EU shipping fleet.

## 2. Materials and Methods

A preliminary model is made for the calculation of WTW emissions for the results derived from an energy system model within a clean energy technology. The simplified system boundary of the model is shown in Figure 1. The energy model describes how various energy sources are segregated and bunkered according to the different types of fossil fuels, biofuels, and synthetic (or e-fuel) fuels. Additionally, the demand for bunkering is estimated based on domestic, international, and intra-EU transportation activity locations.

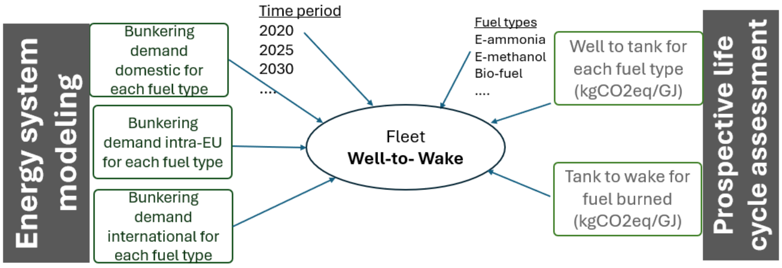

*Figure 1: Description of Figure 1.*

The WTT and TTW energy and GHG emission per fuel type on a per production ($CO_2eq/GJ^{-1}$) basis are derived from two prospective life cycle assessment studies that specifically focused on shipping [4, 5]. These studies include different production pathways including fuel derived from biomass, fossil, and electricity, and also evaluate a wide range of environmental impacts.

## 3. Results and Discussion

Well-to-wake energy demand for the EU shipping fleet is separated into domestic, intra-EU, and international as shown in Figure 2. The shipping sector is expected to predominantly depend on fossil fuels until 2035. It can be noted that there is a projected rise in demand for biomass and electricity, highlighting the need for the shipping sector to develop strategies to ensure their availability to facilitate decarbonization. The production pathways for biofuel and e-fuel for shipping fleets have a substantial impact on the energy demand as the production of these fuels is energy intensive. Developing a targeted shipping strategy is crucial, especially given the competition from other sectors and it is expected that the more demand for biomass.

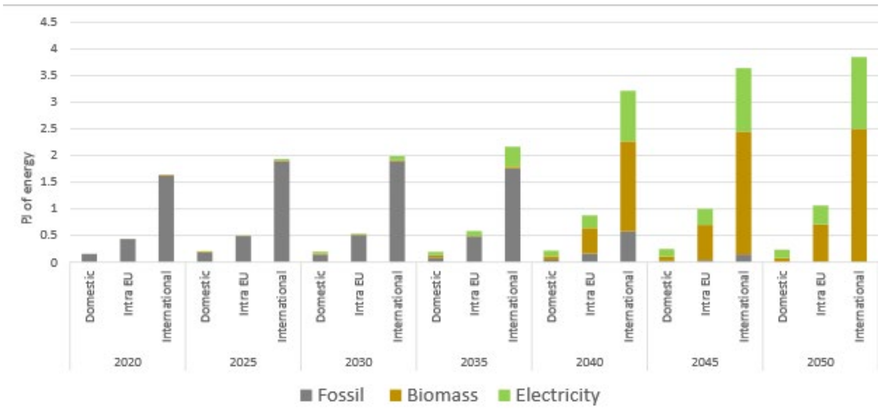

*Figure 2: The Well to Wake energy demand of the EU shipping fleet operating domestically, intra-EU, and Internationally for different years.*

Figure 3 shows the well-to-wake GHG emissions for the EU shipping fleet. Emissions for both the intra-EU and international would rise until 2030 and then begin to decline. However, the emissions for domestic shipping will begin to decline from 2025. This is further supported by the projected increase in biomass and electricity consumption as shown in Figure 2, both of which have a lower climate impact than fossil fuels. With this strategy, progress will be made in reducing GHG emissions from shipping, but more aggressive action will be needed to achieve a net-zero or 80% reduction target by 2050. The findings indicate that fuel production pathways will become increasingly important for reducing carbon emissions in the shipping industry.

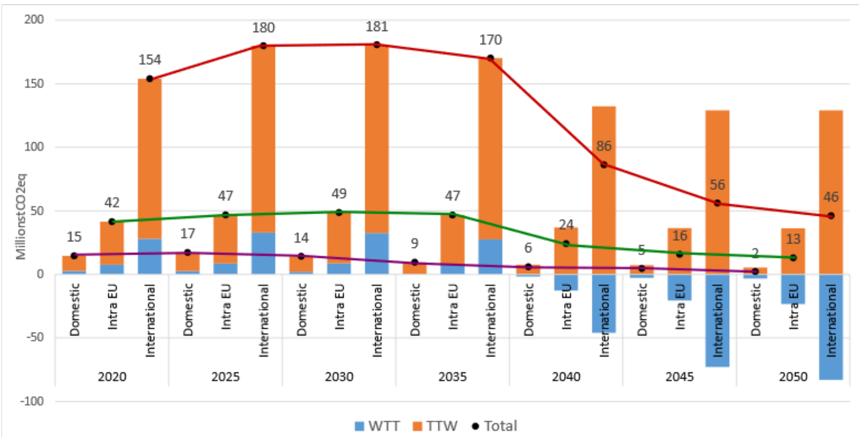

*Figure 3: The Well to Wake GHG emissions of the EU shipping fleet operating domestically, Intra-EU, and Internationally for different years.*

## 4. Conclusions

The model offers insight into the well-to-wake energy demand and the GHG emissions for the EU shipping fleet for time period. Some limitations with this preliminary model include a lack of Integration of the process parameters used both in the integrated energy assessment model and prospective life cycle assessment model, prospective development scenarios considered in both models are not connected, and regional elements are not included. The model needs to be further by linking the process data of the energy system model with the prospective LCA model.

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# Trade-Offs between Technical Parameters, Environmental Impacts and Circular Economy: A Case Study on Using Recycled Fiber-Reinforced Polymer Blends

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## 1. Introduction

Fiber-reinforced polymers (FRP) are high-performance materials used in an increasing amount in various applications. Their reliance on fossil resources and waste treatment present challenges from an environmental point of view. Recycling is promoted according to the Circular Economy (CE) framework to provide secondary materials, create economic value, and reduce adverse effects on the environment [1]. The latter requires verification, e.g. by means of Life Cycle Assessment (LCA). Previous LCA studies show that FRP recycling can provide a potential ecological advantage compared to other treatments at end-of-life (EoL), although this benefit is often depending on the awarding of credits (avoided environmental impacts) for the recycled material substituting virgin or other materials [2]. The latter is not only debatable from an LCA methodological but also from a techno-economical point of view. The reciprocal relationship of technical parameters influencing recyclate usability, concerned methodological choices in LCA, and the connection to the effectiveness of the CE generally are depicted in **Figure 1**.

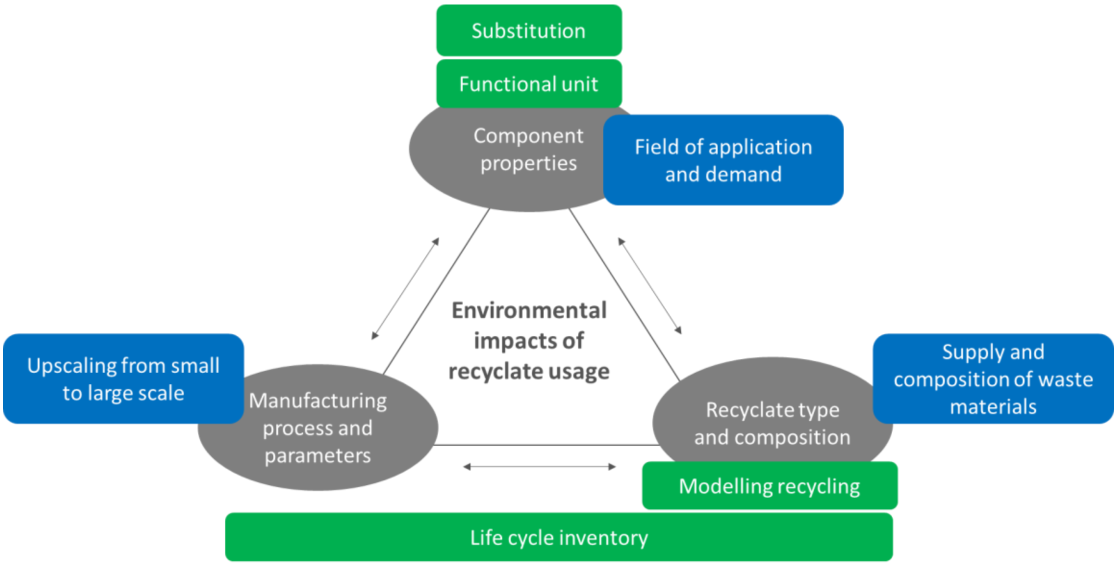

*Figure 1: Schematic overview of the reciprocal relationship of technical parameters influencing recyclate usage (in grey), concerned major methdological choices in LCA (in green) and connection to the effectiveness of the CE generally (in blue).*

As recycling is no end in itself, challenges of using recyclates need to be addressed in order to exploit their resource and environmental potential. Blends of different material composition, e.g. combining virgin and recycling materials orusage of additives and reinforcements, can provide a middle-ground to encounter the challenges of material degradation and inferior material properties. In addition to challenges of recyclate usability, there exist only few LCA studies focusing on the (re-)manufacturing stage of FRP recyclates [3]. Using the case of compounding different blends of virgin and mechanically recycled Polypropylene (PP) with additives and recycled glass fibers (GF), the work at hand aims to

1. Determine the role of blends as pareto-optimal ecological solutions to encounter trade-offs between material composition, processing and component properties,
2. Analyse the processing stage (compounding) in detail including a discussion on options to quantify energy consumption from laboratory experiments and their representativeness for industrial scale, and
3. Reflect on potentials and lessons learned from this case study concerning synergies and trade-offs between environmental impacts and the CE, and their implications on methodological choices in LCA.

## 2. Materials and Methods

A total of 32 compounding trials are performed to test a large variety of material compositions and the influence of processing parameters. The different blends consist of different material compositions of virgin and recycled PP from post-consumer plastic waste in Austria. Additives (such as antioxidants and coupling agents) and recycled GF are varied in terms of mass fraction. Two different types of recycled GF flakes (from unidirectional GF/PP tape and GF/PP organosheet industrial waste), are used to depict a variety of potential waste streams. The different materials are compounded using corotating twin-screw compounder ZSE MAXX (Leistritz Extrusionstechnik GmbH, Germany) with varying rotational speed (150-350 rpm) and throughput rate (6-7.5 kg/h). For the simulated upscaling to industrial production, the throughput rate will be increased up to 60 kg/h.

Environmental impacts are calculated per component (assuming equal functionality) as well as per equivalent tensile strength, and per equivalent Young's modulus. As approaches to model recycling in LCA are not at the center of this research, gate-to-gate system boundaries are chosen including a simple cut-off approach to model the recycled materials, where waste comes burden free from its first life and only carries the environmental impacts of the mechanical recycling itself. The latter is modelled according to literature [4]. No credits for substituting alternative materials are given, as no specific field of application is defined. The actual substitution potential will be discussed as implication on the effectiveness of the CE in general. Life Cycle Inventory (LCI) data are collected from laboratory experiments comprising detailed electric energy measurements and are complemented by ecoinvent 3.9.1 cut-off version data. EF3.1 is chosen as Life Cycle Impact Assessment (LCIA) method and results are calculated using OpenLCA 2.0 software.

## 3. Results and Discussion

The following hypotheses are drafted and will be verified using data and modelling approaches as described above:

- The composition of the blend and the processing parameters have a significant influence on energy demand of the compounding process and on environmental impacts. Environmental impacts of the different blends will vary significantly in regards to the three functional units.
- When upscaling processes, there will be a shift in required type and amount of energy, leading to a total reduction in environmental impacts at higher throughput rates compared to laboratory scale.
- Substitution effects driving the CE depend on the market situation for recycled and substituted materials. The FRP waste generation potential (supply) will be compared to the demand of potential industrial users regarding their volume and material requirements.

## 4. Conclusions

The reciprocal relationship between technical parameters of recycling (including the potential role of blends), the subsequent methodological choices in LCA and the inference on the CE generally studied and discussed in this research is also relevant to other materials and processes. Upscaling from laboratory experiments to large scale production using a well-established process offers insight on realistic effects on the LCI. These considerations and calculations using the throughput rate as a key parameter of optimization can be helpful to other fields of application performing prospective modelling.

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# Cleanliness is relative, laundering absolute – how to facilitate assessments of the rebound effect using LCA

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## 1. Introduction

Technological aids often allow us to trade resources for time. Without the tedious work of cleaning clothes by hand, the washing machine has allowed people to spend more time on increasing household productivity and education [1]. Unfortunately, behaviours are not static. Reduced costs, e.g. time requirements, often lead to increased consumption through rebound effects [2]. For laundering, this seems to be the case; more efficient washing machines prompt higher consumption [3, 4]. Today, people in Europe wash them more frequently than at any other time in history [5]. This extensive consumption also means that the environmental impacts from domestic laundering are higher than at any other time in history. Many initiatives trying to curb consumer behaviour have repeatedly failed [6]. These failures indicate an incomplete understanding of what motivates consumer behaviours and how to incorporate them properly in LCA. This challenge is exaggerated by the lack of consensus on how rebound effects should be included in LCA models [7]. By synthesising the findings from three separate studies, I argue that laundering is mainly socially motivated and that rebound effects stemming from increased consumption must be treated accordingly in the analysis. For this to be possible, contemporary LCA methodology must expand so that behaviours are treated as a systemic component rather than a static value to be optimised. In other words, this work is an interdisciplinary effort that explores how practitioners can integrate behavioural sciences into LCA [8], and whether this changes the analysis.

## 2. Materials and Methods

The proposed thesis is a synthesis of three separate studies highlighting the underlying motivations for laundering and the implications for LCA methodology. The selected studies include:

- A literature study on the common knowledge of motivations for laundering [9].
- An extensive psychological investigation into drivers of laundering frequency in Sweden [10].
- An LCA of domestic laundering that treats behaviours as a systemic component that is socially motivated [11].

## 3. Results and Discussion

The results from the literature review illustrate that individual laundering behaviour is mainly socially motivated. Social norms guide individuals when and how things are to be cleaned, including how cleanliness is defined. Many of these “rules” are often invisible since laundering and cleanliness are seldom discussed outside of the immediate family. Cultural nuances and social norms are important to recognise since they are a strong driver or barrier to laundering behaviours. With respect to LCA methodology, these aspects must be included in the goal and scope of the analysis. The psychological study investigates the most probable emotions that can, directly and indirectly, affect domestic washing frequency in Sweden. The analyses highlight an indirect goal conflict between environmental identity and disgust sensitivity through a set of mediating behaviours.

Taken together, a synthesis of the papers suggests that laundering is a means to an end. Most people wash because the laundry bin is full or because they need a specific item. Contemporary definitions of the function of laundering (i.e. XX kg clean clothes) fail to capture these aspects. This failure is because the functional unit stems from a technical perspective, whereas the function of laundering relates to a social one. In other words, a more appropriate function of laundering would be the function of having access to proper clothes. In order to minimise the risk of these types of logical fallacies, the starting point for LCA of many consumer products and services should shift from a technical system to a social system. See figure 1 for what this might look like for LCA of domestic laundering. This line of reasoning is applied and presented in the third paper, where the rebound effect is not only understood but recognised as an inevitable consequence of, e.g. more energy-efficient washing machines.

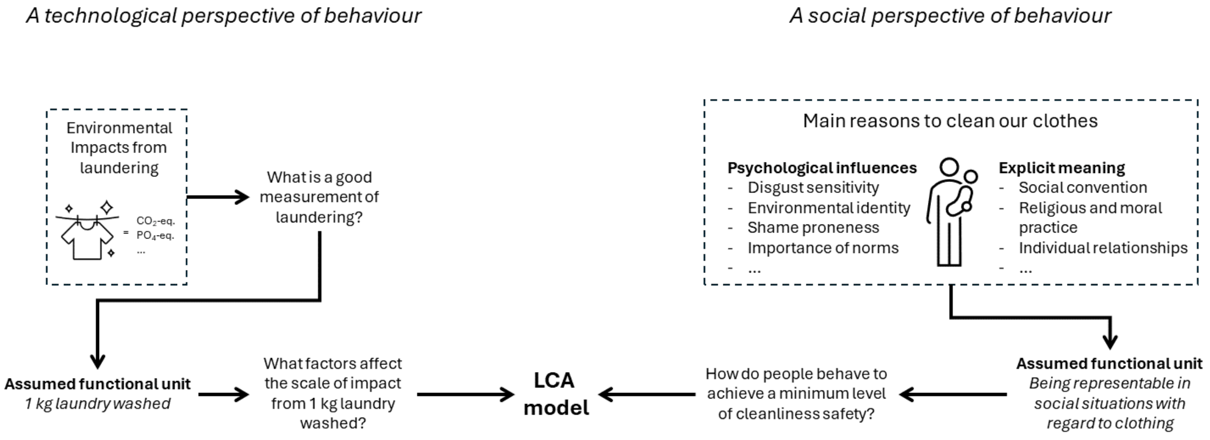

***Figure 1: The two types of analytical line of reasoning for LCA of domestic laundering. The technological or social perspective of behaviour shapes the final LCA model.***

## 4. Conclusions

Understanding human behaviour is crucial when the use phase is the most significant contributor to environmental impacts. Contemporary functional units used in LCAs for domestic laundering tend to be purely technical, i.e., concentrating more on the quantitative outcomes rather than the underlying motivations. The findings presented highlight the need to treat behaviours as a systemic component rather than as a static value. Changing perspectives and integrating insights from behavioural sciences into LCAs allow for a more nuanced assessment of changes in behaviours, such as the rebound effect of domestic laundering. The findings presented in this thesis come from research focusing on domestic laundering. The methodological implications are, however, relevant for all products or services consumed for more reasons than their direct technical capabilities.

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# Sea Use Characterization in LCIA: The case of shellfish farming at Thau Lagoon, France

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## 1. Introduction

Marine and coastal ecosystems encompass a wide range of habitats. Our understanding of those environments is limited [1]. Anthropogenic activities are exerting unprecedented pressures on marine environments [1]. It is crucial to understand the impact of our actions and decisions on the development of marine and coastal areas to achieve sustainable development. Life cycle assessment (LCA) is ideally suited for expanding our knowledge in this area, as it provides a better understanding of the potential impacts of these decisions. However, marine ecosystems are underrepresented in existing LCIA methodologies. The impact category of sea use (SU) is absent from current LCIA methods, which constitutes a major blind spot. This work constitutes a first approach to account for potential impacts of SU on ecosystem quality (EQ) in life cycle impact assessment (LCIA) by calculating characterization factors (CF) in the specific case of shellfish farming in the Thau lagoon (TL).

## 2. Materials and Methods

For consistency purposes, the SU methodological framework builds on the land use model developed by Milà i Canals et al. [3] and to the methodology of de Baan et al. [4] for EQ using species richness (which is integrated in the IMPACT World+ method).

A mechanistic approach is used to calculate the CF for the shellfish farming on TL. With the support of experts in lagoon and coastal ecology, a cause-effect chain was defined to represent the environmental mechanisms induced by SU. Within this chain, we identified the impact pathways already considered elsewhere in LCIA, to focus the present modeling effort on the impact pathways specific to the SU impact category.

For each of those impact pathways, the mechanisms were identified to understand which species functional traits made them potentially vulnerable via that specific impact pathway. A representative list of the species present in the lagoon was drawn. Considering each species' functional traits, the species that could potentially be affected by the different impact pathways were identified.

Based on this information, a potentially affected fraction of species (PAF) due to shellfish farming has been determined, which corresponds to the occupation CF for shellfish farming in TL. For transformation CF, we used data about restoration time from Dajka et al. [5] for impacts due to shading and from Borja et al. [6] for the impact of structures.

## 3. Results and Discussion

### 3.1. Case study results

426 taxa were identified, the majority at species level (337, including the three culture taxa), followed by genus (86) and phylum or order level.

Five impact pathways were taken into consideration: seabed destruction, loss of seagrass beds, impact of new structures presence, shading and increased food supply.

The results show that a large proportion of the organisms present in TL are affected by the installation or the shellfish farming structures themselves (*Fig 1).* Most organisms (61%) suffer impacts related to seabed occupation, i.e. direct loss of seabed space or impacts related to the loss of seagrass beds. Benthic fauna and fish that use the seabed are the most affected. However, due to the use of qualitative data, it is impossible to quantify the intensity of the impact on each organism.

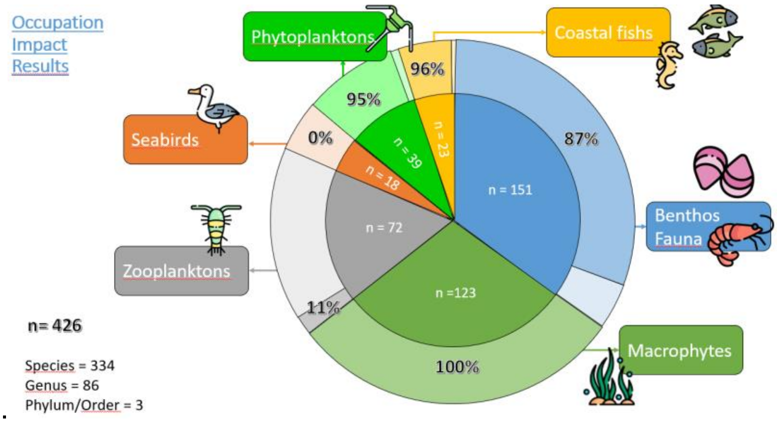

***Figure 1: Proportion of organism potentially affected by the occupation impact due to shellfish farming structure in Thau Lagoon. The darker section represent the impacted fraction.***

The CF for Sea occupation and transformation for the shellfish farming activity at TL are provided in Table 1.

| Impacts | CF | Units |
|---|---|---|
| Occupation | 0.7559 | PAF.m$^2$.an / m$^2$.an |
| Transformation | 2.18 | PAF.m$^2$.an /m$^2$ |

***Table 1: Characterization factors for the sea use category for shellfish farming in Thau Lagoon.***

### 3.2. Discussion PAF and PDF units

This work raise as a side question the relevance of LCIA metrics to exhaustively cover impacts on biodiversity. Depending on the LCIA method, potential impacts on EQ at the damage level are measured using one of various indicators, mainly PDF.m2.an or PDF. Using any of these indicators does not cover the whole range of effects that the specific biodiversity of an ecosystem may experience: many effects can be observed without any (temporary or permanent) disappearance of specie. These approaches need to be challenged. Developing an approach that incorporates indicators in a complementary way with a gradation of effects would paint a more faithful picture. This gradation could be: PAF (all impacts on biodiversity), PDF.m$^2$.year (temporary extinction) and PDF (permanent extinct species).

## 4. Conclusions

These CF lays the groundwork for integrating the Sea Use impact category in Impact World+. The case of shellfish farming in Thau demonstrates the feasibility of the approach and illustrates how it can be operationalized. This research leads to the integration of SU in LCA.

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# Comparative Assessment of Decarbonization Strategies in New Urban High-rise Residential Buildings in cold climatic regions of China based on Consequential Life Cycle Assessment

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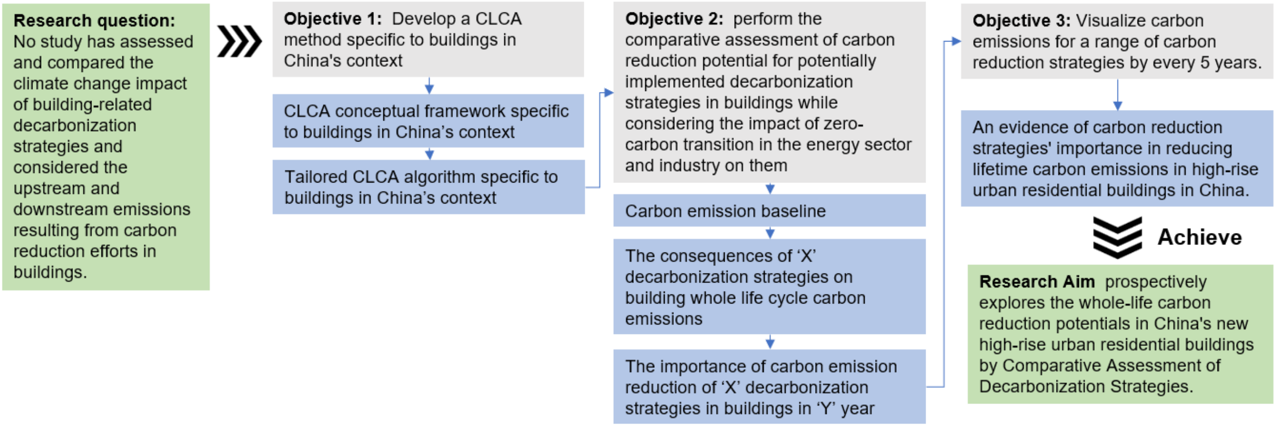
## 1. Introduction

With the progress of the zero-carbon transition in China, the government launched a series of high-level national policies to guide the sectors to achieve the climate target [1]. The sub-departments and local governments developed policies to fit local conditions in agreement with the high-level policies [2]. These policies will dominate the future building market due to the feature of China's Socialist Market Economy and will be the main drivers for change in future buildings [3]. The carbon reduction strategies from those policies are the major guidance for the zero-carbon transition in buildings. However, the lack of evidence regards the long-term effectiveness and cross-sectoral implications of building decarbonization strategies offered by these policies, hinders comprehensive assessment and comparison of their climate change impacts (i.e. GHG emissions).

Tailoring CLCA (Consequential Life Cycle Assessment) to China's context will enable comparative assessment of the performance of technical decarbonisation strategies under future scenarios [4]. This research focuses on the case study of a low/zero residential community in the cold (East/North East) climate zone of China, because this area has high population density, high carbon emissions, and stated urbanization development by the government [5-8]. A community is chosen rather than a single building due to the dominance of District Heating and community-level deployment of PV [9, 10]. The residential buildings considered here are 18-storey multi-residential buildings based on China’s future policies, as these are widely applicable in urban, rural-urban and small city contexts in that area [11, 12]. The decarbonization strategies are selected from Chinese policies from a technical perspective and this study consider whether there are more advanced strategies deployed in the UK and the EU.

## 2. Materials and Methods

The overall aim of this research is to compare the whole-life carbon reduction potentials in China's new high-rise urban residential buildings by Comparative Assessment of Decarbonization Strategies. There are 3 core objectives: 1) to Develop a CLCA method specific to buildings in China's context, 2) to perform the comparative assessment of carbon reduction potential for potentially implemented decarbonization strategies in buildings while considering the impact of zero-carbon transition in the energy sector on them, and 3) Visualise carbon emissions over 5 year periods for a range of carbon reduction strategies (Figure 1).



**Research question:** No study has assessed and compared the climate change impact of building-related decarbonization strategies and considered the upstream and downstream emissions resulting from carbon reduction efforts in buildings.

**Objective 1:** Develop a CLCA method specific to buildings in China's context

CLCA conceptual framework specific to buildings in China’s context

Tailored CLCA algorithm specific to buildings in China’s context

**Objective 2:** perform the comparative assessment of carbon reduction potential for potentially implemented decarbonization strategies in buildings while considering the impact of zero-carbon transition in the energy sector and industry on them

Carbon emission baseline

The consequences of ‘X’ decarbonization strategies on building whole life cycle carbon emissions

The importance of carbon emission reduction of ‘X’ decarbonization strategies in buildings in ‘Y’ year

**Objective 3:** Visualize carbon emissions for a range of carbon reduction strategies by every 5 years.

An evidence of carbon reduction strategies' importance in reducing lifetime carbon emissions in high-rise urban residential buildings in China.

**Research Aim** prospectively explores the whole-life carbon reduction potentials in China's new high-rise urban residential buildings by Comparative Assessment of Decarbonization Strategies.

*Figure 1: schematic representation of research process.*

This research defines a case study high-rise residential building community which implements the newest policies and norms in the building sector. The energy consumption data and material consumption data are

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analysed using Designbuilder and Revit in order to calculate the carbon emissions baseline. Then, future building scenarios are established as the comparative assessment objects, according to the decarbonization strategies. The CLCA is tailored for this research in China's context, in which the Socialist Market Economy dominates the changes in the market constraints, substitutions of products, and affected technologies. The consequential modelling is conducted in line with the socialist market economy, to calculate each scenario's whole life cycle carbon emissions of buildings. In the end, the consequential modelling assesses the climate change impact for each scenario and calculates the carbon reduction potential.

