



The European Commission's Knowledge Centre for Bioeconomy



Report on the Community of Practice Workshop Prospective LCA for Novel and Emerging Technologies for BIO-based products - PLANET BIO



**6th and 7th December 2021
10.00 – 13.00 CET
Venue: Online**

This publication is a workshop report by the European Commission's Knowledge Centre for Bioeconomy. The objective of the workshop was to present the project PLANET BIO, being implemented by the LCA and Environmental Footprint team at the JRC's Land Resources Unit. The points presented in this report summarise the views expressed by the participants and do not imply a policy position of the European Commission, nor any person acting on behalf of the Commission are responsible for the use that might be made of this publication.

The workshop took place virtually on 6-7 December 2021.
Presentations are provided in annex.

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Background / Description of the project:

Bioeconomy related innovations may have a pivotal role in support to a more circular and decarbonised economy. Nevertheless, it is essential to ensure at an early stage of development that such technologies are bringing more benefits than burdens, and that trade-offs are identified and minimized, to guide investment and technology deployment towards a sustainable economy.

Therefore, **this project intends to develop an innovative robust framework - based on Life Cycle Assessment (LCA) - for the environmental assessment of emerging technologies for bio-based products (BbP), as essential decision support for policy makers and investors.** By comprehensively assessing new technologies and their potential upscale, considering alternative development scenarios, the framework will help to foster eco-innovation, to minimise impacts, and to unveil trade-offs, towards a sustainable circular bioeconomy. The development of this framework will be useful for various EU policies such as the Bioeconomy Strategy, the Circular Economy Plan and the European Green Deal.

Scientific importance, impact and added value

There is a great need for the development of methods to support decision making towards a sustainable bioeconomy, informing the selection of sustainable feedstock and pathways, for the production of bio-based products. Along these lines, this project aimed at:

- Contributing to the methodological development of prospective LCA. Prospective LCA has been gaining prominence in the assessment of environmental impacts of emerging technologies, but several methodological challenges exist related with the integration of the dimensions of scale and time. The project addressed these aspects by i) carrying out a systematic identification and classification of emerging processes for bio-based products production and upscaling approaches (scale dimension), and ii) developing an approach that enables the modelling of processes that will be at industrial scale in a future time (time dimension). Additionally, an assessment of the main uncertainty sources inherent to this type of studies is developed.
- Assessing environmental impacts under different technological and socio-economic scenarios. Several factors influence the deployment of the bio-based products technologies. To address them, a scenario analysis is performed by considering several factors that influence the development of bio-based products processes, such as biomass availability, climate conditions, or increase in food production, to provide a firm basis for further technology development.
- Providing support for policymakers and industry in the selection of sustainable pathways. The framework can support policymakers and industry in the selection of sustainable pathways for the production of bio-based products, which are still at an early stage of development. This will allow to steer investment and deployment of technologies that minimise environmental burdens and support the development of sustainable policies for the bioeconomy.

Welcome and adoption of the agenda

Serenella Sala, Deputy Head of Unit, JRC D3

Participants were welcomed and the meeting rules and agenda were presented. The main workshop aim was to gather ideas and comments on the framework developed by JRC by a number of experts selected based on their prominence in the field and complementary expertise.

Tour de Table

46 participants (14 from EC: 9 from JRC, 5 from DG RTD, ENV and GROW, and 32 from organisations and universities) presented themselves and expressed their interest in the project, as well as their expectations.

Introduction to the project and overview on proposed LCA-based framework for the environmental assessment of emerging technologies for bio-based products

Carla Caldeira, Project coordinator, JRC D3

Carla Caldeira presented the overall scope, the context, objectives and expected outcome of the JRC exploratory project PLANET BIO¹.

Ms Caldeira emphasised that selected sustainable pathways should be identified at early stages of their development. This exploratory project aims at developing a framework that decision makers can use to identify sustainable pathways for scaling up bio-based technologies. Several aspects need to be taken into consideration when designing effective policies: e.g. techno-economic assessment, social impacts, feedstock security and the environmental impacts: this is where prospective LCA (pLCA) can be of help.

Prospective LCA looks at the future environmental impacts related to technologies and their products. It would involve identifying emerging processes of bio-based products and upscaling approaches for those products, plus developing an approach that enables the modelling of processes that will be at industrial scale in the future. On top of that, scenario analysis would be used to assess several factors that influence the development of such processes.

To help the discussion along the workshop, the framework has been tested through four case studies: namely, the production of:

- polymers from mango waste
- polyhydroxyalkanoates (PHA) from organic wastes
- bio BTX, a combination of benzene, toluene, and xylene, from agriculture and forest residues and energy crops
- protein from CO₂

The project started in 2020 with data collection on key technologies, the advancement of methodology and scenario analysis, etc. The expected conclusion is in May 2022 with a technical report on the framework.

¹ https://knowledge4policy.ec.europa.eu/publication/prospective-life-cycle-assessment-emerging-technologies-bio-based-materials_en

Prospective modelling to assess the environmental assessment of emerging technologies for bio-based products

Presentation of Stefano Cucurachi and Bernhard Steubing, Leiden University

Stefano Cucurachi firstly explained the prospective LCA **modelling choices**: after going through the standard phases of LCA studies, the differences between standard and prospective LCAs were illustrated from a methodological perspective.

He presented the definition of goal and scope with explicit consideration on the:

- Technology Readiness Level (TRL) of the bio-based system under assessment
- TRL of the incumbent system under comparison
- the function(s) of the system
- system boundaries

Mr Cucurachi mentioned some considerations that can help the analyst define the right functional unit:

Functional Unit Type	Example of functional unit	Focus of Research
output-based	1 kg product	Novel technology, attempting to compare best feedstock to produce a product (useful for comparing incumbent vs novel technology)
feedstock-based	1 ton biomass	Novel use of feedstock, attempting to compare best use of biomass feedstock
land-based	1 hectare	Novel use of land, attempting to compare best use of agricultural land

They developed a series of decision trees, to help the practitioners define the scope of the study (e.g. functional unit, system boundaries). Regarding the functional unit it can be output-based, (to assess novel technologies and compare best feedstocks for a given product), feedstock-based (to assess novel uses of feedstock, i.e. to compare best uses of a given feedstock) or land-based (to assess novel uses of land) (ref to table above). As an example of a case study, comparing microwave extraction vs. conventional acid extraction for the production of pectin from orange peels, the selected functional unit would be output-based (i.e. 1 kg of pectin). A decision tree can also help identify the most suitable system boundaries for the analysis: in the example for comparing a bio-based versus a fossil-based PET (polyethylene terephthalate) bottle, the system boundaries chosen could be “cradle to gate” as the end product is chemically and functionally identical.

They created a decision tree for the allocation system as well. The analyst could verify the existence of a market, and that related data are available to assess the emerging such market for the bio-based products (BbP) system and incumbent. Some aspects they considered: more on allocation and cut-off criteria aspects, related to the inventory data, and upscaling of foreground and background systems. They looked into how to make decisions already in the early stages of the LCA process, related to data, or whether to go for process simulations and/or calculations. They also examined the relationship between proxies and detailed modelling.

Next Bernhard Steubing presented the chapter on **scenario methodology**, by illustrating the main phases. Phase 1 of LCA focuses on the goal and scope of the model. Several issues should be analysed:

- Scenario type (predictive, explorative or normative)
- Time horizon
- TRL (in the current or in the future)
- Foreground and background data
- Identification of alternatives

Phase 2 defines a 4-step procedure to perform the Life Cycle Inventory (LCI) analysis. Here they focus on being practical and provide easy solution for LCA practitioners:

- a) Identification of influencing parameters, where different methodologies can be used, e.g. PESTEL, causal loop diagrams, initial LCI model, etc.
- b) Construction of sub-scenarios for each parameter, i.e. which are the values of these parameters in the future
- c) Creation of scenarios from sub-scenarios, e.g. sub-steps, consistency check, etc.
- d) Implementation of scenarios in the LCI model.

Mr Steubing presented an example for the use of causal-loop diagram, to reconcile the data availability and the direct factors that influence the results, so that limitations can be identified. This diagram also helps communicate what has been modelled in the LCA, such as the parameters included in the LCI, differentiating between 'surrounding parameters' (mostly qualitative and not included in the inventory) and 'technology parameters' (quantitative data as part of the inventory).

A further step of the scenario development aims at performing a consistency check of the considered parameters, identifying morphological fields and developing narratives and scenarios.

Finally, the implementation of scenarios in the LCI model is performed to quantify all the assessed parameters in each scenario for both cases, foreground and background scenarios.

A key learning from the presented exercise: during the development process of scenarios it is very important to engage with stakeholders in the project/sector, which will influence the success of the analysis.

The main take away messages are:

- Scenarios can be developed in many ways;
- The presented approach is a simple, but structured one, tested on several case studies;
- Designing good scenarios is important, as well as the identification of parameters;
- Transparent reporting of how scenarios were generated is crucial for a transparent and useful LCA.

The next chapter focused on **modelling and accounting the biogenic carbon**.

The main issues are:

- Timing of emissions: the sequestration and emissions may have different temporal profiles and thus carbon neutrality may not imply climate neutrality.
- Carbon storage: temporary or permanent (long-lived vs. short-lived products).
- Land use change: direct and indirect.

They collected information on biogenic carbon accounting in scientific literature. Dynamic and conventional LCA have different characteristics in terms of biogenic carbon accounting, namely it is difficult to include in conventional LCA while it dynamic LCA has been designed to account for biogenic carbon. Yet, some challenges remain.

Mr Steubing also talked about the collection of information on standards for biogenic carbon accounting. He mentioned temporary and permanent carbon storage, as well as direct and indirect land use changes.

He presented some general discussion points to address when accounting biogenic carbon:

- Counter-factuality and verification
- Choice of time horizon
- Multi-functionality
- System boundaries

Implications of these points on prospective LCA:

- Issues such as timing of emissions, carbon storage and land use changes fall, by definition, into the realm of prospective LCA, as they rely on assumptions on the future
- Scenario or sensitivity analyses could be performed for different approaches (e.g. alternative biomass feedstocks, sequestration of CO₂, emission profiles related to land use change, temporal carbon change in products, etc.)

Stefano Cucurachi took over the presentation by talking about **uncertainty and sensitivity analysis**.

This section focused on the following aspects:

- Classification of types of uncertainty and sensitivity
- Connection between relevant literature and BbP systems
- Guidance to the analyst/practitioner towards making choices about how to model uncertainty
- Application in an example

First, they collected and classified the information available in the literature. They started with three main dimensions of **uncertainty**: the nature (epistemic or ontic), location (quantity, model structure and context) and level of uncertainty (shallow, medium, deep uncertainty and recognised ignorance).

The statistical analysis to be applied depends very much on the data. The most commonly used classification available in the literature for **sensitivity** distinguishes two types of analyses: local and global².

On the basis of the identified classifications, they proposed a stepwise approach:

1. uncertainty location and identification by LCA phases,
2. uncertainty characterization,
3. qualitative importance ranking,
4. treatment of uncertainty,
5. uncertainty communication.

They recommended that the practitioners work with probability distributions and explain how this approach could be performed by uncertainty assessment (UA), sensitivity analysis (SA) and scenario exploration:

- UA, or the quantification of the uncertainty in the inputs to the LCA model, and the propagation of uncertainty information of the inputs into uncertain model results
- SA, or the study of how the input uncertainties contribute to the output uncertainty
- Scenarios

² Razavi, S., Jakeman, A., Saltelli, A., Prieur, C., Iooss, B., Borgonovo, E., ... & Maier, H. R. (2021). The future of sensitivity analysis: An essential discipline for systems modeling and policy support. *Environmental Modelling & Software*, 137, 104954., [Razavi et al., 2021](#)

They also showed examples to the participants on how to apply Monte Carlo analysis (MCS), sensitivity analysis (SA) and scenario analysis.

The presentation was concluded by bringing up discussion points to be considered during the workshop:

- How can we make our methodology/recommendations **more specific for BbPs**?
- How is **uncertainty** for emerging BbPs different from uncertainty for other emerging technologies?
- How to reconcile theoretical and methodological discussions to the **practical needs** of the analyst/practitioner?
- Which practical conclusions should we draw for the modelling of **biogenic carbon** in pLCA?
- **How to combine the individual parts into a bigger framework?** Is that even a meaningful goal?

Discussion

Carla Caldeira started the discussion by going through the questions posted in the chat and the comments from the participants.

Do you suggest consistent background data for the (EU) future?

For the background scenarios like SSP (Shared Socioeconomic Pathways) 2, the idea is to combine the included parameters from an integrated assessment model with an LCA database for pLCA³.

Regarding the cases that compare replacement of material for another one with the same function: *What about a function basis, like in packaging, and comparison of plastics and fibre packaging?*

The reply referred to the approach generally used in LCA.

Is the assessment of harmful substances somehow included?

The framework will follow the standard procedure for the Environmental footprint method (PEF), which includes human toxicity and eco toxicity.

Why "allocation", and not "basket" or "gross" approach, avoiding allocation?

This is a broader discussion, which we could not cover in the presentation. There has been a lot of work about this in the literature recently. It is an ongoing topic on how to avoid allocation, and when to avoid it. Another point of focus is what kind of other methods there are in place to avoid allocation: i.e. the standard versus common practice.

Does it make sense to design a default list for the surrounding parameters to guide the non-expert practitioners as starting point for phase 2A of the scenario analysis?

The suggestion was well received by the participants and an indicative list can / will be included in the report.

Regarding how to approach the circularity of products: *The units and uses change along the life cycle of products, e.g. woody biomass used first as textile, then as insulation material, and finally for fertiliser or as a source of energy. How could that be modelled in a pLCA? How could the standards cover this?*

It all depends on the scope and the question to be analysed and answered with the LCA. If the practitioner wants to look at a product, it is suggested to use an allocation approach to differentiate the different phases or uses of a product. If the practitioner instead wants to assess wood-based products, then the basket of products approach would be used to include the full set of uses.

The methodology should include these differences to promote those that are investing in circularity (circular processes).

³ Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D. P., Font Vivanco, D., Deetman, S., ... & Tukker, A. (2020). When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. *Journal of Industrial Ecology*, 24(1), 64-79. [When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment - Mendoza Beltran - 2020 - Journal of Industrial Ecology - Wiley Online Library](#)

Is it difficult or impossible to include biogenic carbon accounting in a conventional LCA (referring to one of the slides)? The reference to the accounting methodology in the [ILCD Handbook](#) (and taken up by EN standards) was also mentioned.

The slide intends to say that it is impossible in regular LCA software to perform dynamic carbon accounting at this moment (lack of implementation).

Could you make a clear distinction between different definitions for uncertainty and sensitivity?

On shallow versus deep uncertainty: does the report identify in which stages of the process uncertainty plays a role?

In the literature of sensitivity analysis, there is a lot of inconsistency. We tried to provide some form of classifications on uncertainty. The distinction between uncertainty and sensitivity is not clear, so maybe it should be avoided.

It was surprising that microplastics (and their end of life) were not part of the indicators / impacts of LCA. By looking at the current indicators, we are moving towards an undesired situation (e.g. landfill of plastics show better results than incineration because the release of micro-plastics to the environment are not accounted).

Another comment was about the importance of how pLCA will communicate the analysis and results to a wider community: *Some technologies close to the market may get investments, while future (currently immature) sustainable technologies are hampered, i.e. the pLCA can hamper the development of future technologies, if it compares different technologies with different levels of development.*

Communication to outsiders is key also in scenario methodology. The methodology that is presented may not be the final one and it may be replaced or improved in the future, and this should be communicated.

A methodology or common framework should be made available, so that beginners can apply it, instead of paying for professional pLCA analyses. How could the system be simplified meaningfully, to provide orientation apart from guidance?

The draft methodology shows the state of the art rather than providing guidance for practitioners. It would be more useful to have this guidance-approach and to simplify the process/analysis.

Economic allocation may not be feasible unless there are existing markets for the bio-based products, estimation of which could be the price in the future of a novel-product. Could estimated future prices be used in economic allocation?

The request for funding these kind of projects starts with identifying that the cost of the technology - as it is to be developed - will go down by x percent. There is already the possibility to get information from technical economic analysis and the likes, and understand the prospect already at that stage.

In an early stage of a technology, the expectations are always very optimistic. The economic costs, feedstocks, etc. can be underestimated. This may hamper the further development of the process, i.e. with a mass allocation, this risk is lower than with economic allocation.

Are micro and nano plastics included in the revision of the PEF?

Currently no revision of the PEF is being developed regarding this particular aspect. Methods to address this are still emerging and may be included in the future. In the recent publication of the plastic LCA method there are some suggestions that can be used.

Data for existing processes are available, but they are sometimes old. How can practitioners apply data for new processes or new energy mixes?

There is literature addressing this issue. Future scenario databases are available, including energy mix. The point is relevant though. There is a need for data harmonisation.

One expert proposed that JRC could lead the work on generating future scenarios that represent EU policies and the best data available at EU level. Others also agreed on that. For each practitioner it is impossible to do scenario development, and JRC could help with the data, perhaps also with a focus on the bioeconomy.

Ms Caldeira asked the participants about their views on biogenic carbon: *Would it make sense to include it as a part of the scenario development section and include a sensitivity analyses? Or should it be better defined?* There is an increasing amount of information. The biogenic issue in terms of climate change impacts is relevant for longer life production cycles. The minimum guidance that should be provided is on the climate change scenarios and biomass availability, most importantly for woody biomass. The recently published IEA Task 45 report on science status is relevant in this question. Transparency and disaggregation is key.

There is no harmonised method for biogenic carbon accounting, thus it would be difficult to include in the methodology framework. It would be possible to include as additional information which could also refer to sensitivity analysis on different methods available (Brandao, 2013).

Another comment was on the consideration of recycling of products to refer to temporal or permanent carbon storage.

End of first day

DAY 2 – 7th December 2021

Welcome back and insights from the previous day

Carla Caldeira, Project coordinator, JRC

Ms Caldeira welcomed the participants, repeated the objective of the PLANET BIO project and presented insights from the previous day of the workshop, as well as an overview and general considerations:

- The outcome of the project could be a practical document building on standard for bio-based products; underpinning information can be provided in annex
- Concrete and specific guidance in regards the prospective challenges would be more useful for the practitioner
- JRC is well positioned to develop/manage a database on background data for prospective LCA. This would foster transparency and robustness in the methodology.
- Clear and targeted communication of the outputs of the study to a wider audience is key. If results are misleading, some technologies close to the market may get investments, while future (currently immature) sustainable technologies are hampered. i.e. the pLCA can hamper the development of future technologies if it compares different technologies with different levels of development.

