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A Guide to Applying Life Cycle Assessment Tools to Prospective Technologies at the UFZ

White Paper

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August 2025

Abstract

Great efforts in biotechnology are being made to reduce the use of fossil fuels and to drive a transition toward a bioeconomy. However, these early-stage technical concepts also carry sustainability risks at ecological, social and economic levels due to large-scale biomass flows when scaled to industrial production.

Life cycle assessment methods can help to identify these risks at an early stage and take steps to counteract them. This potential has also been recognized at the UFZ and collaborative efforts between biotechnology developers and modelers have been initiated. Life cycle assessment for prospective technologies, however, presents a number of challenges, such as considerable uncertainty regarding upscaling and the conditions under which the technology will be used in the future.

This white paper addresses challenges and opportunities of prospective life cycle assessment methods in an attempt to clarify common questions. Additionally, a survey explored the needs and expectations of future collaborations. The paper outlines the basics of the life cycle tools available in RU6 and proposes a workflow for future collaborations, concluding with a condensed LCA guide (Mini LCA guide) that summarizes the methodology and requirements for joint project work.

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List of abbreviations

IP – Integrated Platform (UFZ)

LCA – Life cycle assessment

RU4 – Research Unit 4 “Sustainable Ecotechnologies”

RU6 – Research Unit 6 “Environment and Society”

UFZ – Helmholtz Centre for Environmental Research (UFZ)

1. Why a common approach for assessing prospective bio-based technologies at UFZ?

Bio-based technologies pose a distinct challenge because of the numerous early-stage technical concepts designed to advance to a transition toward a bioeconomy. For the early identification and mitigation of environmental risks related to the entire life cycle of an innovative product or process prior to its market launch, life cycle assessment methods (LCA) may serve as an effective tool. However, the incorporation of life cycle assessment findings into decision-making processes remains limited. While some progress has been made in considering environmental aspects, there is still a much larger gap in incorporating the broader socio-economic implications of bio-based technologies.

Acknowledging this deficit, there is an increasing agreement on the importance of fostering collaborative efforts between research units (RU) at UFZ, particularly between technology developers from RU4 and systems modelers from RU6. Some past collaborative UFZ-wide initiatives have shown the potential for evaluating process conditions and design during the initial stages of development. However, amid these scattered efforts, recurring questions and concerns emerged regarding the diverse procedural approaches being considered, the absence of a standardized pathway, the anticipated benefits, and the responsibilities of designated working groups.

This White Paper has been carefully prepared to facilitate further collaborations at the UFZ and should serve as a guide for future LCA-related projects and collaborations. It shows how prospective technologies development at the UFZ can be supported across research units and proposes a procedure how future collaborations could look like.

This White Paper outlines the essential elements for modelers to undertake a sustainability assessment and compiles needs and expectations of technology developers. It describes different assessment methods for prospective technology analysis, in particular life cycle assessment, showing opportunities and challenges associated to prospective technology analysis. A common approach for future cooperation is proposed based on the experience gained on an internal project with several case studies between RU4 and RU6 and an additional survey with the RU4 partners, to identify specific expectations and needs.

1.1. What do we understand as prospective technologies?

Prospective technologies are technologies at a very early development stage (Arvidsson et al. 2018). These innovations hold the potential to significantly influence the environment and sustainability practices but are usually in a pre-commercial, pre-testing phase, which defines the future oriented focus of their assessment. The second critical component of a prospective technology is its focus on novelty and innovation. These technical concepts are defined by their potential rapid growth, prominent impact, uncertainty, and ambiguity (Erakca et al. 2024). Such technologies are unconventional in many ways. They take a departure from traditional methodologies and lead to new resource pathways (Cucurachi et al. 2018). The departure from traditional methodologies leads to high uncertainty, which is another key characteristic of prospective technologies (Thonemann et al. 2020; Bruhn et al. 2023). This uncertainty relates to the feasibility of the technology, its scalability and the associated use of resources as well as its potential environmental, economic, and social impacts (Erakca et al. 2024; Arvidsson et al. 2018).

Prospective technology and emerging technology often have a lot of overlap; rapid growth, coherence, prominent impact, and uncertainty and ambiguity are defining features of both prospective and emerging technologies (Erakca et al. 2024). An emerging technology may have a more established foothold in the market or be further along in the development stage but is still very early in the commercial phase (Arvidsson et al. 2018). They emphasize innovation in the design and materials processes. In certain bio-based technologies this could include new biological processes or materials that aim to replace or complement existing fossil fuel based systems (Erakca et al. 2024; Gaffey et al. 2024).

The analysis of prospective technologies provides early insights that inform investments and policies, for aligning emerging technologies with regulatory frameworks, funding priorities, and societal needs (Wender et al. 2014). This is particularly critical as these technologies progress toward commercialization and market entry and investors and funding bodies increasingly focus on sustainable technology investments. By illustrating their proactive approach to addressing potential challenges, developers can build investor confidence, which in turn encourages financial support for innovative solutions.

1.2. Why assessing prospective technologies?

While evaluating new technologies is certainly fascinating, it can also be challenging. The most critical challenge is that the technology being assessed is still in the research, pilot, or pre-commercial development phase (Thonemann et al. 2020). Some of these technologies may be even in the theoretical or conceptual stages (Erakca et al. 2024). For example, a new biorefining process that uses methane-oxidizing bacteria to produce protein as animal feed from biogas or the production of isocitric acid in a bioprocess, which is currently a niche product, as both studied by RU4. While these technologies are promising, they are still undergoing development and its full potential is speculative at this point.

What are the reasons for the scientific community to have interest in prospective technology analysis, despite of its high uncertainties? The assessment in the early technology stage can lower risks and costs for technology optimization at a later stage. Also, prospective technologies are selected for analysis because of their potential for large scale impact (Bruhn et al. 2023). This is particularly true in the environmental sector where their potential impact for carbon reductions is massive. These technologies are key for potential breakthroughs in the reduction of fossil fuels and the lowering of greenhouse gasses and are also able to aid in the support of the creation of circular economies. This long-term nature of prospective technology makes it challenging to assess it against current technology. It is also necessary to consider how they might interact with future energy grids, regulatory landscapes, market shifts, etc. (Erakca et al. 2024).

Furthermore, biotechnology can raise huge sustainability risks when it is upscaled to an industrial level and absorbs large-scale biomass flows demanding significant exports and imports (Bringezu et al. 2021; Budzinski et al. 2017; Gawel et al. 2019). A growing bioeconomy in Europe has already led to an increase in harvested forest area and imported biomass and may hamper forest-based climate mitigation (Erb et al. 2022; Palahí et al. 2021). If not assessed, foreseen and avoided, such risks can lead to low public 'acceptance' or explicit criticism of bioeconomy (Mustalahti 2018; Stern et al. 2018) as green-washing of business as usual (Gerhardt 2018; Šimunović et al. 2018). An exclusive focus on industrial efficiency, technological changes and innovations, or simple replacement of fossil resources with biomass run the risk of maintaining the same unsustainable production and consumption system as the fossil-based economy if they are not part of a broader social-ecological transformation (Zeug et al. 2023a).

At UFZ, innovative (bio-) technologies are being developed and significant efforts are being invested to optimize these processes, ensuring they are not only effective but also environmentally friendly. RU4 “Sustainable Ecotechnologies” supports the shift in industrial production towards a sustainable circular economy that relies on renewable resources. The innovations focus on the reduction of consumption of fossil organic and scarce inorganic raw materials, the replacement of fossil energy source by renewable energies and prevention of the release of harmful substances to the environment. Processes are developed focusing on the biotechnological production of energy sources including hydrogen, biogas, and liquid fuels and chemical precursors for the polymer, chemical, and pharmaceutical industries, all derived from renewable resources. This biotechnological expertise is developed and bundled in order to enable an effective transfer to business and industry.

The analysis of prospective technologies presents numerous opportunities for the UFZ. The Department System Analysis and Sustainability Assessment of the RU6 (“Environment and Society”) holds this expertise in different life cycle assessment tools, that are able either evaluate environmental as well as social and economic impacts and contextualizing them within a social-ecological transformation. Thus, the UFZ can benefit from the combination of expertise in life cycle assessment (LCA) tools in RU6 and technology development in RU4.