## 3. Results and Discussion

This research is ongoing, and the result is expected by the end of July. The expected results will prospectively explore the whole-life carbon reduction potentials in China's new high-rise urban residential buildings by Comparative Assessment of Decarbonization Strategies in buildings based on CLCA within a chosen temporal window (up to 2060). The result will expose the carbon reduction potential of selected decarbonization strategies in new buildings in 5-year time periods between 2025 and 2060, where the influence of the decarbonization process of the energy sector and industry on those strategies is considered. This will provide evidence for the most important carbon reduction strategies to be addressed in future policy in the appropriate timeframes, to further reduce lifetime carbon emissions in new urban high-rise residential buildings in Cold climatic regions of China. Visualisation of the result over a series of 5-year periods could help inform policymakers on appropriate actions to significantly reduce carbon emissions of new urban residential buildings in the long term.

## 4. Conclusions

The expected contribution of this research is to support the compilation of long-term zero-carbon transition policies in residential buildings in China for responding to international commitments to tackle climate change.

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# Prospective LCA of three German Transformation Scenarios Achieving Climate Neutrality by 2050

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## 1. Introduction

Climate change and its impacts are one of the greatest global challenges of our time. Ambitious and comprehensive measures are therefore needed to limit global warming. In the Paris Agreement of 2015, the parties to the United Nations Framework Convention on Climate Change agreed on a common approach to keep global warming well below 2°C compared to pre-industrial levels. The goal is clear, but how to achieve it is a matter of public debate – in Germany and around the world. Various research projects (e.g. [1], [2]) have developed detailed transformation scenarios that achieve the goal of climate-neutrality for Germany. The question is whether these transitions are associated with side effects that could be avoided?

On behalf of the German Federal Environment Agency, the REFINE [3] project is investigating the environmental impacts of the transition to a climate-neutral and resource-efficient society. Switching to renewable energy leads to significant savings in greenhouse gases and other combustion-related emissions. At the same time, it will require significant infrastructure change and expansion. REFINE is investigating potential environmental side-effects. How will the demand for raw materials in Germany change? What is the relationship between the greenhouse gas emissions saved domestically and those caused abroad by the German energy transition? These questions are addressed by a newly developed prospective life cycle assessment (pLCA) model.

## 2. Materials and Methods

In collaboration with the ecoinvent association, a prospective LCA model has been developed that depicts three transformation scenarios for the years 2020 to 2050 in ten-year intervals. Two scenarios, designated 'GreenSupreme' and 'GreenLate', originate from the RESCUE research project [1] and are designed to achieve greenhouse gas neutrality in Germany by 2050. GreenSupreme entails an ambitious and accelerated transformation of the energy system, characterised by the rapid phase-out of fossil fuels and enhanced material and energy efficiency. In contrast, GreenLate entails a delayed transformation, accompanied by a reduction in efficiency increases and modernisations, as well as a higher demand for imported synthetic fuels. The third scenario, 'Hydrogen' ($H_2$), which was derived from the research project 'Long-term scenarios' [2], lies between the two others in terms of ambition level and relies more heavily on the use of green hydrogen in the transformation.

The data basis for the development was ecoinvent v3.7.1 [4], which comprises over 18,000 activities. To adapt the ecoinvent database to the scenarios, approximately 3,000 datasets and 70,000 parameters per scenario and year were modified or added. Particular attention was paid to renewable electricity generation plants, synthetic fuel production technologies, heat pumps, energy storage and alternative drive systems. In addition, recycling rates, electricity mixes and heat generation were changed throughout the database, new industrial processes (e.g. Direct reduced iron (DRI) and Celitement binder) were introduced and efficiency developments were incorporated. The integration and customisation process was subjected to a series of compatibility tests and plausibility checks. This validation process resulted in a total of 57 iterations.

The final 12 pLCA databases (one per scenario and year) were transferred to an overall model in Brightway [5]. A separate database was created in Brightway to map the age structure of plants that are of key importance for the generation of renewable electricity, namely photovoltaics, wind energy and concentrated solar power. This enables the calculation of environmental impacts in the reference years, which takes into account the specific production situation in the different years of construction of the installed plants. The final energy requirements, differentiated according to energy carriers and consumption sectors, are included in Brightway as further exogenous variables. These result from the energy system modelling of the research projects on the transformation scenarios. In Brightway, they are used as reference flows for the LCA calculations. The final energy demand in Germany thus represents the functional unit for the LCA comparison of the three energy transition scenarios that achieve climate neutrality by 2050.

The original ecoinvent database allows the assessment of a comprehensive set of environmental impacts and indicators according to different characterisation and impact models developed for LCA. These are all available in Brightway-based pLCA model. For this study, environmental impact indicators were selected that represent impacts at the midpoint level and show noteworthy developments of the transformation scenarios. In addition, indicators for the use of energy, freshwater, land use and raw material resources were included. A more detailed description of the pLCA model can be found in REFINE [3] and in the ifeu paper LCAst [6].

## 3. Results and Discussion

The key findings of REFINE are: In the scenarios analysed, national greenhouse gas emissions decrease by 96-99% by 2050, while the underlying final energy demand in Germany only decreases by 20-47% in this period. Although the global production and energy system will be fully defossilised by 2050, greenhouse gases (GHG) will still be emitted (at a low level). The remaining sources of GHG include emissions of refrigerants from heat pumps, sulphur hexafluoride ($SF_6$) from switchgear and substations, nitrous oxide ($N_2O$), especially from the high-voltage transmission of electricity, and methane ($CH_4$), mainly from biogas and synthetic natural gas. While GHG emissions in Germany are reduced by 98-99%, the reduction abroad is at least 84%. In absolute terms, the German energy transition does not result in a shift of GHG emissions abroad; however, the proportion of foreign emissions increases.For the ambitious GreenSupreme scenario, the other environmental impacts and resource requirements also decrease, albeit not as much as the global warming potential. For the GreenLate and $H_2$ scenarios, the impacts in some categories fall less substantially than in GreenSupreme. Land use and cumulative energy demand in GreenLate are even back to the 2020 level in 2050 due to the production of electricity-based synthetic fuels.

The demand of metal raw materials to meet German final energy needs increases sharply in all scenarios: in GreenSupreme by 22%, in GreenLate by 259% and in $H_2$ by 92%. The additional demand for electricity, including for synthetic fuels, is responsible for the increase in demand for metal raw materials. Renewable power generation plants (mainly photovoltaics and wind energy) require large quantities of copper, iron, nickel, gold and aluminium raw materials. This emphasises the need to use raw materials efficiently and to close material cycles at an early stage.

## 4. Conclusions

In collaboration with ecoinvent, a comprehensive pLCA model was developed in REFINE that maps global development for three transformation scenarios. This enables the estimation of possible environmental benefits and side-effects for the final energy demand in Germany depending on the scenarios. Detailed analyses and sensitivities were carried out in Brightway to interpret the results and parameters.

The following research needs and planned further development of the pLCA model include a transfer to premise and the current ecoinvent version, updating and expansion of the adaptation, modelling of aditional (international) transformation scenarios, as well as cooperation with other research groups and development of pLCA reference databases.

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# Leveraging on Digital Data Platform for Data Collection to Underpin Meaningful LCA

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## 1. Introduction

Life Cycle Assessment (LCA) is a methodology used for evaluating environmental impacts. It is valued for its holistic perspective, providing an easily understandable view of a product's entire life cycle, encompassing hundreds of processes, resource usage, and emissions across various locations and timelines [1]. LCA involves compiling the inputs and outputs and evaluating the potential environmental impacts of a product or service throughout its life cycle, from raw material extraction to disposal. Defined by the International Organization for Standardization (ISO) 14040 and ISO 14044, these standards establish methodological frameworks for different LCA applications. The LCA process is typically divided into four main categories: i) goal and scope definition; ii) inventory analysis; iii) impact assessment; and iv) interpretation [2,3].

In order to achieve meaningful results in LCA, a substantial amount of high-quality data must typically be collected in a decentralized and collaborative manner, particularly during the LCI phase. However, the time and effort required for data collection, as well as the creation of customized templates, are often considerable, making the LCI phase highly time-consuming [4, 5]. These limitations make it impractical to collect all data of the highest quality for every process under assessment, due to the associated costs and efforts required [6]. For example, Finnveden et al. [7] highlight the critical importance of the availability and completeness of high-quality LCI data for meaningful LCA studies, identifying it as one of the most significant limitations.

While these challenges are widely recognized in data collection for well-established products or services available in the market, it's important to acknowledge the significance of LCA in products undergoing the development and testing of various technical and functional solutions before becoming established. Early-stage assessment is crucial to determine if new products, such as the development of gellified cells for lithium-ion batteries (LiBs), are trending towards reducing environmental impacts compared to current state-of-the-art solutions. To conduct such LCAs effectively, with high-quality and reliable data must be collected in a decentralized manner from multiple entities, building upon the LCI limitations mentioned earlier.

This abstract aims to introduce SUNDIAL - Digital Data Platform (DDP) and explore how its features can help overcome the primary limitation of obtaining high-quality and meaningful LCA results, thereby facilitating more informed sustainable decisions, particularly in the development of novel LiBs technologies.

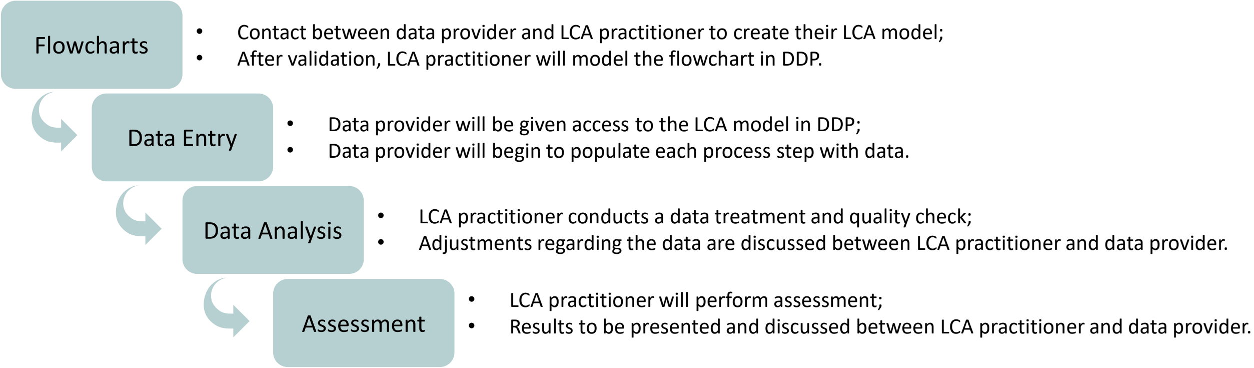
## 2. Materials and methods

As previously noted, the LCI phase is recognized among LCA practitioners as complex and time-consuming, significantly influencing the quality and meaningfulness of LCA results. In light of these challenges, the authors propose utilizing SUNDIAL - DDP to facilitate collaborative LCA data collection. The DDP is specifically designed to support the LCI phase by enabling: a) Management of confidential data; b) Development of visual flowcharts/models; c) Controlled multi-stakeholder access; d) LCI compliance with ISO standards; and e) Easy data validation.

Figure 1, illustrates the sequence of events for developing the LCI using the DDP, outlining the roles of the LCA practitioner and data provider at each step.

The developed DDP is a sector- and product-agnostic platform designed to collect data for environmental, social, and cost analysis and develop data models. This platform facilitates the creation of a reference system in a tree-like structure (flowcharts), simplifying the management and storage of all data for any case study and historical mapping. Data is inputted into previously constructed flowcharts containing all relevant processes for a specific system and scope, with the ability to add respective inputs and outputs for each process. The data inserted pertains to mass and energy flows occurring in the specific study case.

Leveraging a DDP for LCI purposes offers several benefits. It streamlines data collection for each process flow by providing a centralized and confidential repository where stakeholders can input and access relevant information. This approach enhances collaboration by allowing multiple parties involved in the life cycle of a product or service to contribute the right data and insights. Overall, utilizing the DDP for decentralized data collection for underdeveloped technology is proving to be a promising approach to enhancing the effectiveness and transparency of environmental assessments, particularly in LiBs development.



- Contact between data provider and LCA practitioner to create their LCA model;
- After validation, LCA practitioner will model the flowchart in DDP.

- Data provider will be given access to the LCA model in DDP;
- Data provider will begin to populate each process step with data.

- LCA practitioner conducts a data treatment and quality check;
- Adjustments regarding the data are discussed between LCA practitioner and data provider.

- LCA practitioner will perform assessment;
- Results to be presented and discussed between LCA practitioner and data provider.

***Figure 1 – Approach followed for data collection using DDP.***

## 3. Conclusions

In conclusion, the adoption of a DDP for decentralized and multi-stakeholder LCIs significantly reduces the effort required to develop robust data models, thereby enhancing the reliability of LCA results. This platform plays a pivotal role in gathering data for complex products in early development stages by providing easy deployment and enabling data collection from numerous stakeholders and data providers. As a result, the use of a DDP not only streamlines data collection processes but also ensures the generation of more accurate and dependable LCA outcomes for any product.

This DDP serves as a pivotal tool for automating certain aspects of data collection, leading to enhanced efficiency and accuracy. Such a forward-thinking approach is in alignment with the growing imperative to adopt sustainable perspectives during product development, a reality largely propelled by today's capabilities in data acquisition and processing.

Moreover, recent technological advancements have made it feasible to store and leverage vast volumes of data, whether structured or unstructured. Techniques rooted in Artificial Intelligence, Data Mining, and Machine Learning have emerged, enabling the extraction of profound insights through algorithms and statistical models. This, in turn, empowers the use of AI to bridge data gaps in LCI databases.

By harnessing these emerging tools and techniques, numerous workflow processes can be expedited, reducing reliance on human analysis and interpretation. Ultimately, this integration of technology accelerates progress in sustainability initiatives across product development landscapes.

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# A food biodiversity database – Meal Service Company Case Study

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## 1. Introduction

The link between climate impact and food production is well established. The connection between food and other environmental impacts is less explored, especially biodiversity impacts (Tripathi et al., 2022). To fill this gap, RISE has developed a database which features the biodiversity footprint of food items. The focus is on products consumed in Sweden, which includes food produced in Sweden but also imported food, ingredients and feed. The Biodiversity database is open access and was released in 2023 (Figure 1).

The database can be used for comparisons between e.g. meat and vegetarian options, different meals and diets, production systems and/or countries of origin, as well as to identify synergies and trade-offs with other sustainability aspects, for decision making within companies, for setting and following up on biodiversity targets, B2B information and for consumer information.

Foodcat 1: Beverage (not milk)
Foodcat 2: Juice and nectar
Foodcat 3: Flera val
Country: Flera val
Method of production: CONVENTIONAL
Language: ● English ○ Swedish

| Selected countries | Selected products |
|---|---|
| Brazil \| China \| Italy \| South Africa \| Spain | Juice, apple ready-to-drink \| Juice, orange/citrus fruit |

| Product | Country | Production method | fPDF/kg |
|---|---|---|---:|
| Juice, apple ready-to-drink | Brazil | CONVENTIONAL | 117 |
| Juice, orange/citrus fruit | Brazil | CONVENTIONAL | 182 |
| Juice, apple ready-to-drink | China | CONVENTIONAL | 51 |
| Juice, orange/citrus fruit | China | CONVENTIONAL | 83 |

***Figure 1. Screen dump of RISE food biodiversity database. Can be accessed via https://www.biodiversitetsdatabasen.se/***

To evaluate the applicability of the database, connection to reality is needed, which the meal service company Compass Group AB represents. This paper will present findings from the case study with the company.

## 2. Materials and Methods

There are several methods to assess the biodiversity impact of food production and consumption that can be implemented within existing LCA-frameworks, on midpoint or endpoint level (Damiani et al., 2023). Midpoint impact assessments are often based on the land use (area and intensity) in combination with parameters linked to orgin of production. In our database we use the midpoint method described in Chaudhary & Brooks (2018), which is recommended by the UNEP-SETAC Life Cycle Initiative. We intend to examine how to complement the database with other drivers than land use, as well as how to include seafood. The database was applied on a selection of Compass Group's procurement of food. Biodiversity footprints were calculated for each food item, the results were analyzed, identifying hotspots and tracking back to background data to find explanations.

## 3. Results and Discussion

### 3.1. Biodiversity impact from procurement

The impacts from Compass group's procurement for one year will be presented, including high/low-impact commodities and the influence of country of origin (see Table 1 for a preview).

***Table 1: Example of biodiversity impact from food items***

| | Food item | Country of production | Biodiversity impact fPDF/kg | Annual biodiversity impact fPDF |
|---|---|---|---:|---:|
| **High negative impact** | Coffee | Brazil | 109 600 | 54 800 000 |
| | Lamb meat (with bone) | New Zeeland | 54 600 | 35 490 000 |
| **Low negative impact** | Potatoes | Germany | 8 | 3 000 000 |
| | Tomatoes | Spain | 30 | 1 350 000 |

| | | | | |
|---|---|---|---|---|
| **Positive impact** | Lamb meat (with bone) | Sweden | - 470 | -305 500 |

### 3.2. Challenges

The most time consuming task was to assign the food items the correct biodiversity footprint, which is based on the food item, its country of origin and production method. Several challenges arose, linked to data structure, lack of information on the procured food items, or lack of production data on the food items.

Regarding data structure, most of the procurement data was aligned with the Swedish food agency identification numbers, however for some food items this was not available which entailed that parts of the impact from the procurement was calculated manually or excluded.

Lack of information on the procurement data can be explained by lack of traceability in the value chain, which means that the country of origin is not always known. For some food items there are several countries specified but with a distribution or region specified, such as “within EU”. For products consisting of several food items, the country of origin is often only specified for the end product but not for its ingredient. Furthermore, for end products that consists of several ingredients, there is a large lack of information on what shares the ingredients has.

The main problem with production data is the lack of yields for crop/country-combinations, such as for spices, but there is also a shortage of data on animal forage and amount of pasture, as well as data on produced byproducts. There is also lack of yield data on specific production systems such as organic production, as well as data on for example by-products from crops.

## 4. Conclusions

Although there is a need for continued development, there is now a first case study performed with the first version of the Biodiversity database. The database enables inclusion of an additional impact category which we expect to be of valuable use for decision making and target-setting in e.g. retail, wholesale, restaurants, public kitchens, and the food production industry. Future case studies can include applying the database in the support of procurement and procurement decisions, and using the data in communicating meals with guests, and by doing so to further evaluate how applicable the database is and how it can support procurement and strategically planning of meals.

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# Energy-efficiency and environmental performance of lithium-ion batteries as an energy carrier for container ships

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## 1. Introduction

The successive use of fossil fuel (FF) and its associated hazardous impacts on the environment and human health has been gradually raising awareness for sectoral transitioning in the maritime shipping industry (MSI) towards implementing the use of greener energy systems to facilitate sectoral decarbonization. Scholars have shown that complete ship electrification could become one of the most promising substitutes for conventional FF-powered mechanical propulsion (MP) since electric propulsion is connected to grid facilities for energy consumption and does not release harmful emissions [1]. So far, extensive research has been conducted on developing technically feasible and high-performance battery propulsion technologies for marine vessels. Among these batteries, lithium-ion batteries (LiBs) showed satisfactory results regarding energy conversion potential and energy storage capacity due to their higher volumetric energy density, longevity, and safe handling [2]. However, most of the market available LiBs show different physicochemical characteristics due to their variance in chemical composition, which affects the performance and lifespan [1, 2]. As a result, it is necessary to carry out a comprehensive evaluation of energy efficiency and environmental impact assessment of LiBs to understand the pros and cons of these battery technologies before selecting them as energy carriers for vessel electrification. Hence, this research attempts to evaluate the possible application of different LiBs as a prominent energy carrier for container ships by analysing the energy efficiency and environmental performance of the selected battery technologies based on real-time voyaging information. Besides, the secondary objectives include identifying the potential environmental hotspots affecting the ecological footprint within the system and suggesting possible recommendations based on secondary literature for technical improvement.

## 2. Materials and Methods

The methodological approach of this research follows a ‘case study’ approach to investigating the applicability of LiBs for container ships sailing across the Subarctic region since this region is demographically one of the most crucial shipping routes for maritime trading and acknowledged as the ‘Polar silk road’ for MSI [3]. A medium-sized container sailing across the North Atlantic Ocean was selected as a case ship because it represents about 43% of the global fleets [4]. It carries approximately 4460 tons of packed cargo from Iceland to Canada and the United States of America by completing 15 trips per annum using heavy fuel oil (HFO) as a primary energy source. Its designed speed is 19 knots, and the designed power of its main engine is 9000 kWh at 500 rpm [5]. However, the operational speed and engine power varies due to operational scheduling, weathering conditions, and hauling effects [1]. Considering these aspects, the average energy consumption for a round trip was calculated for two different LiBs propulsion systems (e.g., Lithium Nickel Manganese Cobalt oxide (NMC) and Lithium Phosphate Iron (LFP)) and HFO-powered MP following the numeric model suggested by Guven and Kayalica (2023) [2]. Besides, the operational proficiency and energy efficiency of these battery propulsion technologies over MP were analyzed by MATPOWER (v. 8.0) software while considering the developed voyaging interface by Seamatrix (v. 2.5.0.0) software using the annual reports provided by the port authorities under certain assumptions. Finally, the environmental performance of each case scenario was analyzed by the life cycle assessment (LCA) method following a bottom-up integrated system approach. The embodied energy consumption and associated emissions of the case scenarios were evaluated by ReCiPe 2016 midpoint (H) methods upon developing their ‘well-to-wake’ life cycle inventory models by SimaPro software (v. 9.2) using Ecoinvent (v. 3.8) inventory database based on global marine traffic data for 20 years lifespan [5].

## 3. Results and Discussion

The analyzed results of the voyage-based energy consumption and battery capacity for each case scenario have been presented in a tabular form (Table 1) based on the input parameters provided in different simulation software. Besides, the relative environmental performance of different marine power systems obtained from comparative LCA was categorized as various emissions such as life cycle $CO_2$, $NO_x$, and $SO_x$

that were divided into three different stages of the life cycle e.g., well-to-tank (WTT), tank-to-propeller (TTP), and propeller-to-wake (PTW).

| Parameters | NMC battery | LFP battery | HFO |
|---|---|---|---|
| Energy consumption per distance (kWh/nm) | 56.85 | 65.83 | 77.12 |
| Battery capacity (kWh) | 9204 | 9875 | N/A |
| Energy efficiency (%) | 89.80 | 93.63 | 75.82 |

***Table 1: Operational performance of the case scenarios***

The LCA results showed that LiBs can become a suitable environmentally friendly energy carrier for marine vessels to reduce associated adverse environmental impacts by replacing HFO-powered MP. It was observed that using LiBs in container ships for energy supply can lower CO2 emissions by 53% followed by reducing 97% of NOx emissions and 72% of SOx emissions compared to HFO combustion. Perčić et al. (2023) found similar results for using lithium-ion batteries in ro-ro passenger ships sailing across the Croatian coastal shipping zone [1]. Though the results were satisfactory, the reduction of SOx emissions was found relatively lower. In this case, the electricity mix in the Subarctic regions plays a potential factor since fossil fuels constitute a considerable share (54%) followed by hydropower (44%), and wind energy (2%) [6]. However, the application of solar and tidal wave powers is showing emerging aspects to contribute to the regional energy grid, which will eventually reduce the share of FF in the electricity mix. As a result, a higher share of electricity produced from renewable energy resources would completely decrease the emissions in the future [1]. Among the batteries, the LFP battery showed superior energy efficiency and emission reduction compared to the NMC battery because of its higher current conversion capability and prolonged life cycle despite the NMC batteries offering higher energy density and energy storage capacity. Similar results were observed in the study of Guven and Kayalica (2023) [2] on the LCA and LCC of LiBs for passenger ferries conducted for the Bosphorus strait in Turkey. Additionally, the LCA results indicated that battery production accounts for a higher contribution to carbon and SOx emissions, which is relatively higher than the associated emissions in the operational phase or tank-to-propeller stage of HFO consumption. In this context, material extraction from subsequent mining of lithium, minerals, and other metalloids simultaneously contributes to a higher environmental impact. Therefore, including various optimizing technologies such as near-infrared and layer-drying methods will reduce material requirement and material loss during battery production and gradually reduce inline production emissions. Conversely, battery disposal also contributes to a higher contribution to the total footprint and embodied energy consumption, which can be eventually minimized by battery recycling.

## 4. Conclusions

The energy and environmental analysis of LiBs revealed that these battery technologies are the most promising decarbonization approaches for MSI operating in the Subarctic region, and can be considered as a feasible cleaner energy carrier for short sea navigation. However, this study has certain limitations since the results were focused only on the associated emissions and energy consumption for an onboard vessel and limited to the operational stages. Additionally, energy and environmental performance were the main factors to highlight in this study rather than identifying the economic flexibility of device installation and maintenance. Further studies on life cycle costing are encouraged for a detailed analysis of the technical feasibility and financial viability of such technologies, which will emerge pathways for complete ship electrification for longer shipping routes while demonstrating decarbonization for maritime operations.

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# Leveraging digital product passports for automated environmental impact assessment using an information system

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## 1. Introduction

RE-strategies (e.g. recycle, reuse, repurpose) play a vital role in the European Commission's aim of decreasing the use of primary raw materials in value chains. For the effective implementation of RE-strategies, information sharing along the value chain is critical. This is uniquely enabled by digital product passports (DPPs) introduced in the Eco-design for sustainable products regulation.

In this context, the Horizon Europe project CE-RISE aims to develop an information system that makes use of DPP data in order to enable the implementation of circular economy strategies for electronics and renewable energy products. As product environmental impact information is a crucial component needed for the identification of optimal RE-strategy and therefore for RE-strategy implementation, the CE-RISE information system will include an automatic environmental impact calculation procedure based on data included in DPPs.

In this work, we present a prototype of this environmental impact calculation procedure, which allows to calculate environmental impacts from life cycle inventory (LCI) information stored as individual data points in a DPP system, making use of a hybrid life cycle assessment (LCA) framework. We illustrate this functionality by applying it to a case study of PV panel production, using artificially created DPP data (i.e. three scenarios in Table 1). Within this, different options for modelling RE-strategies have been applied – i.e. the cut-off approach, the 50/50 method, and the circular footprint formula [1]. We present preliminary results and discuss identified open problems with this approach and their possible solutions.

## 2. Materials and Methods

### 2.1. System Assumptions

We operate under the assumption that the DPP system includes the required process information, e.g. bill of materials and energy use, including their direct impacts, but not necessarily in a consistent format. We treat different cases, which vary in the amount of value chain actors included in the DPP system.

### 2.2. Outline of impact calculation process

The general envisioned process for calculating environmental impacts from LCIs stored in different product DPPs involves a number of steps, as shown in Figure 1:

- **DPP collection.** Given a product under study, the system needs to collect the DPPs for the value chain of this product, insofar as these are included in the DPP network (e.g. given the product under study is a PV panel, the DPPs for PV cells and silicon wafers need to be included).
- **Foreground/background separation.** Given the data points in the collected DPPs, the system needs to differentiate between interlinked processes (e.g. a PV panel requires PV cells, and the production of PV cells is included as a DPP) and background processes (e.g. the production of a PV panel requires electricity, which is not included as a DPP process).
- **Connecting to the background dataset**. The identified background processes need to be connected to the background dataset (e.g. the electricity required in LCI databse needs to be connected to the "domestic electricity mix" category in the background dataset dataset). These may be named differently, requiring context-based category matching.

- **Life Cycle Impact Assessment**: Given the obtained full product LCIs and the related direct environmental impacts, the life cycle impacts need to be calculated.

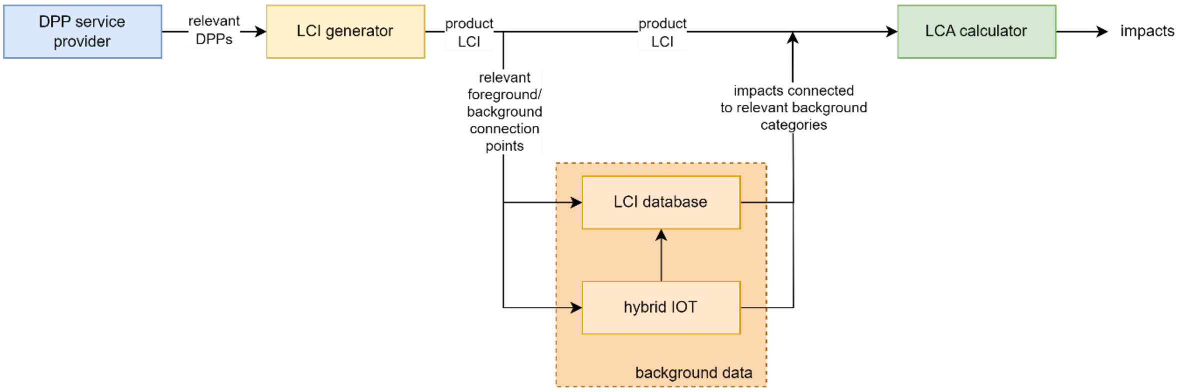

*Figure 1: Environmental impact calculation framework diagram.*

## 2.3. Outline of illustrative case study

We illustrate our envisioned process by performing an environmental impact assessment on a single-crystalline silicon PV panel. Using LCIs collected as part of IEA PVPS Task 12 [2], we firstly create hypothetical DPPs in a format aligning with that of a DPP provider. We secondly illustrate all steps of the process outlined in Section 2.2 using this data and using as background dataset the hybrid version of EXIOBASE 3 [3].