She also mentioned some more specific points raised during the first day of the workshop:

- Recommendation to look broadly at allocation and alternatives when modelling BbP systems
- Designing a default list for the surrounding parameters to guide the non-expert practitioners as starting point for phase 2A shall be included in the report / outputs of the project
- How to deal with biogenic carbon, as part of the scenario assessment, and whether to stick there with recommendations in the PEF or not, is still worth a further discussion
- Make sure to have clear and consistent definitions on uncertainty and sensitivity

Ms. Caldeira brought up some discussion points for the second day:

- How can we make our methodology / recommendations **more specific for BbPs**?
- How is **uncertainty** for emerging BbPs different from uncertainty for other emerging technologies?
- How to reconcile theoretical and methodological discussions to the **practical needs** of the analyst / practitioner?
- Which practical conclusions should we draw for the modelling of **biogenic carbon** for pLCA?

Presentation of Case study 1

Jade Müller Carneiro, University of Coimbra

A case study on the production of biopolymer from mango wastes, illustrating the application of the framework.

As a start, biopolymer films were obtained in the laboratory, extracted from mango seed, intended for packaging applications. The goal of the study was to analyse the future environmental impacts of the biopolymer films, currently at an early research stage (TRL 3) and expected to be deployed in the next 30 years (TRL 9 by 2050). The presentation focused on how the evaluation framework could be applied to this novel technology, including the guidance to select the system boundaries, the functional unit, impact allocation, etc. It specifically addressed the modelling choices and scenario methodology for this value chain. They ended up with 4 pairs of scenarios, depending on the increase of yield, size of the plant and two different policy ambitions, and the results (in terms of GHG emissions) from the scenario analysis were presented.

Ms Carneiro mentioned some thoughts and learnings from the case study, one of which was that there should be a link with the technology experts despite of the flexibility offered by the framework. Another learning was that data from pilot and techno-economic analysis could be combined to have better results. Some other learnings on the type of impact allocation to apply and the guidance of the functional unit to consider were also given.

Discussion:

Why is there a 30-year timeframe to reach TRL 9?

In general, more emphasis should be given to the possibility of achieving a product that is marketable and make a sensitivity analysis there, because quite often people realise during development that they need more processing.

How do you deal with waste streams and how does it influence the calculations, e.g. anaerobic digestion, etc.?

Note: the bigger the scale, the longer the timeframe, in general.

A clarification on whether the resulting material may be used for food contact was also requested. In such a case, the properties of the product should be very specific.

The scale was small, due to the availability of the feedstock: 1–3 kt/yr per year.

The price will depend on the quality of the product. The resulting material could be used for food contact even if a secondary packaging material might be also used.

Have you considered in the scenario what would happen if you did not use the waste? Having chosen cradle to gate as system boundaries, if you compare with the fossil counterpart, the end of life should be included.

In Brazil, there is mainly landfilling, and the avoided emissions will be accounted for. The team is working on the end of life approach, because they need to adjust the functional unit and boundaries, but they will deal with that in the future.

Presentation of Case study 2

Mateo Saavedra del Oso, University of Santiago de Compostela

A case study on the production of polyhydroxyalkanoates (PHA) from organic wastes by open mix cultures, illustrating the application of the framework.

PHA are bio-based and biodegradable polymers with yet a small market size. The TRL is still low (TRL 5), but represents an opportunity for major adjustments. The study focuses on Chapter 3, on building scenarios. It focuses on two phases, goal and scope and the inventory analysis.

The goal of this LCA was to assess the environmental performance of PHA production by Mixed Microbial Cultures (MMC) in future framework where its large-scale production was implemented, and provide environmental guidance to the developers. The researchers have chosen an exploratory approach to see how the process could be developed. They selected the “cradle to gate” approach.

A system multi-functionality addressed by the JRC methodology to break the system down in subsystems was considered with 2030 as time horizon. The background data, sources from the literature on PHA production on pilot-scale and ecoinvent 3.7.1 were used.

Regarding the inventory analysis: they carried out a literature review, expert surveys and workshops with stakeholders and a PESTEL analysis. They conducted a hybrid casual loop diagram, which goes from the big picture to the model parameters. All the consistencies were analysed with the morphological fields through a cross-consistency check. The combination of scenarios was very diverse, so they selected the four most realistic scenarios to be analysed. Finally, they implemented the scenarios in the LCA model and showed the next steps to be addressed.

Mr Saavedra del Oso's experience when using the framework was:

- To further develop the multi-functionality method
- To upscale. It would be nice to have a more detailed methodology to apply process units
- To explore the impact of the most influential parameters

Discussion:

Did you compare your study approach with the activities of Danimer Scientific, the leading global PHA producer?

No, we did not compare the two. The goal of this study is to compare different PHA production routes (e.g., MMC and pure cultures) and assist the decision-making in the development of this process. If we wanted to compare this product with another biopolymer or oil-based plastic, then we would have included the compounding and shaping, use and end-of-life, and use a different functional unit.

Did you take into consideration the stability and homogeneity of the feedstock over the year, and how does it affect the outcome of the results?

No, we just considered the average concentration of each feedstock. However, some parameters on the feedstock characteristics (especially from sludge and wastewater) could be controlled.

About the background data: only electricity mix development or other aspects were included as well?

The integrated assessment models are focused on specific issues, mainly climate change, and energy is an important part in those. Most of the combinations of LCA databases have so far targeted the energy sector, and there are ongoing activities to include other sectors, e.g. steel and cement, and there are some scenarios for some key metals. There is no scenario of everything, some important sectors are missing, like the whole bioeconomy: there are no future scenarios for that at the moment. It would be very important and interesting to develop such scenarios, maybe based on items, or on other data.

We need to complete the future modelling of the economy, or at least cover key sectors. There are several groups developing such future scenarios, and the uptake of that is huge. Everyone is interested in that. Modelling future technologies with current or past data is off.

The data come from SSP2, but they are quite limited for certain processes. For the sake of transparency, this should be stated much more clearly.

Acid use model is not included in the data and it only has scenarios for the energy production. The team will make it explicit in the presentations and publications. Indeed one of the big challenges for the future is to get to an agreement on the scenarios and the documentation of the background data (contrary to theecoinvent database, which is available to all practitioners).

Renewable carbon initiative to combine recycling and CO2 is being explored and could be taken into account in the modelling exercise.

The bioeconomy pushes for using waste streams before other feedstocks, but this is not so easy (stability of the product, availability, etc.).

Presentation of Case study 3

Emma Zuiderveen, JRC / Radboud University

A case study on the production of bio-BTX, illustrating the application of the framework.

Ms Zuiderveen explained what BTX are: important petrochemicals (aromatics Benzene, Toluene and Xylene) commonly made of naphtha, which can be used in several applications. The goal of the study was to model the environmental impact of a bio-BTX production plant (TRL 9) from second generation biomass in 2050 in Europe. This case study focuses on chapter 2 (goal, scope and LCI).

The most promising process currently is the CFP process. Thing to note is the methodological challenge, considering the scarce literature data, and how to apply it to the upscaling.

Ms Zuiderveen applied the decision trees to select the functional unit, and eventually chose the production of 1 kg of BTX as functional unit. She selected a “cradle to gate” approach as system boundary, since she compared three types of feedstocks, namely agricultural residues, forestry residues and dedicated biomass crops (e.g. poplar). She also explained the large uncertainties in the exercise, especially in the technological process development and the future developments, e.g. share renewables in energy mixes.

The prospective LCA approach was therefore:

- (1) Different strategies to upscale lab-scale bio-BTX to industrial scale, based on Piccinno et al. (2016) and van der Hulst et al. (2020).
- (2) Scenario analysis based on the approach of Langkau and Erdmann (2021).
- (3) Systematically change background processes (Steubing et al., 2020).

She also used the decision tree for the upscaling approach from the guidance methodology which suggests in this case to use process calculations (from Piccinno et al., 2016), but some proxies (e.g. for fast pyrolysis) might be also applied. She explained different approaches for the assumptions on the technical development.

Ms Zuiderveen presented some reflections:

- Good guidance in regard to modelling choices
 - Streamlining prospective LCAs makes them more comparable
- Upscaling guidelines are useful, but an extra step would be helpful on how to model generally the technological development of a product
 - E.g. the framework of van der Hulst et al. (2020)
- Upscaling remains very uncertain when there is little information available
 - Uncertainty assessments are therefore very important
- Scenario development: prioritizing parameters in the first place proved difficult (at step A)
 - Engagement of stakeholders
- Good information on state-of-the art biogenic carbon literature and modelling, but practical guidelines on how to actually treat it would further benefit the framework.

Discussion

TRL nomenclature was used wrongly, as TRL9 is commercial production, while a pilot scale is in general TRL 6-7.

There is different literature about the definition of TRL. We would benefit from a harmonised classification and the definition from the Commission is the best available currently. However, the figure which triggered the discussion comes from a published paper.

To clarify the process: you produce first pyrolysis oil from these raw materials and then convert to BTX? If so, note that pyrolysis is already established in commercial scale, so for pLCA only its conversion to BTX is relevant. In this case, fast catalytic pyrolysis was considered so the technological process is different.

In general, I missed the importance of Conceptual Process Design phase, as a step to generate useful data. I think for prospective LCA a good modelling tool is very important and I assume most of us would use that kind of tool. To go one step further and really have a conceptual modelling, it can be very useful to pinpoint the hotspots in the processing part. Just a general remark.

Have you compared the proxy and Piccinno approaches, and if so, how did they compare?
We have not compared them yet, as the research is not at that stage yet.

Presentation of Case study 4

Octavio Wurmböck, Leiden University

A case study on the production of protein from CO₂, illustrating the application of the framework.

Methanotrophic bacteria, using H instead of methane. So far, only two LCA studies have been published.

Fermentation is a millennia old process. Here, the process was to turn air and water into protein powder through fermentation. The technology decouples production from agriculture, it can be produced everywhere as a close system. It does not use pesticides, fertilisers, etc. It keeps the water in a close system, so it is also more efficient.

The result is a meat replacement, which can be used as animal feed or consumed directly by humans.

There are some identified gaps in the literature.

Mr Wurmböck presented the question: What are the environmental impacts of producing 1kg of micro-protein (MP) at manufacturing scale during constant energy and H2 supply, and how do these results compare to the production of 1kg of soybean meal?

He conducted four phases in the study, and the technological setup was also presented: The system depends greatly on the energy, both sources and efficiencies. This plays a big role in the scenario analysis.

There is a pilot plant already available. The current state is TRL 7-8. Thus, the issue of data is marginal compared to other pLCA studies. Mr Wurmböck could not have access to first-hand data, so he used literature data.

Discussion

Why is it wrong to use energy mix for exploring the sensitivity of your system?

The goal was to create realistic scenarios. A constant energy supply is needed, otherwise the microbial proteins get stressed and they might die, so 100% wind power supply was not considered.

The burden of the CO₂ stays with the process it originates from.

Why did you change the temporal reference between the three scenarios and did not keep the year constant?

The technology is already very well established: within the next 5 years, there will be a factory to produce this. In 2035 the market penetration level will be around 30 or 40, which means there will be around 10 factories in Europe to produce this. This technology will probably be at the same or similar level, aside in production in terms of quantity.

There was a discussion on the possibility to compare against the nutritional value (protein) instead of quantity (1kg of meat or soybean).

For the comparison in terms of protein, the quantity in soybean and MP is equivalent. Also, as soybean is being used as aqua feed for the production of fish-based food, it is also a good counterpart to do the comparison with.

Discussion on the overall outcomes of the workshop

Points stressed during the workshop:

- There is an agreed need to develop background databases, but sector specific databases (derived from discussion with specific stakeholders) should be taken into account with caution. In any case, transparency on the data used on the pLCA is a key factor for the success and dissemination of the methodology.
- The suggestion to develop data for future scenarios for the bioeconomy, done by the JRC was welcomed by many participants.
- Regional databases should also be considered. Local approach and management are key and impacting.
- In addition to the modelling challenges, there are regional differences, but the data sometimes are very coarse. There could be hierarchy of scenarios.
- The application of the guidance in the case studies is a perfect test of the methodological framework and conclusions derived from the process should be included in the final report.
- Practical conclusions for the modelling of biogenic carbon should be drawn.
- The scenario methodology and upscaling can be done in different ways, there is no common recipe to follow.

Closure

Carla Caldeira, Project coordinator, JRC

Ms Caldeira thanked the participants for the input provided and invited them to share by mail further insights on the points presented and on potential case studies to be performed in the future. The expert reviewers of the report were also acknowledged.

List of Annexes

Day 1 – 6th December 2021

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Annex 3: Introduction to the project and overview on proposed LCA-based framework for the environmental assessment of emerging technologies for bio-based products - Presentation of Carla Caldeira, JRC

Annex 4: Prospective modelling to assess the environmental assessment of emerging technologies for bio-based products - Presentation of Stefano Cucurachi and Bernhard Steubing, Leiden University

Annex 5: Discussion points

Day 2 – 7th December 2021

Annex 1: Agenda

Annex 2: List of participants

Annex 3: A case study on the production of biopolymer from mango wastes - Presentation of Jade Müller Carneiro, University of Coimbra

Annex 4: A case study on the production of polyhydroxyalkanoates (PHA) from organic wastes by open mix cultures - Presentation of Mateo Saavedra del Oso, University of Santiago de Compostela

Annex 5: A case study on the production of bio-BTX - Presentation of Emma Zuiderveen, JRC / Radboud University

DAY 1
6th December 2021

Annex 1: Agenda

10:00-10:05	1. Welcome and adoption of the agenda
	Serenella Sala, Deputy Head of Unit D3, JRC The presenter will welcome the participants and present the proposed agenda.
10:05-10:20	2. Tour de Table
	All participants The participants will present themselves and express their interest in the project as well as the outcome they expect from it.
10:20-10:45	3. Introduction to the project and overview on proposed LCA-based framework for the environmental assessment of emerging technologies for bio-based products
	Carla Caldeira, Project coordinator, JRC The presenter will talk about the context, objectives, and expected outcome for the project and provide an overview of the framework.
10:45-11:15	4. Prospective modelling to assess the environmental assessment of emerging technologies for bio-based products
	Stefano Cucurachi, Bernhard Steubing, Leiden University The presenter will present relevant modelling aspects for prospective LCA of emerging technologies for bio-based products.
11:15-12:15	5. Discussion
	Carla Caldeira, Project coordinator, JRC The participants will have the opportunity to pose questions regarding the framework.
12:15-12:30	6. Next steps and closure
	Carla Caldeira, Project coordinator, JRC

Annex 2: List of participants

No	Country	Name	Affiliation
1	EU	Carla Caldeira	EC JRC
2	EU	Serenella Sala	EC JRC
3	EU	Jorge Cristobal Garcia	EC JRC
4	EU	Christian Moretti	EC JRC
5	EU	Greet Maenhout	EC JRC
6	EU	Marios Avraamides	EC JRC
7	EU	Javier Sanchez Lopez	EC JRC
8	EU	Maria Teresa Borzacchiello	EC JRC
9	EU	Zsuzsa Turoczy	EC JRC
10	EU	Giulia Fiorese	EC JRC
11	EU	Paraskevi Filippousi	EC RTD
12	EU	Adrian Tistan	EC RTD
13	EU	Silvia Maltagliati	EC RTD
14	EU	Policy officer	EC ENV
15	EU	Maila Puolamaa	EC GROW
16	BE	Alba Soler Estrella	Concawe
17	ES	Almudena Hospido	University of Santiago de Compostela
18	BR	Ana Paula Sampaio	Federal University of Sao Paulo
19	NL	Bernhard Steubing	Leiden University
20	PT	Carla Rodrigues	University of Coimbra
21	BE	Celestin Demuytere	Organic Waste Systems (OWS)
22	BR	Maria Cléa Figueirêdo	EMBRAPA (Brazilian Agricultural Research Corporation)
23	NL	Emma Zuiderveen	Radboud University
24	NL	Ed de Jong	Avantium Technologies
25	NL	Flora Siebler	Leiden University
26	PT	Fausto Freire	University of Coimbra
27	IT	Francesca Braca	Laboratory ARCHA S.r.l.
28	NL	Iris Vural Gursel	Wageningen Food & Biobased Research
29	DE	Constance Issbrücker	European Bioplastics
30	PT	Jade Müller Carneiro	University of Coimbra
31	NL	Mark Huijbregts	Radboud University
32	SE	Marta Behjat	University of Chalmers
33	IT	Matteo Prussi	Politecnico di Torino
34	ES	Mateo Saavedra del Oso	University of Santiago de Compostela
35	NL	Nicolas Navarre	Leiden University
36	DE	Nils Rettenmaier	IFEU
37	BE	Pieter Deckers	Organic Waste Systems
38	SE	Rickard Arvidsson	University of Chalmers
39	CH	Roland Hischier	EMPA
40	NL	Stefano Cucurachi	Leiden University
41	DE	Sabine Langkau	Fraunhofer ISI
42	DE	Anna Sander-Titgemeyer	Technical University of Munich
43	PT	Tiago Lopes	Laboratório Nacional de Energia e Geologia
44	DE	Uwe R. Fritsche	IINAS
45	DE	Horst Fehrenbach	IFEU
46	DE	Gabriele Weber-Blaschke	Technical University of Munich

Annex 3: Introduction to the project and overview on proposed LCA-based framework for the environmental assessment of emerging technologies for bio-based products - Presentation of Carla Caldeira, JRC



Contents

- EU policy and innovation
- Why is prospective LCA relevant in EU policy?
- How can prospective LCA support EU policy?
- The Planet Bio Project

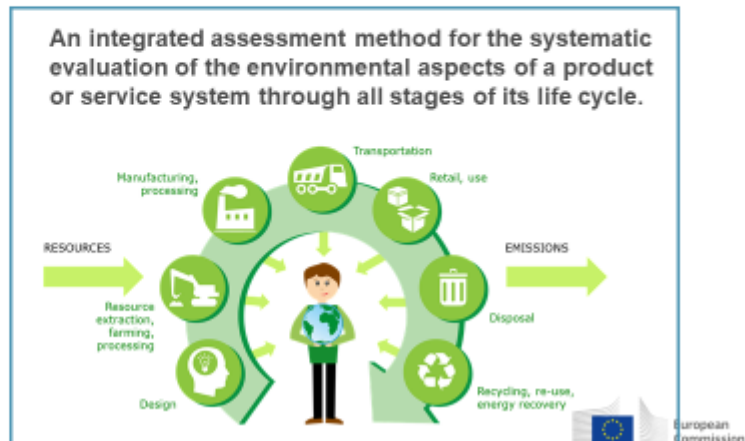
What is Prospective Life Cycle Assessment?