2. Development process of White Paper

The basis of this White Paper is most of all the collaboration of colleagues from the RU4 “Sustainable Ecotechnologies”, Departments Systemic Environmental Biotechnology and Microbial Biotechnology, and RU6 “Environment and Society”, Department System Analysis and Sustainability Assessment. Through the promotion of interdisciplinary and trans-IP collaboration, the aim is to support and accelerate process design and innovation in the bio-based sector. An inter-IP project at UFZ was conducted, which included the conduction of case studies and the development of an internal White Paper to delineate the prospective LCA activities at UFZ as guide for future projects and collaborations around LCA. In preparing the white paper, the experiences from case studies were supplemented by a literature review and a small survey.

Literature review

A literature review was conducted to take a look outside of the UFZ at what prospective technologies are, what are the particularities of applying LCA to prospective technologies, what are the challenges, and what other methods can help to overcome the challenges. The results are presented in section 3.

Collaborative activities between RU4 and RU6

Four case studies were identified from the several technical concepts being developed at RU4 at that time, with the aim of using research results as a database in the best case. It is acknowledged that, at this early stage of technology development, it is unrealistic to expect all the data to be available. As a result, a certain amount of assumptions and values from literature must be used. These general difficulties are mentioned in section 1.2 and coping strategies are outlined in the section 3.2. The aforementioned assumptions and coping strategies were established in regular meetings involving close dialogue. The experience gained during this process has also been incorporated in section 4.

Survey to shape future inter-IP collaboration of RU4 & RU6

To develop the approach in this White Paper it is essential that such approach addresses the needs on side of technology developers (RU4) as well as of the modelers (RU6). In order to integrate further expectations, needs and suggestions, especially from technology developers, a survey was conducted to collect feedback in a structured way, while giving RU4 colleagues the opportunity to take time to reflect in a calm setting. It was shared in the middle of the collaboration with colleagues from RU4, which were involved in the preparation of case studies. The results of this small survey are evaluated in section 4.1.

Workflow and Mini LCA guide

The results of all of this, the implementation of case studies, the literature review and the survey lead to a suggested workflow and a condensed LCA guide including information material. This document is supposed to serve as guide to encourage and facilitate future collaborations (sections 4.2, 4.3).

3. Prospective technology assessment

There exists a set of possible methods in prospective technology assessment. Many of these methods attempt to manage the assumption that are being applied in a prospective LCA. They can test the assumptions and uncertainties being put forth and offer a “forward looking” analysis. However, these assumptions and uncertainties must be clearly identified, justified, and thoroughly assessed to understand their impact on the conclusions drawn from the LCA to ensure the overall validity of the analysis. The accuracy and robustness of these assumptions directly affect the reliability of the LCA results (Thonemann et al. 2020). In the following, a closer look into LCA-based tools in the context of prospective technologies is given with their challenges.

3.1. LCA-based tools

LCA

Life cycle assessment (LCA) is a comprehensive and, if applied in compliance to scientific standards, robust tool to help identifying best solutions to support sustainable development. This internationally acknowledged method attempts to quantify a broad range of potential impacts of all life stages (from cradle-to-grave) of technological systems, products and services. Despite the former focus on environmental impacts, social and economic impacts are increasingly being included as well. LCAs are widely used as decision-making tools, in eco-design, and policy formulation. Its own ISO standardization greatly increased the use of LCA (Hauschild 2018).

The LCA framework defines four methodological phases of a study: goal and scope definition, inventory analysis, impact assessment and interpretation. The goal of a study should be based on why the study is being performed, which questions are to be answered and for whom it is being conducted. The scope can then be set, such as the functional unit (unit to quantitatively describe the function for which the assessment is performed), the product system, the system boundaries (activities that belong to the life cycle of the product), as well as other methodological considerations such as the geographical and temporal conditions.

Inventory analysis describes the collection of data on the physical material and energy flows as inputs and outputs as emissions, waste and products. This is carried out for all processes that belong to the product system within the system boundaries. The life cycle inventory list is used for the impact assessment.

In the impact assessment, the physical flows are used to estimate the potential ecological, social and/or economic impacts. A set of impact categories is selected, each of which is based on a representative indicator and a model to quantify the impact of elementary flows on the indicator. For example, one can choose climate change as impact category with radiative forcing as global warming potential (GWP100) based on the IPCC's 100-year baseline model. The model helps to quantify the influence of the individual flows on an impact category. The standardized scores of each flow are then aggregated into a single indicator that represents the overall impact of the product system in a specific category (example in Figure 1). The impact categories can be further normalized and weighted to allow for comparison of them and common interpretation.

Finally, the results are interpreted with regard to the goal and scope definition. It is an iterative rather than a linear process, which involves many feedback loops between the four phases. Each phase can provide feedback to the previous one. Findings from the impact assessment are used to refine the inventory analysis and the latter can inform the scope definition. At each stage of the study, sensitivity and uncertainty analyses can help to validate key assumptions and identify data associated with uncertainties (Hauschild 2018).

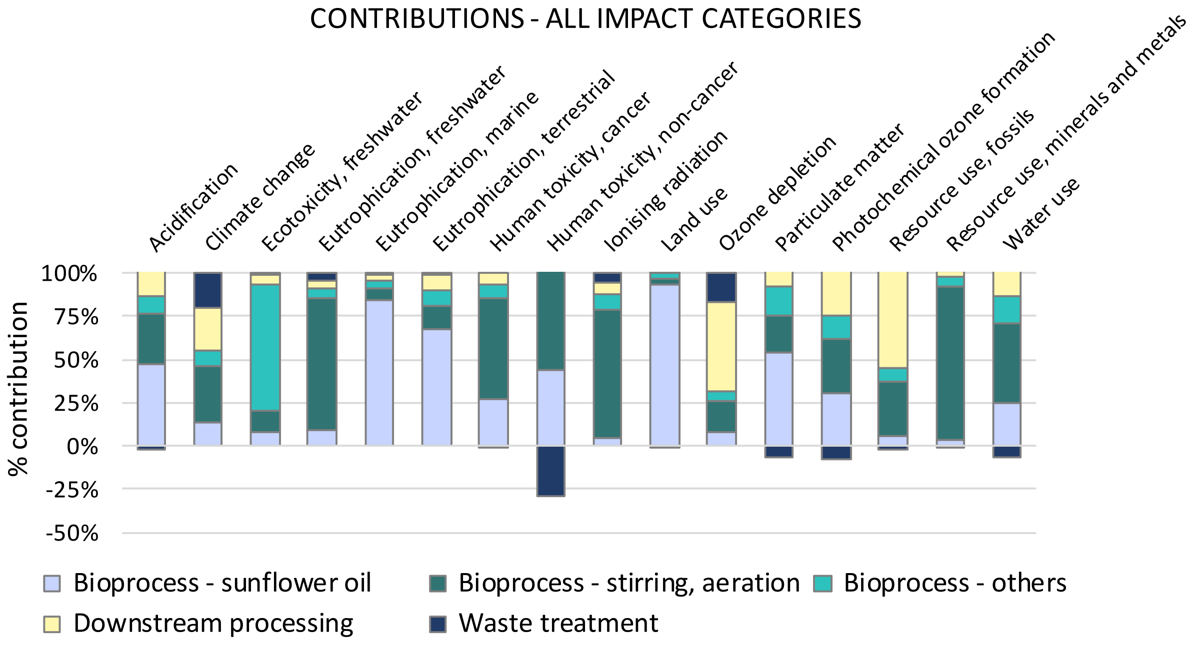

Figure 1: Relative contributions to all assessed impact categories by main contributors (processes and inputs) in isocitric acid production from cradle-to-gate.

A “traditional” LCA usually describes the impacts that a product or service actually causes during its life cycle such as through raw material extraction through materials processing, manufacturing, distribution, use, and disposal and/or recycling. Prospective LCA, also called ex-ante or anticipatory LCA, always has a more future-oriented component beyond the status quo. It deals with the scale-up of novel technologies by employing probable scenarios (using expert assistance, extreme viewpoints, and comparisons with analogous technologies) to estimate their future performance and impacts on the environment, society etc. (Cucurachi et al. 2018). So on the one hand prospective refers to the technology maturity, on the other hand it also indicates the temporal positionality (Arvidsson et al. 2024). Trying to predict future impacts allows for sustainability-oriented decisions to be made in the development stage (Thonemann et al. 2020). This proactive approach is crucial because it enables the identification and mitigation of potential negative impacts, such as high carbon emissions, resource depletion, or waste generation, which are often more difficult and costly to address after technology has matured (Thonemann et al. 2020).