We will perform the impact assessment under the cut-off approach, the 50/50 method and the Circular Footprint Formula [1] for the RE-strategy of recycling.

## 3. Results and DiscussionResults of case study

Preliminary results indicate that the level of detail in the DPP and the availability of LCI data directly affect the uncertainty of the results. A detailed DPP and good LCI data lead to low uncertainty, whereas a lack of detailed information and reliance on background databases like EXIOBASE 3 increases uncertainty.

***Table 1: Environmental impacts (represented by $CO_2$ emissions) per $m^2$ of PV production based on three different scenarios.***

| **Scenarios** | Detailed DPP and good availability of LCI | Less detailed DPP and poor availability of LCI | No info in the DPP, background LCI is linked to EXIOBASE 3 |
|---|---|---|---|
| **Result uncertainty** | Low | Median | High |
| **$CO_2$ emissions (tonne)** | 0.563 | 0.299 | 0.334 |

## 3.2. Discussion

- **Extensive data requirements.**

To enable calculations of environmental impacts, and furthermore, social and economic impacts, the relevant process information needs to be supplied to the DPPs by the producers of both the products under study, their components and materials, and their end-of-life treatment by the recyclers. This requires extensive data collection and extensive data storage capabilities. While the ability to show the impact of an applied RE-strategy might be enough incentive for this for producers, this may not be the case further down or up the value chain. As such, the information system should in some way be able to compensate for limited data availability. For individual products, this may be solved by including extra, openly available, LCI information in the system itself.

- **Background data resolution requirements**.

Accurate calculation of environmental impacts through the hybrid LCA method requires a highly disaggregated background table. Our results show that the resolution of our background table is at the moment not sufficient. Current efforts in the CE-RISE project aim to increase the resolution of our background table for the relevant product components to lower the uncertainty level, but to be of use for a more varied collection of products, different background datasets are needed. In the development of this method, we have ensured that it is background database agnostic, so that different background databases can be used if they include more specific information.

## 4. Conclusions

The CE-RISE project aims to support circular economy strategies for electronics and renewable energy products by using DPPs to facilitate information sharing along value chains. We are developing an automatic environmental impact calculator that uses LCI data from DPPs, as demonstrated in a case study on PV panels. Detailed DPPs with comprehensive LCI data significantly reduce result uncertainty and lower $CO_2$ emissions, while less detailed DPPs and reliance on background databases like EXIOBASE 3 increase uncertainty and emissions. Challenges include extensive data requirements and the need for high-resolution background data, which the project addresses by integrating additional LCI information and ensuring adaptability to various databases.

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# CCU fuels – how circular thinking and climate reductions collide

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## 1. Introduction

Circularity is a means for achieving a more sustainable society. Circularity is, however, not a goal in itself. When using circularity indicators, it is important to distinguish between indicators measuring the degree and the effect of circularity, respectively, of which LCA is a tool for the latter [1]. When discussing CCU fuels, this is often forgotten. One argues that recycling the carbon in $CO_2$ into fuels is part of a circular economy, implying that this is the wise thing to do.

In this presentation the authors will show how this simplification masks the fact that transforming $CO_2$ into fuels are highly energy intensive, and that this energy should instead be used for other purposes. To show the effect of recycling carbon this way, indicators for climate change and use of primary energy resources have been used in an LCA study.

## 2. Materials and Methods

Recommended methodology for LCA of CCS and CCU systems have been used [2-4]; this being connected to system boundaries, the use of system expansion to solve multifunctionality, a joint functional unit, and the inclusion of reference systems. A -1/+1 methodology is used for biogenic $CO_2$, meaning that uptake of $CO_2$ in biogenic matter is modelled as a negative emission and that release of biogenic $CO_2$ is treated the same way as emissions of fossil $CO_2$. Detailed LCA results have been calculated for methanol produced from $CO_2$ compared with methanol produced the conventional way. Three scenarios are compared: a CCU scenario, a CCS scenario, and a scenario without capture of $CO_2$ (reference). All scenarios deliver the same function to society (methanol) and are provided with the same amount of renewable electricity (wind power). Electricity based on natural gas is used as substituted electricity in the CCS and reference scenarios. The Norske Skog Saugbrugs paper mill in Norway is used as case, having a 99.3% biogenic share of $CO_2$ in the flue gas [5, 6]. Amine capture and a capture rate of 90% is assumed.

The functional unit (FU) is defined as: point source emissions from steam production, with or without capture of 1 tonne of $CO_2$; production of fuel corresponding to the captured amount of $CO_2$; and use of renewable electricity corresponding to the produced fuel from $CO_2$, for internal purposes or for substitution.

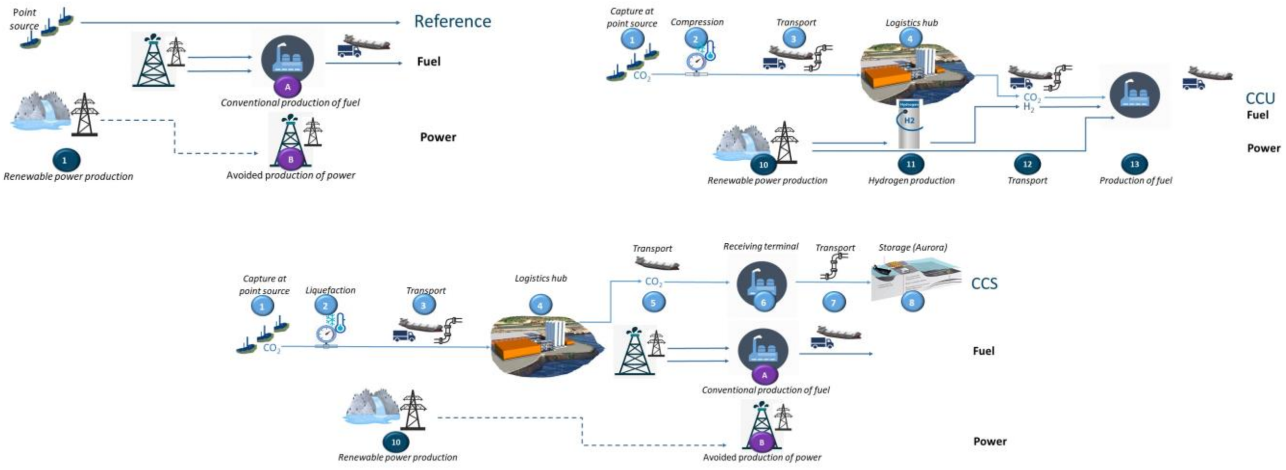

*Figure 1: Flowsheets showing the system boundaries for the compared scenarios.*

## 3. Results and Discussion

The results for climate change and use of primary energy throughout each value chain are shown in figure 2. These show that the CCU scenario has the worst performance for both indicators. This is mainly caused by the large use of renewable electricity, for which the CCS and reference scenarios are given a credit (avoided burdens).

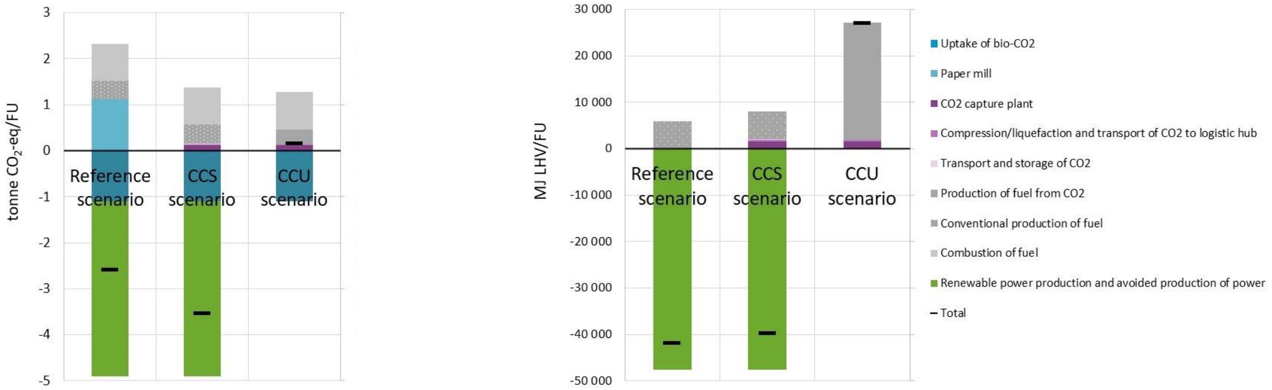

***Figure 2: Results for the indicators climate change and use of primary energy. The EN 15804 + A2 method and Cumulative Energy Demand (CED as MJ LHV) have been used, respectively. Net burdens are represented as black lines.***

Gibbs free energy formula explains the fundamental thermodynamical principles behind the energy requirement for CCU fuels. A sensitivity analysis has been made to see under which circumstances CCU fuels still can be beneficial with regard to climate effects. This shows that the CCU scenario has a better climate profile than the CCS scenario when the substituted electricity has a climate burden below 40 g $CO_2$-eq/kWh (~ photovoltaic). Results from a recent literature study on CCU [7] support the results found by LCA modelling. The literature study concludes that production of CCU fuels/chemicals is a good way of transforming *electricity*, given that there is a surplus of renewable electricity, and if substituting fossil electricity generation is not possible. In all other cases, it is more climate friendly to store the captured $CO_2$ and produce fuels the conventional way, and to substitute fossil electricity sources instead of using large amounts of electricity to transform $CO_2$ into a fuel. Other CCU routes were also investigated in this literature study: direct utilization of $CO_2$ in greenhouses or for algae production seems to be beneficial and mineralisation of $CO_2$ to replace cement can give large climate benefits.

## 4. Conclusions

CCU can be regarded as carbon recycling. It is, however, both more climate friendly and energy efficient to produce *fuels* the conventional way and to use the renewable electricity for substituting fossil electricity. Other CCU options, like *direct use* of $CO_2$ in greenhouses and *mineralisation*, can give climate gains. Hence, production of CCU fuels stands out as a suboptimal carbon recycling option in cases where fossil electricity can be substituted.

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# Life Cycle Assessment for eco-design of bioactive chemicals from biorefinery side-streams

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## 1. Introduction

Borregaard AS is a biorefinery operating in 13 countries in Europe, America and Asia. The biorefinery in Norway produces a range of bio-chemicals based on Norway Spruce. From the building blocks in wood, the biorefinery supplies a wide range of products to various applications in sectors like agriculture, construction, pharmaceuticals and cosmetics, foodstuffs, batteries, and biofuels.

In the project BACS (short for BioActive Compounds from Spruce), the goal was to develop sustainable value-added products that are bioactive or that will stimulate and improve the bioactivity of other compounds in formulations. Sustainability was to be used as a guideline for decision making during process development. The long-term goal was to be able to upscale such processes from lab scale to commercial production. Borregaard and NORSUS have cooperated in several projects over the last decades and have created an open environment for sharing of data and knowledge.

## 2. Materials and Methods

The study was carried out using attributional environmental life cycle assessment (LCA) methodology in cradle to gate analyses. Documenting the process and the results were originally meant for internal use, as a learning process and for development of new products. A functional unit of 1 kg DM product and a system boundary from cradle to gate was chosen, as use of the potential products are many and diverse. Where allocation was unavoidable, burdens were distributed based on dry mass/energy. Economic allocation was found unsuitable because several involved products have no market value, and because over time, no product in the main biorefinery acts as the single driving force of the system. A more detailed description of the allocation method can be found in [1, 2]. The indicators used were connected to climate change, acidification, eutrophication, water scarcity and use of fossil energy resources.

Bark and knots were explored as feedstocks, going into four compounds:

- Terpene from bark
- Bark extract (containing stilbenes)
- Bark residue (containing polysaccharides and tannins)
- Knot extract (containing resins and conidendrin)

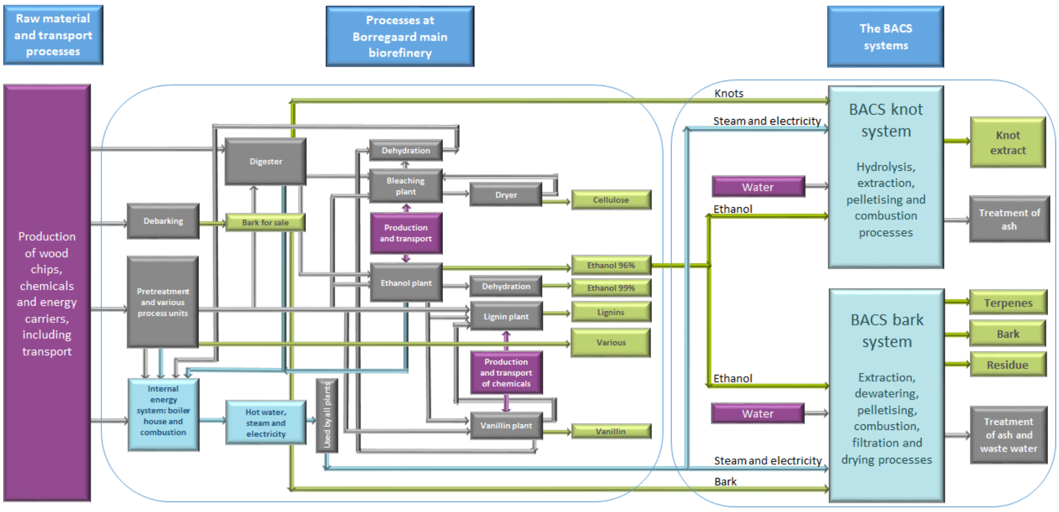

*Figure 1: Simplified flowsheet of the BACS bark and knot systems.*

The analyses are based on modelling of the physical, stand alone processing plants (data from lab scale level). The products are mutually dependent on each other in the sense that one co-product represents a raw material in the production of one or several other products in other installations, creating internal loops in the system. The processes are hence very closely linked, causing a complex process model (*Fig 1*).

LCA was used to give input to the innovation process by identifying environmental hotspots. Draft models were analysed and preliminary LCA results were presented and discussed with representatives from the biorefinery in several rounds. Scrutinizing the burdens of each product and discussing alternative options, focusing on the hotspots and following the burdens upstream, led to ideas on how to optimize the systems. This work process also revealed a couple of human errors; hence it served as a quality check of the input data and modelling.

The draft results were documented as the LCA models were refined in this iterative innovation process. Hence, the development of the results show both how potential improvements in the technical process and how quality checks of the input data and the LCA model itself, have affected the results.

## 3. Results and Discussion

The main hotspot issues found during the project were related to separation of terpene and ethanol recirculation; the first being important for the terpene result while the second affects bark extract and knot extract to a large extent. The main corrections of human errors in the LCA model were related to the pelletizing process and production of steam (shown for bark extract in *Fig 2)*. These last two issues are quite interlinked and led to large changes for bark extract and residue and minor changes for knot extract, however in the end they almost cancelled each other out. For terpene these corrections did not alter the results.

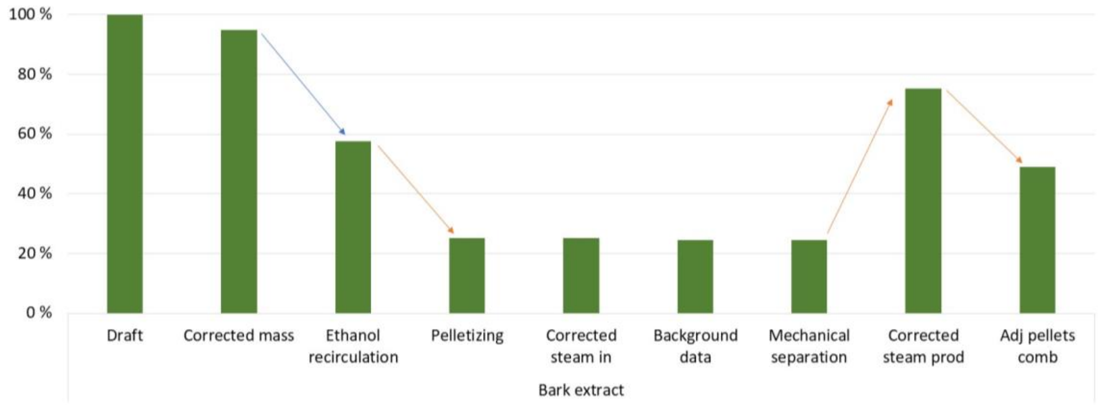

***Figure 2: Development in the climate change (IPCC 2021 GWP 100, IOBC) results caused by hotspot analyses, corresponding corrections of the model (orange arrows) and development of the BACS production processes (blue arrow). The figure is shown for bark extract.***

## 4. Conclusions

Lessons learned are that important environmental improvements, as well as modelling errors, can be found using LCA in such an iterative collaborative innovation process. It is, however, crucial to recognize that misunderstandings can easily arise, and that time must be spent on discussing details as well as the bigger picture during this process. The project findings have emphasised the efforts needed for LCA experts to understand the specific industry and the industrial experts to understand LCA.

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# Are We Trading Lightweight Airframes for Climate Change?

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## 1. Introduction

Modern aircraft manufacturing extensively employs polymers and plastic composites to construct lightweight airframes that still deliver robust performance. These plastics are selected for their outstanding properties, such as high resistance to corrosion and fatigue, which are particularly beneficial under severe environmental conditions. Fibre-reinforced plastics (FRP) are capable of withstanding numerous loading cycles without failure, thanks to their excellent fatigue resistance, offering an effective strategy for reducing fuel consumption. However, what is the environmental cost? On average, the global aircraft retirement rate is about 600 aircraft per year (including various types of aircraft, e.g. civil passenger aircraft, military aircraft, airfreight cargo, etc.) [1]. This means the number of aircraft cabin interiors piling up in the boneyard each year is devastating. Poor waste management in the aviation sector means that the plastic parts of an aircraft often end up in landfill. Meng et al. estimated that 30-40% of half a million tonnes of composite waste from aircraft production will end life in a landfill [2]. The diverse range of composites complicates the segregation and recycling processes at the end of an aircraft's service life. This results in a heterogeneous mix of plastic waste, leading to prevalent disposal methods such as landfill use. The blend of complex plastics and composites presents a significant challenge in achieving a sustainable end-of-life pathway for these materials and fostering a circular economy. To understand this issue, the study examines a few scenarios to observe how circular thinking could be the answer we seek. Aircraft cabin interiors are characterised using spectroscopy, and various polymers were identified. A life cycle assessment (LCA) is performed from cradle to gate and followed by an end-of-life (EOL) scenario considered where recycling potential is measured using a Circular Footprint Formula (CFF) developed by the European Commission. Findings highlighted that FRP contributed the most significant impacts (including acidification, climate change, eutrophication, etc.) among all types of polymers, and the percentage of recycled content should be more than 40% for a more positive environmental return. This project is essential to allow us to design a cleaner and more sustainable exit for aircraft cabin interiors

## 2. Methodological Design

### 2.1. Physical characterisation

Samples from the interior of retired aircraft, including hinges, parts of the passenger safety unit, tubing, window panes, rim holders, panels, and lid covers, were systematically collected and analysed. These samples were sourced from various aircraft types, specifically a 9M-MWF propeller, and A320 and A321 airframes, provided courtesy of Malaysia Airlines (MAS), Malaysia. Some samples were dismantled by the Aircraft Interior Recycling Association (AIRA), a UK-based organisation specialising in the consultancy and recycling of aircraft interior materials. The polymer types within these samples were identified using Attenuated Total Reflectance Fourier-Transform Infrared Spectroscopy (ATR-FTIR) on a Shimadzu IRAffinity-1S instrument. The ATR-FTIR detection area was first cleaned with a 70% ethanol solution. Subsequent analyses involved conducting four scans per spectrum across a wavelength range of 4000–400 $cm^{-1}$ to ensure comprehensive data collection and accuracy in polymer identification. Secondary data was supported by Ecoinvent 3.9, Industry Data 2.0 and Gabi 2.22 (Open LCA).

### 2.2. Life Cycle Assessment (LCA)

The LCA on collected primary and secondary data was conducted using SimaPro 9.1 software and analysed using the European Footprint (EF) 3.1 (adapted) method. An EOL was considered to understand the trade-off of the circularity approach in waste management. The recycling potential was calculated using CFF.

# 3. Results

## 3.1. Cradle to Gate: Midpoint

The midpoint results presented in this section focus solely on the cabin interiors' initial production phase and this approach allows for a clear understanding of the baseline impacts associated with the manufacture of these parts, establishing a foundational reference point for the overall environmental performance of cabin interior elements throughout their lifecycle. Figure 1 shows the sections in the cabin interior contributing to carbon dioxide ($CO_2$), where the wall and ceiling contributed more than 50% of emissions.

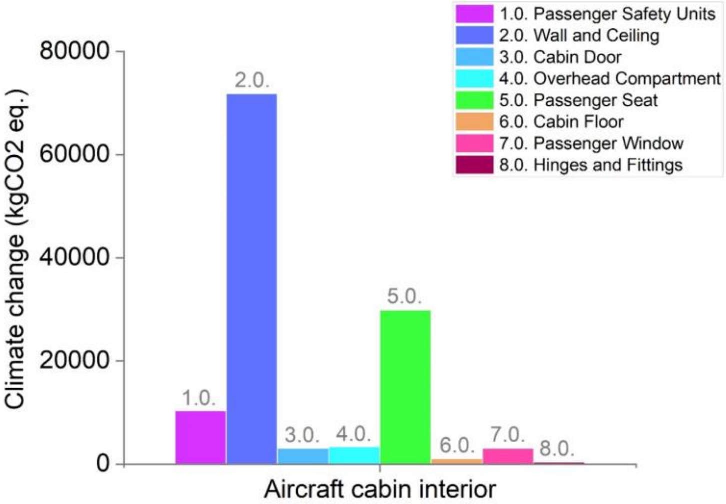

*Figure 1 Climate change impact on the entire cabin interior*

## 3.2. EOL scenario

This scenario utilises the CFF method to evaluate the advantages and trade-offs associated with recycling. This method was selected to quantify the environmental benefits of recycling when EOL data is limited. Two approaches were analysed to assess the environmental benefits of (a) full circularity and (b) semi-circularity in recycling. As anticipated, higher recycling rates markedly reduce $CO_2$ emissions when polymers are cleanly reintegrated into aircraft production and reused in cabin interiors. The semi-circular scenario occurs when recycled polymers are utilised in non-aviation sectors. Notably, emissions from landfilling and utilising 20% recycled content are nearly identical. This suggests that if the application is a non-aviation industry, a higher rate of recycling content should be considered.

# 4. Conclusion

Progress in the aviation industry is focused on decreasing fuel consumption and emissions. This includes the creation of lighter and more aerodynamic aircraft equipped with sophisticated propulsion technologies, the enhancement of air traffic management systems, and the investigation into Sustainable Aviation Fuels (SAFs) sourced from renewable materials. Despite these efforts, detailed research into aircraft cabin interiors and airframes remains insufficient, even as significant numbers of retired aircraft continue to accumulate in boneyards each year. LCA result shows that 50% of the $CO_2$ emissions are attributed to the walls and ceiling. Meanwhile, the CFF method shows that emissions from using recycled polymers in non-aviation sectors are similar to those from landfilling, suggesting that higher recycling rates could improve environmental outcomes in non-aviation applications.

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# Integration of the Circular Footprint Formula with the Material Circularity Indicator to Measure the Textile Circularity

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## 1. Introduction

The transition to a successful circular economy is supported by the European Commission, which has drafted an action plan with defined goals to be achieved by member states. The transition requires infrastructures that empower market actors and the adoption of practices that support sustainable products. In particular, the use of Product Environmental Footprint (PEF) guidance, specifically referring to the Category Rules for Apparel and Footwear (PEFCR A&F), and the related Circular Footprint Formula (CFF) emerge as key tools in assessing the environmental impact of textile products [1]. These methodological tools have the potential to push manufacturers toward informed decisions that reduce their ecological footprint, reflecting a shift toward more conscious and sustainability-focused production [2].

This paper aims to address existing gaps in the definition of the quality factor present in the material component of CFF [3], [4]. In particular, it was shown how the parameter, modeled in a new technical key going beyond the economic definition, closely influences the final environmental impact of a recycled material as a function of the number of recycling cycles. In this regard, the Material Circularity Indicator (MCI) emerges as another tool which focuses attention on elements often overlooked by CFF, such as product lifespan [5]. In conclusion, a possible integration of MCI with CFF could open up promising prospects for making impact assessment more transparent and comprehensive at both the product and company levels. The applicative results refer to a case study of Manteco®'s products.

## 2. Materials and Methods

The application analysis concerned the product ReviWool®, a wool with good environmental performances manufactured by Manteco®. The following equation describes the material and disposal impact components (E) of the CFF, which was applied in accordance with the PEF guidelines [1]:

$$E = (1-R_1)E_V + R_1\left(AE_{rec} + (1-A)E_V \cdot \frac{Q_{Sin}}{Q_P}\right) + (1-A)R_2 \cdot \left(E_{recEoL} - E_V^* \cdot \frac{Q_{Sout}}{Q_P}\right) + (1-R_2-R_3) \cdot E_D$$

The data for impacts on climate change ($E_V$, $E_D$, $E_{rec}$) comes from Environmental Product Declarations (EPDs), [6]. Due to the lack of additional data outside the EPDs, a closed loop ($E_V = E_V^*$ and $E_{rec} = E_{recEoL}$) was assumed. From the guidelines for recycled materials from textiles, the allocation factor A=0.80 was assumed, while the parameters for the recycled content $R_1$, the recycling rate $R_2$ and the energy recovery factor $R_3$ were provided by the manufacturer. The quality factors were calculated for each recycling cycle using a newly developed mathematical model based on the wool fibre lenght.

Subsequently, the $MCI_P$ was calculated following the guidelines using a comprehensive approach for the same product [5]. The data on the compositions of the different products were taken from the EPD [6]. Again, a closed-loop system was assumed, with a conservative efficiency parameter $E_C$=$E_F$, as no specific reference value was found in the literature. The utility factor was assumed to be equal to 1, the proportion of the collected mass that is fed into a recycling process ($C_R$) was assumed to be in line with the company's Zero-Waste Project, and the other parameters included were set to 0 for simplicity.

## 3. Results and Discussion

### 3.1. $E_{CFF}$ impact trend

The analysis was carried out by subjecting ReviWool® fabric to a maximum of five recycling cycles (n) in the ideal case, which shows a progressive change in fibre length. Figure 1 shows a largest decrease between the first and second cycle, which becomes a stable plateau as the number of cycles increases. The graph shows also the data compared to an ideal power curve to improve the overall understanding of the results.

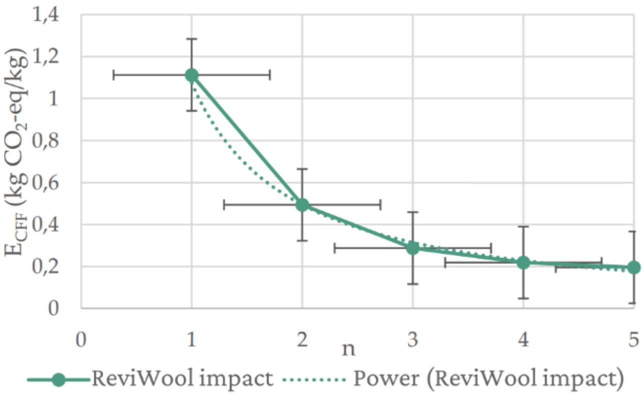

*Figure 1: Trend of the impact of ReviWool® fabric vs number of recycling cycles [7]*

### 3.2. Calculation of the $MCI_P$ value

ReviWool® fabric achieved an $MCI_P$ value of 0.693, exceeding the threshold value of 0.5, which was desirable as we assumed a 100% recycled product, demonstrating that it is a circular and sustainable product. In an alternative scenario with a lower percentage of recycled material, the final result would have been lower, as the assumptions were only based on the change in the percentage of raw material from recycled sources. In addition, the value could be further increased by increasing the efficiency parameter, which shows how much the quality of the recycling process influences the final result.