Prospective

Promote the integration of environmental criteria in early stages of technology development

Methodological challenges to include considerations on scale and time, considering future developments

Life Cycle Assessment (LCA)



Prospective LCA supporting EU policies

EU Green Deal

- European Green Deal aims at having Europe as a **climate-neutral continent by 2030**
- **Bioeconomy related innovations** are fundamental to the development of a more **circular and decarbonized economy**
- Essential to ensure at an early stage of development that such **technologies present indeed less environmental burdens** to guide investment and technology deployment towards a sustainable economy

EU Circular Economy Plan

EU Bioeconomy Strategy

Need to ensure the selection of sustainable production pathways from early stages of development

The example of the bio-based industry

Bio-based Industries Joint Undertaking



BBI JU

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Bio-based Industries Joint Undertaking: a €3.7 billion partnership between the EU and the Bio-based Industries Consortium

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HOME



Several technologies that had achieved commercial scale in bio-based industries would not have passed the research and innovation stages without the BBI JU's support.

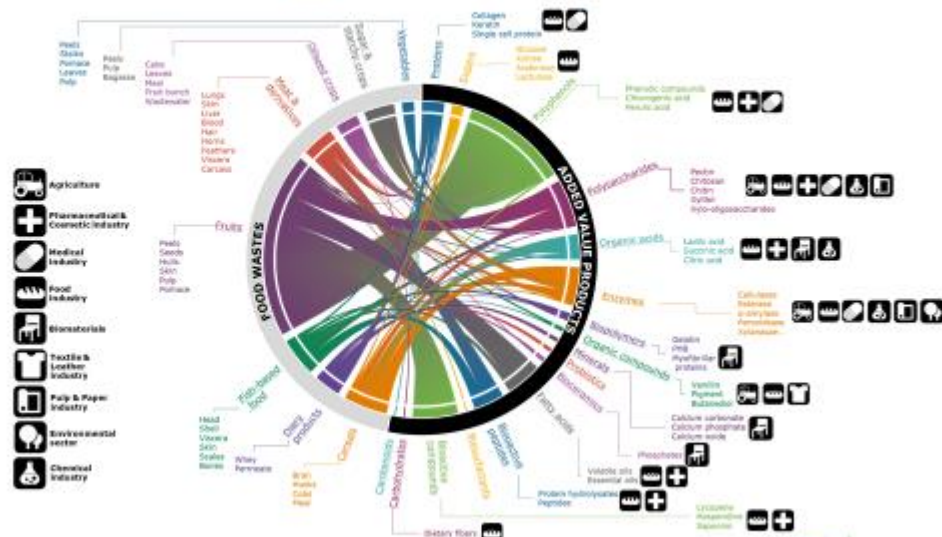
BBI JU found crucial for the transformation of bio-based industries

Read a new scientific article on the impacts of BBI JU.



European Commission

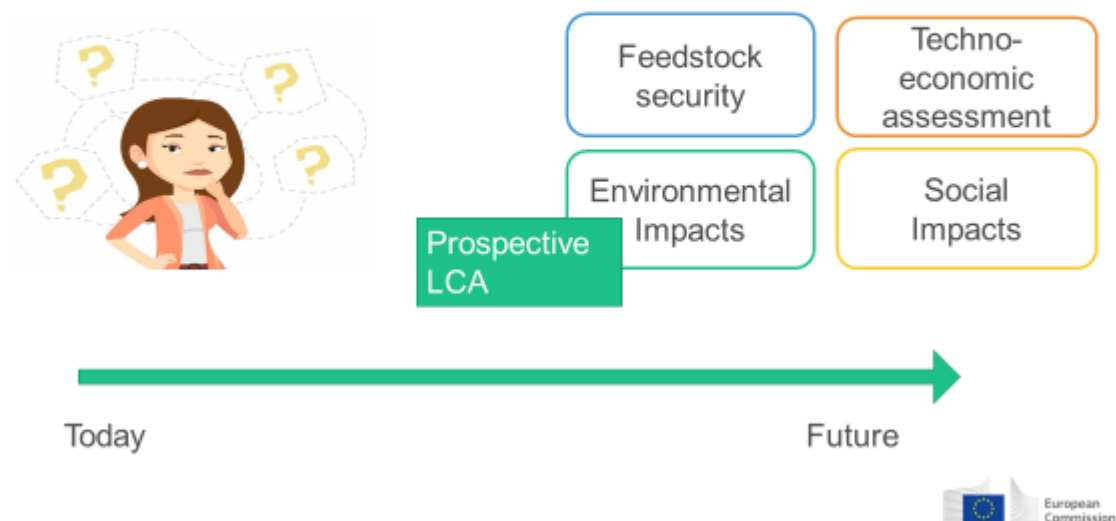
Multiple valorization pathways e.g. food waste



Caldeira, C., Vlysidis, A., Fiore, G., De Laurentis, V., Vignali, G., Sala, S. 2020. Sustainability of food waste biorefinery: A review on valorisation pathways, techno-economic constraints, and environmental assessment. *Bioresource Technology*. 312: 123575.

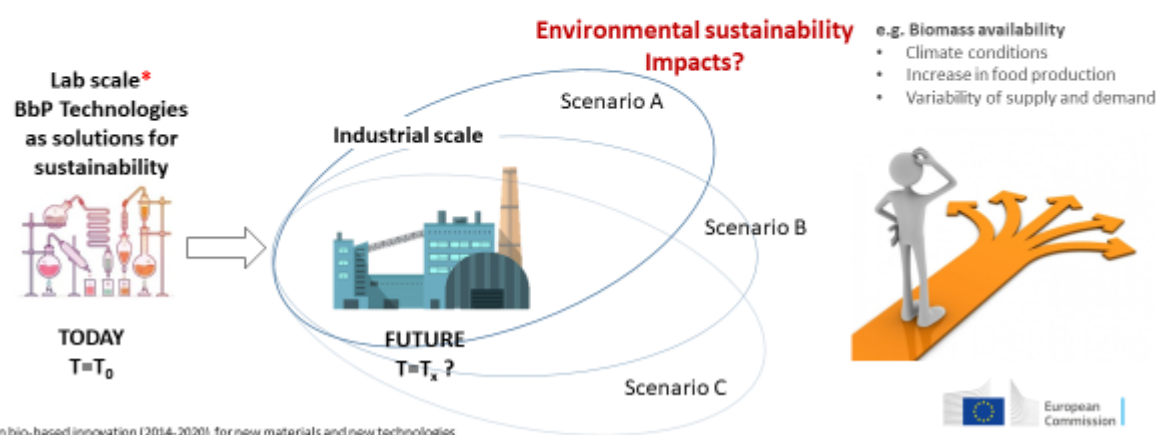


Aspects to consider to design effective policies



Challenges in assessing Innovative and disruptive technologies

Bio-based products (BbP) related innovations are fundamental for the development of a more circular and decarbonized economy



*€3.7 bln in bio-based innovation (2014-2020) for new materials and new technologies

P_{rospective} L_{CA} for N_{ovel} and E_{merging} T_{echnologies} for B_{IO}-based products



Develop a robust framework for environmental assessment of emerging technologies for bio-based products to support policymakers and industries in the selection of sustainable production pathways



PLANET BIO framework

PROSPECTIVE LCA



SCENARIO ANALYSIS

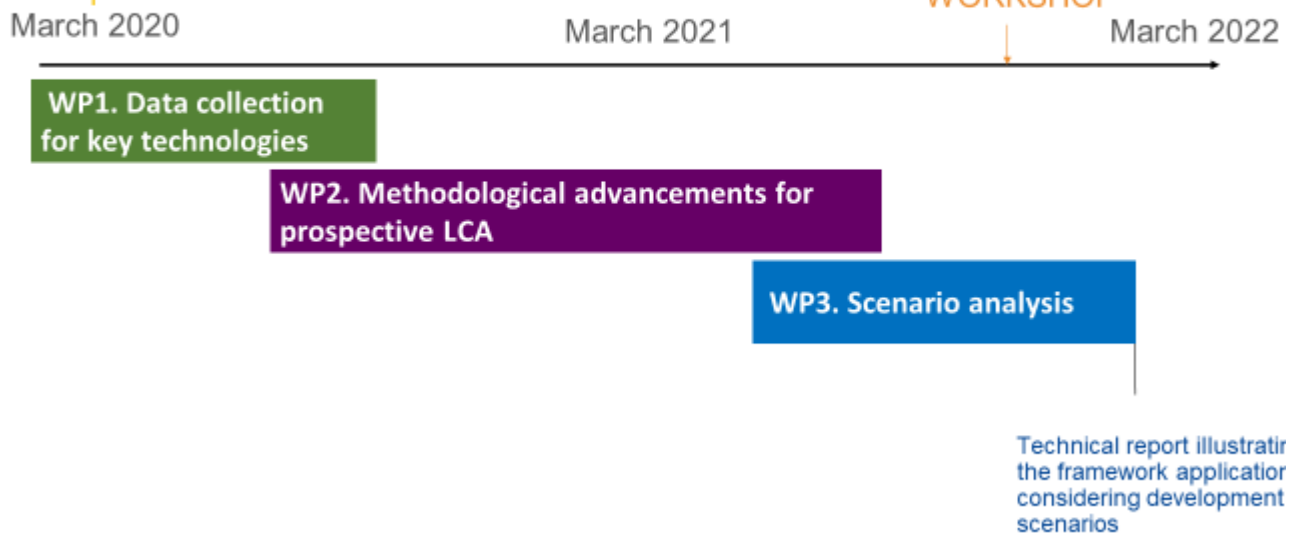
- Carrying out a **systematic identification and classification of emerging processes for bio-based products production and up-scaling approaches** (scale dimension)
- Developing an **approach that enables the modelling of processes** that will be **at industrial scale in future** (time dimension)
- Developing scenario analysis by considering **several factors** that influence the **development of processes for bio-based products**

Tested with case studies

- **Biopolymer** from mango wastes
- **Polyhydroxyalkanoates (PHA)** from organic wastes
- **Bio-BTX** from agricultural and forest residues and energy crops
- **Protein** from CO₂

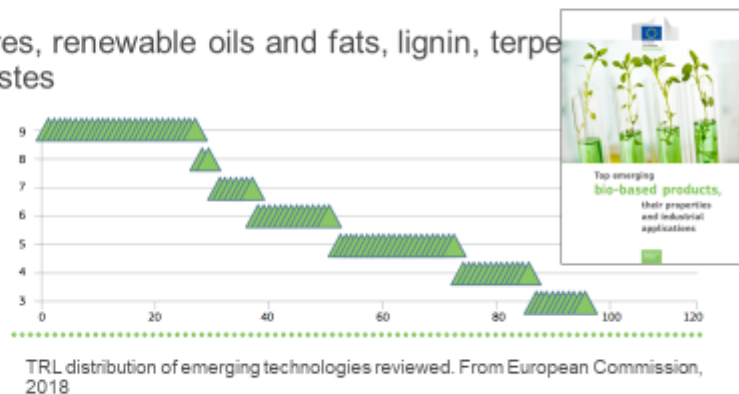


Timeline and expected outcomes



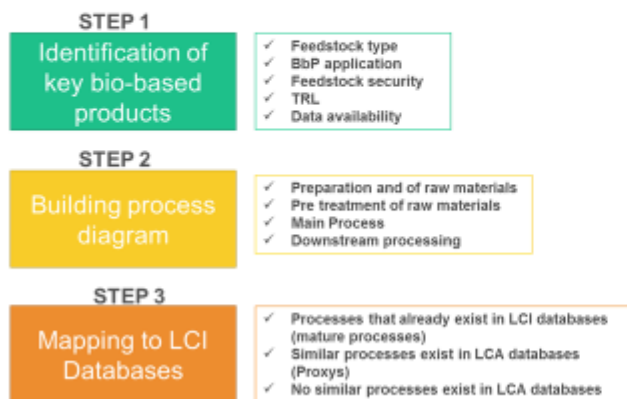
Top emerging bio-based products

- Top emerging bio-based products (BbP).
 - Natural rubber, vegetable fibres, renewable oils and fats, lignin, terpenes, polyelectrolytes, urban biowastes
- Main feedstock used:
 - Food processing waste
 - Agri-based feedstock
 - Urban biowaste



Upscale approaches for key processes

Mapping processes to LCI databases



Other approaches to obtain LCI data

Upscaling approaches can be based on

- operational parameters at different scales including temperature, pressure, yield, energy input;
- governing equations which is an engineering-based approach;
- chemical properties (e.g. stoichiometric ratios and molecular structure).

The methods present significant trade-offs between data intensity and uncertainty, thus the selection of an extrapolation-based upscaling approach must be done on a case-by-case basis (Navarre et al., 2022).



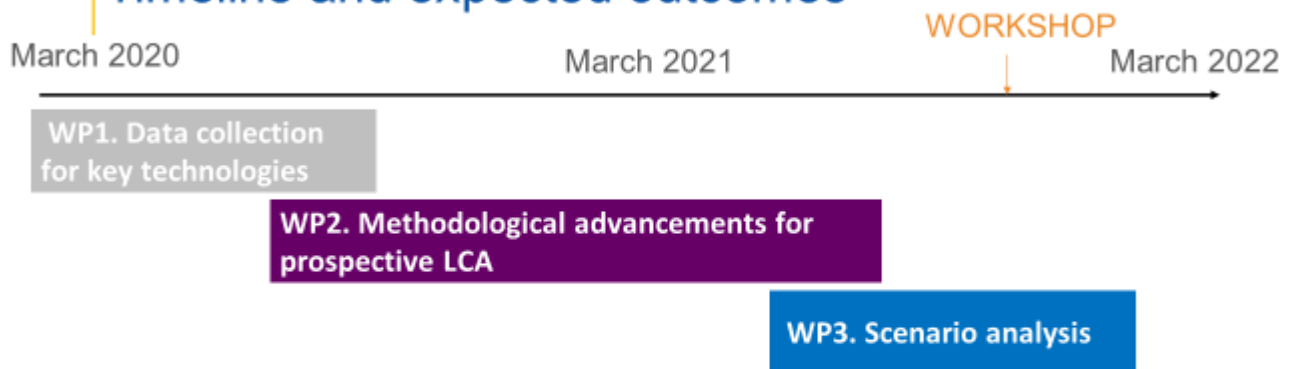
Input Biomass	Main Process*	Output BbP	TRL	Exists in LCI database?	Proxy can be used?	Upscale approach suggested
Sugar Beet Pulp (Alexandri et al., 2019)	Alcoholic Precipitation	Phenolic Compounds	5	No	No	Engineering-based calculations, chemical properties
	Acid Hydrolysis	Pectin	5	No	No	Engineering-based calculations, chemical properties
	Fermentation	Succinic Acid Crystals	4	No	No	Engineering-based calculations, chemical properties
Grape Pomace (Boussetta et al., 2012)	High Voltage Electrical Discharges	Phenolic Compounds	4	No	No	Operational parameters, engineering-based calculations
Potato Pulp (Byg et al., 2012)	Acid Hydrolysis	Pectin	4	No	No	Engineering-based calculations, chemical properties
Citrus Peel (Mandarin) (Ko et al., 2016)	Subcritical Water Extraction	Phenolic Compounds	4	No	No	Operational parameters, engineering-based calculations
Olive Mill Wastewater (Frascari et al., 2019)	Adsorption	Phenolic Compounds	4-5	No	No	Operational parameters, engineering-based calculations
Chicory Grounds (Vauchel et al., 2018)	Ultrasound Assisted Extraction	Phenolic Compounds	3	No	No	Operational parameters, engineering-based calculations
Citrus Peel (Orange & Lemon) (Fidalgo et al., 2016)	Microwave Hydrodistillation	Essential Oils	6	No	No	Operational parameters, engineering-based calculations
		Phenolic Compounds	4	No	No	
		Pectin	5	No	No	
Citrus Peel (Orange) (Boukroufa et al., 2015)	Microwave Assisted Extraction	Essential Oils	4	No	No	Operational parameters, engineering-based calculations
	Ultrasound Assisted Extraction	Pectin	4	No	No	
		Phenolic Compounds	4	No	No	Operational parameters, engineering-based calculations
Pomegranate Peel (Talekar et al., 2018)	Alcoholic Precipitation	Pectin	3	No	No	Engineering-based calculations, chemical properties
	Distillation	Phenolic Compounds	3	No	Phenol production	Proxy, chemical properties
	Fermentation	Ethanol	3	No	Ethanol production from grass fermentation	Proxy, operational parameters, engineering-based calculations, chemical properties

Feedstock and products

	Input Biomass	Main Process	Output BbP
Agro-based feedstock → lignin	Sugarcane bagasse (Ghorbannezhad et al., 2018)	Ex-situ catalytic fast pyrolysis	BTX
	Rice straw (Chen et al., 2018)	Catalytic fast pyrolysis	BTX
	Pinewood sawdust (Huang et al., 2016)	Catalytic fast pyrolysis	BTX
	Non-food biomass (bioBTX)	Cascading Catalytic Pyrolysis	BTX
	Corn stover (Salvachua et al. 2015)	Culturing/ Lignin depolymerization	BTX
Urban biowaste	Wastewater (Ruiken et al., 2013)	Sieving	Cellulose
	Wastewater (Palmieri et al., 2019)	Rotating belt filtration	Cellulose
	Waste sewage sludge (Huang et al., 2020)	Fermentation	Cellulose
	Waste sewage sludge (Honda et al. 2002)	Autoclaving	Cellulose
	Wastewater (www.smart-plam.eu)	Rotating belt filtration	Cellulose
	Wastewater (https://www.resurbis.eu)	Depolymerization	PHA



Timeline and expected outcomes



- **Present and discuss the draft framework**
- **Feedback on relevant aspects to address when performing LCA of bio-based products**

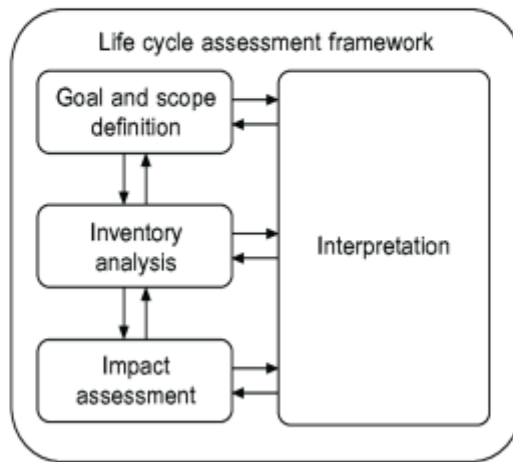


Issues when performing LCA of emerging bio-based products

- No function still defined
- Timeframe – when will the technology be at TRL 9
- No market defined

- Low TRL – data availability
- Upscaling foreground
- Background data

- Biogenic carbon
-



Scenario Analysis

Uncertainty

Sensitivity Analysis



Building on existing guidelines for LCA



JRC TECHNICAL REPORTS

Suggestions for updating the Product Environmental Footprint (PEF) method

Report No. 10

2020



JRC TECHNICAL REPORTS

Life Cycle Assessment (LCA) of alternative feedstocks for plastics production

Part 1: the Plastics LCA method

Report No. 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100

2021



Annex 4: Prospective modelling to assess the environmental assessment of emerging technologies for bio-based products - Presentation of Stefano Cucurachi and Bernhard Steubing, Leiden University