Inventory data for material use, energy consumption, emissions, and end-of-life processes are often unknown or untested at early stage. This creates high uncertainty and is a challenge when doing the assessment. A prospective LCA must use assumptions, projections, and models rather than actual operations data to fill in the gaps in the knowledge, often relying on analogous technology or idealized performance estimates (Thonemann et al. 2020). A closer look into the challenges is taken in section 3.2.

HILCSA

Prospective LCA can encourage “responsible innovation” by uncovering potential future issues like land-use change, resource depletion, or socio-economic distributions, prompting early adjustments to avoid negative consequences (Wender et al. 2014). Traditionally, LCA tools have concentrated mainly on environmental concerns. However, recent initiatives have sought to integrate social and economic dimensions to deliver a more holistic sustainability assessment. Furthermore, in light of the shift toward a bioeconomy, specialized tools have been developed to assess regional effects and trade-offs linked to the adoption of bio-based technologies, in alignment with planetary boundaries and sustainable development goals (SDGs). In that way, LCA helps ensure that technology development aligns also with broader societal values. An innovative tool at UFZ, which assesses social, ecological and economic sustainability and reflects more on societal implications of a prospective technology, is the innovative “Holistic and Integrated Life Cycle Sustainability Assessment“ (HILCSA) method.

HILCSA is an LCSA (life cycle sustainability assessment) based method, able to assess and analyze holistic and integrated sustainability according to ISO 14040 and 14044 (ISO 2006a, 2006b), which reflect the international LCA standards. This interdisciplinary method is based on social sciences, engineering & economics and includes transdisciplinary elements of stakeholder participation. HILCSA integrates about 100 social, economic and environmental indicators in one method addressing 14 of 17 SDGs. Accordingly, material, energy and socio-economic inputs and outputs must be considered for modelling. The aim is to identify synergies, trade-offs and hotspots in production and consumption systems (Zeug et al. 2022; Zeug et al. 2023b). The results of qualitative and quantitative indicators are presented on four levels: detailed indicators, aggregated indices, a total index, and clear figures and maps with interpretations. One results of a case study about prospective biomass to liquid production in Germany is displayed in Figure 2.

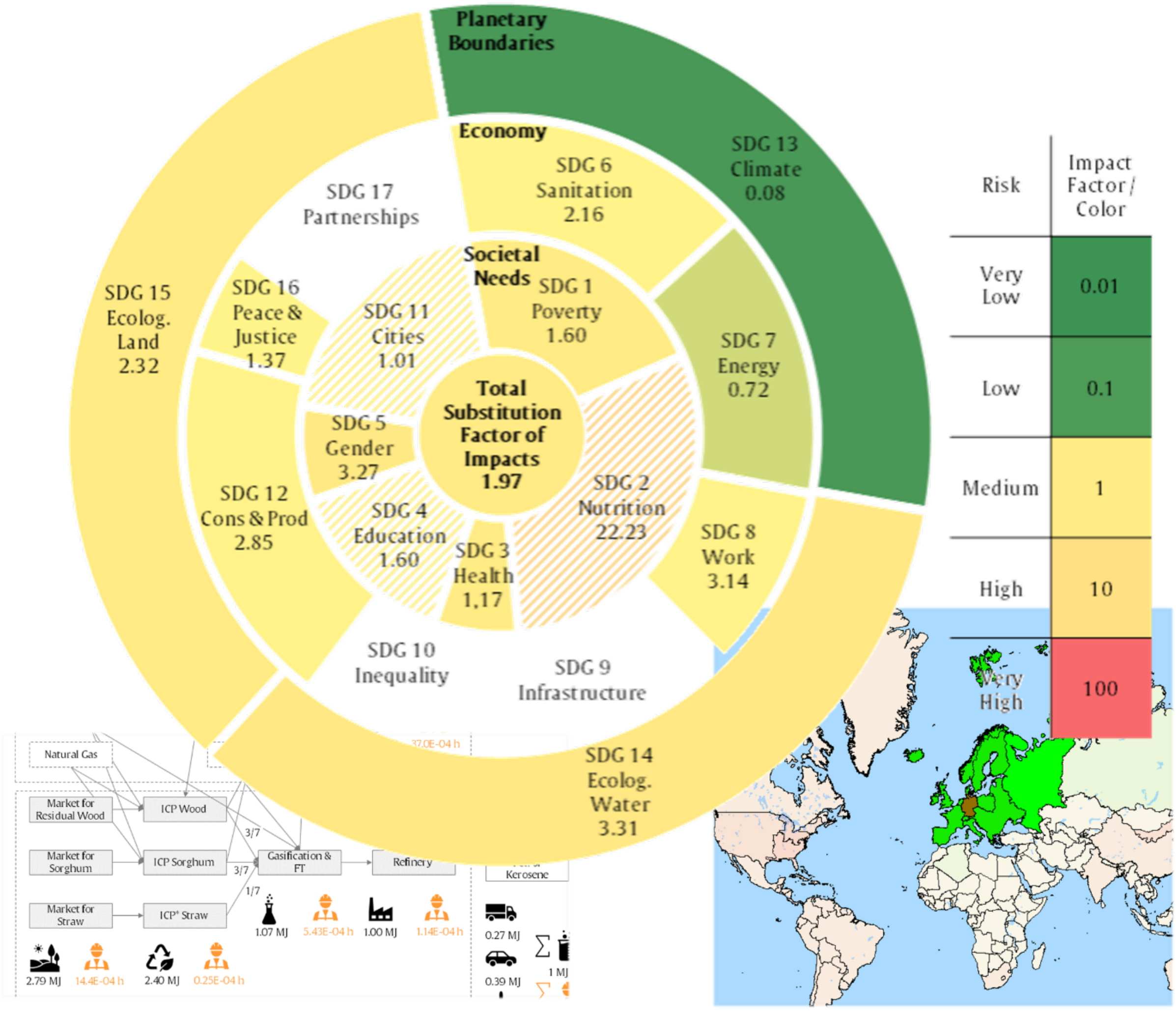

Figure 2: Example of HILCSA results including social, ecological and economic impacts aggregated to indices addressing the SDGs. Hatched/white fields indicate insufficient or missing data (Zeug et al. 2023b).

HILCSA has been available for both non-commercial and commercial use since 2024, being utilized by SMEs and research institutions. It has been proven in several current and past research projects (Gan Yupanqui et al. 2024; Zeug et al. 2022, 2023a; Zeug et al. 2025; Zeug et al. 2023b) and is part of teaching at Leipzig University.

3.2. Challenges in the assessment of prospective technologies using LCA tools

Prospective LCA presents its own set of unique challenges compared to traditional LCA. While traditional LCA is able to examine in detail each stage of a technology's life cycle (Arvidsson et al. 2018), prospective technology deals with multiple gray areas and unknowns. Some of them are also present in a traditional LCA study, but they are amplified in prospective LCA. These unknowns present distinct complexities and pose particular challenges for LCA studies: uncertainty, data and comparability (Thonemann et al. 2020). The characteristics of prospective technologies explained in section 1.1 and challenges posed by them are compared in Figure 3.

Characteristics of prospective technology	Challenges for (LCA-) assessment
Early development stage • Still in research, conceptual, or pilot stages and not established commercial or industrial applications	• Lacks empirical data • Relies on assumptions, literature, expert opinions and analogue technologies
Innovation and novelty • Technologies often represent a departure from conventual methods, emphasizing innovation in design, materials or processes • Key characteristics: rapid growth, novelty, ambiguity	• Needs close interaction with technology providers to get a detailed understanding • Concentrates on known processes rather than full value chain
High uncertainty • Very high uncertainty in terms of feasibility, upscaling, market-uptake and consumption • Lack data to fully account for the entire life cycle until the end-of-life	• Relies heavily on projections and models rather than actual operations data • Sketches results, scenarios, strategies with less detail than traditional LCA
Potential for large-scale future impacts • Promise to significantly improve current industrial processes • Uncertain interaction with future environments in terms of society, environment and the economy	• Must model potential long-term impacts, considering future scenarios of energy grids, regulations, market shifts, etc.