## 4. Conclusions

The study highlights key findings on recycling concepts, product impacts and the application of sustainability tools such as CFF and MCI in the textile sector. The case study shows how the quality of the recycled wool fibres is critical to maintaining the performance of the fabric. Increasing the proportion of recycled wool the environmental impact is reduced, but product quality and recycling efficiency must be prioritised. The validated method, although limited to one product in a closed loop system, showed consistent quality results. The transition to a circular economy in the textile sector requires collaboration to improve the responsibility of companies. The introduction of complementary tools promotes environmental performance and consumer education and extends research to other materials that can promote sustainability in the textile industry.

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# Environmental viability of recycling flame retardant cotton workwear

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## 1. Introduction

Textiles are being produced in increasing amounts and their environmental impacts are growing globally [1]. Textiles have been identified as a key value chain in the EU circular economy action plan [2] and subsequently, the European Commission has formulated an EU strategy for sustainable and circular textiles [3]. The EU strategy envisions that by 2030 textile products placed on the EU market are long-lived and recyclable, made of mainly recycled fibres, free of hazardous substances and produced in respect of social rights and the environment [3]. The EU member states are obliged to set up separate collection for textile waste from the beginning of 2025 [4]. Solutions for recycling these textiles are needed.

To enable environmentally and economically viable recycling of textiles, several challenges need to be solved. Besides many other difficulties, the use of chemical finishes and dyes hinder the recycling potential of textile waste [5] as chemicals and dyes are often unwanted in recycled products and complicate the current recycling processes. For a large share of the chemicals and dyes used in textile manufacturing, the effects they have on the recyclability of the products is not fully understood [6].

A group of rather homogenous textile waste for recycling with large and constant volumes is occupational workwear [7] that can be collected, sorted and treated in bulk. In the EU, the majority of used workwear is disposed of by landfilling or incineration [8]. Workwear is often treated with different types of chemicals to increase e.g. safety. To enable recycling of chemicals containing textiles, different treatment is required for different types of chemicals. The treatment causes environmental impacts which – in the worst case – may outweigh the benefits of recycling. Therefore, systemic assessments of the life cycle impacts of alternative end-of-life scenarios are required to identify the environmentally most promising pathways for increasing the circularity of workwear.

To support the development of circularity in workwear, this study aims to investigate the chemical recycling potential of cotton workwear containing chemical residues from an environmental perspective. The focus is on workwear treated with flame-retardants (FRs), but the textiles include dyes as well. We aim to find answer to the research question of how do the FR chemicals and dyes used in the textile affect the environmental performance of chemical recycling of textiles. This main question is studied through life cycle assessment (LCA) of three different recycling scenarios: a) recycling with no chemical and dye removal for closed loop recycling for new FR textiles b) recycling with FR chemical removal for textiles with similar color and and any use and c) recycling with both dye and FR chemical removal for textiles of any use and color.

## 2. Materials and Methods

In this study, LCA is used to evaluate the environmental impacts of three different recycling scenarios (Figure 1) of cotton FR textile: recycling with no chemical and dye removal, recycling with FR chemical removal and recycling with dye and FR chemical removal. These three scenarios are compared to the linear option of incinerating the textile after the use phase. The European Commission's PEF guidance [9] and the PEF category rules (PEFCR) draft for apparel and footwear are utilized as methodological guidance for studied impact categories and general assumptions when primary data is unavailable.

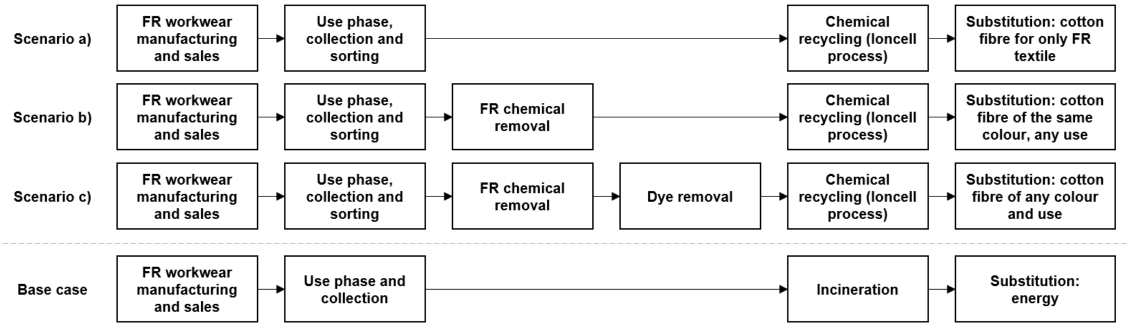

*Figure 1: Studied scenarios*

The scope covers the full life cycle of the garment, focusing on the novel chemical recycling process (lab-scale) called Ioncell as well as material substitution. Primary data is gathered from the manufacturing and recycling phases. Primary data from the recycling of the material is received from Aalto University Bioproducts laboratory, who are in charge of the testing the materials in the recycling process. Laboratory data is upscaled for the LCA calculation using a framework published by Piccinno et al. [10]. Secondary data is collected from the Ecoinvent database and literature.

## 3. Results and Discussion

Results of the LCA calculations are expected to be finished during the summer of 2024. The results will indicate the amount of resources needed for chemical recycling of cotton workwear impregnated with dyes and FR chemicals and thus will provide information of the practical environmental viability of recycling the FR textiles through different recycling scenarios (closed loop for textile material with FR chemical still present and safe recycled material with no FR chemical for many uses) compared to the linear case of incinerating the textiles after use.

The results can be utilized for decision-making when determining whether to put efforts in chemical recycling of FR workwear (closed or open-loop) or to concentrate on other options like mechanical (closed-loop) recycling. With caution, the results could also be extended for textiles with other chemical finishes.

## 4. Conclusions

Conclusions of the study will provide information on which of the studied recycling scenarios seems the most environmentally viable for cotton FR workwear – or if the resource use in the treatment phase even outweighs the benefits of chemical recycling and other circularity options should be focused on.

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# Beyond Data Sharing: Addressing the Reproducibility Challenge in LCIA through a Software-Agnostic DSL

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# 1.Introduction

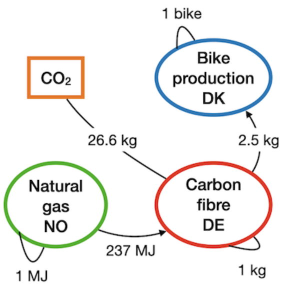
We introduce an early-stage Domain-Specific Language (DSL) prototype dedicated to enhancing the reproducibility of sustainability assessments, with a specific focus on the foundational stage of building life-cycle inventories life-cycle assessment (LCA). The proposed DSL is designed to enhance reproducibility in sustainability evaluations, providing a robust framework for researchers and practitioners to analyze and compare sustainability studies with transparency.

# 2.Materials and Methods

To showcase the practical implementation of the DSL, we present a demonstration utilizing the free and open-source LCA framework Brightway. The parser implementation, grounded in Brightway, serves as an initial exemplar of the DSL's potential application, emphasizing the separation of syntax from the underlying software. The prototype development required the design of a grammar for the DSL, as well as an interpreter implemented using python. The basic syntax elements included in the DSL are related to inventory creation: syntactic elements to create activities and exchanges compose the grammar.

We illustrate how the agnostic DSL prototype facilitates transparency and reproducibility, laying the groundwork for standardized life-cycle inventory building irrespective of the chosen LCA software. The prototype implementation was built using the python programming language, using the textx [3] python framework for building DSLs.

A sample text file that can be fed to the DSL command line tool would look as follows, building an inventory for the following toy example:



```
Preamble
            LIST PROJECTS
            WORK ON PROJECT "lcalang-sample-project"
Preamble end
DELETE DATABASE NAMED 'Sustainable bikes'
CREATE DATABASE NAMED 'Sustainable bikes'
CREATE ACTIVITY NAMED 'Bike baseline' WITH UNIT 'bike' WITH LOCATION
'GLO' IDENTIFIED BY 'BK_A' IN DATABASE 'Sustainable bikes' WITH REFERENCE
PRODUCT 'basic bike'
CREATE ACTIVITY NAMED 'Bike option 1' WITH UNIT 'item' WITH LOCATION 'GLO'
IDENTIFIED BY 'BK_B' IN DATABASE 'Sustainable bikes' WITH REFERENCE
PRODUCT 'basic bike'
CREATE ACTIVITY NAMED 'Carbon fibre' WITH UNIT 'kilogram' WITH LOCATION
'DE' IDENTIFIED BY 'carbon_fibre_de' IN DATABASE 'Sustainable bikes' WITH
REFERENCE PRODUCT 'carbon fibre'
CREATE ACTIVITY NAMED 'Natural Gas' WITH UNIT 'megajoule' WITH LOCATION
'NO' IDENTIFIED BY 'natural_gas_no' IN DATABASE 'Sustainable bikes' WITH
REFERENCE PRODUCT 'natural gas'
```

# 3.Results and Discussion

The DSL prototype, in its early proof-of-concept stage, introduces a unique paradigm where the syntax remains clearly separated from the intricacies of the LCA software. Unlike traditional approaches, this separation allows for a higher level of transparency, enabling researchers to articulate and share the specific steps taken to arrive at LCA results rather than focusing solely on the raw data. What sets this DSL apart is its independence from the specific LCA software used for LCIA computations. This agnosticism eliminates barriers to collaboration, enabling researchers to seamlessly share and reproduce life-cycle inventory data across various software environments. The DSL prototype aims at incorporating syntax and semantics to facilitate the creation of reproducible workflows for sustainability assessment.

# 4.Conclusions

This work offers a glimpse into the potential of the DSL prototype, acknowledging its early stage while laying the groundwork for future advancements in sustainability assessment methodologies that prioritize reproducibility and collaborative research efforts.

Challenges remain regarding the inclusion of parameters in the different parts of the inventories, data ingestion to input values to be used in the creation of the inventories. Further work can also be focused on contribution analysis, uncertainty evaluation as well as data quality. All these can be further developed using a modularized re-implementation of the DSL that would incrementally improve the syntax of the language.

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# Use of LCA and LCT within technology development of carbon capture, utilisation and storage

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## 1. Introduction

Technology development is the process of creating, enhancing, or improving technologies to address specific needs, solve problems, or produce desirable products. It often involves interdisciplinary collaboration and may encompass both incremental improvements to existing technologies and the creation of entirely new innovations. In the initial stages, technology development prioritizes the discovery of feasible materials and technical resolutions, alongside tackling scientific or engineering challenges. Research typically emphasizes technological advancements, with less emphasis on considering the environmental and social impacts of potential solutions. Employing life cycle assessment (LCA), typically as prospective LCA, at this stage presents significant challenges due to the various difficulties associated with early technology development. This is because, during the initial phases of R&D, there is often considerable uncertainty about the technical viability and feasibility of the technology [1].

Carbon capture, utilisation and storage (CCUS) are technologies that convert carbon dioxide ($CO_2$) into products that store the carbon, while CCU is the same but without the storage. Many CCU(S) technologies are at an early stage of technology development and LCA is often used to assess the technology’s performance, process designs, carbon reduction potential et cetera. The focus of these LCAs is often to prove the viability of the technology or evaluate process design choices. However, according to Sandin et al [2], LCA can play a variety of roles in interdisciplinary and inter-organisational technical R&D projects depending on the projects’ characteristics, but depending on the role, the way of doing LCA will be different.

Drawing from the firsthand experiences of LCA practitioners involved in two CCU(S) projects, the study explores the diverse knowledge requirements encountered during the early technology development process.

## 2. Materials and Methods

This research uses methods of social sciences to analyse LCA practice in two collaborative R&D projects. Through LCA work conducted in two different CCU(S) projects, we investigate various types of knowledge requirements and examine how different forms of LCA can serve distinct purposes in the early stages of technology development.

Case study 1: The objective of the DECREASE project is to advance a $CO_2$ utilization technology that leverages industrial byproducts and $CO_2$ to generate insoluble carbonate minerals or organic carbonates. DECREASE represents a collaborative effort spanning multiple disciplines, including chemical engineering, fluid dynamics, and environmental systems analysis. The LCA is planned to evaluate the environmental benefit of the proposed solutions.

Case study 2: The goal of the project is to demonstrate the PYROCO$_2$ process producing acetone from industrial $CO_2$ and green hydrogen. The project aims to produce *climate-positive* acetone that can be further processed into chemicals and materials with a *negative carbon footprint* [3]. The LCA is part of the sustainability assessment evaluating techno-economic, environmental and social implications but is also planned to ensure that the new technology leads to carbon reduction.

## 3. Results and Discussion

### 3.1. Case Study 1: DECREASE

The LCA work was performed for a project stage at Technology Readiness Levels (TRL) 3-4. The project proposal planned for just one type of LCA aimed to evaluate the environmental benefit of the proposed technology solutions. However, LCT and LCA supported the project in various ways. First, there was a need to facilitate the development of life cycle thinking around the system and raise awareness of the upstream (e.g., feedstock processing) and downstream (e.g., filtration, drying of and use of the product) processes, which significantly affect the performance of the studied technology. Second, semi-quantitative screening and prioritization of potential feedstock candidates and analysis of final product utilization alternatives were performed. Third, simplified quantitative LCAs were conducted to identify the directions for experimental work to enhance system performance in terms of $CO_2$ reduction [4]. Overall, LCT and LCA were used as learning tools to improve the project group's understanding of the system's properties, the implications of process design decisions, and the directions of future work. All in all, there were 3-4 different knowledge needs addressed by different LCAs.

### 3.2. Case Study 2: PYROCO$_2$

The LCA work was performed for a project starting at TRL 4-5. First, at the beginning of the project, a preliminary (cradle-to-gate) LCA was performed on an initial process design to compare the impacts of PYROCO$_2$ acetone to the impacts of conventional acetone, find hotspots and explore how foreground (e.g. yield) and background (e.g. electricity mix) systems affect the environmental performance [5]. Second, there was a need to explore the impacts of different sources of $CO_2$. This was done through a carbon flow analysis in combination with an LCA of cement production and biomass combustion, with carbon capture added [6]. Third, there was a need to assess the PYROCO$_2$ process at a later development stage, halfway through the project. Another preliminary LCA was performed with similar goals to the first LCA but investigating a more probable design and exploring more scenarios (documented in an internal report, 2024). All in all, the LCAs were used to learn about activities with high impact, the potential to produce acetone with lower impact than conventional methods, implications of process design outcomes, implications of location and the choice of carbon dioxide. Furthermore, additional knowledge needs in the project were identified by the LCA practitioner by listing potential questions (such as comparing process scheme alternatives, scaling up to industrial scale, and upgrading to different products). Based on discussions with the project consortium, one of these questions could become the focus of the next LCA.

### 3.3. Analysis and Discussion

One dilemma of using "ordinary" quantitative LCA during technology development lies in the lack of data and the absence of concrete designs to study in the early stages [7]. Another dilemma is that there is not a single knowledge need to address but rather a multitude. Thus, during the case studies, it was not feasible to conduct a single LCA. Instead, the LCA practitioners had to adapt their work to the project's development stage, and the knowledge needs of the participants, resulting in several different LCA studies. The influence of the LCA information on the decision-making process and development of the project seemed to be highly influenced by each project participant's perspective on the system and their openness to the LCA aspect. Many aspects of LCA practice were not merely methodological issues but rather challenges related to communication and shared understanding, which were crucial for the success of LCA work in the project.

## 4. Conclusions

This study shows that six types of LCA approaches were required for nine identified knowledge needs in just the earlier stages of these two projects. In conclusion, there are different approaches to using LCA depending on the knowledge needed in a project. The current thinking around LCA needs to change, requiring a shift in perception from both practitioners and commissioners. The LCA practitioner should strive to better understand the context before determining the goal of a study, ensuring that the scoping aligns with the goal. Emphasizing the versatility of LCA methodology to fit various knowledge needs and design choices throughout the technology development process is crucial. Better understanding the context of technology development will lead to more effective LCA studies.

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# Social and environmental impacts of lithium-ion battery end of life

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## 1. Introduction

Lithium-Ion Batteries (LIBs) are considered a key technology for climate-neutral society, and the number of LIBs has increased in recent years. However, the various life-cycle stages of LIBs are associated with environmental and social impacts. Most studies focus on the environmental impacts of mining and production processes for LIBs, but also responsible End-of-life (EoL) solutions are becoming increasingly important.

The LIB EoL value chain is complex and international, and several recycling processes, such as hydrometallurgy and pyrometallurgy, exist. However, the environmental and social factors of EoL processes of LIBs are still relatively unexplored and largely unknown, especially in the context of the social perspective. Therefore, an environmental and social sustainability assessment is needed to map the processes and evaluate the social and environmental impacts of EoL processes of LIBs.

## 2. Materials and Methods

The main methods for this environmental and social sustainability assessment environmental and social life cycle assessments (ELCA and SLCA). Both methods consist of goal and scope definition, inventory analysis, impact assessment, and interpretation. The system boundaries for the first assessment were set to the hydrometallurgy recycling process within Europe (including Turkey for cell production).

The inventory analysis and impact assessment for these assessments are created through value chain mapping, stakeholder consultation (workshops, interviews, surveys), and literature review. Furthermore, ecoinvent and the social hotspot database (SHDB) are used. This approach is in line with the recommendations provided in the UNEP guidelines [1] and the ISO standards for LCA [2].

The stakeholder consultation suggests an EoL value chain starting with the collection of batteries in southern Europe and transportation to recycling companies in Germany and France. Further recycling activities are performed in Belgium before the materials are transported to Turkey, where new battery cells are produced. A schematic illustration of the value chain is provided in figure 1 below.

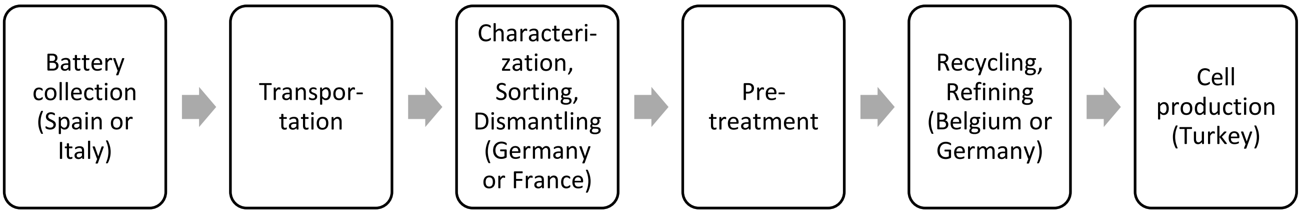

*Figure 1: LIB EoL value chain for inventory and impact assessment*

The concept of a digital battery passport (DBP) as a tool to provide information along the value chain is currently under research and plays a major role in the legislation. Therefore, the DBP is also used in addition to obtain more information that can be used for the assessment of social and environmental impacts. Several workshops and interviews with different LIB EoL actors indicate an indirect benefit on social and environmental impacts by informing about State of Health, battery chemistry, and providing value chain- and repairment information. This information can potentially be used to improve the processes so that negative environmental and social impacts can be avoided. [3].

## 3. Results and Discussion

The key social hotspots identified are health and safety as well as transportation related. The attribution of the environmental impacts is still ongoing but potential aspects are global warming potential, toxicity and resource depletion. Table 1 below gives an overview of the inventory and selected social and environmental aspects associated with the LIB EoL process steps.

| Process step | Inventory | Social aspects [1] | Environmental impacts [4] |
|---|---|---|---|
| Collection | Transportation | Driving hours, safe transport | Global warming potential, Human toxicity, Ecotoxicity, Fossil depletion |
| Characterization | Business services | Thermal runaway, exposure to toxic materials, exposure to electricity, chemical leaks, explosion | Human toxicity, Ecotoxicity, land occupation |
| Sorting | Business services | | |
| Disassembly/Dismantling | Manufacturers nec | | |
| Pre-treatment | Motor vehicles and parts | Chemical leaks, physical and respiratory harms | Human toxicity, Ecotoxicity, land occupation |
| (Hydrometallurgical) Recycling | Chemical, rubber, plastic products | Exposure to reagents, dangerous raw materials | Water depletion, Ecotoxicity |
| Refining | Metal products | | Metal depletion |
| Cell production | Electronic equipment | | |

***Table 1: Selected social and environmental impacts of different process steps***

## 4. Conclusions

This work presents the application of different methods to shed light on the social and environmental impacts in the EoL of LIBs. To extend and validate the existing results, future research will increase the sample size and analyze the sensitivity through different scenarios. The results can be used to treat potential social and environmental “hotspots” with extra care e.g. because of the increased risk of thermal runaway in the dissassembly process, divers precautionary measures can be taken to reduce this risk. Furthermore the results can be benchmarked with conventional battery cell production to propose a shift towards a Circular Economy.

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# Absolute Environmental Sustainability Assessment of aviation transition scenarios

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## 1. Introduction

The aviation sector is currently responsible for 2-3% of annual anthropogenic CO2 emissions and for 5-6% of the recent climate impact [1]. In order to assess its climate footprint over time, the sector and its various stakeholders have developed numerous prospective scenarios (e.g. [2][3]) incorporating different assumptions about traffic growth, fleet renewal, the introduction of new technologies, and the use of alternative fuels. These scenarios are primarily used to evaluate their potential for decarbonization by comparing them to a "business-as-usual" reference scenario.

However, the various solutions proposed are only assessed through the prism of climate. The primary decarbonization lever being considered is the introduction of alternative fuels. If we take the example of fuel produced from biomass, the increasing resource demand could give rise to issues pertaining to land-system change, water use, and the application of nitrogen or phosphorus-based fertilizers. Alternative fuel sources, particularly liquid hydrogen and electrofuels, which rely on electricity as their primary energy source, may also cause environmental displacement issues.

The Planetary Boundaries framework [4] provides a reference for absolute environmental sustainability at the global scale. By reducing the scale from global to sectoral, this framework can be used to perform an Absolute Environmental Sustainability Assessment (AESA) of contrasted prospective scenarios for the aviation sector.

The literature about the operationalization of Planetary Boundaries (PB) at smaller scales has undergone significant development in recent times. Based on recently developed tools and methodologies [5][6][7], this study brings methodological and conceptual advancements to enable dynamic and prospective AESAs and present applications to aviation prospective scenarios.

## 2. Materials and Methods

### 2.1. Prospective LCA

The prospective assessment of impacts of aviation requires both prospective scenarios of the sector's energy demand and prospective emission factors associated with the production and use of these energy quantities. Prospective scenarios have been generated by making various assumptions regarding traffic evolution, technological and operational improvements, the nature of alternative fuels introduced into the fleet, and their integration pace. These illustrative scenarios are representative of the wide range of scenarios proposed by various stakeholders: industrial, academic or institutional.

Emission factors must be prospective to conduct a coherent study. Even though the focus here is on the aviation sector, its transition scenarios are part of a global transition scenario. For example, the climate impact of electrofuels is closely tied to the emission factor of the electricity used to produce them. The evolution of this emission factor, and more broadly of the entire technosphere underlying the satisfaction of our energy demand, is aligned with the global scenario SSP2-RCP2.6 using the *premise* tool [6].

### 2.2. Linking prospective LCA and planetary boundaries

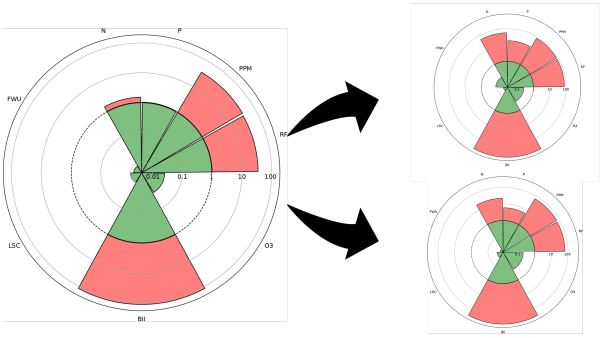
Our approach regarding the link between LCA and PB is based on the PB-LCIA methodology [5] adapted to the scope of our study. We aim to assess the impacts of dynamic scenarios, where emissions vary from year to year. Using PB-LCIA characterization factors directly related to climate change and biosphere integrity would lead to temporal inconsistency. Therefore, we rely on the Bern simplified carbon model to dynamically evaluate the impact on these two key processes.

## 2.3. Comparing prospective impacts to downscaled planetary boundaries

To conduct an AESA, it is essential to compare the impacts of our activity to a reference of absolute environmental sustainability. This reference can be derived from the PB framework. To achieve this, a downscaling step is necessary to move from the global scale to the activity scale.

Heide et al. [7] developed a method based on the concept of sufficientarianism (ensuring everyone has enough – method called FHN for Fulfilment of Humand Needs). The method relies on the notion of "safe and just" reference countries. This publication serves as a proof of concept with some limitations (application to certain PB only due to lack of data), which we aim to address through our approach, using other sources of data concerning the PB footprints of reference countries.

# 3. Results and Discussion



2050 prospective aviation
Refuel EU type

2022 aviation

2050 prospective aviation
100% biofuel HEFA

***Figure 1 - AESAs of 2022 aviation and two potential 2050 aviations***

Historical aviation (1940-2022) already exceeds its FHN-based Share of Safe Operating Space (SoSOS) for climate change, biosphere integrity, and nitrogen cycle. Scenarios using alternative fuels have a lower climate impact than the 100% fossil fuel scenario, but generate new potential environmental problems, such as the disruption of the phosphorus cycle. Among the 217 scenarios studied, none can be classified as absolutely sustainable.

# 4. Conclusions

By using new tools and developing an appropriate methodology, our work highlights the potential and the limits of alternatives fuels to reduce the environmental impacts of aviation. It also shows the absolute environmental unsustainability of the aviation sector in the years to come, within the context of a FHN-based downscaling. Furthermore, the development of this methodology opens up the possibility of conducting prospective and dynamic AESAs for all sectors of activity, enabling the anticipation of sustainability issues as well as the displacement of environmental problems in a context of decarbonization of activities.

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# Agro2Circular Circular Solution Life Cycle Assessment Approach

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## 1. Introduction

Globally 17 % of total food production is wasted in households, in the food service and in retail [1]. In Europe, the fraction of fruits and vegetables of household food waste is almost 50 % [2]. Currently the food waste is used in animal feed, compost or fuel. However, the food waste contains valuable compounds which could be upcycled to create other products. Also, multilayer plastic packaging and agriculture films are used extensively but they are mostly landfilled or incinerated instead of recycled. [3].

The Agro2Circular (A2C) project [4] aims to address these challenges by creating a territorial circular systemic solution which aims to be replicable in other EU countries. This solution will upcycle residues from the agriculture (including fruits, vegetables, and multilayer plastics) and food packaging into valuable products. The process will be facilitated by a digital tool and designed based on a scalable and replicable systemic approach. By performing a life cycle assessment (LCA), the environmental sustainability of the circular solution can be evaluated. The aim of the presentation is to describe the LCA approach of a territorial agri-food industry circular solution. The goal is not to demonstrate the LCA results, but rather to describe the process from an LCA practitioner point of view.

## 2. Materials and Methods

To evaluate the environmental sustainability and the circularity of the A2C systemic solution, an LCA will be carried out together with qualitative evaluation of the suitable metrics of circularity. The A2C demonstrator is a regional circular economy system to be located in Murcia, Spain. The two evaluations will be performed for this demonstrator.

The whole A2C systemic solution shown in Figure 1 will be evaluated with LCA, and the two chains (agri-food and plastic) will be connected. Both plastic and agri-food chains will be evaluated by modelling the A2C demonstrator units (demos) each having an own task in the systemic solution. Prior to the final LCA, a screening LCA was conducted, but the assessment had limitations which prevented to evaluate the overall sustainability of the A2C solution. Namely, the LCA covered only part of the whole solution, only carbon footprint was calculated and there were challenges in finding suitable benchmarks of the agri-food chain case. These issues are solved in the final LCA.

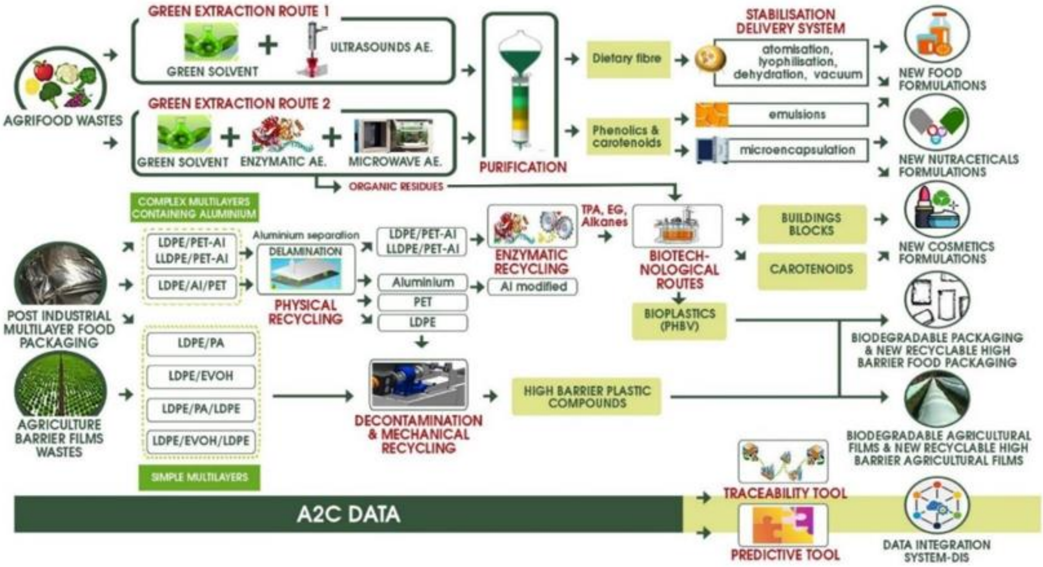

*Figure 1. Agro2Circular concept [3].*

In the A2C project, the circularity will be evaluated qualitatively by setting up a circularity monitoring framework compiled from the existing scientific literature. The framework will be presented in the upcoming deliverable in 2025. This presentation does not describe the circularity monitoring in detail but aims to present the principles of the framework drafting process.