Prospective modelling for the environmental assessment of emerging technologies for bio-based products

PLANET BIO Workshop

Stefano Cucurachi, Bernhard Steubing, Flora Siebler, Nic Navarre

06/12/2021



Universiteit
Leiden
The Netherlands

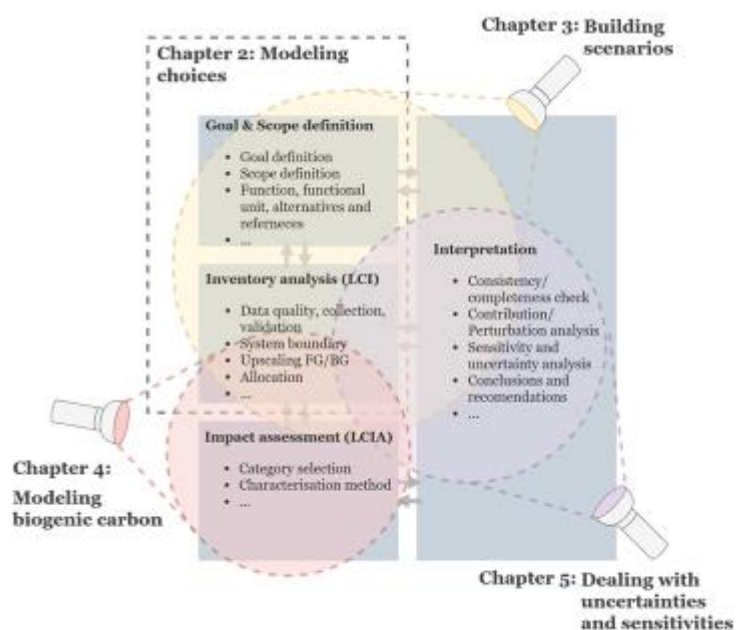
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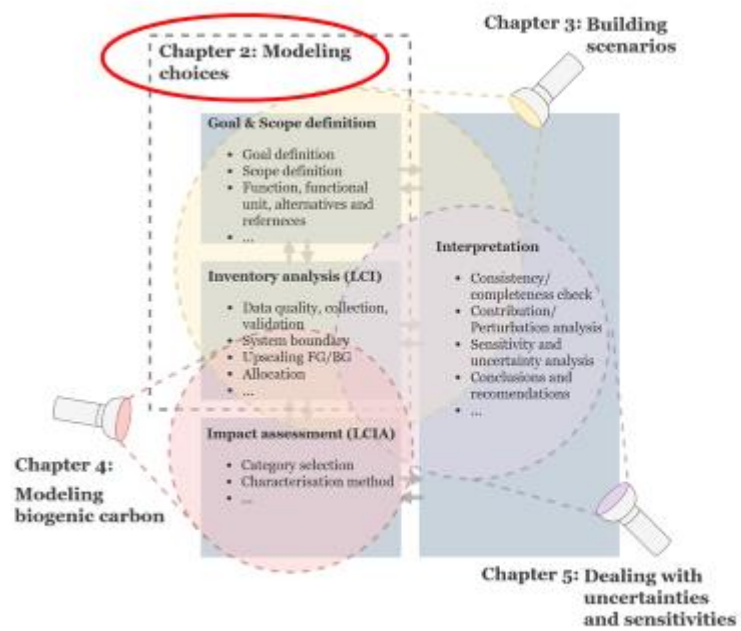
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Report overview

1. Introduction
2. pLCA modeling choices
3. Scenario methodology
4. Biogenic C accounting
5. Sensitivity and uncertainty analysis



Chapter 2: Modeling choices



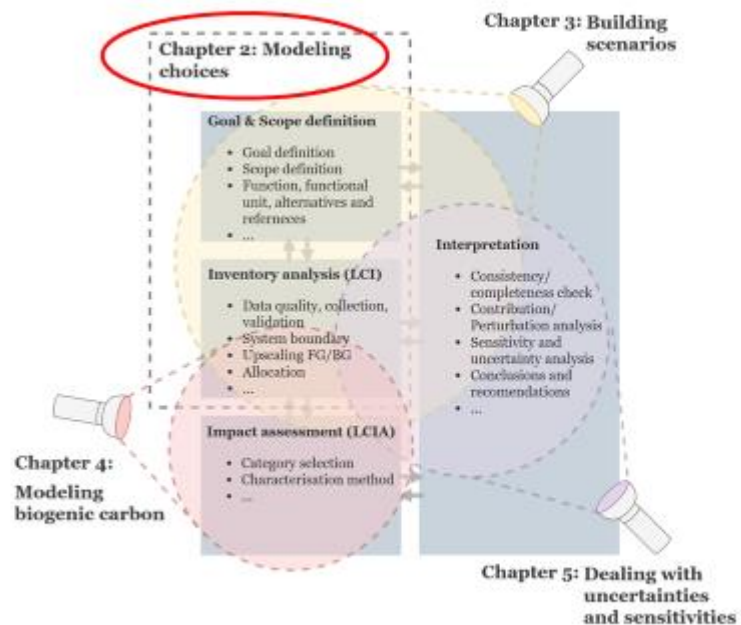
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Chapter 2: Modeling choices

This chapter is intended as a companion to assess the analyst evaluating emerging BBP.



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Guiding criteria to support the analyst: some examples

Definition of goal and scope with explicit consideration of the:

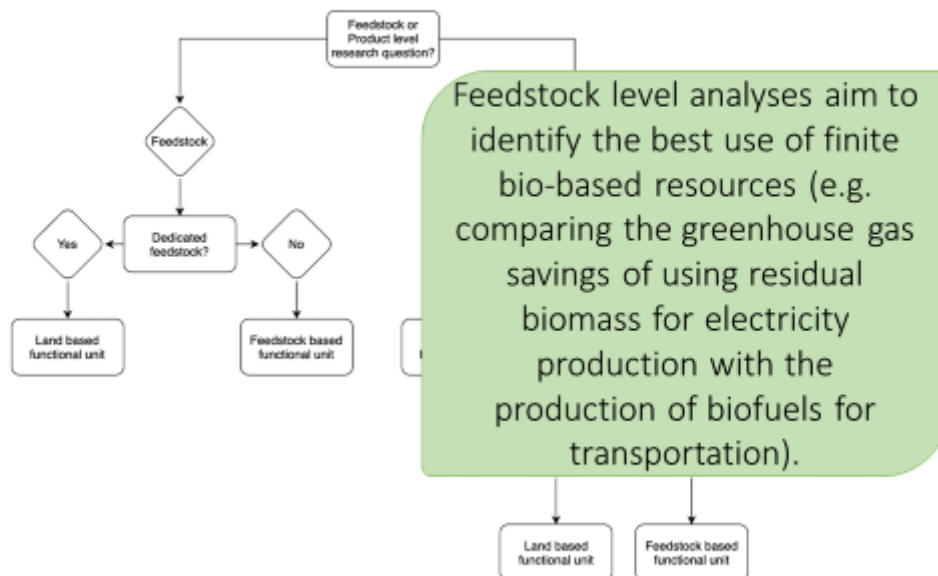
- TRL of the BB system under assessment
- TRL of the incumbent system under comparison
- At low TRLs the function or functions of the system might not be yet defined
- System boundaries

Functional unit

Some considerations that can help the analyst defining the right functional unit

Functional Unit Type	Example of functional unit	Focus of Research
output-based	1 kg product	Novel technology, attempting to compare best feedstock to produce a product (useful for comparing incumbent vs novel technology)
feedstock-based	1 ton biomass	Novel use of feedstock, attempting to compare best use of biomass feedstock
land-based	1 hectare	Novel use of land, attempting to compare best use of agricultural land

Functional unit – decision tree

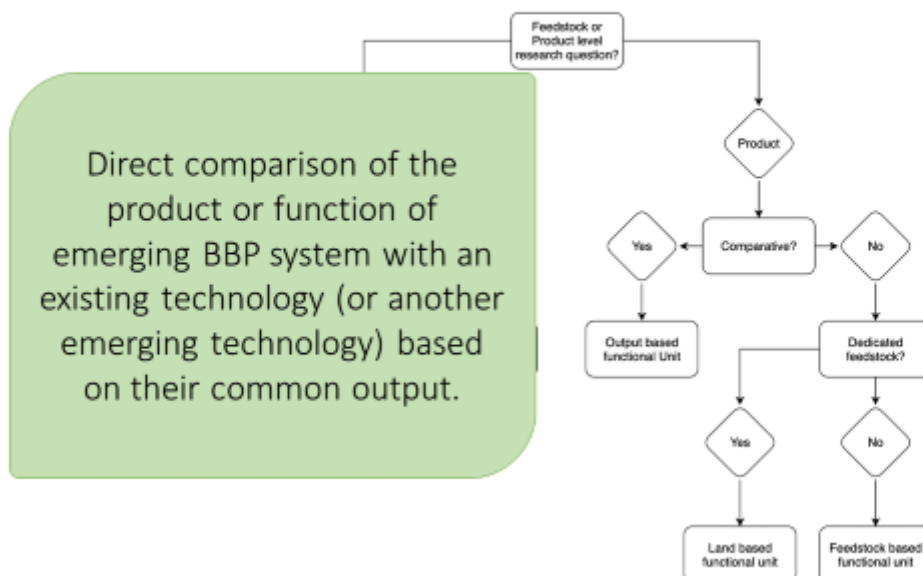


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Functional unit – decision tree



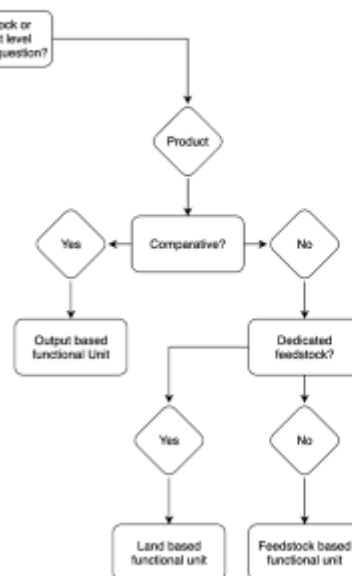
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Functional unit – decision tree

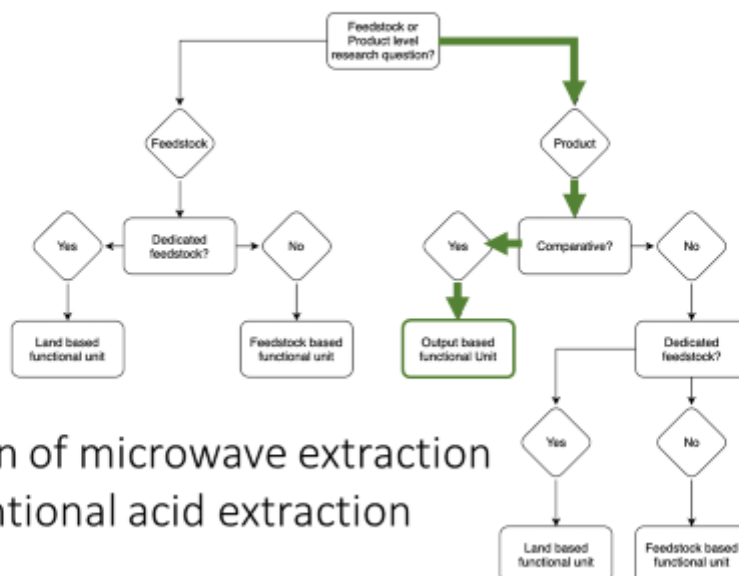
In such studies, the emerging technology has a clear incumbent it is attempting to replace, therefore the analysis could focus on a single output



Functional unit – decision tree

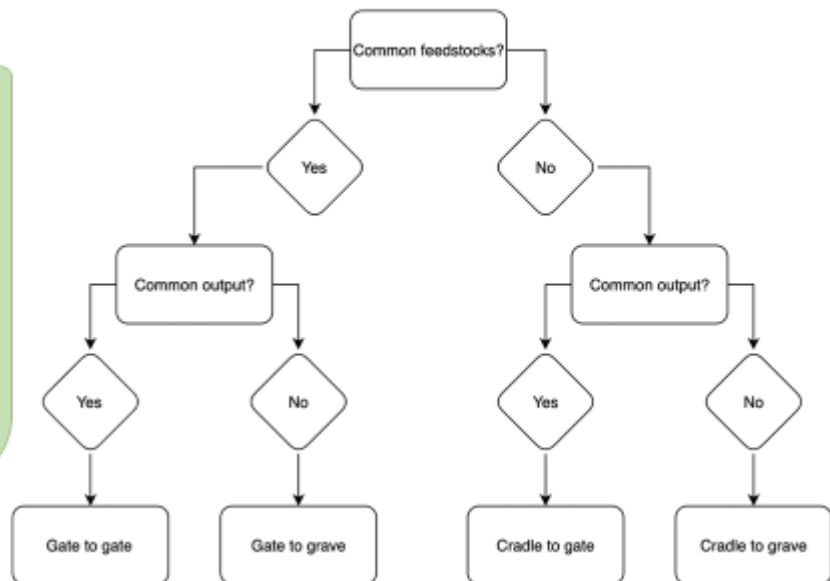
BBP case study:

Comparison of microwave extraction and conventional acid extraction



System boundaries – decision tree

For systems with identical outputs to the incumbent technology, a full cradle to grave analysis may not be necessary if the output used and end-of-life systems are identical.



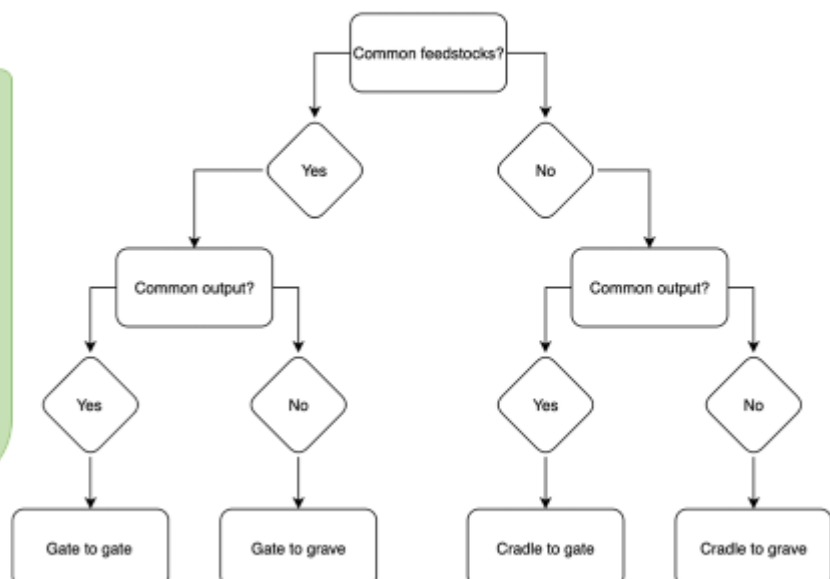
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System boundaries – decision tree

Example: bio-based PET bottles versus petrochemical PET bottles, different feedstock, but chemically and functionally identical factory output.



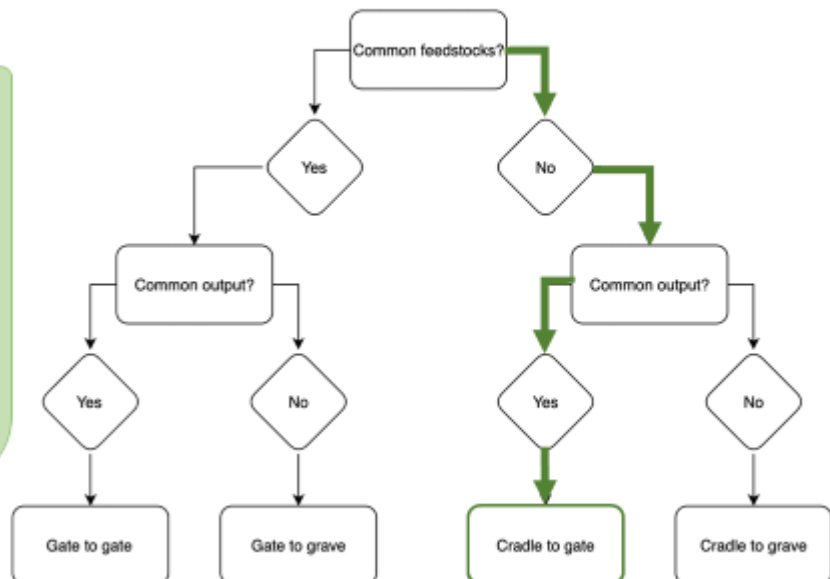
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System boundaries – decision tree

In such an instance, the two systems do not have a common feedstock but do have a common output, therefore a cradle to gate analysis might be sufficient.

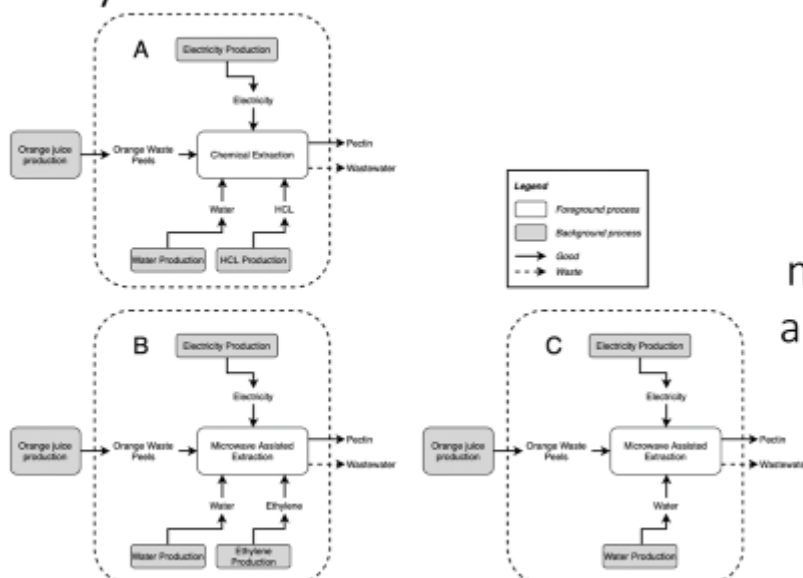


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System boundaries – decision tree



BBP case study:

Comparison of microwave extraction and conventional acid extraction

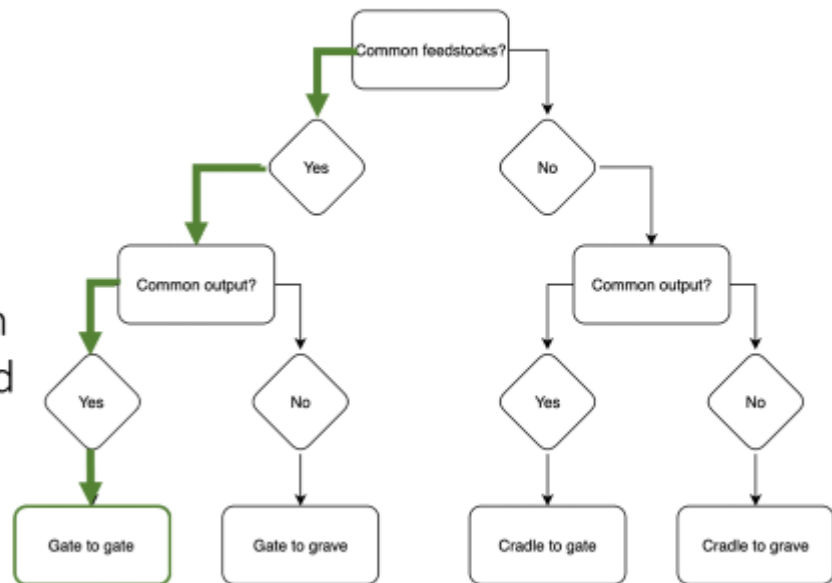
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System boundaries – decision tree

BBP case study:
Comparison of microwave extraction and conventional acid extraction



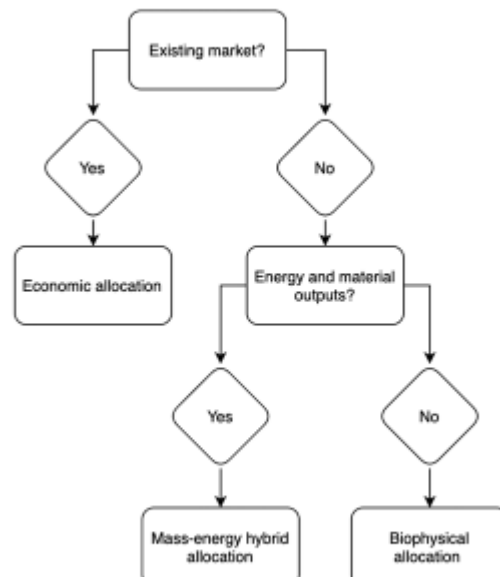
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Allocation– decision tree

The analyst could verify the existence of a market, and that related data are available to assess the emerging such market for the BBP system and incumbent.