Figure 3: The box outlines the characteristics of prospective technologies and the challenges they pose for life cycle assessment (LCA).

Especially, regional and social assessments show how technical production processes can have significant impacts in global supply chain by externalization of social deprivations (Zeug et al. 2022; Zeug et al. 2023b; Backhouse et al. 2021). Such effects get visible by integrated and holistic methodologies and would probably be neglected in conventional and non-prospective LCA (Zeug et al. 2023a). Addressing social aspects in prospective LCA is crucial for reflecting real-world impacts across the entire value chain, such as working conditions, the use of critical raw materials, poor labor practices, unfair wages, or unsafe environments, but also opportunities for positive contributions such as job creation and community development. Omitting social considerations can undermine the relevance and accuracy of sustainability assessments and miss key risks that are increasingly important for business reputation and regulatory compliance (Murphy and Gusciute 2024; Mancini et al. 2018).

Data – uncertain input quantities

Uncertainty is a key characteristic of prospective LCA and due to that it leads to major challenges in assessing a prospective technology. One of the major uncertainties is insufficient data availability and data quality (Bruhn et al. 2023). Lots of prospective technologies in these early stages do not have data available for the full life cycle of the product it is examining as input for the various aspects of LCA (Erakca et al. 2024). Additionally, variations in materials inputs, product design, and production process lead to high variability in parameters which makes it difficult to define accurate environmental impact metrics. So, there is a statistical uncertainty or uncertainty on measurements and given parameters. Every analysis of future technologies, therefore, offers a set of answers instead of providing “the one” answer (Olsen et al. 2018).

Even if exhaustive laboratory values are available, several assumptions must be made as to how the assessed technology would perform after upscaling. Not all processes can be scaled up linearly, as other devices and practices might be used on an industrial scale. The assumptions made during a prospective LCA may result in over/under estimations of resource needs, emissions, and waste generation (Langkau et al. 2023). Alongside these assumptions, practitioners must consider the rapid technological growth: Prospective technologies evolve quickly, which means prospective LCA data/information may be outdated before it can be published (van der Giesen et al. 2020). Continuous advancements may alter energy demands, material requirements, and waste outputs. This means that assessments need frequent updating (McManus and Taylor 2015).

Foreground data, which relates to the processes specific to the assessed product system, and background data, which is considered to be provided by a homogeneous market with an average of suppliers, are both subject to change over time. For foreground data, there is often primary experimental data available (laboratory or pilot scale). Where there is no quantitative data, qualitative methods such as expert opinions, questionnaires, statements or scenarios must be used (Olsen et al. 2018). Secondary data sources can be scientific articles, patents, chemical equations, simulations and patents. The background data is usually mainly based on secondary data from LCI databases such as Ecoinvent or GaBi (sphera), i.e. databases that contain the inventory data with all material and energy flows for doing LCA of typical processes.

Uncertainty – dealing with future developments and frameworks

Beside the quantitative uncertainty in data, there is the more qualitative scenario uncertainty of future frameworks. This can be the assumption on future policies, energy systems, socio-economic frameworks etc. Since prospective technologies aim to address a gap in the market, their growth may be heavily affected by these factors (Olsen et al. 2018; van der Giesen et al. 2020). Normative choices in the modeling can have major impact on LCA outcomes. This scenario uncertainty already occurs in the early LCA phase when defining goal and scope as well as boundary conditions for up-scaling.

Assumptions have to be made about the characteristics of the technology, in which use contexts it will be applied, how widely it will spread and other open questions with as yet unknown, unmeasurable answers. Often the focus is on certainties and the uncertainties are neglected, which has also become known as the tradition of objectification or purification (Latour 1993).

A sensitivity analysis can help to identify the influence of key assumptions and parameters on LCA outcomes (Cellura et al. 2011), e.g. for technological parameters of high uncertainty such as residual heat use (Zeug et al. 2023b). Through the systematic variation of input values, a sensitivity analysis provides insight on which factors drive uncertainty. The result is higher clarity and refined models that guide research priorities (Gaffey et al. 2024). A sensitivity analysis is a valuable tool in areas with uncertain key input parameters, interactions in complex systems or dependency on external factors like policy that significantly impact outcomes.

In order to account for the framework changes over time, the data must be projected into a possible future. On the one hand, there is the option of using a predictive scenario as a basis, which assumes likely developments based on the status quo, or the option of extreme scenarios ranges to find a best-case scenario (Thonemann et al. 2020). The results are often sketches rather than objectified results as in traditional LCA, and reflect strategies within the framework of scenarios. Scenario modeling is a powerful tool to analyze prospective technology because it provides a structured way to explore uncertainties and potential futures (Thonemann et al. 2020). Unlike traditional approaches, scenario modeling examines a range of possible outcomes (Langkau et al. 2023). Scenario modeling is particularly effective when simulating future technology systems, i.e., transportation and energy grid systems identifying the most robust strategies for success (Spielmann et al. 2005).

Comparability – aim, system boundaries, functionality

There are a few other key uncertainties that make assessing prospective technology challenging. Due to the large uncertainties at early stages and the assumptions that must therefore be made, comparability issues arise in prospective LCA. For example, a specific time frame in the future must be agreed to be modeled, and sometimes also one or more future scenarios. There is the additional challenge of establishing appropriate functional units. Functional units, which serve as a reference value for determining product performance, are necessary in order to compare impacts but this can be difficult or complex when for technology with undefined or evolving functions (Bruhn et al. 2023). Furthermore, the functional unit can change with upscaling. Output-based functional units such as the production of 1kg of a specific chemical is more suitable than an input-based one.

The system boundaries are of great importance for the comparability of LCA results. They set the start-to-end point of an assessment and define considered processes and stages across a product's life cycle. System boundaries for traditional LCA are difficult and complex to define (Li et al. 2014), however they are necessary to understand the scale and scope of the technology being assessed. Defining the system boundaries for prospective technology becomes more difficult because identifying the full life cycle and scope of something not yet developed at scale is inherently challenging (van der Giesen et al. 2020). Ideally, the system boundaries should be drawn from cradle (raw material extraction) to grave (end-of-life treatment). Especially at early stages, the use phase and the end-of-life are uncertain, like e.g. recycling possibilities in the future. Additionally, innovations aimed at circularity may have unintended impacts, such as new waste streams or secondary materials. These new end-of-life challenges are difficult to quantify in the early stages of development (Niero et al. 2021).

It is therefore particularly important to give a sound definition of the aim of the assessment, the functional unit and system boundaries. For example, the intended application of the technology can be essential. In a comparative study, it must be ensured that the comparison is made with the same technological maturity. Additionally, if uncertainties regarding the use phase and end-of-life are significant, a cradle-to-gate analysis can be conducted, focusing on product production.

4. Cooperation at UFZ – discussion of experiences, expectations and future workflow

There exist several examples of collaborations involving colleagues from RU4 "Sustainable Ecotechnologies" and RU6 "Environment and Society" inside UFZ like an LCA study considering environmental aspects and costs of a novel large-scale biogas upgrading process in a plant located in Saxony (Kohlheb et al. 2021). More recently, several case studies were carried out at UFZ in an internal project 2024/2025. The goal was the evaluation of early-stage bio-based technologies using an LCA toolbox. The project aimed to promote interdisciplinary cooperation between LCA practitioners and technology developers to enhance process design and innovation in this area.

The following points summarize some of the general expectations expressed in the meetings during that project. The collaboration should:

- Provide information on whether an innovative process is really more sustainable than its conventional counterpart or a different research process
- If different approaches exist, derive which researched technology processes are the better ones in terms of effectiveness and sustainability
- Demonstrate potential improvements through recycling
- Have a clear objective for the cooperation process from the beginning, e.g. a joint publication, process optimization, etc.
- Indicate what impact the product will have when it reaches the market (on the environment or upscaling), e.g. protein as human food
- Assess the potential for reducing material, energy, time and costs already during process development
- Serve as a nice opportunity to get in touch with colleagues from another research unit
- Support sustainable technology development already in the development phase
- Explain the significance and meaning of the LCA results in the end
- Be used in the best case as advertisement for technology

In order to validate these statements and capture the perspectives of more colleagues, a small survey was conducted (4.1). Based on the experiences of this survey and the most recent case studies, a workflow was developed (4.2) and helpful materials were collected to facilitate future cooperation and provide an introduction to the world of LCA (4.3).