## 3. Results and Discussion

### 3.1. Characteristics of the A2C LCA approach

Agri-food waste can be utilised in several ways in A2C demonstrator's operations. Only the most feasible waste treatment options for each waste fraction are considered in the LCA. The first selection of the fractions is carried out based on the TRL of the industrial processes, data availability, circularity of the processes at the regional level and replication potential for Lombardy and Lithuania. These two countries are used as the case studies in the A2C project for the replicability of the systemic solution. After the first selection, three suitable agri-food waste types are identified. Then, the possible A2C outputs of three agri-food waste fractions are evaluated based on the availability of the conventional substituting product LCI data. Other key LCA decision is to define the system boundary. In this case, the LCA will be cradle-to-gate taking into account the possible changes of the final consumer product that the A2C could cause. The data collection is carried out in demo level in which the unit processes are connected in the inventory stage, and eventually the two chains, food and plastic, are connected to each other.

### 3.2. Challenges

Observations and challenges of conducting a complex, circular and multi-input and output system LCA are described in the presentation. Research has been conducted to find the most feasible upcycling route and reference product for each waste stream. Overall, the performed LCA is complex due to the novelty of the studied unit processes and multi-step processing the of waste streams.

## 4. Conclusions

In the Agro2Circular project, the environmental sustainability of a territorial circular agri-food and plastic systemic solution in Murcia will be evaluated using LCA method. The LCA of the A2C circular solution is complex, and it needs to address the following aspects: multi input options (agri-food waste) and multi output product options, demo unit thinking that contains unit processes which flow from one demo to other, crossing of the two waste chains, analysing if the A2C output changes the characteristics of the final B2C product, and how to compare the novel A2C products with conventional ones finding suitable LCI data. In the presentation, data gaps and improvement methods of such complex regional LCA will be proposed.

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# Innovating Life Cycle Assessment with Artificial Intelligence: A Generative Pre-trained Transformer Exploration

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## 1. Introduction

In recent times, there has been a notable shift in the focus of society and politics towards sustainable development. This is particularly evident in Europe, where the Green Deal has emerged as a key initiative in this regard [1]. One instrument that may be employed to facilitate sustainable development is the Life Cycle Assessment (LCA), as defined by the International Organization for Standardization (ISO) in its standards 14040. The LCA can be utilized to identify environmental impacts along the value chain or life cycle of a product [2, 3]. The life cycle inventory (LCI) is of particular significance in this context, as it serves as the foundation for the calculations. In consequence of the European Green Deal, there has been a reconsideration of the field of mobility with regard to e-mobility. This has resulted in the formulation of the European Battery Directive, for example. The battery is a significant focus in the assessment of environmental impacts due to its use of critical materials [4]. The requirements set forth in the Battery Directive for calculating the carbon footprint and data collection are addressed by the aforementioned LCI in accordance with ISO 14040. Given the intricacy and time-consuming nature of this stage of the LCA, there is a pressing need to identify a streamlined and effective solution [5]. Artificial intelligence (AI), such as large language models (LLM) or generative pre-trained transformers, could provide a solution to this problem. For instance, they could be used to simplify the literature search for secondary data. In our work we compared the effectiveness of traditional search engines, such as Google Scholar, with that of AI, such as a standard commercial LLM, in identifying secondary data.

## 2. Materials and Methods

Given the significant impact of batteries on the environmental impact of an electronic vehicle, this study employs the critical material natural graphite. In order to facilitate comparison, studies regarding the life cycle invenetory of natural graphite production are initially searched via Google Scholar. One found study is selected as a reference point for comparison with the results of the research conducted with a standard commercial LLM. In order to achieve the optimal result for a given search, prompts are created based on specific requirements. The responses generated by a standard commercial LLM are subjected to evaluation and compared with the reference study. In addition, the consistency of the standard commercial LLM is tested by asking the first prompt three times in the same chat and three times in a new chat. These answers are also compared.

## 3. Results and Discussion

### 3.1. Comparison between literature and GPT-generated inventory data

The comparison indicates that a standard commercial LLM, such as ChatGPT can provide an initial impression of the process steps and input and output flows. The process steps are generally similar or occasionally presented in a slightly more differentiated manner in the generative pre-trained transformer (GPT). Additionally, the numerical values provided for the flows are sometimes markedly disparate. It can therefore be said that the information provided by the AI,at this point of time and under the described circumstances, can serve as a basis for gaining insight into the processes, but that the individual materials and values would have to be checked and verified in order to serve as a database. However, the AI also states these limitations when asked about the data.

### 3.2. Consistency check

The consistency check indicated that the responses exhibited less variation when the same question was posed three times in the same chat than when it was posed in three different ones. However, none of the responses were identical to another. It can therefore be concluded that there is no consistency in the responses. Nevertheless, it can be posited that the responses from the GPT are sufficient to obtain a preliminary overview.

## 4. Conclusions

In this study, the potential of a standard commercial LLM was evaluated in comparison with traditional literature research and recent research in order to identify data that could be used for the LCA of natural graphite production. The findings indicate that while the GPT can provide a rudimentary framework and potential values for such process chains, it is incomplete and exhibits discrepancies when compared to the literature. Consequently, the utilization of a standard commercial LLM for such purposes should be approached with caution, as the AI provides inconsistent results. Nevertheless, the results are sufficient for an initial representation of the process. The discrepancies in the results may be attributed to the fact that the GPT was trained with general data sets rather than data specific to LCA or battery knowledge. Consequently, it is recommended that further research and development be conducted to create an GPT that is specifically designed for batteries and LCA. This would help to minimise the time spent on searching for LCI data and improve decision support.

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# 9,000+ deforestation carbon footprints for agricultural commodities: a global life-cycle inventory database

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## 1. Introduction

Our food systems are key drivers climate change, and unless we reduce agricultural greenhouse gas emissions we will not be able to meet the climate targets agreed upon in the Paris Agreement [1]. A key component of agricultural greenhouse gas mitigation is halting the conversion of tropical forests and other natural ecosystems to cropland and pastures: carbon emissions due agricultural commodity-driven deforestation is estimated to 2.3 GtCO2 annually [2], constituting 20-25% to total food system greenhouse gas emissions [3, 4]. Understanding the deforestation risk and associated carbon footprint of agricultural commodities and products is therefore crucial for guiding efforts to reduce agricultural commodity-driven deforestation, be it through private sector initiatives [5] or public policy [6].

Despite this, most life cycle databases still rely on old data sources and crude models to estimate life cycle inventory (LCI) data on land-use change (or ‘land transformation’ [7]) for agricultural products. For instance, the world’s most comprehensive LCI database, Ecoinvent, adopts the methodology developed by the World Food LCA database [8] (hereafter referred to as the WFLCAD method or model) to estimate land-use change LCIs for crops [9]. This model simply allocates deforestation to the crops that have expanded in area over the last 20 years, based on country-level data from the FAO on forest loss and crop area expansion, and estimating carbon emissions using IPCC tier 1 carbon pool default factors. This approach does not utilize recent years’ major advances in data pertaining to forest loss [10] and associated carbon emissions [11], allowing a better understanding of agricultural commodity-driven deforestation and its climate impacts [12]. It also excludes peatland emissions, which constitute about a fifth of total agricultural land-use change emissions [2]. Moreover, the WFLCAD model’s  simplified assumptions fail to account for key land-use change dynamics — land competition between cropland, pasture and other land-uses other, as well as cropland and pasture degradation and abandonment — important for the causal attribution of deforestation to agricultural commodity production.

## 2. Materials and Methods

Here we present a harmonized LCI database of deforestation and peatland drainage footprints for all crops in the FAO database, calculated using a model based on our current understanding of land-use change processes and available data on forest loss and carbon stocks. The LCI data is based on the Deforestation Driver & Carbon Emission (DeDuCE) model [13], which aims to identify deforestation—the permanent replacement of natural forests by other land-uses—across the globe to expanding croplands, pastures, and forest plantations. It then links this deforestation to the commodities produced on the deforested land and estimates the carbon dioxide emissions resulting from this land-use change.

The model does so by overlaying satellite data on forest loss with maps of specific crops (e.g., soybeans, oil palm, cocoa, and rubber) or of broader land-uses (e.g., croplands, forest plantations, and pastures) or deforestation drivers. Through a procedure that prioritizes data with higher spatio-temporal accuracy and detail, the model identifies where deforestation occurs and attributes this directly to a commodity using spatial data (e.g., soybeans) or to a broader land-use (e.g., agriculture or cropland). Where deforestation cannot be spatially attributed to a specific commodity, the model uses non-spatial agricultural and forestry statistics to assess commodity-driven deforestation in a two-step procedure: first, deforestation attributed to broad land-uses (e.g., agriculture or commodity production) is further subdivided between cropland, pastures, and forest plantations based on their relative (gross) expansion in a region (typically at country-level); second, deforestation attributed to cropland expansion (either based on cropland maps or statistics) is further allocated between different crop commodities in proportion to their respective increase in harvested area.

Finally, the model estimates carbon losses due to deforestation using maps of forest carbon stocks—in above- and below-ground biomass, dead wood, litter, and soils—and accounts for the carbon sequestered in the replacing land use. Furthermore, carbon dioxide emissions from peatland drainage are estimated by overlaying the identified deforestation data with a map of the global extent of peatlands.

The DeDuCE model leverages the computational capabilities of Google Earth Engine (GEE), enabling the processing of terabytes of high-resolution spatial data. The utilisation of GEE's vast processing capabilities, combined with Python's open-source programming, aligns with FAIR data policies, promoting accessibility and transparency. This way, we aim not only to ensure data integrity and replicability, but also to foster community engagement, inviting researchers and stakeholders to contribute, enhance, and broaden the model's scope, ultimately making it a valuable resource for the broader land-use and LCA community.

## 3. Results

The DeDuCE model provides over 9,100 unique deforestation and carbon footprint estimates—encompassing 176 countries and 184 commodities—for the period 2001 to 2022 (see www.deforestationfootprint.earth for data and visualizations). Here we present LCIs for year 2022, calculated using a 20 year amortization period. The dataset also includes a quality index for each LCI estimate, reflecting the accuracy and detail of the underlying data producing a given deforestation footprint. The higher the quality index, the more likely it is that the attribution represents direct deforestation for that commodity, identified using spatial data; a low index, on the other hand, reflects attribution using national-level statistics and hence can be used as a proxy for differentiating between direct land-use change (dLUC) and statistical land-use change (sLUC) estimates.

The database also includes sub-national LCI data for Brazil and Indonesia, which account for approximately 40% of annual tropical forest loss. Incorporating a model of international agricultural commodity trade, we enhance the accuracy of lowest-tier land-use change LCIs by replacing global production-weighted averages with consumption-weighted averages based on sourcing countries, providing a more precise estimation of carbon footprints.

## 4. Conclusions

Our study improves existing LCI databases by refining methods for estimating the deforestation footprint of agricultural commodities. This work supports private sector initiatives (such as corporate reporting under the SBTi FLAG initiative) and public policy (such as the EU Deforestation Regulation) in addressing agricultural commodity-driven deforestation and its climate impacts, representing a crucial step towards more sustainable food systems and effective climate action.

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# Prospecting for a biobased alternative – climate assessment of an industrial surfactant

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## 1. Introduction

Life cycle assessment (LCA) of a product under development is frequently hampered by questions of life cycle inventory (LCI) data availability. These range in character from the non-existence of fundamental data, through the challenge of scale-up, to intellectual property restrictions.

The case in question here is the development of a biobased alternative to a surfactant in use in the pulp and paper industry. Conventionally, the particular surfactant is a product of esterification of polyethylene glycol (PEG) with hydrophobic byproducts of the pulp and paper industry. The PEG is of petrochemical origin and therefore the target of substitution attempts in a recent Swedish research project aiming for a more circular chemical economy. Our laboratory work has investigated using glycerol products as an alternative to PEG. In practice, these products would have to come from an international supplier.

A fundamental question to be asked in such substitution efforts towards carbon cycle circularity is: do they generate a net environmental benefit or do aspects of the process outweigh the expected benefits of avoiding a fossil ingredient? Answering this question entails challenges associated with prospective LCA.

## 2. Materials and Methods

To answer the question, a simple greenhouse gas LCA was attempted with the functional unit being the production of a tonne of surfactant. Modelling was performed in an LCA for Experts (formerly Gabi) environment. The data availability was heterogenous. For the conventional system, primary industrial scale data for the foreground system were available. For the biobased system, primary laboratory scale data were available for the foreground system. Some commercial database information was available for background systems. However, the international supplier of the glycerol product was unwilling to share detailed data outside a non-disclosure agreement, making the creation of a transparent, publicly available LCA difficult. So we identified several possible raw materials for this chemical, including palm oil, sunflower oil and canola oil. As a starting point, palm oil was selected due to the relative abundance of such data, though future work would usefully consider the others.

One of the challenges in this LCA was the estimation of the energy requirement for initiating the esterification reaction. The forest industry byproduct is a blend of hydrocarbons for which obtaining heat capacities was not the straightforward question that it is for other substances of consulting the NIST database, for example. Therefore for this purpose a simple quantitative structure-activity relationship model was applied [1].

Another challenge was the identification of appropriate LCI data for the production of the glycerol product, which can depend on imaginative use of search terms. Among more than a dozen datasets that can be purchased from commercial suppliers with various raw materials for the glycerol and alternative allocation rules, the normal Sphera Managed Content (formerly "Gabi Professional Database") contains a model for glycerol production from palm oil methyl ester production. However, it cannot be found searching for glycerol – the synonym glycerine is necessary. Moreover, using the ecoinvent database in LCA for Experts additional glycerine data sets are available, but most of them are not shown unless the user searches using the term "esterification". This was more readily apparent by searching in the GLAD or openLCA Nexus metadatabases than in the original databases themselves. Other methodological matters are discussed further in the next section.

## 3. Results and Discussion

This is ongoing work and the outcomes are subject to refinement. The impact assessment results at this point are shown in Table 1. Allocation choices are present in background system data and unfortunately not always described in adequate detail for analysts to consider. For example, whether allocation between coproducts in the hydrophobic byproduct process is consistently rendered in relation to allocation within palm oil glycerol production may be asked. Under these circumstances, the analyst needs to be assured that the potential differences between bottom lines for alternative products are different enough to withstand potential uncertainties in allocation methods. In this case the biobased alternative appears to be preferable to the conventional product by almost a factor of 3. The superiority of the biobased product in this regard was expected but not taken for granted, given previous experience in the assessment of e.g. proposed biobased nappies which revealed the opposite [2], and other work on fuels and carbon fibres where the outcomes were sensitive to methodological choices [3,4]. In this case it is expected that even if alternative glycerine sources or allocation choices are taken into account the biobased product will retain the lowest impact.

| Case<br>Major contributor | Conventional | Biobased |
|---|---|---|
| | kg CO2-e/tonne surfactant | |
| forestry + kraft pulping | 280 | 235 |
| acidulation | 10 | 8 |
| distillation | 13 | 11 |
| ethylene oxide | 824 | |
| glycerine | | 414 |
| electricity | 7,3 | 10 |
| catalyst | | 0,0009 |
| other | 10 | 9 |
| EoL emissions | 824 | |
| | 1968 | 687 |

***Table 1: Preliminary results of product comparison***

An additional methodological question arose during the calculations regarding how to best consider the embodied carbon in the biobased product versus the fossil product. One possibility would be to report the contributions to climate change of a cradle-to-gate LCA including biogenic carbon, in which case the biobased product would show a credit and the fossil product none. Instead we chose a consequentialist alternative: to use an indicator that excludes the biogenic carbon and also to count the emission of carbon dioxide on breakdown of the fossil product after use. While this creates disconnected system boundaries over the life cycle (cradle to gate, no use phase, plus part of the end of life) there are precedents for this (e.g. [5]). Experiments with the former approach generated some strange results on account of the need to instead allocate emissions (and carbon sequestration) between wood products and byproducts built into the LCI database, so we were happy to avoid this - ISO14044 instructs us to avoid allocation if possible.

## 4. Conclusions

This work showed the value of QSAR application in LCI data acquisition, the benefit of looking to LCI metadatabases, the need to be creative using search terms in commercial software and the value of selecting system boundaries and indicators in a way that is consistent with the question under evaluation. It also quantitatively showed a benefit in substitution of biobased raw materials in an industrial chemical.

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# Applying LCA on Artificial Intelligence (AI) systems

## Status quo, challenges, and opportunities

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## 1. Introduction

The use of AI-based technologies is expanding to all aspects of modern life, from everyday-life applications to politics, defence, healthcare, economy, science, and others. An area of extended efforts covers AI applications that solve sustainability issues or contribute to the Sustainable Development Goals (SDGs). However, AI systems are complex, requiring advanced infrastructure, large quantities of data, and high use of energy, which result to various environmental/sustainability impacts throughout their life cycle. These impacts should be identified, assessed, and quantified through practices similar to other industrial sectors. In this study, we created an overview of the scientific work that has been done in this field, and recorded the so-far studied environmental impacts, as well as the applied methodologies and specifically the use of Life Cycle Assessment (LCA) on AI systems. The goal of this study was to shed light to the following research questions: Which environmental impacts of AI systems have been assessed so far? Is LCA a broadly used methodology for this purpose? What are the challenges and opportunities of applying the LCA method on AI systems? This is an initial step to the long trip that will enhance the environmental responsibility of the AI community.

## 2. Materials and Methods

To answer our research questions, we carried out an extensive literature review on the environmental impacts of AI systems and the relevant methodologies that have been applied. We used three different approaches, as shown in Table 1: key word search in classic search engines (Scopus and Google Scholar), AI-based tools for literature review (Connected Papers), and snowballing.

| **Approach** | **Explanation** |
|---|---|
| Key words | “environmental impacts” and “artificial intelligence”; “LCA” and “artificial intelligence”; “green AI”; “sustainability of artificial intelligence”; “sustainable AI”; “life cycle assessment” and “machine learning”; “general purpose AI systems” and “environment”. |
| AI-based tool | Graph with publications relevant to [1] created with Connected Papers. |
| Snowballing | Backward and forward from [2], as a reference publication with applied LCA on AI systems. |

***Table 1: methodological choices for the literature review.***

The literature review was carried out in November-December 2023 and refined in March 2024. As this is a rapidly evolving sector, new publications may have been released in the meanwhile. With this work, we would like to acknowledge and stress the urgency for action in systematically studying the impacts of AI systems.

## 3. Results and Discussion

Through these three approaches we identified 634 publications in total. By screening the abstracts and removing duplicates, we ended up to 39 eligible studies and 17 relevant supporting publications for knowledge building (Figure 1). Importantly, the LCA methodology has been used or mentioned in four publications, but only one presented in detail its application on the estimation of environmental impacts of AI systems.

**Main findings:**

a. The first, few publications on the topic appeared in 2018-2019, following the AI burst that started in the early 2010s. The published work presents a significant increase in the years 2020-2023, with an exception in 2021 (assumingly due to the period of pandemic, which slowed down all activities).
b. Most studies assess the climatic impacts of AI systems by estimating energy consumption and/or GHG emissions. The assessments refer to specific life cycle stages (e.g. algorithm training), and in few cases to the whole life cycle of AI systems.

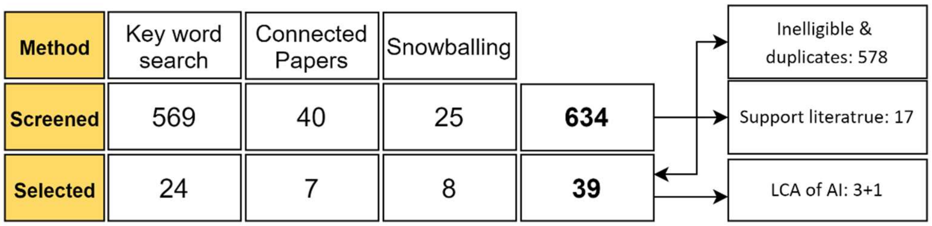

***Figure 1: Overview of results of literature review.***

c. The methodological approaches present a broad variability and are often own-developed methodologies. Among others, two online, open-access applications offer researchers the possibility to calculate the carbon footprint of their AI models: ML $CO_2$ impact [3] for machine learning models, and Green Algorithms [4] a carbon footprint calculator of computation.

d. Publications with LCA as key methodology: i. [5] introduces the life cycle perspective of AI systems in 2020 by developing a practical guide for ML practitioners for the estimation of carbon emissions and the energy consumption during the whole life cycle of ML models; ii. [2] goes beyond the assessment of energy use or carbon footprint and study all 1st order impacts and suggest an attributional LCA framework to reflect the complete life cycle of AI systems; iii. [6] presents a holistic life cycle approach by including impacts from manufacturing and product use and refer to LCA for quantifying carbon footprint; iv. [7] presents LCA of ICT goods, networks, and services, and is included here as a complementary (if not basic) set of guidelines for applying LCA on AI systems.

e. Researchers indicate the need for deployment of LCA for assessing “the usefulness of AI services” [2], for adjusting further the LCA methodology (attributional & consequential), and for including sustainability assessment in the quality and system performance evaluations [6]. [8] proposes a methodological framework for LCA of AI systems, but the framework has not yet been tested.

f. Applying LCA on AI systems can be beneficial for the assessment of the environmental impacts of AI thanks to the incorporation of the life cycle perspective and the expansion of assessed impacts. Potential challenges include the definition of system boundaries and functional units of the service provided by AI.

## 4. Conclusions

The results of this study uncover the lack of common methodological approaches and the limited application of LCA for assessing the environmental impacts of AI systems. What is missing from the big picture is the active contribution of sustainability professionals and LCA practitioners that will provide scientifically sound estimates and analyses through cross-discipline collaborations with AI/software developers and data scientists, but also with other scientists that will contribute to understanding other (direct and indirect) implications and risks imposed by AI. Methodological challenges are also to be addressed for a valid evaluation of the environmental impacts of AI systems throughout their life cycle.

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# Application of LCA to document Carbon Dioxide Removals (CDR) from Pyrolysis and Incineration of Waste

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## 1. Introduction

Pyrolysis is a waste treatment method which, in the same way as incineration with energy recovery, can be combined with Carbon Capture and Storage (CCS). Based on the amount of biogenic carbon in the waste, both pyrolysis and incineration with energy recovery have the possibility of removing carbon dioxide from the atmosphere. This study aims to demonstrate how LCA can be used to model different treatment methods to comparably document their Carbon Dioxide Removal (CDR) potential. This is relevant for upcoming certification schemes for CDR, such as the EU carbon removal certification framework of which the European Parliament and the Council of the EU reached a provisional agreement on February the 20th 2024 [1] and the Puro Standard [2], a standard for carbon removal methods in the voluntary carbon market.

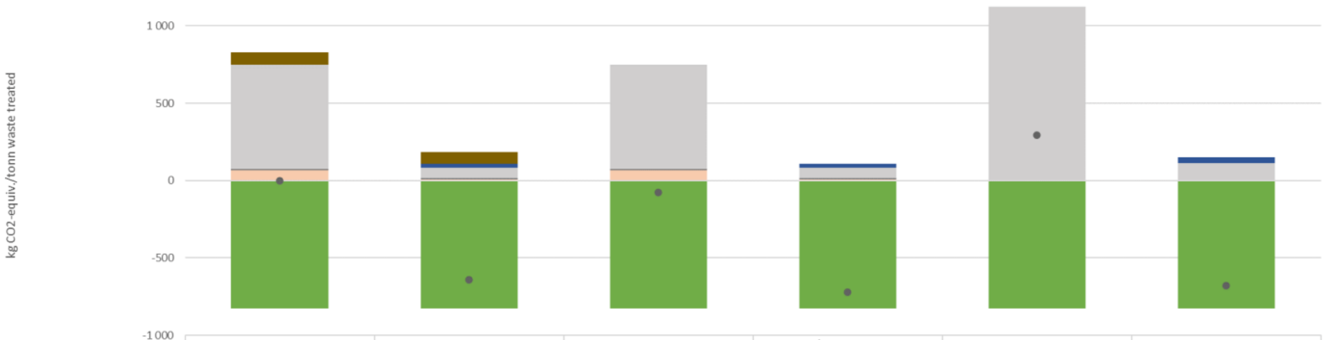
## 2. Materials and Methods

A scenario-based screening life cycle assessment (LCA) approach is applied through a zero-burden approach for waste LCA modelling in SimaPro® [3]. The functional unit is treatment of one tonne of waste with a certain share of biogenic and fossil carbon content. According to [4], an important criterion for determining whether a technology results in negative emissions is that the total quantity of atmospheric greenhouse gases removed from the atmosphere and permanently stored must be greater than the total quantity of greenhouse gases emitted to the atmosphere. The selected system boundaries for the analysed system are hence of importance.

In this study, both uptake and release of biogenic CO2 is included in order to visualize the biogenic share of the waste. Uptake of biogenic CO2 is connected to the biogenic carbon content, which is a physical characteristic of the waste. Emissions of biogenic CO2 are assumed to cause the same climate change as fossil CO2. In total, uptake (biogenic carbon content in the waste) and emissions of biogenic CO2 will cancel each other out, if not biogenic CO2 is stored. Two scenarios are analysed for pyrolysis: 1) the main scenario assuming that the charcoal consists of 20 % volatile carbon, which is released as CO2 [5], and 2) a scenario assuming that no volatile carbon remains in the charcoal, such that 100% of the carbon content in the charcoal is permanently stored [6, 7]. When adding negative and positive emissions throughout the value chain, potential net negative emissions are documented as CDR. The pyrolysis and incineration systems are analysed with and without CCS connected to the emission point source being the flue gas from either combusting the pyrolysis gas or from incinerating the waste.

## 3. Results and Discussion

The results for net negative emissions, as well as contributions for the included life cycle stages, for the analysed scenarios are shown in Figure 1.



| | Pyrolysis | Pyrolysis w/CCS | Pyrolysis_char permanently stored | Pyrolysis w/CCS_ char permanently stored | Incineration | Incineration w/CCS |
|---|---|---|---|---|---|---|
| ■ Char storage | 77 | 77 | | | | |
| ■ Capture and storage | | 26 | | 26 | | 39 |
| ■ Combustion pyrolysis gas/waste | 677 | 68 | 677 | 68 | 1122 | 112 |
| ■ Pyrolysis process | 9 | 9 | 9 | 9 | | |
| ■ Drying process | 65 | 6 | 65 | 6 | | |
| ■ Biogenic CO2 content | -829 | -829 | -829 | -829 | -829 | -829 |
| ● Negative emissions | -2 | -644 | -78 | -720 | 293 | -678 |

***Figure 1: Results for net negative emissions and contributions from the included life cycle stages, for the analysed systems and scenarios. Net negative emissions are presented as grey dots.***

As seen in the figure, all the scenarios, except incineration without CCS, lead to net negative emissions. Pyrolysis might result in net negative emissions even without CCS since treatment of the charcoal itself leads to carbon storage. If CCS is added to the combustion process of the pyrolysis gas, the net negative emissions will increase radically. For waste incineration with energy recovery, net negative emissions can only occur in the combination with CCS.

## 4. Conclusions

The study shows how potential Carbon Dioxide Removals (CDRs) from different waste treatment methods can be modelled in LCA by including the uptake of biogenic CO2 as biogenic content in the waste under study.

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# Is the current LCA practice really measuring the environmental consequences of material circularity?

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## 1. Introduction

Industry is nowadays under pressure to fulfill and align with many environmental policy-related requirements, at different scale (product, process, plant, corporate) and that in many cases requires the application of methodologies that are not coherent each other. Companies are asked to report on circularity and on other environmental aspects (e.g. Climate change), and LCA is clearly mentioned and in some cases also prescribed as the methodology to quantify results and track progresses.