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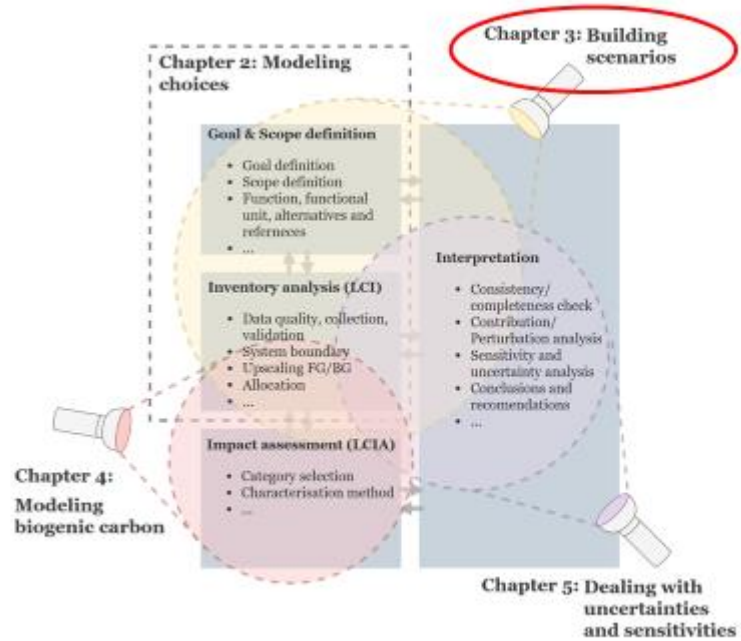
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Other aspects we consider

- More on allocation and cut-off criteria
- LCI data
 - Upscaling of foreground & background systems
(see next section on scenarios)
 - Process simulation vs. process calculations
 - Proxies vs. detailed modelling

Chapter 3: Scenario methodology

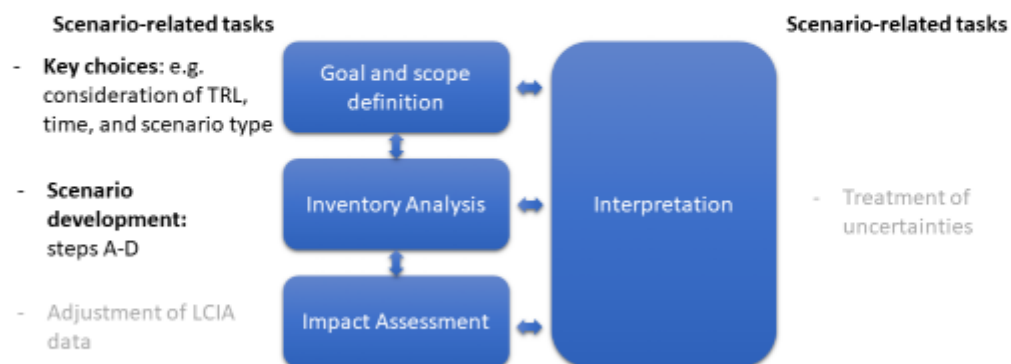


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Focus on phases 1-2 of LCA framework



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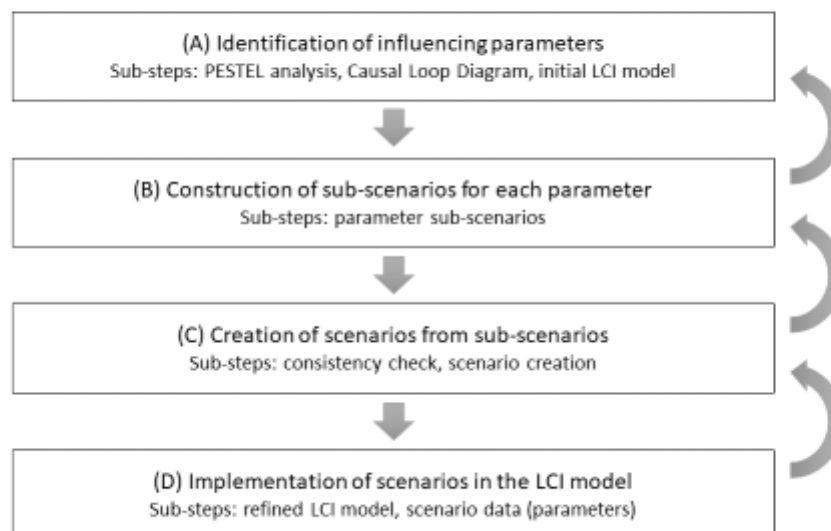
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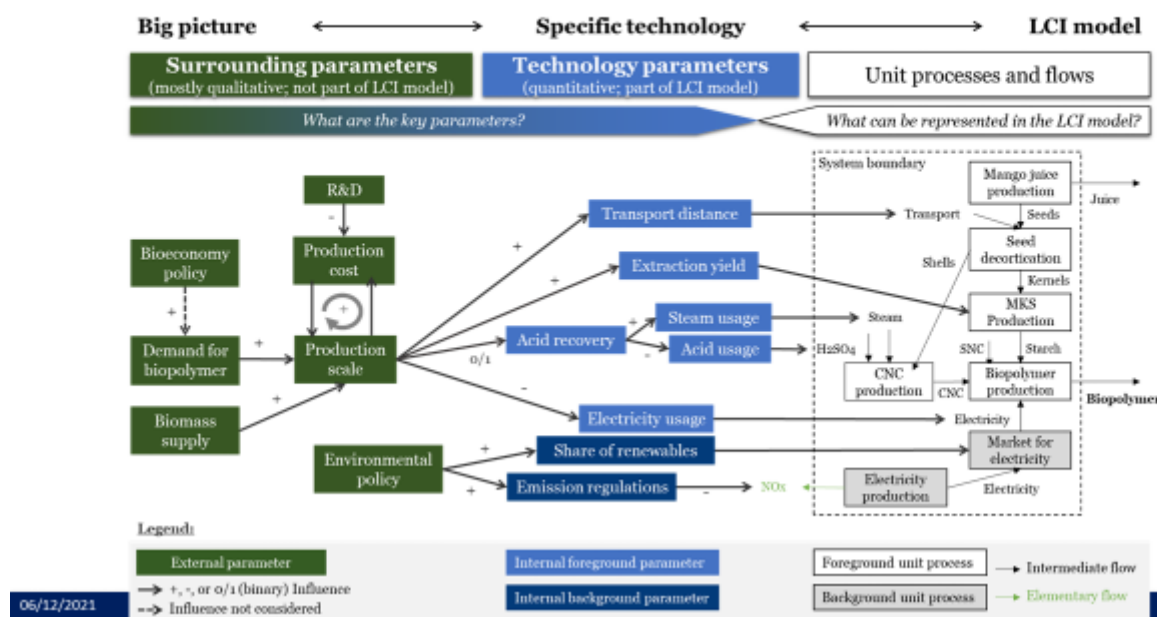
Phase 1: Goal and scope

- Scenario type (predictive, explorative, normative)
- Time horizon (how far in the future?)
- TRL (current? future?)
- Foreground and background data (data to build upon)
- Identification of alternatives (which systems should be modelled?)

Phase 2: Inventory analysis



A) Identification of influencing parameters



B) Parameter sub-scenarios

Parameter	Type	Sub-scenario 1	Sub-scenario 2	Sub-scenario 3	Additional explanation
Production scale	Qualitative	Small	Medium	Large	The number of sub-scenarios is specific for each parameter
Environmental policy	Qualitative	Liberal	Strict	-	
Acid usage	Qualitative	Low	High	-	
Acid usage	Quantitative	0.1 kg / kg CNC	0.5 kg / kg CNC	-	Can also be quantified at this stage already
Share of renewables	Qualitative	Low	High	-	This could be a sufficient classification, when working with background scenarios

This may require further data estimation and up-scaling, which was not a specific focus of this part.

C) Scenario development

- Consistency check
- Morphological fields
- Development of narratives and scenarios

Parameter	Sub-scenario	Production scale			Environmental policy		Acid usage	
		Small	Medium	Large	Liberal	Strict	Low	High
Environmental policy	Liberal	3	3	3				
	Strict	3	3	3				
Acid usage	Low	3	2	1	3	3		
	High	1	2	3	3	3		
Share of renewables	Low	3	3	3	3	1	3	3
	High	3	3	3	1	3	3	3

Legend:

Inconsistent	1
Maybe consistent	2
Fully consistent	3



a)

Production scale	Environmental policy	Acid usage	Share of renewables
Small	Liberal	Low	Low
Medium	Strict	High	High
Large	-	-	-

b)

Production scale	Environmental policy	Acid usage	Share of renewables
Small	Liberal	Low	Low
Medium	Strict	High	High
Large	-	-	-

c)

Production scale	Environmental policy	Acid usage	Share of renewables
Small	Liberal	Low	Low
Medium	Strict	High	High
Large	-	-	-

C) Scenario development

Parameter	Sub-scenario	Scenario 1 "worst case"	Scenario 2 "Narrative X"	Scenario 3 "Narrative Y"	Scenario 4 "best case"	...
Production scale	Small	x		x		
	Medium					
	Large		x		x	
Environmental policy	Liberal	x	x			
	Strict			x	x	
Acid usage	Low		x		x	
	High	x		x		
Share of renewables	Low	x	x			
	High			x	x	

D) Implementation of scenarios in LCI model

	Parameter	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	...
Foreground	Acid usage	kg / kg CNC	0.5	0.1	0.5	0.1	...
	Wind power share	%	20%	20%	50%	50%	...
	Solar power share	%	10%	10%	40%	40%	...
	Electricity use	kWh	...	...	...	...	...
	Transport distance	km	...	...	...	...	...
	Extraction yield	%	Full quantification required				...
	Steam usage	MJ	...	...	...	...	...
Background	Electricity use	kWh	...	...	...	...	...
	NOx emissions	kg	...	...	...	...	...
	Parameter	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	...
	Share of renewables		SSP2-base	SSP2-base	SSP2-RCP2.6	SSP2-RCP2.6	...

Choice of BG scenario consistent with FG system required

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Take-aways scenario part

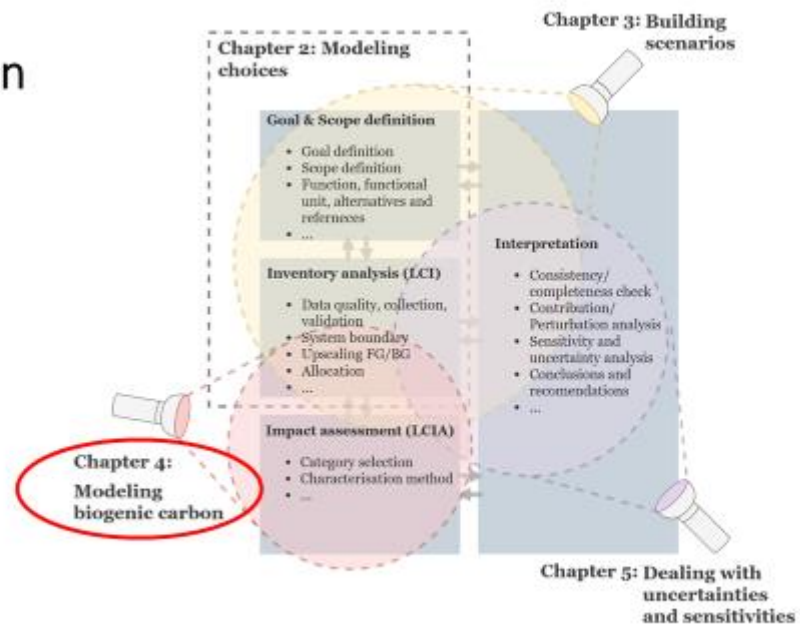
- There are **many ways** in which scenarios can be developed
- What we present here is a **simple, but structured approach** that has been tested and adapted throughout a number of case studies
- **Designing good scenarios is really important** and the **identification of parameters** that could play a role in the future is an **important step/learning by itself** (→ part of the value of a study can/should come from the development of scenarios rather than the final LCA results)
- The **transparent reporting** of how scenarios were generated and which assumptions they are based on is **crucial for a transparent and useful LCA**

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Chapter 4: Biogenic carbon accounting



Important issues

- Timing of emissions
 - Carbon sequestration and emissions may have different temporal profiles and thus carbon neutrality must not imply climate neutrality
- Carbon storage
 - Temporary
 - Permanent
- Land use change
 - Direct
 - indirect

Biogenic carbon accounting (in scientific literature)

Conventional vs. Dynamic LCA

Issue	Conventional LCA	Dynamic LCA	Remaining challenges
Timing of emissions	Difficult to include	Designed to be included	Choice of time horizon
Temporary and permanent carbon storage	Difficult to include, although certain simplified accounting methods have been proposed	Designed to be included	Choice of time horizon; verification of storage;
Land use change (LUC)	Can be included based on an allocation of LUC emissions over time	Can be included based on a dynamic model	Data to model LUC Allocation of LUC emissions over time Quantifying indirect land use change

Biogenic carbon accounting (in standards)

ISO 14067, PAS 2050, GHG Protocol, PEF

- **Temporary carbon storage** is generally not included in the CF, but can in certain standards be reported separately, using weighting factors to account for the temporal delay in emission.
- **Permanent carbon storage** is not considered in the CF in the ISO 14067 and PEF standards, but can be reported separately. In PAS 2050 and carbon storage beyond the time horizon of the study is considered permanent and included in the CF.
- **Direct land use changes** are included in all compared standards, yet they are to be separately reported except for PAS 2050.
- **Indirect land use changes** are not included in any of the standards, but can be separately reported at least in the GHG Protocol. ISO 14067 states that it "shall be considered [...] once an internationally agreed procedure exists".

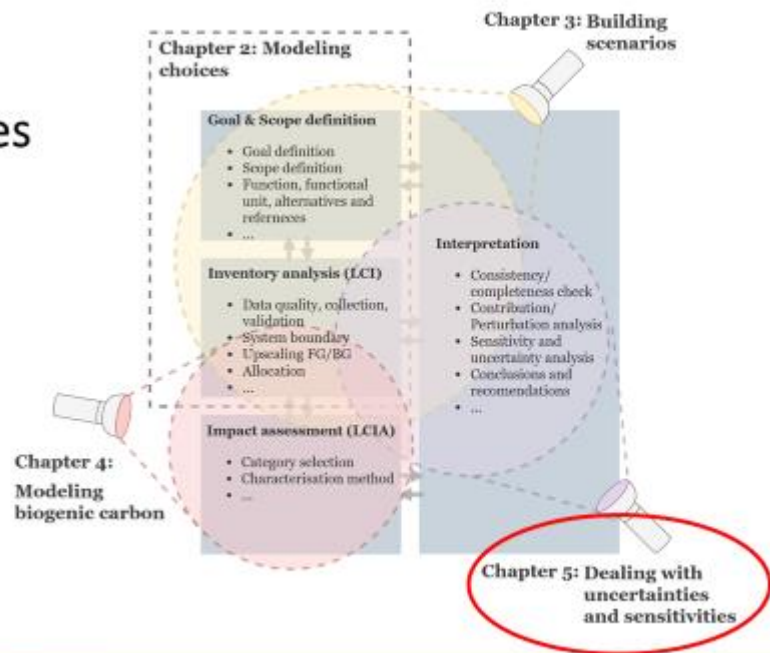
Discussion (general issues)

- **Counter-factuality and verification** (carbon sequestration and temporal/permanent storage happen in the future)
- **Choice of time horizon** (subjective choice / convention)
- **Multi-functionality** (general LCA challenge; allocation corrections based on carbon content may be necessary))
- **System boundaries** (cradle to gate vs. cradle to grave; advantage of BBPs difficult to see if EoL is excluded)

Implications for prospective LCA

- issues such as timing of emissions, carbon storage, and land use changes fall, *by definition*, into the realm of prospective LCA, since all rely on **assumptions about the future**.
 - **Scenario or sensitivity analyses** could be performed for:
 - **alternative biomass feedstocks** and in relation to that
 - the **sequestration of CO₂** over time
 - emission profiles related to a **land use change**
 - the time of **temporal carbon storage** in products
 - **EoL options** leading to different quantities of biogenic carbon re-used, recycled, or otherwise released and/or permanently stored
 - ...
- ➔ Should we draw other/additional conclusions here? (question for discussion)

Chapter 5: Uncertainty and Sensitivity analyses



Focus of the chapter

- Classification of types of uncertainty and sensitivity
- Connection between relevant literature and BBp systems
- Guidance to the analyst/practitioner towards making choices about how to model uncertainty
- Application in an example

Classification of uncertainty and uncertainty dimensions

We start with three main dimensions of uncertainty: the nature, location and level of uncertainty (Walker et al., 2003).