4.1. Expectations and challenges - survey results with focus group

A short survey was conducted with a focus group of six involved colleagues from RU4, to gather their perspectives on future collaboration between the two research units. Four questions were asked about their expectations, interests and requirements for a collaboration. As a fifth question, they were asked for feedback regarding a flow chart for future cooperation (see Figure 6). In the following, the outcomes of the survey are summarized.

1) General expectations: What are your general expectations of the collaboration between RU4 and RU6? How would you like to use the results?

The answers of this open question can be summarized in three main aspects:

The results should support the development of environmentally friendly and competitive technologies.

- Ideally, identify bottlenecks and benchmarks that must be reached in order to provide economically competitive and environmentally friendly technologies
- We should answer the question: What impact would an implementation of the respective technology have and is an implementation really feasible?

An iterative work flow is fundamental to help in technology development.

- For a realistic view, the early stage is not enough. It is helpful to divide LCA studies into the early stage, the development stage and the pilot stage. A suitable modular system for LCAs should contain, for example, the definition of system boundaries in the various phases, as well as the most important parameters (in- and outputs, social and economic aspects) in the different phases. Any parameter can be the bottleneck in the end
- An iterative working loop for LCA-TEA would help technique development, but that would require RU6 partners to be available for small tasks from time to time, which might not be practical. Results should be used for technique development and for technique capacity justification tailored to special scenarios

This collaboration should result in publications and grant opportunities.

- Chances for the production of publications that partially contain aspects of LCA
- It is expected to obtain grants that would otherwise be impossible without a systems perspective

2) Expectations: How important are the following aspects to you?

The second question offered participants the opportunity to evaluate certain aspects about a collaboration and usage of the results (Figure 4). The survey revealed that the most important aspect is to prove whether an innovative technology is more sustainable than a conventional alternative. Thus, a process optimization is aimed at with regard to environmental impacts, material inputs and energy. This is followed by costs optimization. The assessment of social impacts and political and economic framework conditions gain less attention. Furthermore, the aim should be to develop interesting new studies that can lead to joint publications. Increasing the visibility of own research within the UFZ is less important than the opportunity to make contact with colleagues from other RUs.

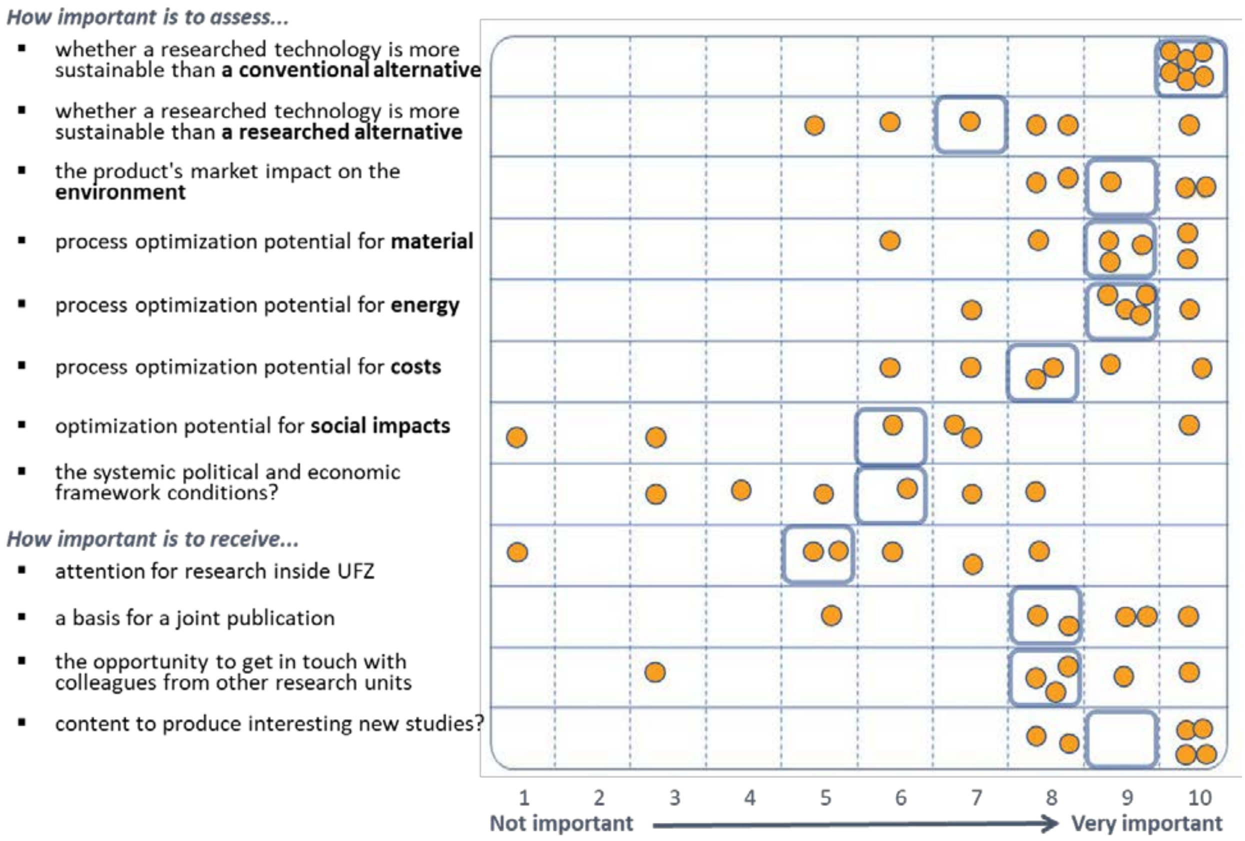

Figure 4: Expectations about certain aspects in a collaboration between RU4 and RU6. Most important is the assessment of environmental impacts to optimize the material and energy inputs, and in the best case to derive interesting new studies and joint publications from it.

3) Challenges: What are the challenges that you have faced in any (past) collaboration of this nature? Which challenges could arise in an internal UFZ collaboration?

The answers of this open question went into two directions:

Human resources

- We are not short in willingness to work together but in time and persons conducting this work. A skilled long-term technical support person could help for such kind of “on call” collaborations.
- Acquisition of joint (third-party funded) projects with integrated LCA offers the opportunity to provide additional personnel for intensive collaboration on specific bio-process developments.

Finding a common language and looking beyond the horizon

- Translating a process into an LCA requires a common language and looking beyond the horizon for all involved.
- Differences in knowledge about concepts and definitions of sustainability sometimes make exchanges difficult and lead to misunderstandings.
- Soft criteria are very open to interpretation. What do you mean when asking for an opinion on social impact? How are you going to define these criteria in a useful way?

- Looking beyond the horizon means also to include consequences of not implementing a technology because it is suboptimal today.

The workflow and LCA cookbook in section 4.3 are aimed to help at least to mitigate the concerns about finding a common language.

4) Requirements: What do you need in terms of content and format of resulting outputs?

The fourth question aimed more at the desired contents and formats. Most of the participants are interested in the environmental impact of the technologies, followed by economic impacts. The results should show in detail impacts of dedicated value chain steps/processes to provide a hotspot analysis. Formal, graphics like bar charts and hard numbers in Excel tables are desired rather than elaborated explanations and recommendations. Social impacts for now are again rated as least important, which shows that further sensibilization about the importance of social impacts in technology development might be necessary.