A key point of discussion in the scientific community is the modelling of waste and scraps, both pre- and post-consumers. In the current LCA practice, a scrap from a previous and different product system is basically marked as recycled material, then it is considered to substitute (partially or totally) virgin materials. While such consideration seems to be logical and aligned with the circular economy concept to feed used materials back into the product system (among others), it does not necessary capture properly the environmental footprint of a product using that scrap as input in the subsequent product's cycles. Indeed, there is not consideration about the scrap source (pre or post-consumer) and, in the case of pre-consumer scrap, about the origin of material from which the scrap originates (primary or post-consumer).

While existing LCA standards do not specify modeling requirements connected to scrap source, few guidelines and/or product categories rules [1] require to consider the pre-consumer scrap as a co-product, suggesting allocation approaches for the accounting of related impacts, e.g. on a mass base or on an economic base. This has consequences on the footprint of products using pre-consumer scrap, which can be higher or lower, depending on the specific material and/or the specific step of the value chain.

Currently, discussion is ongoing about several aspects linked to scraps modelling, which range from the need to define common rules for the specific sector [2], investigating the potential approaches and their implementability, to the assessment of (and availability of data) innovative recycling technologies, such as chemical recycling, especially in the plastic sector.

The article presents two simplified case studies on metals and plastic products where scrap is used as input, as basis for arguing about the implication in the environmental footprint assessment and on consideration about product's circularity. Variation of the environmental footprint of circularity is measured as a consequence of assigning a scrap with a material impact or not. Considerations and insights are provided to support key message associated to benefits/impacts of Circular Economy practices.

## 2. Materials and Methods

Two simplified case studies are analyzed where recycled material can be used to cover 100% of material input. The first case study is an extruded aluminium profile made out of a secondary ingot from the remelting of pre-consumer scrap only, whereas the second one is a plastic extruded profile manufactured with granulate coming from grinding of waste pipes at pipes producers. Table 1 reports the characteristics of the analyzed products.

| | **Material** | **Recycled content** |
|---|---|---|
| **Plastic profile** | Regrinded polypropylene | 100% |
| **Aluminium profile** | Remelted alumium | 100% |

***Table 1: Description of case studies***

In both cases the study considers the raw material supply and the extrusion process at the extrusion site, both modeled with European average processes and for sake of simplicity, the extrusion scrap is set at minium (less than 1%). Both case studies are analyzed with a two-fold approach:

- Approach “zero material burden”: since the input material is from scrap, which is considered to have no environmental burden
- Approach “pre-consumer scrap as co-product”: the post-consumer content in the scrap entering the process is considered. No information is available about it, thus it is conservatively set to 0%.

To this regard, when applying the zero material burden approach, the aluminium impact is only due to the remelting process for ingot production and the plastic impact is only due to the recycling process (shredding and washing). When applying the pre-consumer scrap as co-product approach, aluminium takes the impacts of the average primary aluminium consumed in Europe, whereas the plastic is fully modeled as virgin granulate. The environmental footprint is quantified with the Life Cycle Impact Assessment (LCIA) method recommended by EN15804+A2 and reported with reference to the Global Warming Potential total (GWPtot) and Resource use, mineral and metals (ADPe).

## 3. Results and Discussion

Results show that the approach on how to consider the scrap has a significant influence of the environmental impacts of the analyzed products. In absolute terms, results according to the zero-burden approach are significantly lower than results according to the co-product approach. In addition, when applying the co-product approach, the material pops up as key contributor to the product impact (Figure 1).

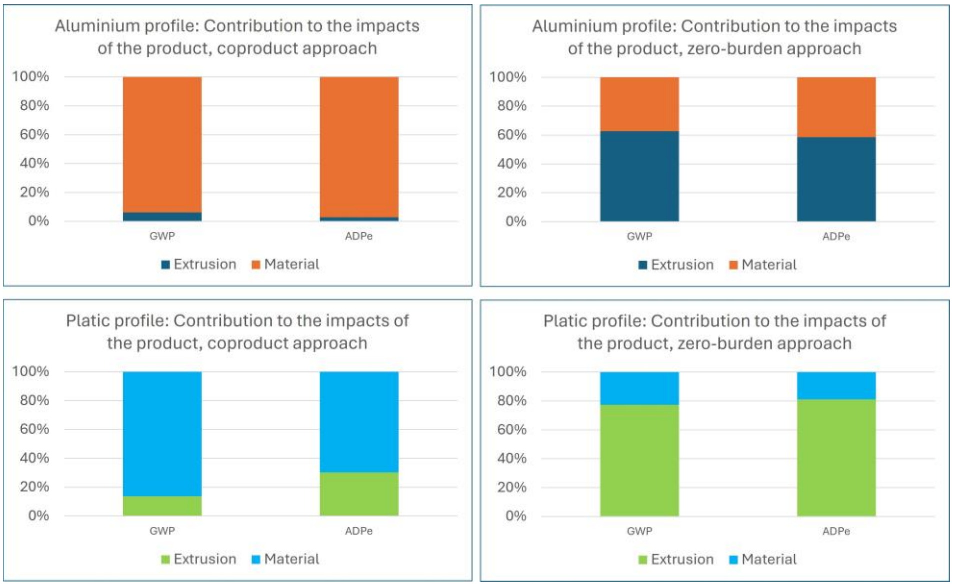

*Figure 1: Contribution of material and processing to the impacts of the analysed products.*

The analyzed case studies are extreme case studies intented to describe the range of impact variation. Of course, the effective variation is depending on several other factors. Apart from the scrap content in the used material (which can be lower than 100%), for some materials/applications, considerations should be done on the quality of recycled materials. Moreover, the % of scrap produced at the extrusion site also affects the results. Lastly, the reported case studies are cradle to gate as they are intended to raise the point on what each value chain actor can and has to communicate to avoid bias. In a life cycle perspective, the end of life has to be included, which is also affected by the decision applied for the cradle to gate and would also deserve further considerations related to the uncertainty of end of life scenarios.

## 4. Conclusions

The LCA is a powerful tool to assess the environmental impacts and to allow a conscious selection of products by consumers and, to this aim, the approach applied to modeling scrap should be always clearly communicated. In addition, when the LCA role is also to support the environmental improvement of the businesses and sectors, further considerations should be done on the way in which the circularity benefit is quantified, to avoid misleading claims and to effectively support circularity strategy implementation.

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# Comparing Life Cycle Assessment between bio-based and fossil-based products – transition to a bio- and circular economy demands fair comparisons.

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## 1. Introduction

The use of biobased resources is part of the solution of a circular society and are in many cases compared with fossil resources for products delivering the same function. However, such comparisons are often influenced by inconsistent handling of in the LCA set-up, such as system boundaries, modelling assumptions and data asymmetry in the inventory. These circumstances challenges attempts to make fair comparisons, both on policy level but also on more detailed levels.

Compared to fossil-based products, innovative bio-based products are still a smaller sector with less market coverage while their potential contribution to reducing climate impact in many product systems can be significant. It is thus important that credible and trustworthy LCAs are performed, both to gain increased knowledge about newer product systems and to make comparisons that can point to important differences and lead development towards increased circularity in the society.

## 2. Method

Several approaches have been made to give framework and guidance to the sometimes-challenging prerequisites to make trustworthy and credible LCAs for comparisons using the two different sources for resources.

There are several published guidelines and frameworks concerning the issue, yet the experience in many situations is that comparisons between bio-based and fossil-based use of resources for equivalent functions are failing. It can be already in the basic assumptions for the goal and scope of the LCA, like performance of the product and system boundaries since the systems are often fundamentally different. For the inventory it can be data asymmetry that is not solved properly, as data for the fossil system often are based on processes that are developed since long, compared to in many cases emerging technologies for the bio-based systems. This creates challenges that must be dealt with for meaningful comparisons. It can further be decision rules for assumptions and finally of course the impact assessment; whether to use 0 as characterization factor for biogenic carbon, or -1/+1, i.e., how to handle emissions and removals of the biogenic carbon.

## 3. Result

Mandated in 2012, the European standardization committee for 'Biobased Products', CEN/TC 411, has developed a set of standards for supporting the biobased sector. European standards were developed for measuring and reporting on biobased content, how to perform LCA on bio-based products, the sustainability aspects of these products and valid terminology to mention some.

In 2021 the technical report of the Joint Research Center “Life Cycle Assessment (LCA) of alternative feedstocks for plastics” was published. The work did involve stakeholders, but the final technical report was in some cases found to not fully solving the issues of these comparisons as indeed they are a complicated issue.

As a further effort for correct comparisons between bio-based and fossil product systems work started in 2022 to initiate yet another standard document for the support of LCA comparing these systems. The suggested work was approved and under the Dutch standardisation body and Swedish leadership and secretariat there is now the development of the European standard, EN 18027: *Additional requirements and guidelines for comparing the life cycles of bio-based products with their fossil-based equivalents*. The document was out for enquiry ballot in 2023.

During the enquiry ballot of a CEN standard the draft is sent for public review in all the 34 member countries. This means that the draft standard is publicly available for commenting. prEN 18027 gained 100% approval. 6 countries provided comments as well as ECOS (Environmental Coalition on Standards, a collaboration between environmental NGOs for the purpose of standardization). Informal comments were also received from the European Commission (DG GROW and JRC). Now, these comments are addressed by the responsible working group, CE/TC 411/WG 4 Bio-based products – Sustainability criteria, life cycle analysis and related issues. This is expected to be finalized before the summer and the standard is expected to be published at the end of 2024.

One focus area of the standard is issues that are especially important for this type of comparisons, where differences between the product systems easily can appear and needs to be handled in a structured way for the modelling and calculations.

In addition, the standard stresses the fact that it is important to perform comparisons correctly following the international LCA standards, ISO 14040, and ISO 14044. The latter document gives clear guidance when doing comparisons between systems by listing pre-requisites and requirements for fair and transparent documentation of system boundaries, methodological assumptions, assumptions in models and evaluation and use of data. Differences between the two systems shall be thoroughly investigated and analysed in the Interpretation phase of the LCA to make correct conclusions of a comparison study. This means that the document not necessarily comes with the exact descriptions, data sources and strict calculation rules for the comparisons, it is rather an attempt to encourage and urge for applying what there already is in the international LCA standards when it comes to comparisons between systems.

## 4. Conclusions

Performing LCAs to establish environmental profiles of materials and products to give important guidance for product development and support findings of improvement areas, compare alternatives and eventually also support self-declared claims for consumer products finds of course numerous challenges. However, for improved circularity in the society, including evaluation and assessments of alternative materials, it is increasingly important to also relate to what has been in the international standards for LCA since the very beginning. Make clear and transparent LCAs, justify and document different choices and assumptions. Data quality requriements shall be stated and the data quality shall be assessed when the assessment is done. Yes, choices can very well be value based, but there is nothing saying that value based choices cannot be done in a scientific and structured way, again by documenting transparently the choices.

As for the important LCA phase of interpretation, do the necessary parts such as identification of significant issues, evaluation of completeness, sensitivity and consistency check meaning that assymetry or imbalances of the compared systems are dealt with. Finally, let the conclusions reflect the findings of the earlier steps of the phase and present limitations and recommendations in a clear and transparent way. There are many challenges when comparing product systems that can differ in maturity as well as in basic prerequisites, but to perform a good LCA will still give good information to be used.

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# Future Nordic developments through learning from successful life cycle network

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## 1. Introduction

The Swedish Life Cycle Center, established in 1996 and hosted by Chalmers University of Technology, is a center of excellence that fosters collaboration among academia, research institutes, industry, and government agencies. Its goal is to advance and apply Life Cycle methodologies. The Center is a recognized player within the field with its multidisciplinary methodology and collaboration between researchers, practitioners and decision makers. By gathering Swedish life cycle competence and front running companies, it has been instrumental in development and adoption of the life cycle perspective in society, making important contributions to international initiatives. Insights, outcomes from collaborative dialogue groups and projects will be shared during the presentation. What can be learned from a long and successful journey and how can the center and the strong Swedish network be of benefit for the future development of Nordic LCA collaboration and development?

## 2. Materials and Methods

To address challenges expressed by our partners the Swedish Life Cycle Center makes use of collaborative methodologies, bringing together diverse stakeholders. The Center's activities include regular meetings, workshops, seminars, and the establishment of working and expert groups as well av providing opportunities for networking and competence building. These methods enable the Center to gather and analyze data, share best practices, influence policy development and create joint learning within the network. The network of partners form a platform for e.g., sharing best practice, common strategic intelligence, discussion on hands on issues, education and learnings from different business sectors. Three initiatives will be more thoroughly presented at the conference:

### Government Agency group

Since 2016, the Center has organized a dialogue group involving nine Swedish government agencies. This group meets regularly to share experiences and collaborate on national initiatives, such as LCA-data.

### Expert Group on Environmental Footprint

The Center has since 2014 hosted a national expert group on Environmental Footprint, focusing on EU Environmental footprint methodologies. The group actively supports and coordinates Swedish representatives in the Technical Advisory Board (TAB) and is an arena for both discussions, sharing of strategic business intelligence as well as initiation of research projects.

### Nordic Dialogue Forum for LCA, Climate, and Buildings

During 2019-2023 the Center hosted the Nordic Dialogue Forum for LCA, Climate, and Buildings. This forum was aimed at creating a dialogue around harmonization of Nordic building regulations concerning climate emissions. The Swedish Life Cycle Center coordinated a working group and Dialogue forum that included representatives from Nordic building authorities, academia, and industry.

## 3. Results and Discussion

Operating as a neutral platform, the Centre allows for mutual project development and co-creation among researchers, practitioners, and decision-makers. This neutrality is supported by a strong academia base, ensuring scientific credibility and transparency. The Swedish Life Cycle Center emphasizes cross-sector solutions, facilitating dialogues and common projects across different sectors in the life cycle field. The Center, by uniting Swedish life cycle expertise and leading companies, has played a key role in promoting life cycle approaches in Sweden’s society, industry, and government agencies. It has fostered learning and competence through the development of methods, tools, and practices, involving numerous individuals and organizations. The Center has also contributed significantly to international initiatives and global harmonization, initiating new collaborations. With almost 500 professionals across the Swedish Life Cycle Center formal network of partners and with its government agency dialogue, the Centre has been invaluable to Sweden’s capacity-building in the life cycle field, within companies, among government agencies and at universities.

The Expert group Environmental footprint has contributed to a better understanding of the methods and their impact, both from a policy perspective and from an industry perspective. It has also been a successful arena for initiation of new research projects and competence building activities.

The dialogue group for government agencies has enhanced competence among agencies and influenced life cycle-based policies in Sweden, particularly in areas like building and construction, procurement, and sustainable consumption.

By facilitating the Nordic Dialogue Forum for LCA, Climate, and Buildings the Center took a step towards the Nordic arena and outputs from working group meetings and the dialogue forum have been highly valued input for the building authorities in the development of regulations concerning climate emission from buildings. In 2023 a roadmap for harmonising building regulation concerning climate emissions was published as one of the outcomes from the collaboration.

## 4. Conclusions

The Swedish Life Cycle Center has played a pivotal role in advancing LC methodologies and fostering collaboration among key stakeholders. Its work has significantly contributed to policy development, competence building, and the practical application of LCA in various sectors. The Center's initiatives, such as the government dialogue group and the expert group on Environmental Footprint, have influenced national and EU-level policies and increased the adoption of life cycle thinking. The Nordic Dialogue Forum has successfully contributed to the process of harmonizing building regulations which highlights the importance of collaborative efforts. These findings underscore the relevance of the Center’s work and its potential to drive future advancements in life cycle competence and sustainable practices. The opportunities created for mutual learning and capacity-building impact upon society and drive the life cycle field forward.

We would like to ask the session participants a question: What can be learned from a long and successful journey and how can the center and the strong Swedish network be of benefit for the future development of Nordic LCA collaboration and development?

# LCA modelling of the environmental impacts of river sand and aggregates mining

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## 1. Introduction

Mainly used in the construction and maintenance of buildings and infrastructures, sand and gravel (hereafter grouped under the name “aggregates”) account for 68% of non-metallic materials extracted worldwide [1]. Global demand for aggregates sharply increased during the last century: between 50 and 60 billion metric tons of aggregates are extracted every year, 41% of which extracted in Europe from rivers (Fig. 1). The impacts of river aggregates extraction are numerous: changes to the hydro-geomorphological functioning of rivers, modification and direct destruction of aquatic habitats, turbidity, pollution, scouring of structures, etc [2]. This proposal aims at (I) characterizing and classifying environmental impacts related to river aggregates extractions, (II) defining a methodological framework to take into account the hydrogeomorphological impacts associated with such extractions, in a Life Cycle Assessment (LCA) perspective.

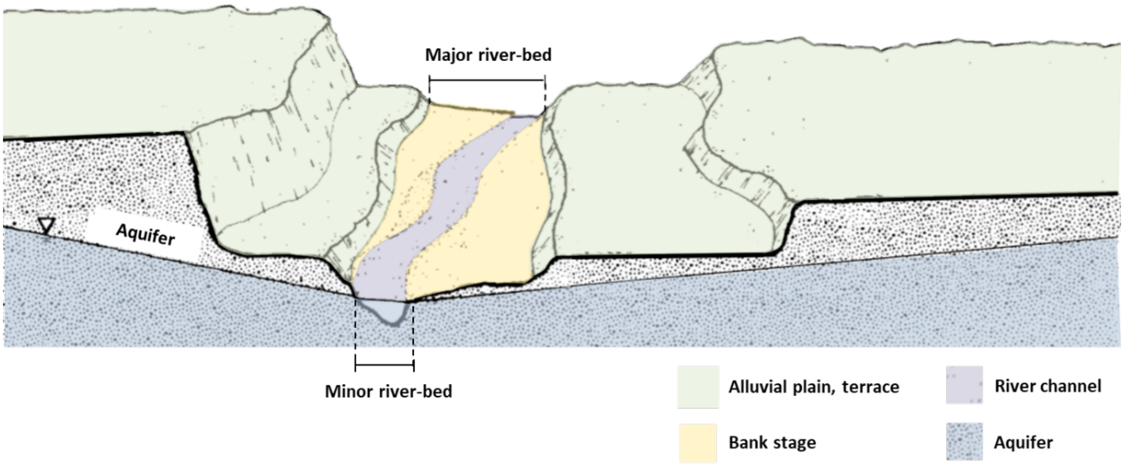

*Figure 1: River section.*

## 2. Materials and Methods

We propose a characterization and classification of extractions based on two parameters: extraction zone (dry or wet) and extraction technique (mechanical or hydraulic). The impacts associated with river aggregates extraction for a given technique and area are organized into four interdependent categories: impacts on the physical environment, impacts on the natural environment (impacts on the quality of the environment, living organisms and habitats), impacts on the landscape and human impacts (Fig. 2). The physical (hydro-geomorphological) impacts are more specifically described in terms of upstream erosion, downstream erosion, lateral instability and bed and banks coarsening. Finally, a revised list of instream incision impacts is given [3, 4].

## 3. Results and Discussion

Based on this categorization of impacts and considering existing life cycle impact characterization models, we define a methodological framework for the modelling of hydro-geomorphological impacts at midpoint level. A modelling of the causal chain from minor river-bed extraction to incision and subsequent lowering of the water table is proposed (Fig. 3). It links a mass of aggregates extracted from the minor river-bed to a water deficit per surface unit. Two sub-models are used: one to describe the topography of the valley, the other the lowering of the water table [5, 6].

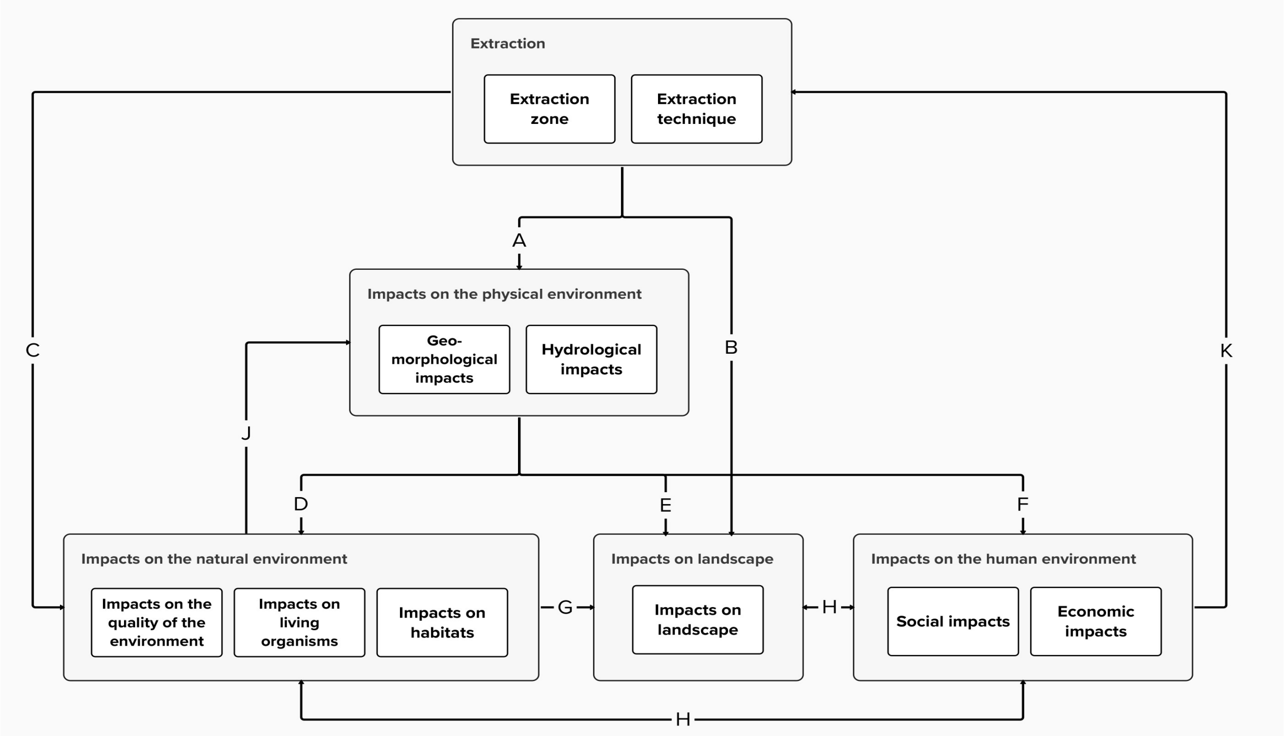

***Figure 2: Categorization of impacts related to river sand extraction.***

The model is tested for a simple configuration. It describes the evolution of the river profile as a function of time and the evolution of local groundwater deficit as a function of the mass of aggregates extracted from the minor river-bed.

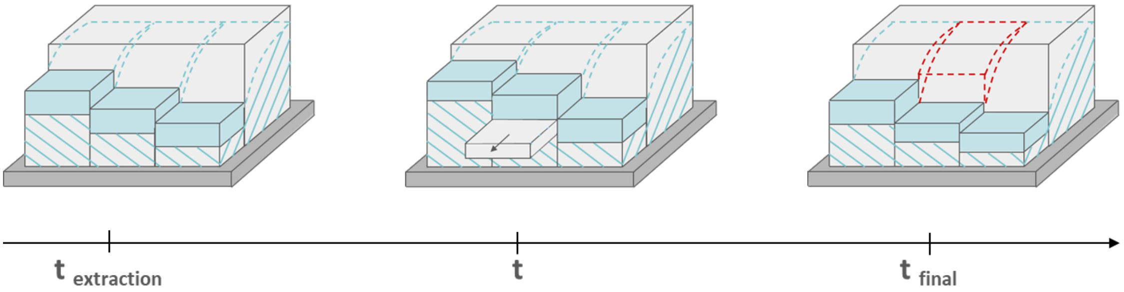

***Figure 3: Midpoint modelling: from minor river-bed extraction to incision and subsequent lowering of the water table.***

## 4. Conclusions

This work sets the basis for the characterization of impacts of aggregates extraction in rivers. Particular attention should be paid to archetypes of extracted aggregates, considering river and climate types, extraction zones and extraction techniques. Another challenge is to have the corresponding elementary flows available in life cycle inventories.

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# Environmental Product Declarations in Procurement – Practical Experiences with focus on Concrete Sleepers

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## 1. Introduction

Climate change have increased the emphasis on environmental sustainability across many sectors. The European Union (EU) has established ambitious climate goals, accompanied by stringent legal requirements for climate mitigation. In the construction and civil engineering sector, the production of construction materials constitutes some of the most energy and carbon-intensive processes. The development and implementation of innovative techniques and methods to reduce these emissions are critical to achieving the EU's climate goals.

In Sweden, the Swedish Transport Administration (STA) has implemented climate requirements in the procurement process [1]. The aim is to support the zero-emission target by 2040 and ensure that the agency's actions align with Sweden's and the EU's climate goals. Environmental Product Declarations (EPDs) has played a crucial role as verification documents for climate requirements. This abstract aim to consolidate practical experiences of EPDs in the procurement process as well as highlighting success factors and challenges. Practical experiences from STA's work with climate requirements, as well as experiences from the current suppliers of concrete sleepers (Sateba Sweden and Heidelberg Materials) will be used as examples.

## 2. Materials and Methods

This abstract encompasses a compilation of the STA's procurement process and experiences of climate requirements on construction materials such concrete sleepers. In addition, two semi-structured interviews were conducted with representatives from the current suppliers of concrete sleepers focusing on how the requirements functioned in the procurement process, as well as the resulting climate mitigation measures.

## 3. Results and Discussion

In 2016, STA developed a process to set climate requirements for construction materials. The STA has also developed complementary percentage-based climate requirements for entire projects [1]. The climate requirements were inspired by the results from a collaborative industry project titled 'Verified Climate Impact of Construction Structures' [2], in which EPDs according to EN 15804[1] were suggested as a standardized way to verify the climate impact of construction materials.

The process of using EPDs as verification documents for climate requirements has evolved over time. Concrete sleepers were one of the first covered construction materials. Initially, STA only required the suppliers to provide an EPD. This gave STA information about the magnitude of climate impact for concrete sleepers. Subsequently, climate requirements were introduced, based on an industry average. The suppliers needed to perform at least as well as a predefined threshold. The STA further developed the climate requirements by introducing a bonus that was granted to the sleeper suppliers if their climate performance was better than the predefined threshold and capped at 2% of the total sales price. The maximum amount of bonus could be achieved if the suppliers performed 10% better than the predefined threshold. Today, requirements on EPDs and climate performance as well as bonuses are integrated elements in the procurement process at the STA, for concrete sleepers, rails as well as other materials. The predefined thresholds are continuously being sharpened over time (adjustments are being made when renewing framework agreements).

The gradual sharpening of climate requirements has stimulated the suppliers to progressively integrate climate mitigation into their business models. Climate requirements have led the suppliers to map and analyze their processes, defining actions to reduce climate impact, such as reducing the climate impact from

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[1] EN 15804 is a European standard that provide Product Category Rules (PCR) for Type III environmental declarations of construction products or services [3].

purchased goods and services, developing new concrete recipes, and sourcing of renewable energy [4, 5]. Notably, one supplier mentioned that their production philosophy was expanded such that the productivity should not come at the expense of climate performance [5].

For STA, the decision to use EPDs as verification document has been successful, partly due to i) Transparency: EPDs are third-party verified and publicly available through program operators, ii) Predictability: Common calculation rules to ensure consistency, iii) Equity: Assessment on equal terms. However, there are also some challenges associated with the use of EPDs as verification documents. One of the challenges pertains to the Mass Balance Approach (MBA). This technique involves allocating flows with specific characteristics (such as inputs and outputs of biobased materials or recycled content) within the manufacturing process to specific products. MBA is sometimes also being used for allocation of electricity with Guarantees of Origin (GoO). ECO Platform[2] stated on the 19th of January 2023 that MBA shall not be used, but there is not yet consensus among all program operators regarding the use of MBA. The handling of published EPDs applying MBA has also been different depending on the date of publication [6]. Hence, the STA might receive EPDs with different approaches to MBA which affects the comparability. This also had implications for one of the suppliers who needed to revise their EPD due to their subcontractor's use of MBA in their EPD [4]. There has also been insufficient guidance in EN 15804 related to data quality requirements. For instance, the STA has noticed that in some cases a choice of average data over supplier-specific has led to improved EPD-results regarding Global Warming Potential (GWP).

Questions have arisen regarding whether the STA should introduce supplementary requirements on EPDs beyond those outlined in EN 15804, when there are ambiguities or not enough clarity in the standard. However, the STA's standpoint is not to introduce additional requirements so far. The reason is to avoid complicating the process and to ensure consistent climate requirements independent of procuring organization.

Climate mitigation measures have traditionally not been cost-prohibitive. However, a noticeable trend shift is occurring, prompting to question the cost of climate transition for procuring organization as well as private companies [4, 5]. Recent calculations by the STA, based on predicted prices for allowances, indicate that reaching EU's climate goals imply a cost corresponding to approximately 2% of the total budget for construction, operations, and maintenance over the next 12-year planning period [7]. The suppliers need to transform to climate neutral technologies to stay competitive and financial incentives will most likely be needed. It is yet uncertain to what extent this can be met by procuring organizations. To find a mutual approach for the different stakeholders that enables the necessary steps to be taken towards climate neutrality is an urgent issue for the years to come.