Classification of uncertainty and uncertainty dimensions

		Uncertainty examples	Goal & Scope	LCI	LCIA
Nature	epistemic (knowledge uncertainty/ uncertainty)	• accuracy or representativeness of an indicator towards an area of protection			X
		• data availability/ representativeness of background processes used		X	
	ontic (variability uncertainty/ aleatory uncertainty/ variability)	• variability of performance characteristics (are the functional units comparable?)	X		
		• variability of characterization factors (CF)			X

Classification of uncertainty and uncertainty dimensions

		Uncertainty examples	Goal & Scope	LCI	LCIA
Location	quantity (inputs and parameters)	representativeness of data used for each flow		X	
	model structure (structure, parameters and variables)	variability of LCIA indicator relationships			X
	context (modelling context and experimental frame)	technological representativeness	X		

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Classification of uncertainty and uncertainty dimensions

Level	shallow uncertainty (probability distributions)	representative statistical data available
	medium uncertainty (rank ordered scenarios)	multiple possible futures or alternative model structures (perceived likelihood)
	deep uncertainty (probability measure ignorance)	multiple alternatives without being able to rank order the alternatives
	recognized ignorance (sample space ignorance)	uncertainty where no alternative states can be determined

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Classification of sensitivity

The most commonly used classification available in the literature for sensitivity distinguishes two types of analyses: local and global (Razavi et al., 2021).

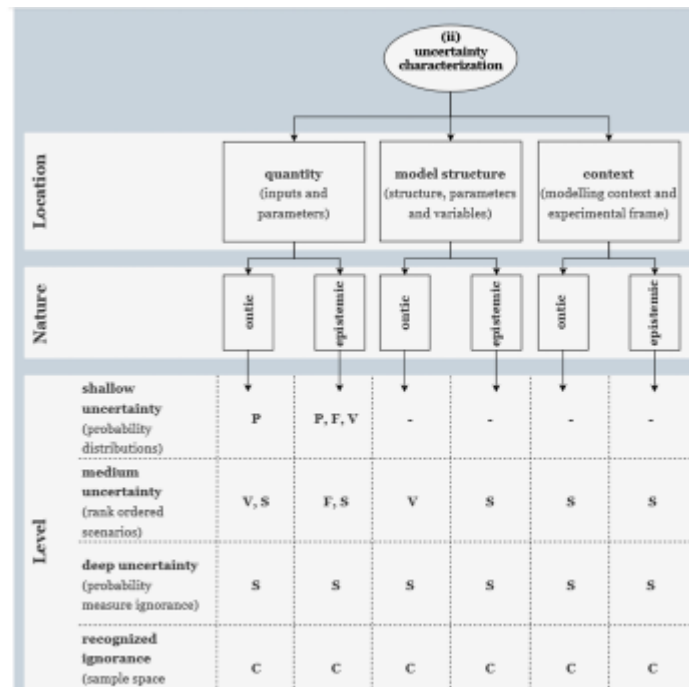
On the basis of the identified classifications, we propose here a stepwise approach

- (i) Uncertainty location and identification by LCA phases,
- (ii) uncertainty characterization,
- (iii) qualitative importance ranking,
- (iv) treatment of uncertainty,
- (v) uncertainty communication.

[after (Baustert, 2021; R. Heijungs et al., 2019; Henriksson et al., 2015)]:

Characterization of uncertainty

Uncertainty expression: (P) probability distribution, (V) variance, (F) fuzzy sets, (S) multiple scenarios and (C) uncertainty communication only.



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Treatment

- UA, or the quantification of the uncertainty in the inputs to the LCA model, and the propagation of uncertainty information of the inputs into uncertain model results
- SA, or the study of how the input uncertainties contribute to the output uncertainty
- Scenarios

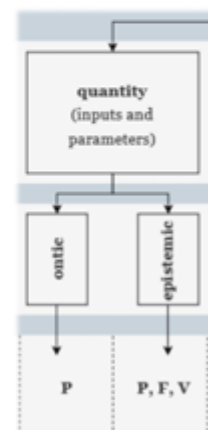
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Treatment: UA, example

Available methods	Characterization (expressed by)	What is needed?	Result/ output
Monte Carlo sampling (MCS)	P	Distribution type (e.g. log-normal, triangular) and central values (e.g. mean, dispersion, standard deviation)	Probability distribution of environmental impact (e.g. comparison of dispersion between two studies)



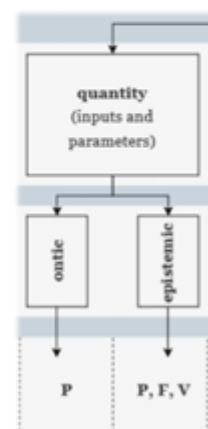
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Treatment: SA, example

Available methods	Characterization (expressed by)	What is needed?	Result/ output
Moment independent Global Sensitivity Analysis	P	Distribution type and central values (Brightspace 2.0 and Activity Browser)	Considers correlations with inputs (importance and interaction effects)



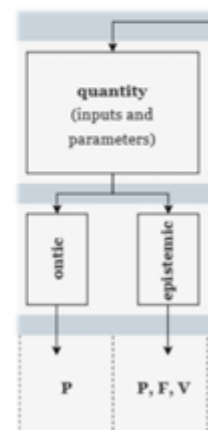
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Treatment: SA, example

Available methods	Characterization (expressed by)	What is needed?	Result/ output
Scenario analysis	S	Multiple conceptual models and expert judgment	Usually, output ranges from best (optimistic) to worst (pessimistic) case



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BBP case study:

Comparison of microwave extraction and conventional acid extraction

(i) uncertainty location and indication by LCA phases		(ii) uncertainty characterization										(iii) ranking					
		location				nature		level									
		quantity	model	structure	context	ontic	epistemic	shallow	uncertainty	medium	uncertainty	deep	uncertainty	recognized	ignorance	→	uncertainty expression
Goal & Scope:	technological representativeness (CE, MAE1+2)			x		x		x							→	S	2
	representativeness of performance characteristics			x		x		x							→	S	3
	geographical representativeness (Sicily, IT)			x		x		x							→	S	1
LCI:	variability in orange juice production	x				x				x					→	V,S	1
	representativeness of flows considered		x				x	x							→	S	4
	representativeness of BG processes used		x				x		x						→	S	3
	representativeness of data for FG processes used	x					x	x								P,F,V	1

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Questions to guide the discussion

- How can we make our methodology/recommendations **more specific for BBPs**?
- How's **uncertainty** for emerging BBPs different from uncertainty for other emerging technologies?
- How to you reconcile theoretical and methodological discussions to the **practical needs** of the analyst/practitioner?
- Which practical conclusions should we draw for the modeling of **biogenic carbon** in pLCA?

Perhaps also?

- **How to combine the individual parts into a bigger framework?** Is that even a meaningful goal?

Thank you!

Contact

b.steubing@cml.leidenuniv.nl

s.cucurachi@cml.leidenuniv.nl

Annex 5: Discussion points

Discussion points

- How can we make our methodology/recommendations **more specific for BBPs**?
- How's **uncertainty** for emerging BBPs different from uncertainty for other emerging technologies?
- How to reconcile theoretical and methodological discussions to the **practical needs** of the analyst/practitioner?
- Which practical conclusions should we draw for the modeling of **biogenic carbon** in pLCA?
- **How to combine the individual parts into a bigger framework?** Is that even a meaningful goal?



Day 2
7th December 2021

Annex 1: Agenda

10:00-10:30	1. Welcome back and insights from the previous day
	Carla Caldeira, Project coordinator, JRC The presenter will welcome the participants back and present insights gained from the discussions in the previous day. Discussion with the participants.
10:30-10:50	2. Presentation of Case study 1
	Jade Müller Carneiro, University of Coimbra A case study on the production of biopolymer from mango wastes will be presented, illustrating the application of the framework. Discussion with the participants.
10:50-11:10	3. Presentation of Case study 2
	Mateo Saavedra del Oso, University of Santiago de Compostela A case study on the production of polyhydroxyalkanoates (PHA) from organic wastes by open mix cultures will be presented, illustrating the application of the framework. Discussion with the participants.
11:10-11:20	Coffee break
11:20-11:40	4. Presentation of Case study 3
	Emma Zuiderveen, JRC / Radboud University A case study on the production of bio-BTX will be presented, illustrating the application of the framework. Discussion with the participants.
11:40-12:00	5. Presentation of Case study 4
	Octavio Wurmböck, University of Leiden A case study on the production of protein from CO ₂ will be presented, illustrating the application of the framework. Discussion with the participants.
12:00-12:50	6. Discussion
	Discussion with the participants.
12:50-13:00	7. Next steps and closure
	Carla Caldeira, JRC

Annex 2: List of participants

No	Country	Name	Affiliation
1	EU	Carla Caldeira	EC JRC
2	EU	Valeria De Laurentiis	EC JRC
3	EU	Jorge Cristobal Garcia	EC JRC
4	EU	Marios Avraamides	EC JRC
5	EU	Javier Sanchez Lopez	EC JRC
6	EU	Maria Teresa Borzacchiello	EC JRC
7	EU	Zsuzsa Turoczy	EC JRC
8	EU	Giulia Fiorese	EC JRC
9	EU	Adrian Tistan	EC RTD
10	PT	Researcher	-
11	ES	Almudena Hospido	University of Santiago de Compostela
12	IT	Fabio Fava	University of Bologna
13	NL	Bernhard Steubing	Leiden University
14	PT	Carla Rodrigues	University of Coimbra
15	BE	Celestin Demuytere	Organic Waste Systems (OWS)
16	BR	Maria Cléa Figueirêdo	EMBRAPA (Brazilian Agricultural Research Corporation)
17	NL	Emma Zuiderveen	Radboud University
18	NL	Ed de Jong	Avantium Technologies
19	NL	Flora Siebler	Leiden University
20	PT	Fausto Freire	University of Coimbra
21	IT	Francesca Braca	Laboratory ARCHA S.r.l.
22	NL	Iris Vural Gursel	Wageningen Food & Biobased Research
23	PT	Jade Müller Carneiro	University of Coimbra
24	NL	Mark Huijbregts	Radboud University
25	SE	Marta Behjat	University of Chalmers
26	IT	Matteo Prussi	Politecnico di Torino
27	ES	Mateo Saavedra del Oso	University of Santiago de Compostela
28	NL	Nicolas Navarre	Leiden University
29	DE	Nabil Abdalla	IFEU
30	DE	Nils Rettenmaier	IFEU
31	DE	Octavio Wurmböck	Leiden University
32	BE	Pieter Deckers	Organic Waste Systems
33	SE	Rickard Arvidsson	University of Chalmers
34	CH	Roland Hischier	EMPA
35	NL	Stefano Cucurachi	Leiden University
36	DE	Sabine Langkau	Fraunhofer ISI
37	DE	Anna Sander-Titgemeyer	Technical University of Munich
38	PT	Tiago Lopes	Laboratório Nacional de Energia e Geologia
39	DE	Uwe R. Fritsche	IINAS
40	DE	Horst Fehrenbach	IFEU
41	DE	Gabriele Weber-Blaschke	Technical University of Munich

Annex 3: A case study on the production of biopolymer from mango wastes - Presentation of Jade Müller Carneiro, University of Coimbra



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Application of the pLCA methodology

Prospective life cycle assessment of nano-reinforced biopolymer films based on mango processing wastes

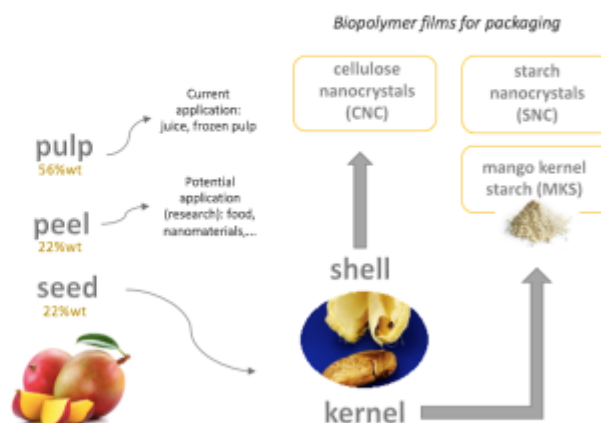
Jade Müller Carneiro, Carla Rodrigues, Fausto Freire

7th December 2021

Introduction

- Biopolymer films were obtained in the laboratory* from a waste from mango pulp/juice industry (mango seed) intended for packaging application
- The goal is to analyse the future environmental impacts of two biopolymer films, currently at an early research stage (TRL 3), and expected to be deployed in 30 years (TRL 9 **by 2050**)

*Experiments by Oliveira et al.(2018) and Silva et al. (2019)



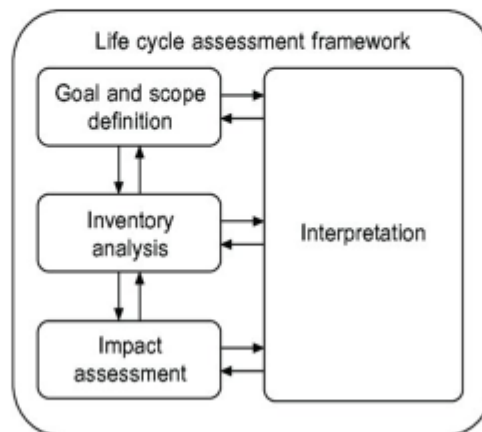
pLCA methodology issues addressed

pLCA modelling choices

- No function defined
- Timeframe – when will the technology be at TRL 9
- No market
- Upscaling foreground defined (allocation)
- Background data

Biogenic carbon accounting

...



Scenario analysis

Uncertainty

Sensitivity analysis

3

Application of the
framework for pLCA
modelling choices

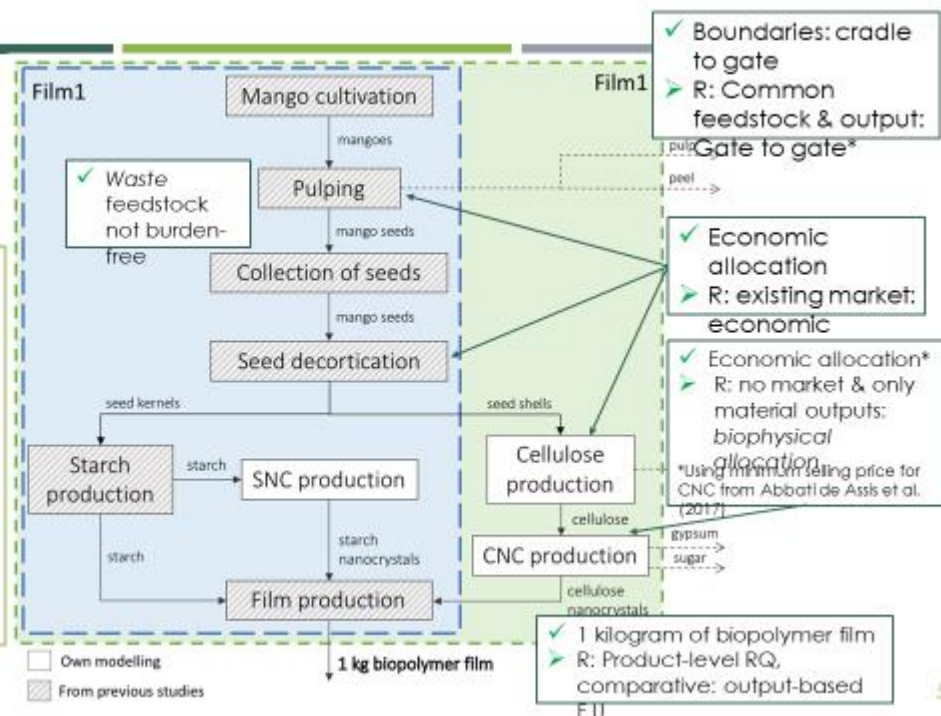
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pLCA modelling choices

Research questions

Which biopolymer film formulation has lower environmental impacts?

How can the environmental performance of the biopolymer films be improved?



Applying the pLCA framework – allocation

Economic allocation of co-products from CNC production

Co-products	Amount (kg)	Price (\$/kg)	Total revenue (\$)	Allocation factors
CNC	1.00	5.80	5.80	74%
Sugar	4.42	0.40	1.77	23%
Gypsum	25.46	0.01	0.24	3%
Sum			7.81	

Highly uncertain CNC prices:
Market projections between 4.4-11\$/kg (Cowie et al., 2014)
Between 69% and 85% of the burdens could be allocated to CNC

Effect of CNC prices on the LCIA results

Global warming potential (IPCC 2013, 100y)	Default	Minimum	Maximum
CNC production (kg CO ₂ -eq/kg CNC)	83.64	77.99	96.07
%Change		-7%	15%
Film2 total impact (kg CO ₂ -eq/kg film)	6.19	6.12	6.34
%Change		-1%	2%

Considerable change in CNC impact (-7%/+15%)
But little effect on total biopolymer film impacts

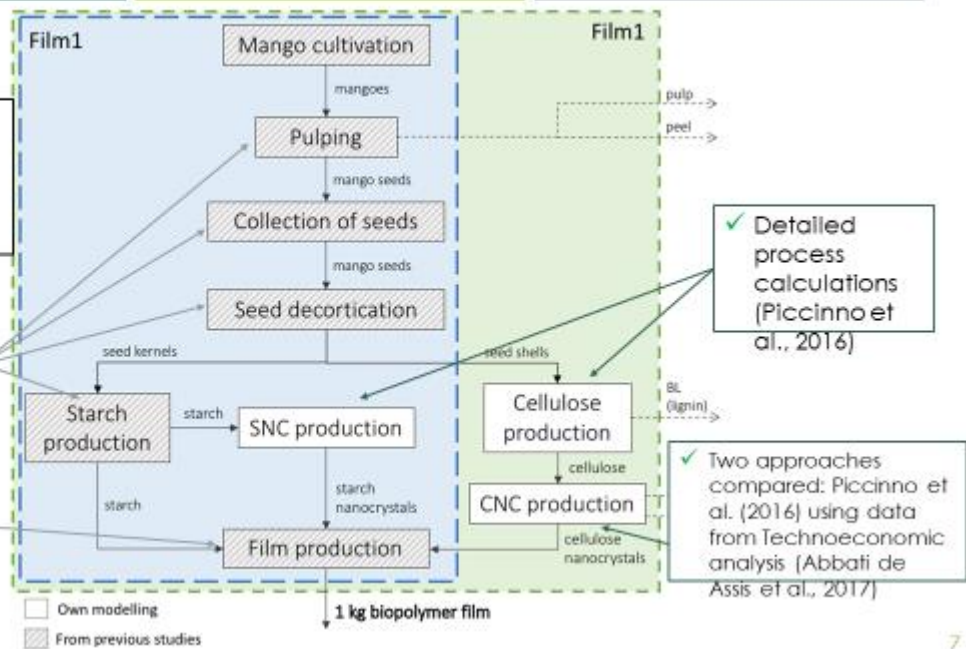
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Upscaling

➤ R: Operational parameters known, no access to simulation software: **Detailed process calculations**

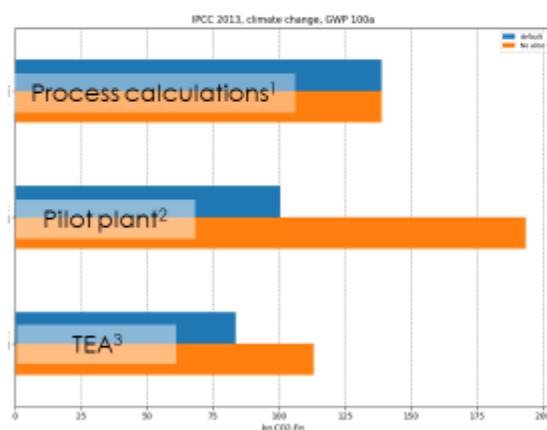
✓ Simulation from previous study (Pereira da Silva et al., 2021)

✓ Extrusion data fromecoinvent and Kent (2018)



Applying the pLCA framework – upscaling

Cellulose nanocrystals production



1- Using Piccinno et al. (2018) from lab-scale, CNC from mango seed shells; 2- Modified from Gu et al. (2015), CNC from kraft pulp; 3- Modified (yield) from Abbati de Assis et al. (2017), from pilot, CNC from kraft pulp.