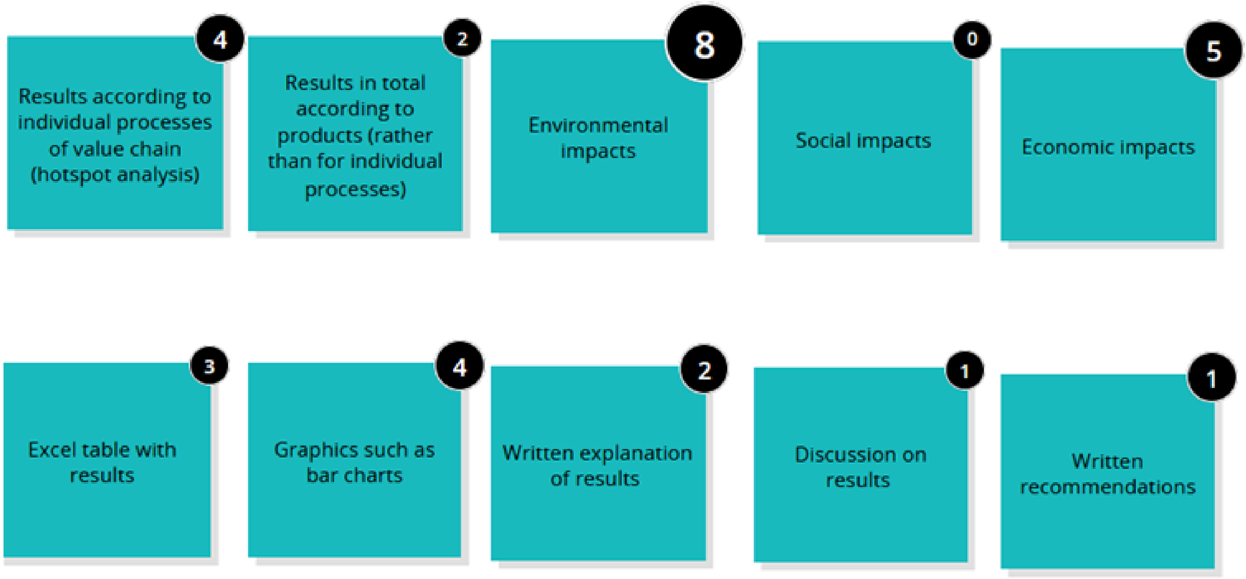

Figure 5: Result of survey question 4 with a RU4 focus group. Each participant could give 5 votes to the notes, which are preferred the most as part of the results.

5) Future collaborations work flow: The aim of the White Paper is to facilitate future UFZ collaborations. A flow chart is intended to serve as a rough guideline for the steps with which such cooperation can be approached and successfully concluded. Please use the notes to give us feedback on the work flow.

The last part of the survey was about gathering feedback about a draft of flow chart about future UFZ collaborations. The final flow chart, which considers the feedback of the RU4 partners, can be found in section 4.2.

Here, the importance of defining the expected output at the beginning, such as a publication or a joint project in a certain period of time, was emphasized. Another contribution even suggested that such assessments should always be organized in concrete, joint projects.

Regular meetings with clear timelines are considered important on the one hand, but on the other hand it is suggested that these should be kept to a minimum for capacity reasons. It was also noted that the uncertainties at the early stage should be more emphasized. It was discussed whether such a workflow would always lead to half-finished projects, as the application for funding is not easy. Another opinion was that LCA would never lead to fully finished projects, but that the results would simply be documented and published at a certain point.

4.2. Suggested workflow for future cooperation

The realization of case studies in 2024/2025 and a small survey with RU4 colleagues were the basis to extract the elementary steps for future cooperation at UFZ regarding prospective technology assessment (Figure 6). First, expectations and questions were gathered from experiences in the regular meetings and in an additional survey, which are presented in section 4.1. The following steps in a RU4/RU6 collaboration on prospective technology assessment should be taken to define an interesting study, that meets the expectation of each party (Figure 6). It can serve as an inspiration for applying for joint projects with LCA part and give an overview of what to consider.

The first step is to initiate contact between technology developers and the LCA modelers to explore case studies that colleagues from RU4 work on and both find suitable for prospective technology assessment with LCA-based tools. In the best case, experiences or initial results should already be available for the selected processes. At a very early stage, the outcomes should be defined in terms of the expected goal as well as the modus and output of the collaboration (e.g. a publication, proposal of a funding project, etc.). Then ideas are narrowed down to specific and suitable case studies and the goal, scope and methods to analyze them are determined. This includes defining the objectives of the assessment, for example whether it should be a comparative analysis and possible scenarios, the system boundaries, i.e. which processes should all be included in the analysis, and also the methods, and i.e. to what extend environmental or social and economic impacts should be considered and why a holistic sustainability assessment is important. This enables the establishment of a common understanding of the technology and the assessment methods, which is essential to start the analysis. To get an overview of the assessed cases, it is recommended to create flow diagrams with the most important processes. The flow charts should reflect the expectations of all representatives. For example, the system boundaries can be set to cradle-to-gate or gate-to-gate. A comparative analysis with another conventional or researched reference can be considered.

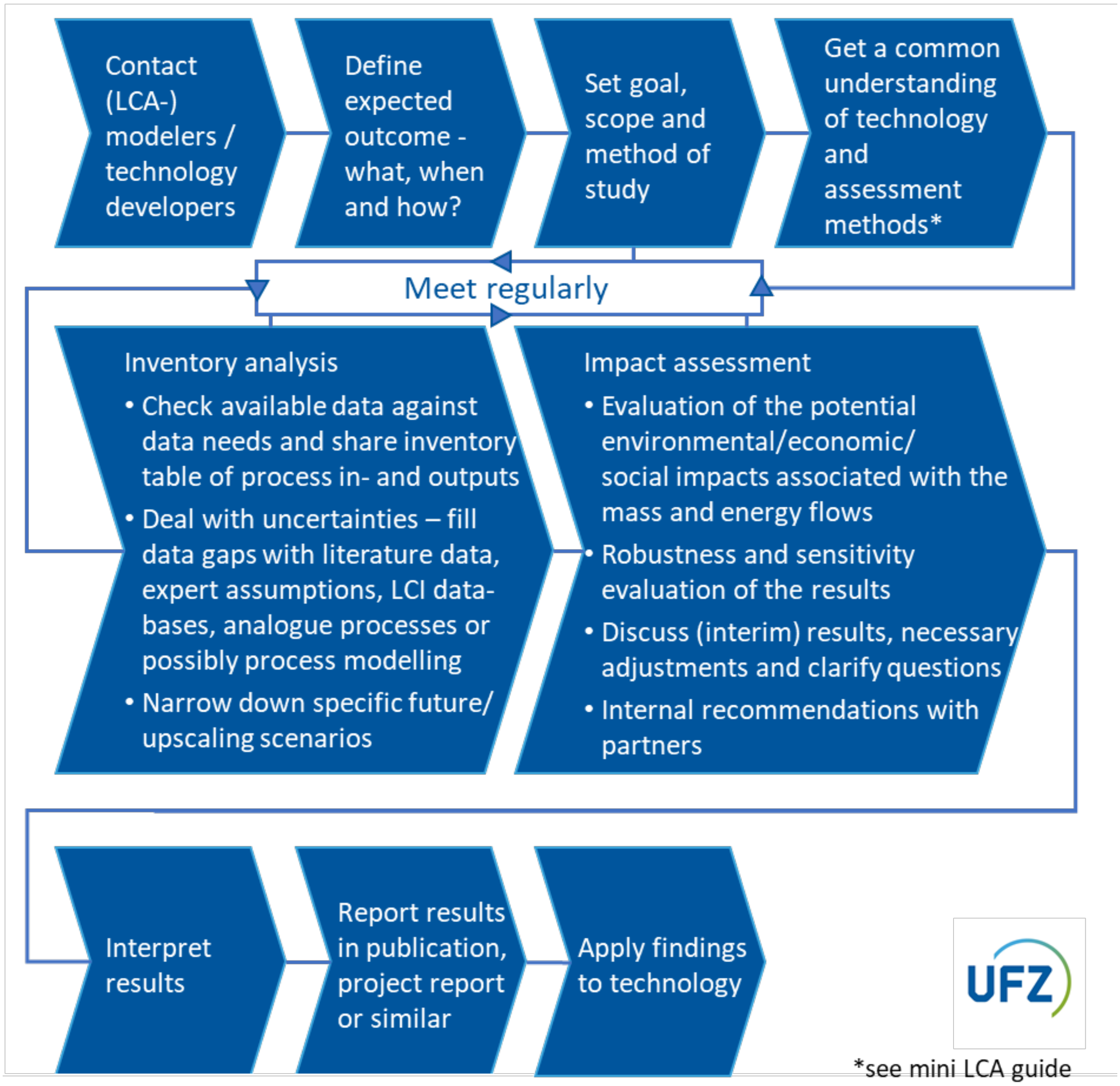

Figure 6: General steps to initiate and successfully conclude prospective technology assessments at UFZ.