## 4. Conclusions

EPDs serve well as verification documents for climate requirements in procurement process. However, there are certain pitfalls such as inconsistent usage of MBA as well as unclear data quality requirements. Climate requirements based on EPDs have contributed to climate mitigation measures and has become a guiding mechanism from a business perspective. However, when striving for climate mitigation, finding the right balance between climate transition and financial feasibility becomes crucial.

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[2] The ECO Platform is an organization of European EPD program operators.

# Addressing logistics optimisation in Life Cycle Assessment

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## 1. Introduction

Road transport is a major source for several types of impact categories across the world. Yet, the current LCA databases providing LCI's for transport are static and crudely representative generic transport. The current road transport and freight LCI's are limited to only a few standardized scenarios, which in a dynamic and rapidly changing world loses its representativeness. Parameters often addressed for logistics optimisation are load capacity utilisation, driving patterns, fuel sources, logistics planning etc. Another challenge is the lack of addressing microplastics (MPs) which is a source of plastic emissions [1] which is a well-known environmental problem [2]. MP's originate from tyre wear and road wear, which again is strongly linked to vehicle weights, number of wheels and distance driven etc. This study develops upon existing database transport LCI's and analytical approaches towards creating a simple to use road transport life cycle inventory calculator which can be exported and used in several types of LCA software or in online LCA tools for LCA assessments or EPD development. The goal of the study is twofold:

i) The model shall enable addressing scenario specific road freight laps and logistics.

ii) Easy to implement into a broad spectre of LCA programs, such as SimaPro and Brightway.

## 2. Materials and Methods

In LCA today, road freight is centered around the unit of tkm. To understand the tkm unit is important for developing and interpreting road transport and freight LCAs. In this study we apply the well established well to wheel fuel consumption quantification per tkm based on net capacity utilisation also for infrastructure (vehilce prodction, mainenance, EoL, and tyre and road wear) emissions. In Equation 1, capacity utilisation is a main driver for quantifying the net vkm needed to transport the equivalent of a full (100% CU) vehicle. The inventory is established per km driven. To transform the unit from km to tkm, the inventory is divided on the average load in the vehicle (Equation 2). Data on MP per wheel and load are to be developed and quantified for different vehicle types along with more commonly addressed impact categories in LCA, and multiplied with the vkm found pr tkm. The same approach is used to quantify the need for vehicle infrastructure activities.

$$vkm_{i,j} = \frac{km_f}{CU_i}$$

Equation 1: quantifying vkm representing a 100% loaded vehicle pr km driven using a specific capacity utilisation.

$vkm_{i,j}$ is the total vehicle driving distance necessary to compensate for the unfilled load capacity. CU is the capacity utilisation in region or scenario (j) for the vehicle type or cohort (j). $Km_f$ is the intended freight distance in km. Equation derived from [3].

$$I_{tkm,c} = \frac{I_{km,f,c}}{L_{i,j}} = \frac{I_{km,f,c}}{(CP_{i,j} * CU_{i,j})}$$

Equation 2: Estimating cargo freight life cycle inventories per tkm based on inventories per vkm driven.

Itkm,c represent the inventory per tkm (the functional unit) for parameter category (c). Ikm,f,c is the inventory per km freight for inventory category (c). Li,j is the average load (trip-return trip) in kg per scenario (j) in vehicle type or cohort (i), CPi,j is the average payload capacity and the CUi,j is the average capacity utilisation, both in region or scenario (j) for vehicle type or cohort (i).

## 3. Results and Discussion

### 3.1. Influence of capacity utilisation across multiple impact categories

The results (figure 1) demonstrate that with a decreacing capacity utilisation all impacts increase exponentially but not equally across the three vehicle cohort sizes. These results are without impacts of tyre wear, but will be incorporated in the presentation. This demonstrate that for road transport and freight scenarios which in LCA and EPDs are often variable based on the volume and density of the cargo, vehicle types employed and with different logistic optimisation, the capacity utilisation is a key data pont which should not be missed.

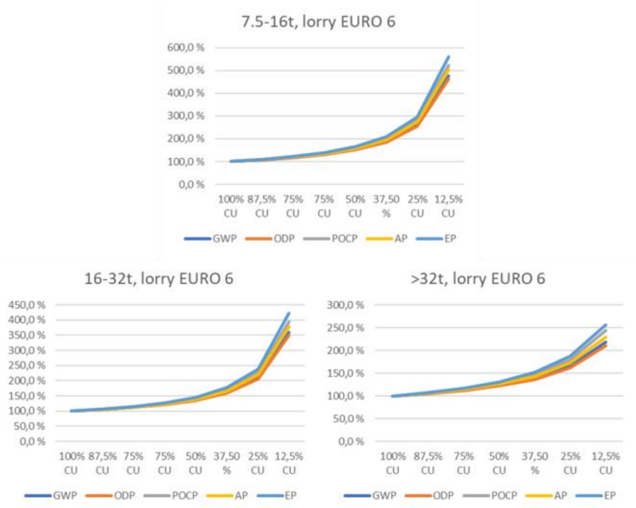
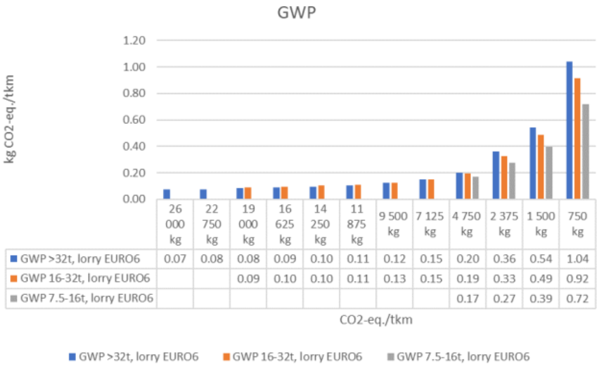


*Figure 1: Impact profile at different capacity utilisation rates*



| | 26 000 kg | 22 750 kg | 19 000 kg | 16 625 kg | 14 250 kg | 11 875 kg | 9 500 kg | 7 125 kg | 4 750 kg | 2 375 kg | 1 500 kg | 750 kg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ■ GWP >32t, lorry EURO6 | 0.07 | 0.08 | 0.08 | 0.09 | 0.10 | 0.11 | 0.12 | 0.15 | 0.20 | 0.36 | 0.54 | 1.04 |
| ■ GWP 16-32t, lorry EURO6 | | | 0.09 | 0.10 | 0.10 | 0.11 | 0.13 | 0.15 | 0.19 | 0.33 | 0.49 | 0.92 |
| ■ GWP 7.5-16t, lorry EURO6 | | | | | | | | | 0.17 | 0.27 | 0.39 | 0.72 |

*Figure 2: Impact profile of different vehicle cohorts with varying degree of load*

### 3.2. Vehicle cohort impact at different loads

The results (figure 2) demonstrate that smaller vehicles cause less impact with a lower load per tkm freight. This correlates LCA findings with common vehicle optimisation. The developed model allows for quantifying at which load different vehicles are beneficial. Vehicle load may be limited by road size, but also for single deliveries or products which are not carried in bulk or mass distributed. As such, environmental logistics optimisation should be incorporated into LCA. In addition, tracking specific vehicle transport laps enable spatial and temporal quantificatio of direct emissions such as MPs. MPs are to be added in the final results.

## 4. Conclusions

This reseach is tuned towards designing an LCA tool/module for road transport which are reflecting the dynamics of modern environmental logistics optimisation, new impact categories such as MPs and improved emissions factors of different fuel types. A sample of key parameters and their significant influence on logistics environmental impacts are here demonstrated but the developed tool/module is not limited to these. Ammonia addititves, biodiesel or alternative fuels, with or without cooling/freezing compartments, and infrastructure parameters are all parameters which can be specified for a specific vehicle and transport lap and integrated in a big scale logistics assessment. The ability to assess temporal and spatial emissions profiling of key logistics emissions can help further environmental reseach in assessing expected pollutants in a regionalized environmental compartment caused by the freight of goods and services.

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# Assessing sewage sludge treatment from a life cycle perspective – critical gaps in the impact assessment of per- and polyfluoroalkyl substances

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## 1. Introduction

The treatment of sewage sludge from wastewater treatment plants has been a challenge over time, mostly due to its high moisture content. However, over the last decades, a significant number of studies have raised awareness and concern linked to the potential presence of toxic compounds in wastewater sewage sludge and to their potential toxicity impacts on human health and the environment [1-3]. Per- and polyfluoroalkyl substances (PFAS) are a class of persistent and highly fluorinated chemicals that have been used for their non-stick and oil and water repellent properties and they may be found in wastewater sewage sludge. These persistent pollutants constitute a significant problem as they present a molecular structure with a strong carbon–fluorine bond, making PFAS compounds extremely stable and difficult to break down, and hence bioaccumulative and persistent in the human body and in the environment. There is a lack of fundamental knowledge on mechanisms that are important for the identification and quantification of PFAS [4]. Furthermore, there is uncertainty regarding the degradation rates of PFAS and the products that result from this process of degradation [5]. Over 12,000 types of PFAS compounds have been identified [6], perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) being two of the most commonly used PFAS compounds and the focus of this case study.

There are several impact assessment methods that can be applicable to PFAS, namely Usetox, TraCi, ReCiPe, and the Ecological Scarcity Method (ESM), however, they have associated weaknesses. For example, there are currently no characterization factors (CFs) for PFAS available in Usetox or ReCiPe. The ongoing GLAM work will soon be resulting in PFAS CFs later in 2024. Meanwhile, TraCi uses PCBs as a surrogate for PFAS. While the ESM contains several characterized PFAS, the method may not always be relevant to the research study in question because of its basis on environmental impact points (UBP (Umweltbelastungspunkte)). The UBP characterization is largely reliant on the Swiss political system because the eco-factor of a substance is derived from legislation or corresponding political objectives. Furthermore, when the current emissions or resource consumption exceeds the set environmental protection target, the eco-factor becomes greater, this is what the UBP reflects. Therefore, there is a relevant research gap in impact assessment of PFAS in that there is a need for more detailed CFs based on ecotoxicity assessment [7]. This knowledge gap may be hindering an accurate understanding of the effects that PFAS may have on the environment and human health.

Different wastewater sewage sludge treatment technologies have been assessed from a life cycle perspective, specifically anaerobic digestion and pyrolysis as these are the most commonly considered sludge-to-energy technologies[2, 8-10]. Anaerobic digestion is one of the most widely used technologies to treat wastewater sewage sludge, resulting in the production of biogas and sludge digestate. As the resulting digestate still has associated energy potential, pyrolysis has been assessed as a potential technology to convert the digestate to syngas and biochar and nonetheless, as a potential technology to remove the PFAS that may be present in the digestate [3, 11].

The aim of this study is to assess the treatment of wastewater sewage sludge by anaerobic digestion followed by pyrolysis of the resulting digestate, and to compare pyrolysis with anaerobic digestion treatment, over a life cycle perspective. The goal is two-fold: to assess the potential human health and environmental impacts of PFAS that may be present in the wastewater sewage sludge by applying different impact assessment methods; and to contribute to the ongoing discussion about PFAS fates in pyrolysis products and emissions.

## 2. Materials and Methods

The LCA will be conducted according to the ISO 14040 and 14044 standards. The wastewater sewage sludge treatment by anaerobic digestion and pyrolysis will be modelled in the LCA software SimaPro V9.6

Multiuser and the ecoinvent database V3.9 will be used to model processes in the background system. The following impact assessment methods will be applied: UseTox, TraCi, ReCiPe and ESM. Figure 1 illustrates the system boundaries of this study and the functional unit is defined as the "*treatment of 1 tonne of wastewater sewage sludge after anaerobic digestion and pyrolysis*".

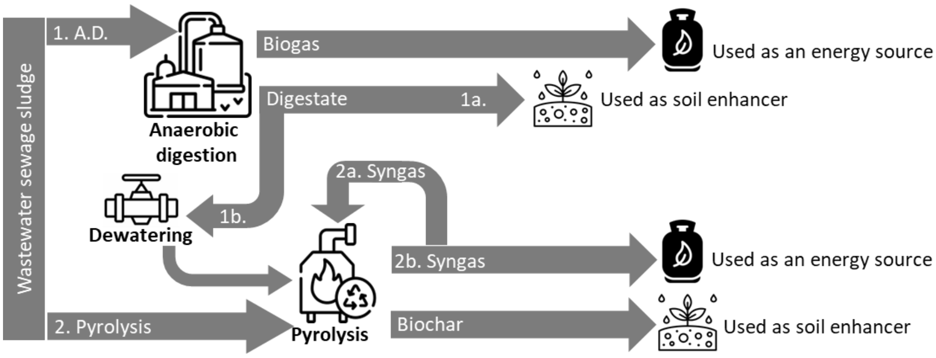

***Figure 1: Illustration of the system boundaries considered in this study.***

## 3. Results and Discussion

Results will be presented comparing anaerobic digestion and pyrolysis in the treatment of wastewater sewage sludge, and differences in results will be discussed when different impact assessment methods are considered.

## 4. Conclusions

This study aims to support decision making in the implementation of emerging technologies linked to wastewater sewage sludge treatment by addressing its potential toxicity impacts on human health and the environment. Results show that pyrolysis applied to wastewater sewage sludge treatment leads to a decrease in PFAS emissions compared to anaerobic digestion. Further, this study shows that human health and environmental impacts linked to the treatment of wastewater sewage sludge present significant differences when different impact assessment methods are applied. The existing impact assessment methods have shortcomings when it comes to PFAS, showing a need for further improvement and testing.

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# Integrating Life Cycle Assessment with Life Cycle Cost Analysis for Automotive Polymer Injection Mould Production: A Parallel Approach

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## 1. Introduction

The global mould market in 2018, reached 23 billion dollars in value. Portugal's mould industry figure as a significant player globally, ranking 3rd in Europe and 8th worldwide [1, 2], with over 80% of production exported to 93 markets. The automotive mould industry, renowned for its stringent technical demands and high-performance standards, constitutes a significant portion of this figure. Based on this the INOV.AM Agenda aims to boost Portugal's international competitiveness by developing projects with an innovative hybrid mould using Additive Manufacturing (AM), focusing on a more economical and sustainable approach. During the design phase, mould production should not only prioritize technical performance but also evaluate the economic and environmental implications throughout the mould's lifecycle [3]. Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) represent modern cost management tools internationally recognized. LCC encompasses the costs incurred throughout the life cycle of a product or service [4], while LCA focuses on evaluating the environmental impacts of processes and products, specifically targeting emissions throughout their life cycle [5]. When applied together posed to integrate economic and environmental analysis, diverging from traditional short-term accounting practices by adopting a long-term perspective on costs. Although LCA and LCC have been widely used in the field of sustainability research to support decision-making processes [6], the combination of two methods is still a challenge in the mould industry. This study aims to apply LCA and LCC combined to analyse the production of a polymer injection mould.

## 2. Materials and Methods

LCA and LCC methodologies were combined and applied sharing the declared unit, and development criteria for mould production. Following ISO 14040:44 standards, the LCA was conducted through four steps: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation [6,7]. The LCC methodology resembles the same phases, combining external and internal costs of mould production. LCA and LCC studies employed a cradle-to-gate approach, through production development phases (Figure 1). The declared unit, from which the environmental and economic impacts were normalised, and defined as the production of one mould, weighing 428 kg. The analyses were conducted using SimaPro v9.6 software. Primary data for the inventory were collected from a mould production company in the year 2022 while secondary data used were the Ecoinvent database (v3.10), with mass allocation per cutting unit ("Cut-off, U") and, where applicable, data-specific to Europe ("RER"). The ReCiPe Midpoint (H) method was employed for the LCIA, applying the Pareto rule. The LCC analysis combined the external and internal costs of mould production; however, infrastructure and maintenance costs were not considered. The LCC considered the inputs from the LCA, as raw materials, energy consumption, transport and waste.

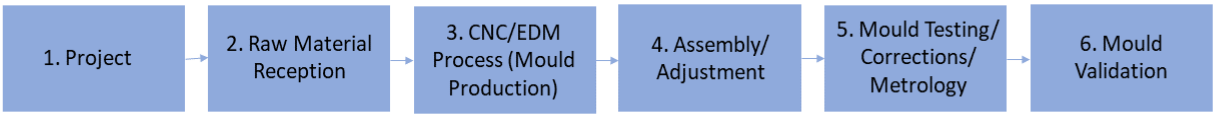

***Figure 1- Mould production flowchart***

## 3. Results and Discussion

Regarding the LCA analysis, and applying Pareto's rule, the environmental impact categories Terrestrial Ecotoxicity, Marine Ecotoxicity, and Human Carcinogenic Toxicity constitute 86% of the total impacts (Table 1). The aggregate value of the environmental impacts has been quantified at 2.34E+01.

*Acknowledgement* - This work is carried out within the framework of the "Agendas para a Inovação Empresarial" [Project nº 49, acro-nym "INOV.AM"), supported by the RRP - Recovery and Resilience Plan and by the European Funds NextGeneration EU. http://www.recuperarportugal.gov.pt/

*Table 1- Environmental impacts of mould production*

| Impact Category | Normalised results (year) | Baseline |
|---|---|---|
| Terrestrial ecotoxicity | | 1.20E+01 |
| Marine ecotoxicity | | 5.17E+00 |
| Human carcinogenic toxicity | | 2.99E+00 |

*Table 2 - External costs of mould production*

| Impact Category | Baseline (Euro €) |
|---|---|
| Ozone Formation, Terrestrial Ecosystems | 6.59E+02 |
| Global Warming | 4.17E+02 |
| Human Carcinogenic Toxicity | 1.23E+02 |

The mould production stage (Figure 1) is identified as being responsible for an overwhelming 99% of the total environmental impacts. This significant impact is predominantly attributable to the input of steel, which emerges as the primary contributor. This thorough quantification is crucial for informing subsequent decision-making processes aimed at mitigating these impacts and enhancing sustainability. Using the Pareto rule, it was possible to account for the external environmental impacts that make up 83% (corresponding to 1 198,60 euros) of the total impacts, namely Ozone Formation, Terrestrial Ecosystems, Global Warming, and Human Carcinogenic Toxicity (Table 2). Through a comprehensive analysis of LCC, it was possible to ascertain the financial requirements for producing a mould weighing 428 kg. The analysis revealed that the total cost for the mould production process amounted to 3 194.00 euros (Table 3), with the understanding that expenses related to infrastructure, human resources and maintenance were not included in this evaluation.

*Table 3 - Economical costs of mould production*

| LCC (total) | Euro (€) | Internal | External |
|---|---|---|---|
| 3.19E+03 | | 1.75E+03 | 1.45E+03 |

The total cost is divided into 55% internal costs, which include expenses directly associated with manufacturing operations within the organisation and purchases of raw materials, and 45% external costs, which correspond to environmental costs that would normally be considered externalities under the current conventional economic system. The most significant economic impact is the mould production phase, accounting for 93% of all internal economic impacts and 97% of all external impacts. This is primarily due to the acquisition of raw materials, specifically steel.

## 4. Conclusions

Despite the complexity of the methodologies applied, this study contributes to decision-making by integrating economic and environmental perspectives in the production of polymer injection moulds for the automotive industry. Combining LCA and LCC methodologies, the research promotes both environmental and economic efficiency. The combined methodology was crucial for informing subsequent decision-making processes aimed at mitigating these impacts and enhancing sustainability in the mould industry. A comparative analysis of this baseline to a hybrid mould will proceed in future phases of the project. This will allow assessing the environmental and economic aspects of additive manufacturing technology against conventional technology. Additionally, a sensitivity analysis of the project stage will be considered to further refine the understanding of the impacts and benefits of these manufacturing processes.

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# Utilization of Life Cycle Assessment (LCA) in Printed Circuit Board (PCB) Recycling – A Bibliometric Analysis Approach

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## 1. Introduction

The escalating production of Waste from Electric and Electronic Equipment (WEEE) has raised environmental concerns due to its potential for generating significant environmental impact associated with poor End-of-Life (EoL) management [1, 2]. Printed circuit boards (PCBs) are a fundamental component of these devices, accounting for 3-6% of total WEEE weight [3]. Their complex and heterogeneous composition, consisting of materials within the following categories: organic materials (30%), ceramics (30%), and metals (40%), underscores the necessity for a multifaceted management strategy for their EoL [4].

According to the zero-waste strategy, downstream management strategies for PCB recycling and material recovery need to be developed [5]. However, the presence of toxic heavy metals and brominated flame retardants can pose a challenge to the valorisation of these materials [6]. In contrast, the high content of precious and base metals can reshape this perspective, highlighting that PCBs can be a source of secondary resources, providing an unique opportunity towards the circular economy (CE) [7].

Still, there is no standardized methodology for PCB valorization, new technologies and processes have been under research. Life Cycle Assessment (LCA) allows for a resourcefull comparison between strategies and methodologies in terms of their negative environmental impacts, which can provide insightful information, specially where these themes coincide. Therefore, through a bibliometric analysis, this study intends to evaluate the introuction and the utilization of LCA in the context of PCB recycling and its material recovery [8].

## 2. Materials and Methods

The bibliometric review was conducted using “Web of Science (WoS)” and “Scopus” as the primary databases. Two search queries were used: “TITLE-ABS-KEY ("waste" AND "printed circuit board" AND "recycl*")” and “TITLE-ABS-KEY ("waste" AND "printed circuit board" AND "recycl*" AND “life cycle assessment”), refered to as S1 and S2 here, respectively. The addition of LCA in the second query allows to compare results and identify the introduction and relation of LCA in the broader theme. No limitations on type of source or time periods were stablished. The data retrieved from both databases was joined in a single document using R-Studio and Excel Power Query. Duplicates were removed and the data was meticulouslly cleaned and analysed complementary through Bibliometrix R and VOSViewer [8, 9].

## 3. Results and Discussion

A total of 1644 publications were identified for S1, spanning from 1979 across 578 sources, while S2 yielded 42 publications from 26 sources, beginning in 2004. However, production escalated and stabilized after 2004 for S1 and 2012 for S2 (Figure 1 - i). Consequently, the mean age of publications was close, averaging around

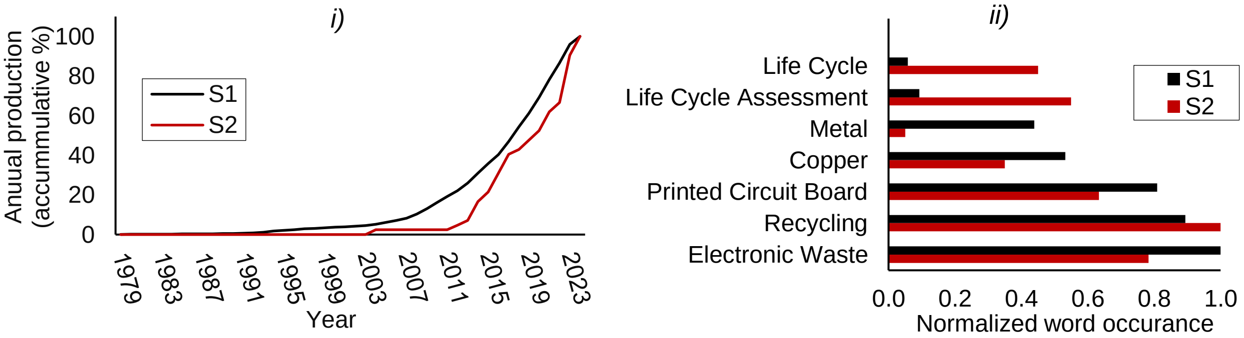

*Figure 1: Plots of production over time for S1 and S2 of i) Accumulative percentage of publications ii) Top 5 most used words.*

7.71 for S1 and 5.02 for S2. Overall, 3459 authors from 67 countries were identified having 4.4 co-authors per document for S1, whereas for S2, there were 189 authors from 17 countries, with an average of 4.6 co-authors per document. Countries with the greatest production on both searches were the same, namely China, India, the USA and Brazil, with the exception of Japan in S1 and Australia in S2. Most relevant sources were the Journal of Cleaner production, Waste Management, Resources Conservation and Recycling and, Environmental Science and Pollution Research. The Journal of Hazardous Materials was the third most relevant source for S1 and did not appear in the top five sources for S2, in which Environmental Science and Technology appeared.

The co-occurrence analysis of all keywords for S1 illustrated that, even though LCA was not identified among the most important items (Figure 1 - ii), surrounding themes such as life cycle analysis, life cycle, environmental impact, environmental protection, environmental monitoring, environmental pollution, pollution, and pollution control were all featured in the resulting network. An additional analysis placing all those words under the same category, generated an item with significant relevance in the network, indicating that although LCA doesn't seem to be a prominent theme in PCB recycling research, environmental impact, as a broader subject fundamental to LCA, is. The recent emergence of ISO 14040 and 14044 in 2006, could help explaining the lack of a unified term and methodology for assessing different scales and categories of environmental impact assessment. This can also be noted by the slight increase in publications having LCA in the title, abstract or as a keyword shown by S2, from 2012 forward (Figure 1 - i).

A citation analysis of the most relevant authors revealed that Zhenmin Xu was among the top five authors for both S1 and S2, with each top author having two publications. A co-occurrence words analysis of the author's production indicates his focus on studying new and sustainable technologies directed at toxic components removal from PCBs and the environmental impacts associated since 2007. Except for Roland Hischier, who focused on LCA in all his publications related to PCB recycling, Xu's pattern was also evident among publications by other authors in the top five of S2. This suggests that this approach could be extended to other researchers in the field, concomitant to research on LCA methodology which can result in enhanced databases and analytical methods. This in turn, can lead to more robust analysis and a broader and more intentional adoption of LCA as a tool in this specific field.

## 4. Conclusions

After conducting a comprehensive bibliometric analysis, our findings indicate that LCA is not prominently a recurring theme in PCB recycling research. However, the occurrence of adjacent subjects presents a promising prospect for future research merging both fields. This also alludes to the fact that LCA is not widely adopted as unified approach for environmental impact analysis in this area of research. Nonetheless, the convergence of key authors, countries and journals from across both searches underscores the intricate relationship between both themes suggesting potential collaborative strategies to advance jointly in both scientific fields.

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# Life cycle thinking to reduce bread waste

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## 1. Introduction

As food waste negatively impacts the environment, people and the economy, preventing food loss and waste is high on the international sustainability agenda, despite this large amounts are wasted every year [1-4]. Researchers have labelled food waste as a “wicked problem” due to its complex nature where food waste is influenced by a broad spectrum of factors across the entire food value chain, including technology, business models, policies, economy, psychology as well as social- and cultural aspects [5, 6]. There is thus no such a thing as a “one size fits all” solution to the food waste challenge that calls for systematic change and collaboration across the value chain [7]. To solve the complexity of environmental issues within the food system an “outside the box” Life Cycle Thinking (LCT) approach has been suggested [8]. However, studies have shown that food value chain actors tend to solely focus on their own food waste and rarely apply an LCT-perspective when addressing food waste [9]. This paper seeks to shed light on how LCT can play a role in solving the food waste challenge using the bread value chain in Norway as a case study.

More specifically, this contribution will discuss the topic of barriers and drivers related to waste of bread. Bread is one of the most wasted food categories and has been reduced the least within the Norwegian food value chain [10, 11]. Furthermore, studies have shown that bread waste in the supply chain often occurs within the bakery-retail interference and that retailers and bakeries can adopt measures to reduce consumer bread waste [12-14]. This entails that reducing bread waste requires an LCT-approach. The hypothesis underlying this study is that actors across the bread value chain have different perspectives on how to reduce bread waste, and that bread waste reduction requires collaboration across the bread value chain where an LCT-approach using insights from the whole value chain is crucial to avoid sub-optimal solutions and problem shifting. Our study adds to the state of the art by providing empirical insights to this issue within the context of bread waste. In this presentation we will report research that is currently being undertaken and we can therefore not anticipate the results. In the following, only the materials and methods will be reported. The results and discussion will be completed before the SETAC conference.

## 2. Materials and Methods

Twenty semi-structured interviews with experts across the bread value chain were conducted, aiming to explore barriers, pitfalls and solutions for reducing bread waste using an LCT-perspective. Each expert was first asked general questions about bread waste, and then was presented 3-4 of a total of 5 scenarios (due diligence, donation, discounting, competence and consumer) based on the Food Waste Committee’s recommendations of measures for halving food waste in Norway by 2030 [15]. The interviews were recorded, transcribed and the text analysed using systematic text condensation (STC) and triangulation [16].