- ❖ Enormous acid consumption (same as lab, 140 kg H₂SO₄/kg CNC)
- ❖ Electricity use increase
- ❖ Process change (neutralisation/separation)
- ❖ Reduction in acid consumption (-73%)
- ❖ Co-products

- ❖ Electricity use reduction
- ❖ Reduction in acid consumption (-85% than in the lab)

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Application of the scenario methodology

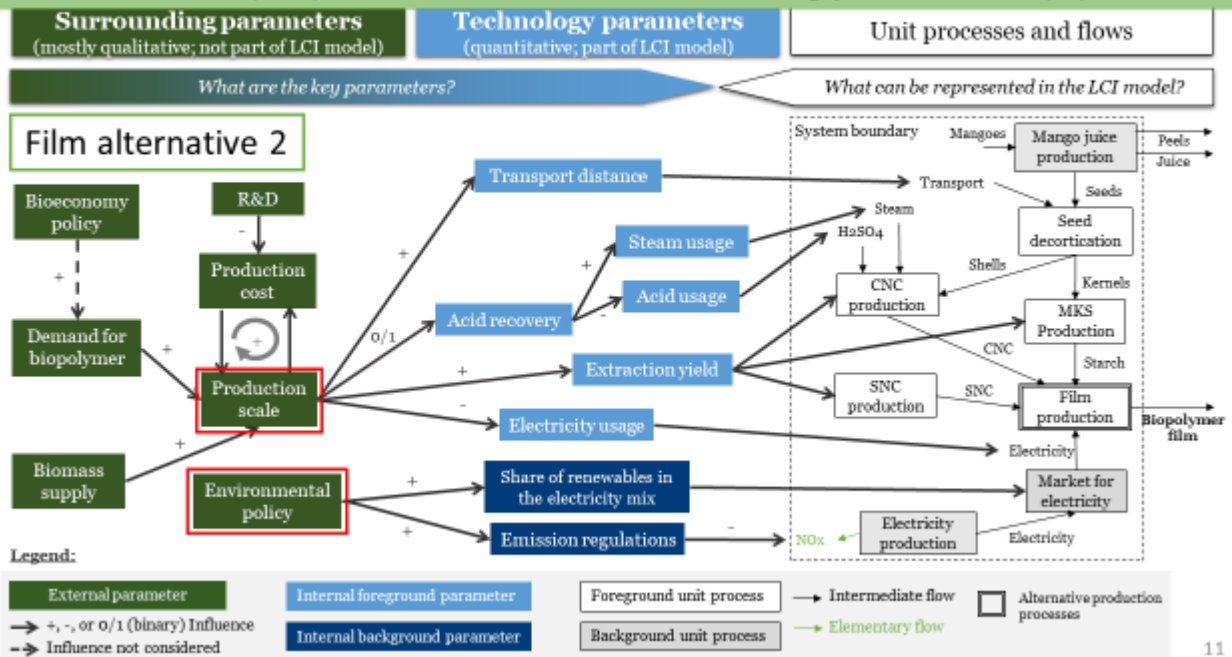
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Phase 1: Goal and Scope

- Technology readiness level (TRL): **3**
- Timeframe: **30 years** – expected to reach TRL 9 by 2050
- Scenario type: **Explorative**
- Background scenarios: **SSP2-base** (liberal climate policy) and **SSP2-RCP2.6** (strict policy)

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Phase 2 (LCI): Identification of influencing parameters (A)



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Sub-scenario creation (B)

Cross-consistency assessment

Parameter	Sub-scenario	Production scale		Acid recovery		Environmental policy	
		Small	Large	No	Yes	Liberal	Strict
Production scale	Small						
	Large						
Acid recovery	No	3	3				
	Yes	1	2				
Extraction yields	Low	3	2	3	2		
	Medium	3	3	3	2		
	High	2	3	3	2		
Share of renewables	Low	3	3	3	3	3	1
	High	3	3	3	3	1	3

Legend:

Inconsistent	1
Maybe consistent	2
Fully consistent	3

Morphological fields

Production scale	Acid recovery	Yields	Environmental policy	Share of renewables
Small	No	Low	Liberal	Low
-	-	Medium	-	-
Large	Yes	High	Strict	High

Production scale	Acid recovery	Yields	Environmental policy	Share of renewables
Small	No	Low	Liberal	Low
-	-	Medium	-	-
Large	Yes	High	Strict	High

➤ 8 internally consistent scenarios

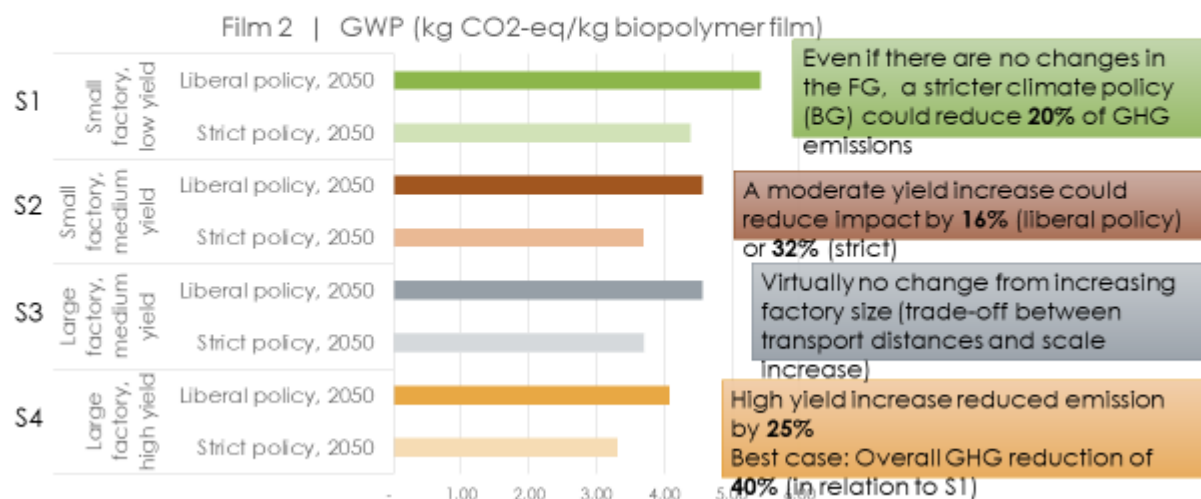
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Scenario creation (C) and implementation in LCI (D)

Scenario creation		Same FG, different BG: Moderate yield increase Factory size increase, no change in yield Yield increase (max)							
Parameter		Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b	Scenario 4a	Scenario 4b
Production scale	Small	x	x	x	x				
	Large					x	x	x	x
	Low	x	x						
Yields	Medium			x	x	x	x		
	High							x	x
Environmental policy	Liberal	x		x		x	x	x	x
	Strict		x		x				
Share of renewables	Low	x		x		x		x	
	High		x		x		x		x
Translation to LCI model									
Parameter	Unit	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b	Scenario 4a	Scenario 4b
Yield MKS	% (MKS/kernels-dry)	39%	39%	47%	47%	47%	47%	55%	55%
Yield SNC	% (SNC/MKS-dry)	32%	32%	37%	37%	37%	37%	42%	42%
Yield CNC	% (CNC/cellulose fibre-dry)	16%	16%	33%	33%	33%	33%	50%	50%
Electricity use (film)	MJ/kg film	3.15	3.15	3.15	3.15	1.9	1.9	1.9	1.9
Transport distance	Tkm feedstock/kg film	0.5	0.5	0.5	0.5	2.3	2.3	2.3	2.3
Share of renewables	-	Low	High	Low	High	Low	High	Low	High
With background scenarios									
Parameter	Unit	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b	Scenario 4a	Scenario 4b
Share of renewables	background scenario	SSP2-base	SSP2-2.6	SSP2-base	SSP2-2.6	SSP2-base	SSP2-2.6	SSP2-base	SSP2-2.6

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Scenario results



14

Thoughts and learnings from the framework application

- For coproducts with no market prices, it may be more practical to apply **economic allocation** using price estimations and assess sensitivity to prices
- More specific guidance on the **functional unit** definition could be useful, e.g., comparing fossil- and novel bio-based materials considering substitution potential
- It can be difficult to build comprehensive and consistent scenarios if there is no access to technology experts
- Possibility to **combine upscaling approaches** to overcome some of their limitations(?)
- In addition to given upscaling methods, it can be useful for practitioners to get information from TEAs and pilot plant to guide FG modelling.

15

Thank you

Obrigada

Jade Müller Carneiro
Jade.muller@dem.uc.pt

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Annex 4: A case study on the production of polyhydroxyalkanoates (PHA) from organic wastes by open mix cultures - Presentation of Mateo Saavedra del Oso, University of Santiago de Compostela

Applying a systematic scenario methodology within prospective LCA: a case study of PHA production

Mateo Saavedra del Oso | CML-IE & CRETUS



Universiteit
Leiden
The Netherlands



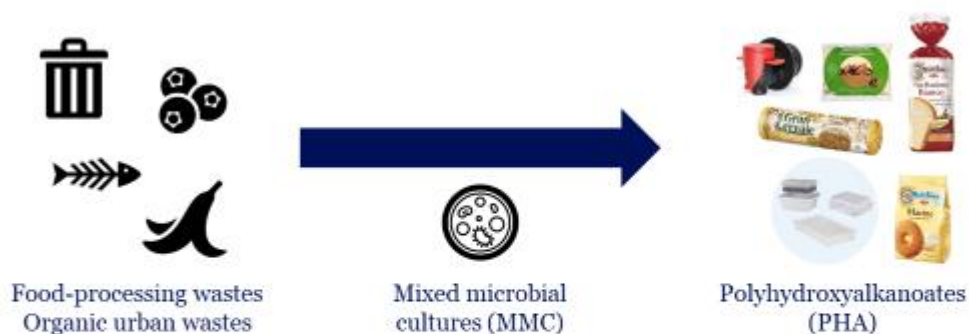
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1

A new biobased value chain



PHA production from rich-carbon wastes can diminish both environmental impacts and production costs



Low TRL: 5
Opportunities for major adjustments

Prospective LCA to ensure environmental guidance

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2

Combining a systematic scenario methodology with prospective LCA

- Phase 1: Goal and scope
 - Scenario type (predictive, explorative, normative)
 - Time horizon (how far in the future?)
 - TRL (current? future?)
 - Foreground and background data (data to build upon)
 - Identification of alternatives (which systems should be modelled?)
- Phase 2: Inventory analysis
 - (A) Identification of influencing parameters
 - (B) Construction of sub-scenarios for each parameter
 - (C) Creation of scenarios from sub-scenarios
 - (D) Implementation of scenarios in the LCI model



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3

Goal and scope

- The goal of the current LCA is to assess the environmental performance of PHA production by MMC in future framework where its large-scale production is implemented, and thus, provide environmental guidance to the developers.

Scenario type: explorative

- Developing alternative narratives or by assessing "what-if" type of questions

Addressing system multifunctionality: JRC guidelines

- System function: producing PHA powder than can be further processed into high-performance bioplastics
- System partitioning: (SS1) anaerobic fermentation, (SS2) biomass selection and accumulation, (SS3) downstream processing, (SS4) anaerobic digestion, (SS5) CHP
- Allocation based on COD (SS1, SS3, SS4) and exergy (SS5)

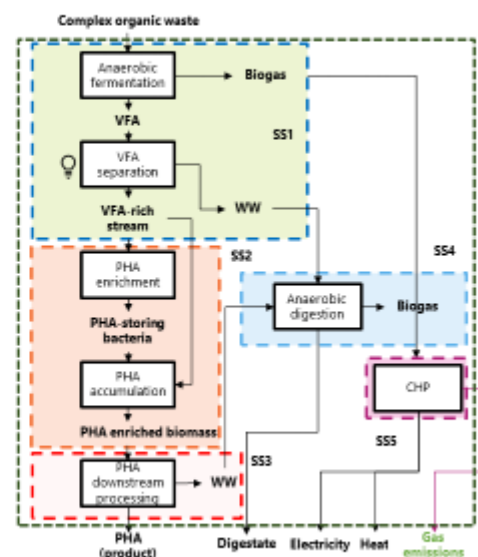
Time horizon: 2030

TRL: 5

Foreground and background data

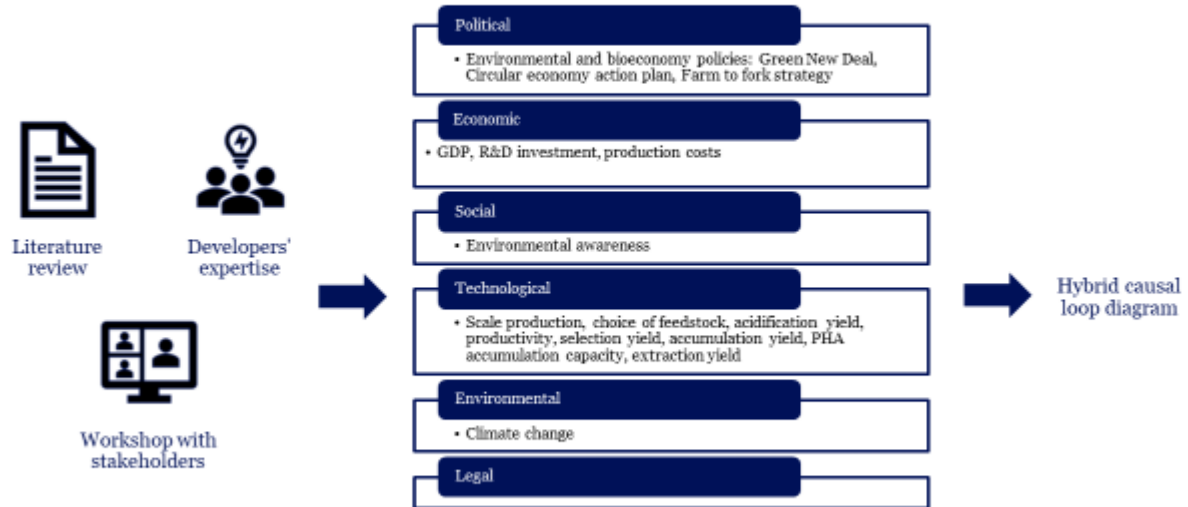
- Foreground: literature on PHA production on pilot-scale
- Background: ecoinvent 3.7.1 IMAGE 2030

System boundaries: cradle-to-gate



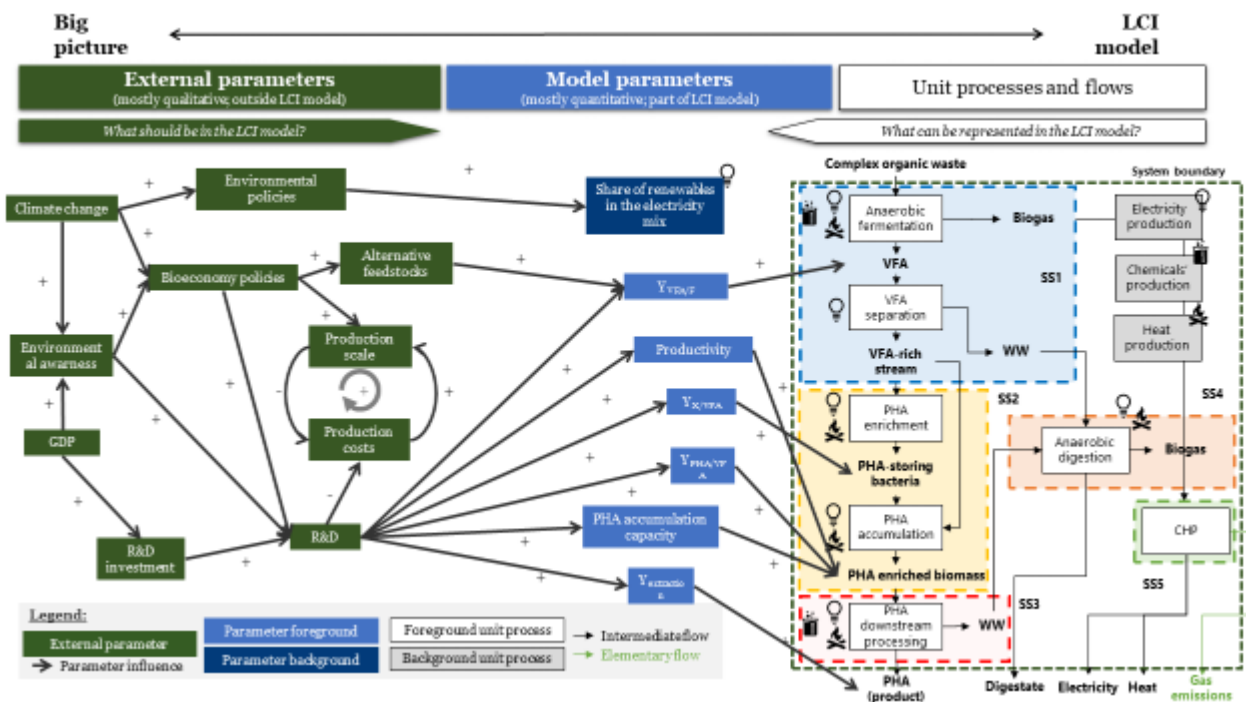
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Inventory analyses: (A) identification of influencing parameters



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Inventory analyses: (B) Construction of sub-scenarios for each parameter