Regular meetings with key contact persons should be organized, but should be kept to a minimum according to the survey results. The meetings are essential to clarify questions, verify the agreed method and assumptions or discuss necessary adjustments. In that way, understanding of the technical aspects and assessment methods is deepened along the way and misunderstandings are cleared.

The first vital aspect of the meetings is the exchange of available information and data on the value chains, to collect an inventory for the assessment. These can be laboratory data, available inhouse studies/reports and data from relevant literature. It is recommended to create a shared inventory table where everyone can add input and output data. As one of the characteristics of prospective technologies is uncertainty, the discussion of how to deal with it is another important topic of the meetings. It should be decided where which assumptions should be made and where secondary data sources should be used (data from literature, from life cycle inventory (LCI) databases, from analogies to similar technologies or process modelling, if possible). For the data inventory, it is also crucial to agree on scenarios that represent the upscaling of the technology in the future, e.g. a specific area of application, a production volume, etc. A discussion is needed to find a way to scale the processes. For manual processes at laboratory scale linear upscaling wouldn't make sense and process modelling could be helpful. After a first inventory is set, the mass and energy flows of the assessed case can be used for the impact assessment, which evaluates the potential environmental, economic and or social impacts.

Sensitivity studies can be used to determine the influence of assumptions and impact of certain parameters set in the model and check the plausibility and robustness of the model. These interim results can be discussed and improvements of the modelled processes can be developed. Again, here it is important to integrate the needs of the technology developers in the evaluation and interpretation, for example to include impact categories and processes they are interested in the most or to provide a specific presentation/formatting of outputs. Also, it is desired to explain the results and associated indications. The following typical questions were discussed in the regular meetings during the prospective technology assessment:

- What kind of data is needed for the assessment?
- What kind of data is available (from the experiments/laboratory, own studies)?
- How can we fill data gaps (process modelling, literature data, databases, …) and what assumptions need to be made?
- Can we have a comparison of our innovative approach with a conventional product?
- Should we consider the whole value chain of the product or only our particular bio-process (cradle-to-gate or gate-to-gate system boundaries)?
- What extension of the system is still worth the information output (complexity vs. derived added value of information)?
- What scale should be modelled?
- What kind of assessment outputs are interesting and needed for technology developers in the end (outcomes by process steps, certain impact categories, ...)?
- Can the results serve as the basis for a joint publication? Are there problems with confidential data?

Discussions of the results can lead to the conclusion that adjustments need to be made to the inventory or even the previously defined system boundaries. These steps must therefore be seen as an iterative process to improve the model. Once the model has undergone some of these feedback loops and is considered sufficient, a final interpretation can be reported. In the ideal case, the results of the life cycle assessment can afterwards not only be summarized in a publication or report but also contribute to improving the sustainability of the technologies.

4.3. Mini LCA guide for technology developers and others

This section presents a short summary on information on LCA-based tools, what can be expected and what is needed for such an assessment in future collaboration. More details on the LCA method can be found in section 3.1 and additional informative material in the Annex.

LC…what?

Life Cycle Assessment (LCA) is an internationally acknowledged method for evaluating the potential impact of products and services. LCA tools are able to quantify a comprehensive set of potential impacts at all stages of a product or service's lifecycle in order to minimize impacts and optimize processes. While traditional LCA tools primarily focus on environmental issues, more recent efforts aim to incorporate social and economic factors in order to enable a more comprehensive support of sustainable development. They are commonly utilized as tools for decision-making, eco-design, and the development of policies (Hauschild 2018).

Why LCA?

By showing the environmental, social and economic impacts of all life cycle stages, it helps to assess and reduce (not) expected impacts of products and activities and increases transparency in sustainability claims. Adopting a life cycle approach can prevent burden shifting if achieving a specific goal such as reducing greenhouse gases has unexpected negative effects. Applied in the early technology stage, it lowers risks and costs for technology optimization.

What can LCA do?

It can answer questions like:

- Is product X more socially, ecologically and economically sustainable than Y?
- How can the overall impact of X be minimized with the least effort?
- Does a certain change in process X increase or decrease the impact of my product?
- What are substitution effects, hotspots, trade-offs, and synergies?
- Under which technical, economic and social conditions would products and technologies be environmentally, socially and economically desirable?

What data is needed for an LCA?

Reliable and accurate results depend on using the right data. The inputs and outputs of a product's life cycle must be quantified properly, such as energy consumption, raw materials, products, wastes and emissions. They are combined in the so-called life-cycle inventory (LCI) (European Commission 2024):

- First the relevant processes need to be identified. The assessed subject, which is mostly a product, passes various steps or processes from resource extraction to the end of its life. A flowchart can help to map them (Figure 7). Each process step requires materials, energy and produces products, emissions and/or waste.

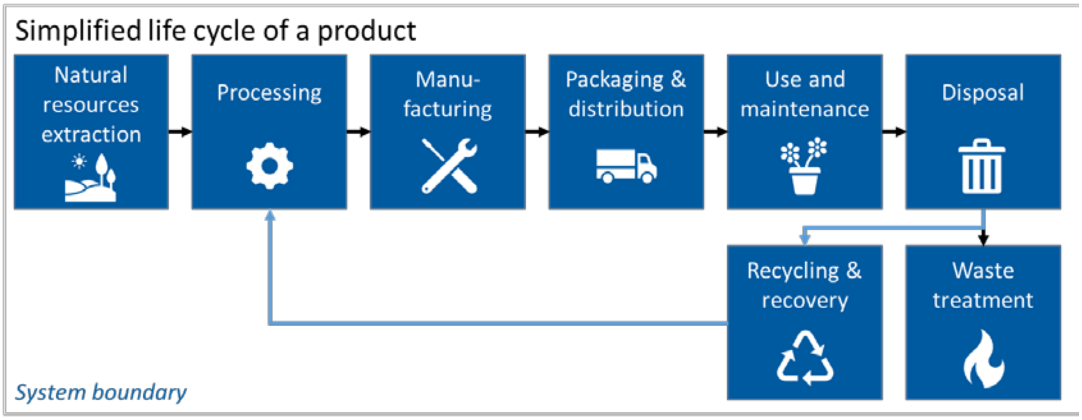

Figure 7: Simplified and generalized product's life cycle.

- A data sheet for the LCI is shared between partners. Examples of an inventory and a data collection sheet are given in the Annex.
- The best option is primary data, which is collected directly from own operations (e.g. electricity consumption).
- Primary data is complemented by secondary data, mostly for the background processes (e.g. the production mix for electricity from the grid) obtained from life cycle inventory (LCI) databases or literature. If processes are missing also in the LCI databases, other ways have to be taken such as to create own processes with available datasets (Kohlheb et al. 2021).

Four LCA steps

The LCA evaluation includes the following standardized steps, with steps 1) Goal and scope definition, 2) Inventory analysis and 4) Interpretation being carried out together with the project partners (Figure 8). The steps are considered as an iterative process, which involves many feedback loops between the four phases. Each phase can provide feedback to the previous one.