The questions regarding bread waste in general included what the participant thought would be required for halving food waste by 2030, if there were any barriers that could not be solved by the different actors alone, and if so- what would be required to solve these barriers. The participants were also challenged with questions regarding solutions, such as what they would do if they were responsible for reducing bread waste throughout Norway. The questions regarding the scenarios included what would happen if the scenario was implemented, what would be needed to achieve the scenarios, whether the scenarios are feasible or not, if the scenarios are missing something, who would bear the costs and whether the scenarios would lead to any unintended consequences (negative or positive).

## 3. Results and Discussion

### 3.1. Results

Based on the experts' insights, the results will aim to present barriers and solutions against bread waste from producer to consumer in Norway. Special emphasis will be placed on evaluating the suitability and LCT potential of the five scenarios recommended to the government by the Norwegian Food Waste Committee for halving food waste in Norway by 2030, for the case of bread.

### 3.2. Discussions

Without anticipating the results, we expect that the experts have different, complementary and potentially conflicting views regarding barriers bread waste reduction. Their perceptions of the bread waste issue may vary based on their position in the value chain and the type of issues or other impulses they are exposed to on a daily basis. Other contributions in the bread waste literature point to packaging optimization, nudges or tools to promote desired consumer behaviour (such as freezing or toasting bread at home) as well as the need to balance skewed economic incentives and the power relationship between the various supply-chain actors as key solutions to reduce bread waste [12, 14, 17]. We will discuss our results in light of this literature. A limitation of the study is that a small sample of experts is utilised as representants of a large value chain, and that the data are subjective by nature. Although measures have been adopted to avoid bias and interpretation errors from the researchers there is always a risk related to interviewer bias and systematic text condensation.

## 4. Conclusions

This study can shed new light on how the perspectives of the actors in the bread value chain are positioned by their roles and whether or how this is related to LCT. The results can be used to inform industry and/or policymakers on how to ensure a holistic approach to bread waste reduction using a life cycle perspective.

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# Prospective LCA applied to emerging production process of a novel protein from woody by-products: a tentative analysis.

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## 1. Introduction

The demand for farmed fish is on the rise, leading to an increased need for fish feed. In Norway, since 2017 the number of farmed fish overcame the wild catches [1]. Marine ingredients have historically served as a prevalent protein source in aquaculture feeds. However, there is a global trend of some fish farms replacing these marine sources with plant-based alternatives like soybean meal, a shift that carries potential environmental and health ramifications [2]. Meeting the growing demand necessitates diversifying feed ingredient production. Hence, various novel protein ingredients are currently under investigation.

Emerging protein feed ingredients such as bacteria, algae, yeast, and filamentous fungi, known as single-cell proteins (SCPs), offer a unique advantage: they can be cultivated on substrates like methane and carbohydrate-rich waste streams [3]. This characteristic allows them to convert energy sources previously unusable for feed production into valuable protein feed ingredients, ultimately contributing to food production. A promising substrate for SCP is syngas, sourced from sawmill by-products such as saw dust and woodchips. Usually wood-based waste streams (e.g. sawmill residues) are used in the energy sector, especially in combined heat and power plants and heat-generating plants [4]. An emerging process combining pyrolysis, syngas conditioning, and fermentation processes is under development. This process aims to transform such solid biomass into high value raw material for fish feed ingredients to be used in aquaculture industry. An additional by-product of this process is biochar that can be used as a ~~feed~~ additive for animal feed or upgraded to biocatalyst for tar cracking purposes.

Life Cycle Assessments (LCAs) of SCP are scarce [5] and recent studies with different feedstock for SCP cultivation shows diverging results, likely based on type of growth substrate used and methodological differences [6-8]. The demand for energy, especially during the drying process, appears to be the main factor affecting the results.

The aim of this study is to assess the environmental impacts of producing SCP from sawmill residues with the goal of achieving lower greenhouse gas emissions, reduced land and water use and overfishing, compared with using soybean and fish meal as feed ingredients.

## 2. Materials and Methods

A prospective attributional LCA of early-stage technologies is the methodology used in this study for investigating the novel process as an alternative route for wood-based waste streams and to current protein feed options for farmed fish. The study assesses the environmental impacts at an early stage, i.e. lab-scale, and at a later stage when the process fully is implemented, i.e., full-scale. The state-of-the-art technologies described in this paper are the base for establishing a foreground system model, which is essential for conducting prospective LCA [9]. The methodological framework of Thonemann et al. [10] and Arvidsson et al. [11] are tested in this study.

Currently, data is being collected from lab-scale studies. Primary data encompass details regarding necessary raw materials, energy use, consumables, emissions, waste streams, and other factors across the various technological process stages. Additionally, data consist of information about machinery, infrastructure, and spatial requirements. Furthermore, data linked to anticipated efficiency enhancements during the transition from a low technological readiness level (TRL 4) to prototype pilot scale (TRL 6) will also be collected. Several environmental impact categories such as climate change, land use, water scarcity, resource scarcity and biodiversity are examined.

## 3. Results and Discussion

Preliminary results for the production of SCP at early-stage development will be presented for finding hotspots and give recommendations to the technology developers. Several parameters such as water and energy requirements, amount of chemicals used, equipment capacity, generated process water, emissions, and waste fractions, etc. may change when the full-scale production process is implemented, hence affecting the environmental performance of novel production process. Therefore, to assess different operative conditions when moving from a lab to a full-scale production process, an upscaling analysis needs to be performed. This will be done by using power laws and scenario analysis to simulate the future full-scale operation conditions.

## 4. Conclusions

Fish is an important source of protein for the human diet, and the growing demand for feed sources raises worries regarding the potential impacts of obtaining these sources. Food safety and costs are also raising concerns.

The results of this study will provide a step forward in the development of LCA results for alternative protein sources, as such results are scarce.

The novelty of the study is to complement research gaps in LCA literature, addressing the environmental impacts (not only climate change) of emerging technologies in waste handling and feed production.

The results of the study can support industry in the phase of implementation of emerging technologies.

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# Terrestrial characterization factors for microplastics ingestion and additives release in the terrestrial compartment: from experimental data to LCIA

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## 1. Introduction

Polyhydroxyalkanoate (PHA) and polylactic acid (PLA) are plastic biopolymers (BPs) which can be combined to produce biobased and biodegradable polymers, potential substitutes for petrochemical plastics such as polypropylene (PP) and low-density polyethylene (LDPE)) provided their quality and environmental performance meet certain standards.

Although guidelines for quantifying the environmental impacts of plastics exist [1], the majority of Life Cycle Assessments (LCA) of conventional plastics have ignored mismanaged plastics, both due to losses at the production stage and, mainly, due to poor end-of-life (EoL), underestimating their long-term effects. The main reasons for that are lack of data at the life cycle inventory (LCI) and impact assessment (LCIA) stages. Regarding the former, the Plastic Leak Project (PLP)[1] guidelines allow estimation of plastic leakage of different sources into different environmental compartments (freshwater, ocean, air, soil and other terrestrial compartments) and for the latter, the MarILCA Project[2] has developed characterization factors (CFs) for the marine compartment. However, to the best of our knowledge, the available literature neither include mismanaged plastics released to (and keep in) the terrestrial compartment, nor the effects caused by the presence of additives in the plastic based item; so, this work aims to develop the correspondent CFs for both biopolymers and petrochemical ones released to the terrestrial compartment.

## 2. Materials and Methods

According to Rosenbaum [2], the calculation of characterization factors (expressed in Potentially Affected Fraction of species (PAF)·$m^3$·day·$kg^{-1}$) requires a fate (FF), an effect (EE) and an exposure (XF) factors as stated in eq 1:

$$CF = FF \cdot EF \cdot XF \qquad \text{(eq. 1)}$$

Where the FF (expressed in days) represents the residence time of the plastic in the environmental compartments; the EF (expressed in PAF·$m^3$·$kg^{-1}$) the sensitivity of the species to the released pollutant; and the XF (dimensionless) the availability of the released plastic in the environmental compartment.

Accelerated photooxidation studies were performed on 5 samples of BPs provided by ANFACO-CECOPESCA. All of them were based on a combination of PHA and PLA, at varying ratios, with triethyl citrate (TC) or coconut oil (COCO) as additives (i.e. PHA (100%); PHA:PLA (50:50); PHA:PLA (30:70); PHA:PLA:TC (27:63:10); and PHA:PLA:COCO (27:63:10)). changes in mass, functional groups [Fourier-transform infrared spectroscopy (FTIR)], thermal properties [Differential scanning calorimetry (DSC)] and colour were followed during more those 2,000 hours (master thesis) to obtain the FFs for terrestrial compartment as Corella-Puertas [3] did for the aquatic compartment. Literature data for LDPE (with bis(2-ethylhexyl) phthalate (DBHP) as additive) and PP (with dibutyl phthalate (DBP) as additive) were collected and the correspondent FFs were also derived.

EFs were developed following [1] based on literature data on the ecotoxicological effects of the ingestion of microplastics and additives. Finally, XFs were derived based on the PLP guidelines, which estimated the proportion of microplastics deposited in the terrestrial compartment that remained within it.

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[1] https://quantis.com/who-we-guide/our-impact/sustainability-initiatives/plastic-leak-project/
[2] https://marilca.org/

## 3. Results and Discussion

The developed FFs (Table 1) depend on the selected location rather than the polymer conformation due to their dependence on solar radiation, the EFs depend more on the additives present in the samples than on the ingestion of microplastics, and the XF is the same for all of them and equal to 0.7 since the assumption that 70% of the microplastics deposited in the terrestrial compartment remain there.

| Polymer type | Additive type | Location | FF (days) | EF (PAF·m$^{3}$·kg$^{-1}$) | | CF (PAF·m$^{3}$·day·kg$^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | | | | Additives | Microplastics ingestion | Additives | Microplastics ingestion |
| BP | TC | Santiago de Compostela | 46.0 | 25.28 | 2.76E-03 | 813 | 8.88E-02 |
| | | Granada | 36.0 | | | 638 | 6.96E-02 |
| | | Stockholm | 63.4 | | | 1121 | 1.22E-01 |
| | | Cairo | 29.1 | | | 515 | 5.62E-02 |
| PP | DBP | Santiago de Compostela | 16.7 | 54.21 | 7.74E-03 | 633 | 9.05E-02 |
| | | Granada | 13.10 | | | 497 | 7.09E-02 |
| | | Stockholm | 23.03 | | | 874 | 1.25E-01 |
| | | Cairo | 10.57 | | | 401 | 5.73E-02 |
| LDPE | DBHP | Santiago de Compostela | 115.09 | 9.48 | 5.61E-03 | 763 | 4.52E-01 |
| | | Granada | 90.27 | | | 598 | 3.54E-01 |
| | | Stockholm | 158.75 | | | 1052 | 6.23E-01 |
| | | Cairo | 72.84 | | | 483 | 2.86E-01 |

***Table 1: Fate, effect and characterization factors of microplastics ingestion and additives of the plastics studied.***

The CFs of the BPs have been grouped as they do not differ significantly based on their conformation (% PHA and PLA). For additives, the CFs are 3 to 4 orders of magnitude higher than microplastic ingestion, reflecting the higher environmental risk of additives in the terrestrial compartment. And concerning the aquatic compartment, the CFs developed by Corella-Puertas [3] for the ingestion of PP and LDPE film fragments and the EFs for additives developed by Casagrande [4] are 8 and 3 orders of magnitude higher than ours, respectively, which is consistent with the higher mobility and accessibility of plastics and additives in the aquatic compartment.

## 4. Conclusions

Although as expected the factors are lower than in the aquatic compartment, it is crucial to consider the terrestrial compartment to have a holistic picture of the impacts of mismanaged plastics as well as not to overestimate impacts in the aquatic compartment. In addition, the data reflect that the factors for BPs do not differ significantly from those for petrochemical plastics (PP and LDPE), suggesting that the best environmental performance of BPs requires proper EoL management, highlighting the importances of proper waste management.

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# Requirements and Guidelines for Comparative LCA of Bio-based Products with their Fossil-based Equivalents

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## 1. Introduction

The methodology to perform life cycle assessment (LCA) of products is described in general standards like ISO14040/14044, ISO14067 [1] and, more specific for biobased products (BBP), in EN16760 [2]. Yet, the existing standards and guidelines for LCA do not provide specific rules for several methodological aspects. Yet, the results of a LCA study may strongly depend on these choices. European Commission promotes the use of the Product Environmental Footprint (PEF) method [3]. It provides specific methodological and modelling rules to ensure increased consistency, reproducibility and robustness of the study. The use of the PEF method is already foreseen in the context of EU policies and legislation such as the Taxonomy Regulation and Carbon Removal Certification Framework. However, this method could not resolve all issues for making fair comparative LCAs between bio based and fossil based product systems that can result in an unlevel playing field. This calls for additional requirements and guidelines to make sound comparisons between bio-based products and their fossil-based alternatives. This study, which is used in the development of the European standard prEN 18027, addresses these specific challenges.

## 2. Methods

The additional requirements and guidelines are developed based on a sound review of existing approaches not only in other relevant EN and ISO standards but also in scientific literature in collaboration with a team of European experts as part of the CEN Technical committee 411 ‘Bio-based products’, Working group 4 ‘Sustainability criteria, life cycle analysis and related issues’. The technical topics identified and addressed include: Accounting of biogenic carbon and temporary carbon storage; Handling of emerging technologies; Data asymmetry; Modelling end-of-life scenarios; Inclusing of biodiversity and indirect impacts.

## 3. Results and Discussion

One of the key topics is accounting for removals and emissions related to biogenic carbon and its temporary storage. As presented in Table 1, currently there is no consensus on internationally recommended approach in dealing with this topic. There is a need for a harmonized and transparent approach on how the biogenic carbon removals and emissions are to be handled.

The devised guidelines for this is as follows. The inventory of biogenic carbon flows shall include both the removals and the emissions with dedicated elementary flows. For cradle to gate studies, biogenic carbon content in the products shall be reported separately to allow calculation of biogenic carbon emissions in end-of-life. The biogenic carbon removal shall be characterized in the LCIA as −1, while emissions of biogenic carbon correspondingly shall be characterized as +1 (referred to as the +1/-1 approach). If biomass is harvested and biogenic carbon is stored in bio-based products, emissions can be temporarily delayed or avoided long-term. For the assessment of effect due to temporary biogenic carbon storage dynamic approach is recommended. The portion of the stored carbon not emitted to the atmosphere within the chosen time period may be treated as permanently stored.

| | ISO 14067 **[1]** | EN 16760 **[2]** | PEF **[3]** | PAS 2050 **[4]** | GHG Protocol **[5]** | ILCD Handbook **[6]** | ISO 21930 **[7]**<br>EN 15804 **[8]** |
|---|---|---|---|---|---|---|---|
| Biogenic carbon removals and emissions to be included in the inventory/modelling | Yes | Yes | Yes[1] | Yes, except for food and feed | Yes | Yes | Yes |
| Impact assessment of biogenic carbon emissions and removals | -1/+1 | -1/+1 or 0/0 | 0/0 | -1/+1 [2] | -1/+1 | -1/+1 | -1/+1 |

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[1] Unless a simplified modelling approach (where only biogenic $CH_4$ emissions are modelled) is selected in a specific PEFCR.

[2] Not explicitly reported in the standard, but it can be inferred from provisions related to other relevant aspects.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Biogenic carbon content in intermediate products to be separately reported | Yes | No requirement | Yes | No requirement | Yes | No requirement | No requirement |
| Delayed emissions due to temporary carbon storage included in the assessment | No, can be reported separately, a minimum storage time of 10 years is considered. | No, should be taken into account where relevant but reported separately. | No | No, can be reported separately together with the main results | No, can be reported separately. | No, can be taken into account if directly required in the goal of the study. | No, ISO 21930 state can be reported separately. |
| Calculation method for including the effect of delayed emissions specified | No | Yes, the calculation method specified in the ILCD Handbook may be followed. | No | Yes | No | Yes | No |
| “Permanent” carbon storage included in the assessment | Yes[3] | Yes, can be reported separately. | No | Yes, carbon storage of >100 years is considered permanent | Yes, a minimum time period of 100 years considered.[4] | Yes, inventoried separately using 100 year time-frame; emissions occurring after 100,000 years not accounted | No |

*Table 1: Overview of key aspects of approaches for biogenic carbon accounting adopted in relevant standards and guidelines*

The requirements and guidelines concerning other technical topics identified are provided in the prEN 18027.

## 4. Conclusions

Problems often arise when comparative LCA’s need to be performed between biobased and fossil based products and different methodological choices can be made. Since these LCA comparisons are a part of building policies for BBP in Europe and since they are used by many stakeholders for decision making about the choice of materials, it is evident that a guidance is sought after for making sound comparisons. This study identifies and addresses specific challenges in carrying out comparative LCA between BBP and their fossil-based counterparts. It is used in developing additional requirements and guidelines for carrying out such comparative LCAs as part of a new European standard prEN 18027.

## 5. References

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[7] ISO-21930. 2017. Sustainability in buildings and civil engineering works—Core rules for environmental product declarations of construction products and services.
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[3] The standard does not report any specific time horizon (or assessment period) after which carbon removed from the atmosphere (e.g. during biomass growth) shall be considered as no longer released, and hence as “permanently” stored.

[4] Companies shall report the time period of the inventory. Companies shall report the amount of carbon contained in the product or its components that is not released to the atmosphere during waste treatment and therefore is considered stored.

# In-Depth Assessment of the Need for Life Cycle Competence in Swedish Industry and Authorities

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## 1. Introduction

To address our sustainability challenges related to an unsustainable consumption and production system, resource depletion, and inevitable climate change, significant changes are needed in society to accelerate the green transition to a circular economy, with new technically sustainable innovations and a sustainable energy system. For this, a holistic approach is needed that includes the environmental, social, and economic aspects of all our activities in society, within industry, politics, and everyday life.

The life cycle perspective takes a holistic view that provides a basis for decisions, enabling the avoidance of shifting problems to another part of the chain or from one environmental impact to another, as well as identifying where the greatest potential for improvements and efficiencies lies. Life cycle thinking has many applications today, for example in product development and public policy contexts. A survey of real product development processes showed the benefits of life cycle thinking for, among other things, the choice of technical alternatives, the prioritization of research budgets, and communication with markets [1].

Both nationally and at the EU level, the development of legislation with a life cycle perspective is advancing rapidly. Examples of important policy initiatives where the life cycle perspective is highlighted as significant include: the EU Environmental Footprint, the EU directive on verification and communication of explicit environmental claims, the Ecodesign Directive, the EU Public Procurement Directive, the EU Corporate Sustainability Reporting Directive. Additionally, the life cycle perspective is prominent in the Roadmap to a Resource Efficient Europe and the EU Energy Roadmap 2050 (see e.g. [2-7]).

In Sweden, the Swedish Energy Agency's report "Helhetssyn är nyckeln" [8] from 2015 highlighted the life cycle perspective as an important part of many different applications (buildings, transport) and is increasingly emphasized by Swedish politicians as important for addressing and implementing measures to tackle society's sustainability challenges (e.g. [10]). The climate declaration of new buildings is an example of Swedish legislation that includes a life cycle perspective [10].

In addition to policy initiatives, there is a great demand in the market for increased responsibility and transparency, both from customers and consumers who want to know more about the products and services offered to make more informed choices. Companies also experience internal pressure from their employees and their investors [11].

## 2. Materials and Methods

The project “In-Depth Assessment of the Need for Life Cycle Competence in Swedish Industry and Authorities” aims to map the industry-identified need for competence to meet these increasing demands while maintaining or achieving a leading role in a sustainable society. This project deepens the understanding of these competence needs by examining upcoming legal requirements that include a life cycle perspective and incorporating a larger survey. It also includes Swedish national authorities, as they will often be responsible for implementing these requirements. In this presentation, we will present results from a survey among industrial companies and authorities, mapping the competence needs within the life cycle perspective.

The project employed a comprehensive survey distributed to a wide range of industrial companies and national authorities in Sweden. The survey aimed to gather detailed insights into the current state and future needs of life cycle competence within these organizations.

## 3. Results and Discussion

In this presentation we will, among other things, present results from both industry and national authorities on the following areas:

- Motives for working with the life cycle perspective.
- Relevant existing and upcoming standards, regulations, or policies.
- Satisfaction levels with the implementation of life cycle perspectives.
- Challenges faced during application.
- Strategies for addressing limited expertise.
- Evolution of demand for life cycle perspectives over the past five years.
- Anticipated competencies needed in the next five years.
- Competencies and skills in demand to meet future legal requirements and maintain sustainability leadership.

## 4. Conclusions

The findings provide valuable insights for policymakers, industry and educational institutions to design targeted programs that build the necessary competencies in the workforce. Future research should focus on developing practical tools and training programs to support the integration of life cycle perspectives across various sectors.

The project is carried out within the framework of the Swedish Life Cycle Center, a national competence center for applied life cycle research at Chalmers University of Technology.

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# Towards an Environmentally Sustainable Economy within Planetary Boundaries - A UK Case Study

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## 1. Introduction

A truly sustainable economy requires keeping its environmental impacts within the Earth's ecological limits. The Planetary boundaries (PBs) framework, which defines a safe operating space (SOS) for human activities (Steffen et al. 2015), has emerged as an effective tool in absolute environmental sustainability assessment (AESA) (Vea et al. 2020). While global PBs assessment on transgressions are documented in the latest study (Richardson et al. 2023), there remains a significant gap in understanding PBs transgressions at country-level and sectoral contributions of such exceedance, inhibiting effective decision-making for environmental impact mitigation at the sub-global level. In addition, the latest iteration of PBs framework has introduced new control variables (CVs) and updated associate SOS (Richardson et al. 2023). However, previous studies in the assessment of PBs have shown limitations in the CVs coverage and alignment.

To fill these gaps, the present study proposes a national-level PBs-based absolute environmental sustainability assessment (PBs-AESA) method. Given the limitations in CVs coverage and alignment identified from previous studies, a new characterization factors (CFs) model is developed to align with the latest PBs framework. The new CFs model is employed to translate the national environmental footprints to metrics with the updated CVs, with the UK taken as a case study.

## 2. Materials and Methods

The proposed method (Figure 1) consists of four main steps. Step 1 entails defining the SOS for eight critical Earth's system processes expressed via twelve control variables (CVs) (Richardson et al. 2023; Steffen et al. 2015) and then allocating the global SOS to relevant systems using different sharing principles. In step 2, Environmental Extended Multi-Regional Input-Output Analysis (EEMRIOA) is adopted to derive the environmental footprints associated with the UK's economic activities, EXIOBASE is selected due to its comprehensive coverage of environmental extensions. In step 3, a new CFs models is developed to translate the environmental footprints into impact metrics on the updated CVs of the PBs. In step 4, the PBs transgressions and sectoral contributions are analysed and interpreted.

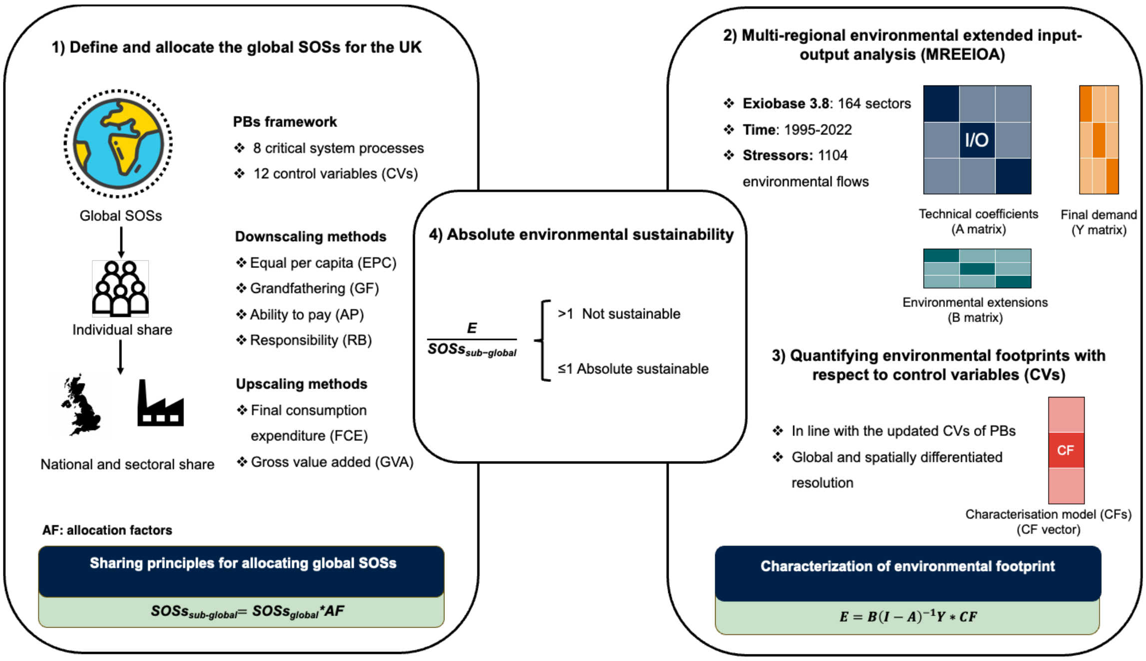
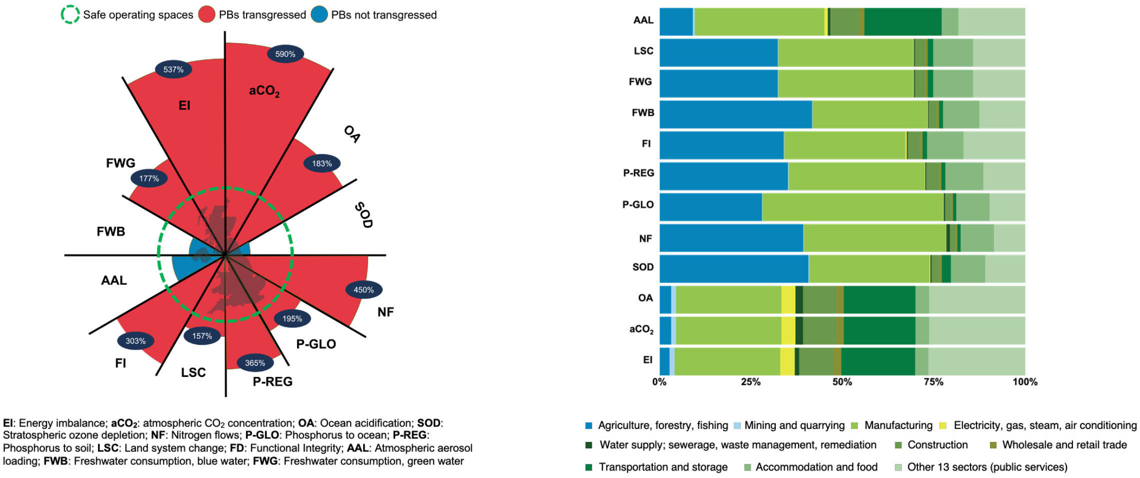


*Figure 1: Methodology roadmap.*

# 3. Results and Discussion

## 3.1. UK's national and sectoral environmental performance against PBs

Figure 2 shows that for the UK nine of the twelve CVs are exceeded, with climate change (energy imbalance and atmospheric $CO_2$ concentration) and nitrogen flows suffering the most severe transgressions above fixe times the allocated SOS. Only three PBs are not transgressed: stratospheric ozone depletion, aerosols loading, and freshwater use-blue water. The sectoral contribution analysis indicates that manufacturing and transport sectors are the main contributors to climate change and ocean acidification PBs, while agriculture and manufacturing sectors significantly impact other PBs.



**EI**: Energy imbalance; **aCO₂**: atmospheric $CO_2$ concentration; **OA**: Ocean acidification; **SOD**: Stratospheric ozone depletion; **NF**: Nitrogen flows; **P-GLO**: Phosphorus to ocean; **P-REG**: Phosphorus to soil; **LSC**: Land system change; **FD**: Functional Integrity; **AAL**: Atmospheric aerosol loading; **FWB**: Freshwater consumption, blue water; **FWG**: Freshwater consumption, green water

***Figure 2: UK's PBs transgression levels and sectoral contributions.***

# 4. Conclusions

In the present study, a national-level PBs-based absolute environmental sustainability assessment (PBs-AESA) method is proposed. This method introduces a new CFs model to address the limitations of CVs coverage and alignment identified in previous studies. The proposed PBs-AESA method with the new CFs model is then demonstrated through a case study of the UK. Results indicate that the UK has transgressed nine out of twelve CVs, except for stratospheric ozone depletion, aerosol loading, and freshwater use-blue water. The agriculture and manufacturing sectors contribute to the majority of the impacts. The UK's national and sectoral environmental performance against PBs could provide insights for implementing technology pathways and policy strategies towards absolute sustainability. Furthermore, the proposed method is applicable across countries and sectors, thereby supporting global efforts towards sustainable development. To achieve this, future studies will be focused on improving the spatial resolution of the CF models.

# 5. References

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