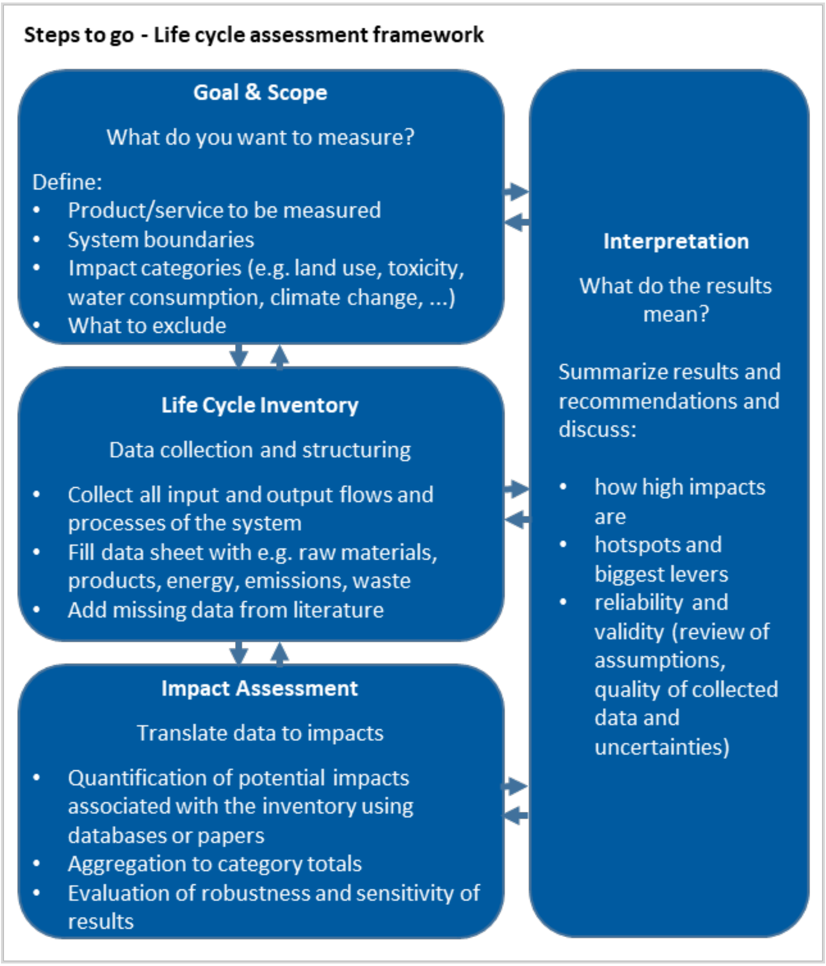

Figure 8: Life cycle assessment framework, which has four iterative steps: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment and 4) Interpretation.

0) Selection of case studies

1) Goal and scope definition

Answer the question why and for whom the study is performed. Select the **functional unit,** which is the unit to quantitatively describe the function for which the assessment is performed (e.g. one kg of a product, one MJ, 100 kilometers driven, etc.). The functional unit establishes the reference flow of the product, that scales the data collection. Set the **system boundaries** and decide which processes belong to the product's life cycle (Figure 9). Select geographical and temporal boundaries as well as methodological settings[1] of

[1] Modelers choose between attributional approach (allocation at the point of substitution), consequential approach (system expansion) or cut-off approach

the study. Choose the assessed **impact categories** (e.g. land use, water consumption, climate change, eutrophication, toxicity, particulate matter, etc.).

2) Inventory analysis

Data collection is aimed at characterizing the input and output flows of the technologies involved, depending on the goal and scope. This includes: raw materials, energy, water usage, emissions and waste generation. Data is collected for all processes of the product system within the system boundaries. The life cycle inventory (LCI) is analyzed in the impact assessment.

3) Impact assessment

The environmental, social and/or economic impacts of the individual process steps collected in the LCI are quantified. They are aggregated to one indicator presenting the overall impact of the case study per each impact category. The robustness and sensitivity to key assumption and parameters is evaluated. RU6 uses currently openLCA (and its characterization models) in combination with the database Ecoinvent or SOCA (examples of results are presented in Figure 2 and Figure 1).

4) Interpretation and reporting

The results of the impact assessment are interpreted with regards to the goal and scope definition. Most relevant factors in terms of their contribution to selected impact categories are identified. A closing report describes the effects of the studied case, identifies areas for improvement in the processes, prioritizes hotspots, and describes the uncertainties/limitations of the LCA study.

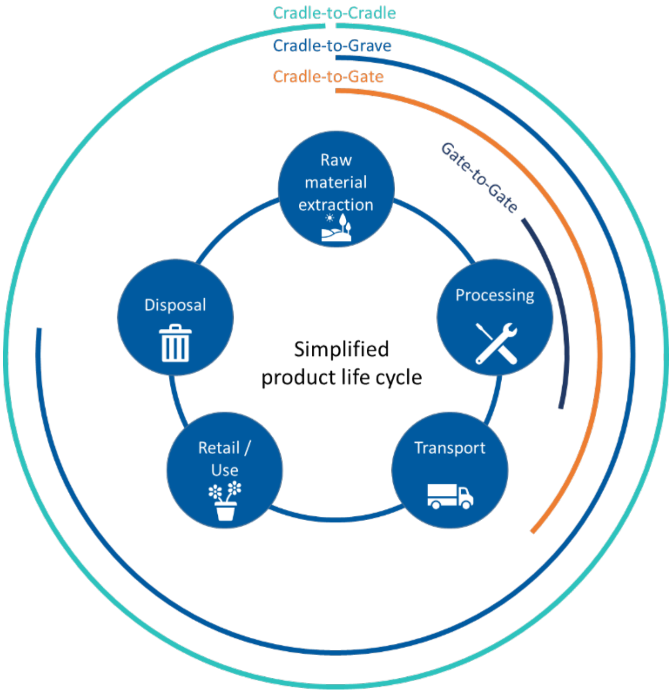

Figure 9: General life cycle stages with typical system boundaries for life cycle assessments.

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6. Annex

Informative Material / Templates

Table 1: Skeleton of a data collection template to be adapted to the case study.

Process	Input / output	Amount	per functional unit	If not available in database: Similar product/process	Ecoinvent process
Process 1					
In	Material 1		kg		
	Material 2		kg		
	Water		m^3		
	Electricity		kWh		
	Steam		MJ		
Out	Waste water		m^3		
	Waste stream 2		kg		
	Emission		kg		
	Product A		kg		
	By-product		kg		
Process 2					
In	Material 1		kg		
	Material 2		kg		
	Water		m^3		
	Electricity		kWh		
	Steam		MJ		
Out	Waste water		m^3		
	Waste stream 2		kg		
	Emission from X		kg		
	Product B		kg		
	By-product		kg		
[To be continued for all processes...]					
Output					
Main product/service		1	Functional unit		
By-products			kg		
PARAMETER					
E.g. production of product A per year			Kg per year		
Moisture content			%		
...					

Table 2: Excerpt of inventory data list from a study with RU4 partners including two processes to produce monopotassium isocitric acid.

K-Isocitric acid inventory	Amount	per kg K-ICA	Ecoinvent process
Fermentation			
Air	X	m^3	Market for compressed air, 1000 kPa gauge – RER
KOH 50%	X	kg	Market for potassium hydroxide - GLO
	X	kg	Water production, deionised - Europe without Switzerland
Sunflower oil	X	kg	Own process based on rapeseed oil
Pre-culture	X	kg	Own process
Water	X	kg	Water production, deionised - Europe without Switzerland
(NH4)2SO4 50g/L	X	kg	Market for ammonium sulfate - RER
	X	kg	Water production, deionised - Europe without Switzerland
Calcium chloride	X	kg	Market for calcium chloride - RER
FeSO4 x 7 H2O	X	kg	Market for iron sulfate - RER
	X	kg	Water production, deionised - Europe without Switzerland
KCl	X	kg	Market for potassium chloride - RER
KH2PO4	X	kg	Own process
MgSO4x7H2O	X	kg	Magnesium sulfate production - RER
	X	kg	Water production, deionised - Europe without Switzerland
Sodium Chloride	X	kg	Sodium chloride production, powder - RER
Thiamin x HCl	-	-	Not available, but only small amounts and impact, therefore neglected
Itaconic acid	X	kg	Replaced by equivalent sugar proxy: Beet sugar production | sugar, from sugar beet - RoW
Trace elements	X	kg	Compilation of elements in own process
Electricity	X	kWh	Market for electricity, low voltage - DE
Steam	X	MJ	Steam production, as energy carrier, in chemical industry | heat, from steam, in chemical industry - RER
Out: Carb. Dioxide emission	X	kg	Carbon dioxide, non-fossil
Cross-flow filtration			
Membrane	X	kg	Market for cellulose fibre – RoW
Spacer of filter	X	kg	Market for polypropylene, granulate – GLO
Electricity	X	kWh	Market for electricity, low voltage – DE
[more processes excluded here…]			
Overall output			
Monopotassium isocitric acid	1	Kg	-
Credit for anaerobic digestion of biomass residues	-X	Nm^3	Treatment of used vegetable cooking oil by anaerobic digestion | biogas | APOS, U – RoW