Parameter	Environmental policy	Bioeconomy policy	Production scale	Feedstock	YVFA/F	YX/VFA	YPHA/VFA	Productivity	PHA content in biomass	Extraction yield
Type	Qualitative/Categorical	Qualitative/Categorical	Quantitative/Numerical	Qualitative/Categorical	Quantitative/Numerical	Quantitative/Numerical	Quantitative/Numerical	Quantitative/Numerical	Quantitative/Numerical	Quantitative/Numerical
Sub-scenario 1	BAU	BAU	Small	Fruitwaste	0.3	0.4	0.5	3	0.46	0.7
Sub-scenario 2	Moderately ambitious	Moderately ambitious	Medium	OFMSW & SS	0.35	0.45	0.65	6	0.59	0.8
Sub-scenario 3	Ambitious	Ambitious	Large	-	0.75	0.55	0.8	8	0.8	0.9
Units			tPHA/year		g COD/g COD	g COD/g COD	g COD/g COD	g PHA-L-1-d-1	g PHA/g PHA enriched biomass	g PHA/g PHA

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Inventory analyses: (C) Creation of scenarios from sub-scenarios: cross-consistency check

Check the consistency of scenarios is to critically evaluate whether a chosen set of parameters values makes sense when assessed against the previously developed CLD

Parameter			Productivity			PHA content in biomass		
Parameter	Sub-scenario		Low	Medium	High	Low	Medium	High
PHA content in biomass	Low	0.46	3	2	1			
	Medium	0.59	2	3	2			
	High	0.8	1	2	3			
Y _{extraction}	Low	0.7	3	2	1	3	2	1
	Medium	0.8	2	3	2	2	3	2
	High	0.9	1	2	3	1	2	3

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Inventory analyses: (C) Creation of scenarios from sub-scenarios: Morphological fields

Environmental policy	Bioeconomy policy	Production scale	Feedstock	$Y_{SFP/food}$	$Y_{X/SFP}$	$Y_{PHA/SFP}$	PHA content in biomass	$Y_{extraction}$
BAU	BAU	Small	Fruit waste	Low	Low	Low	Low	Low
Moderately ambitious	Moderately ambitious	Medium	OFMSW & SS	Medium	Medium	Medium	Medium	Medium
Ambitious	Ambitious	Large		High	High	High	High	High
BAU	BAU	Small	Fruit waste	Low	Low	Low	Low	Low
Moderately ambitious	Moderately ambitious	Medium	OFMSW & SS	Medium	Medium	Medium	Medium	Medium
Ambitious	Ambitious	Large		High	High	High	High	High
BAU	BAU	Small	Fruit waste	Low	Low	Low	Low	Low
Moderately ambitious	Moderately ambitious	Medium	OFMSW & SS	Medium	Medium	Medium	Medium	Medium
Ambitious	Ambitious	Large		High	High	High	High	High
BAU	BAU	Small	Fruit waste	Low	Low	Low	Low	Low
Moderately ambitious	Moderately ambitious	Medium	OFMSW & SS	Medium	Medium	Medium	Medium	Medium
Ambitious	Ambitious	Large		High	High	High	High	High

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			Scenario 1	Scenario 2	Scenario 3	Scenario 4
Environmental policy	BAU		X			
	Moderately ambitious			X	X	X
	Ambitious					
Bioeconomy policy	BAU		X			
	Moderately ambitious			X	X	X
	Ambitious					
Production scale	Small	1500	X	X		
	Medium	3000			X	X
	Large	7500				
Feedstock	Food processing waste		X	X		
	Urban waste and OFMSW & SS				X	X
Y_{waste}	Low	0.3				X
	Medium	0.55	X		X	
	High	0.75		X		
$Y_{X/waste}$	Low	0.4				X
	Medium	0.45	X		X	
	High	0.55		X		
$Y_{PHA/waste}$	Low	0.5				X
	Medium	0.65	X		X	
	High	0.8		X		
Productivity	Low	3				X
	Medium	6	X		X	
	High	8		X		
PHA content in biomass	Low	0.46				X
	Medium	0.59	X		X	
	High	0.8		X		
$Y_{extraction}$	Low	0.7				
	Medium	0.8	X		X	X
	High	0.9		X		

Scenario 1

- A small-scale on-site production plant within a juice beverage facility under "business as usual" bioeconomy policies

Scenario 2

- A large-scale production plant that uses fruit waste as feedstock under ambitious bioeconomy policies

Scenario 3

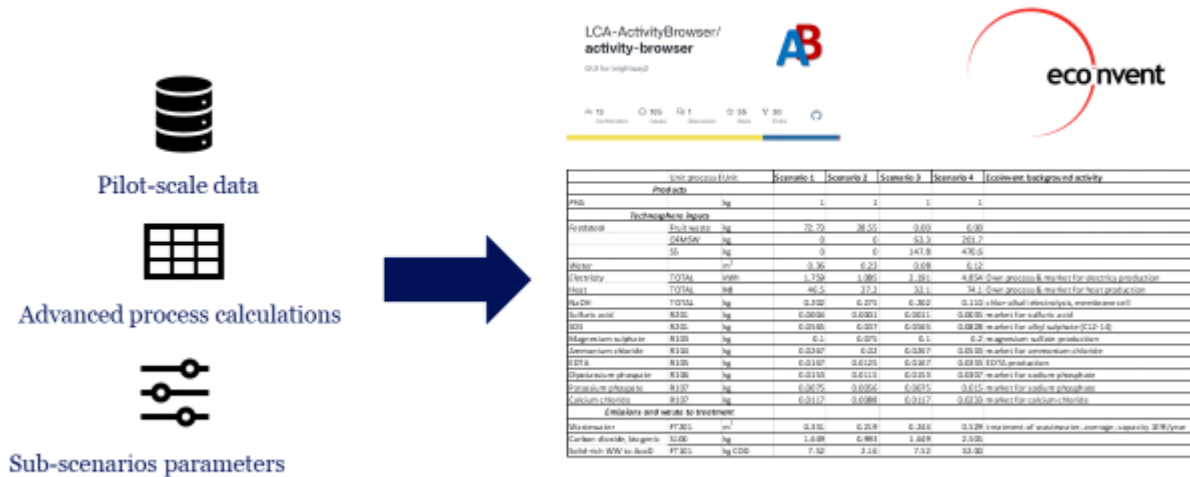
- A large-scale on-site production plant within an urban waste and wastewater biorefinery under ambitious bioeconomy policies and medium process performance parameters.

Scenario 4

- A large-scale on-site production plant within an urban waste and wastewater biorefinery under ambitious bioeconomy policies and low process performance parameters.

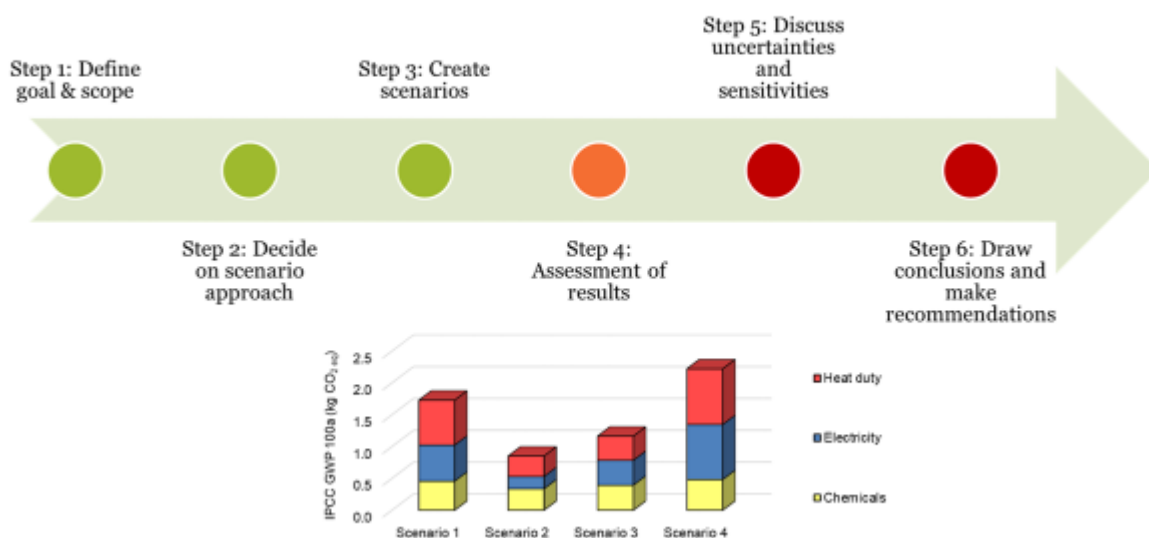
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Inventory analyses: (D) Implementation of scenarios in the LCI model



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Next steps



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Thank you

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Annex 5: A case study on the production of bio-BTX - Presentation of Emma Zuiderveen, JRC / Radboud University



PLANET BIO Case study Bio-BTX

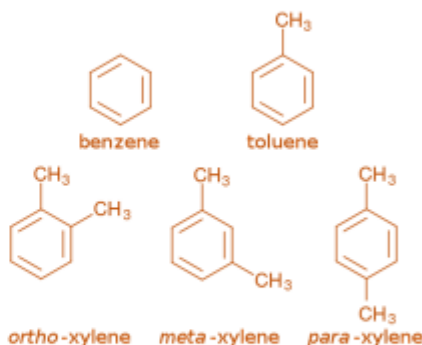
December 7th, 2021
Emma Zuiderveen
Radboud University, Joint Research Center



Introduction Goal & Scope LCI: Upscaling Road ahead Reflections

What is BTX?

- BTX: Benzene, Toluene and Xylene.
- Single-ring aromatic compounds.
- Most common process: catalytic reforming, from naphtha.
- Important intermediate for many materials.





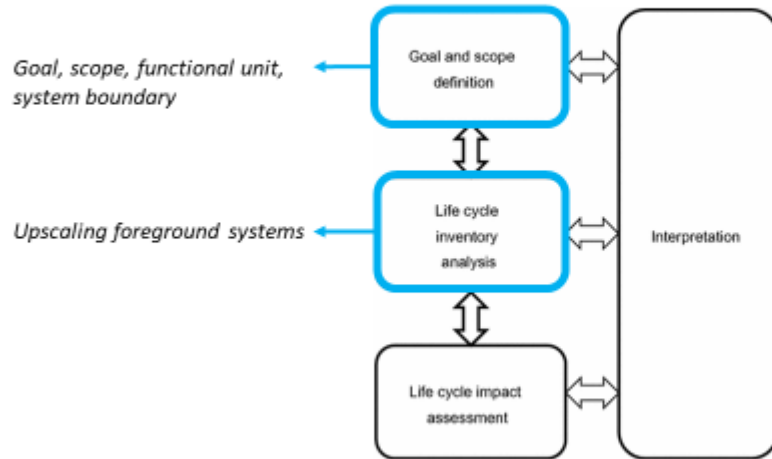
Starting point:

- Bio-based replacement of a large scale petrochemical
- Second generation biomass
- State-of-the-art CFP process
- Upscaling from lab-scale literature: how to deal with this?





Focus on Chapter 2



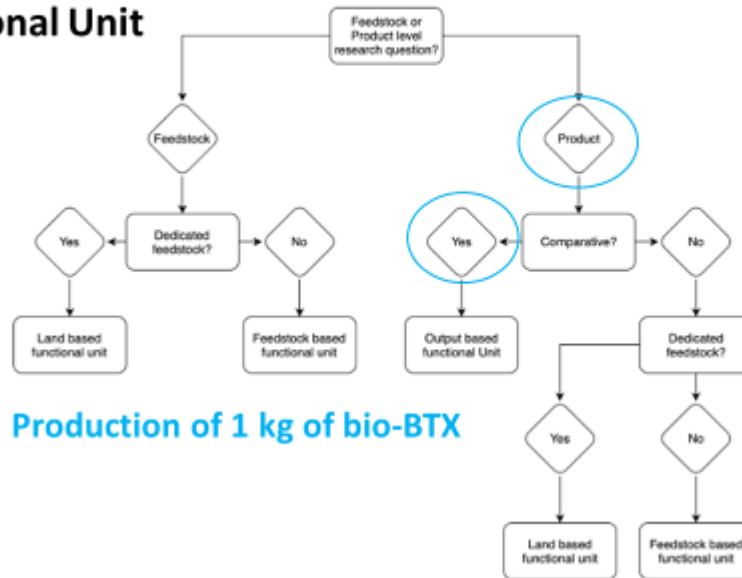
Goal & Scope

- *The goal of the study is to model the environmental impact of a bio-BTX production plant (TRL 9) in 2050 in Europe.*
 - Temporal scope: 2021 – 2050
 - Geographical scope: Europe (EU)

General steps bio-based production:

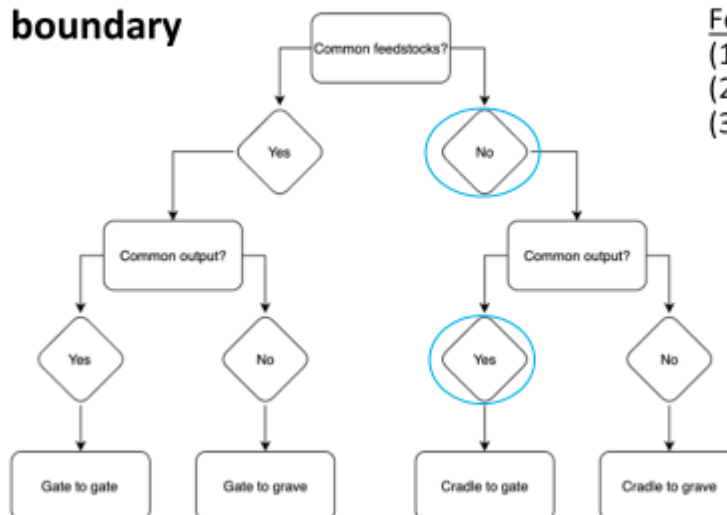


Functional Unit



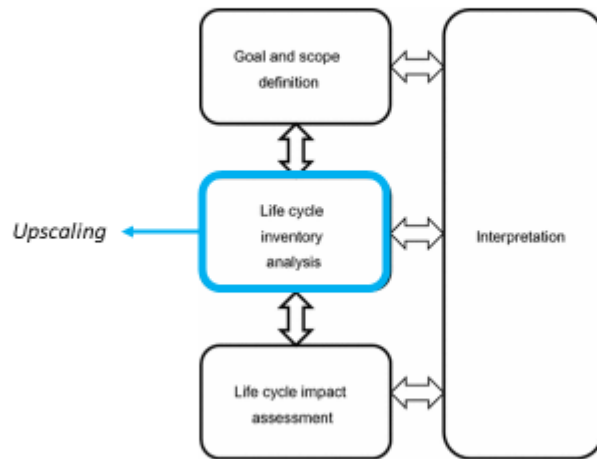
Production of 1 kg of bio-BTX

System boundary



Feedstock:
 (1) Agricultural residues
 (2) Dedicated crop
 (3) Forestry residues

Cradle-to-gate

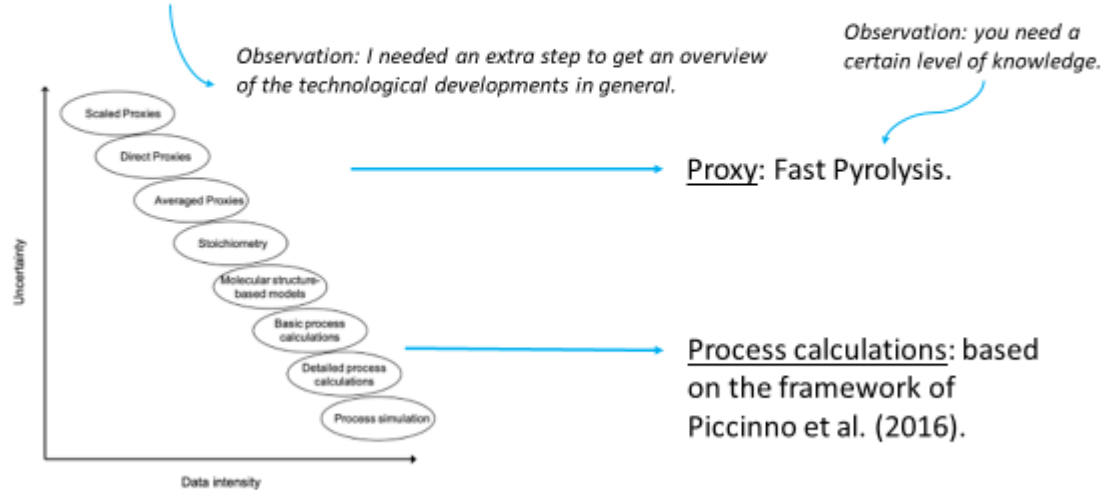


Goal & Scope

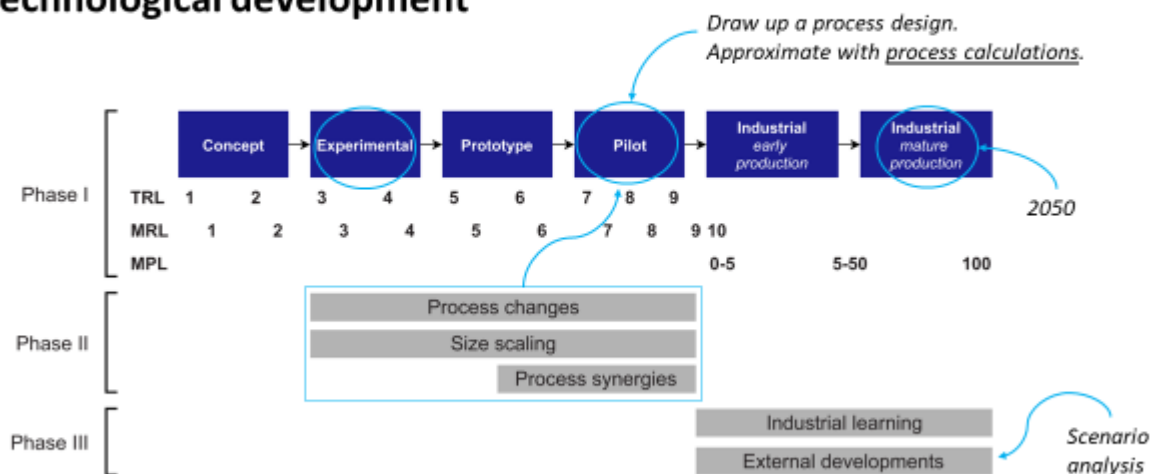
- *The goal of the study is to model the environmental impact of a bio-BTX production plant (TRL 9) in 2050 in Europe.*
- There are large uncertainties in prospective LCA regarding:
 - Technological process development
 - Future developments, e.g. share renewables in electricity mixes.
- The prospective LCA approach will therefore:
 - (1) Different strategies to upscale lab-scale bio-BTX to industrial scale, based on Piccinno et al. (2016) and van der Hulst et al. (2020).
 - (2) Scenario analysis based on the approach of Langkau and Erdmann (2021) .
 - (3) Systematically change background processes (Steubing et al., 2020).



There are different strategies for upscaling



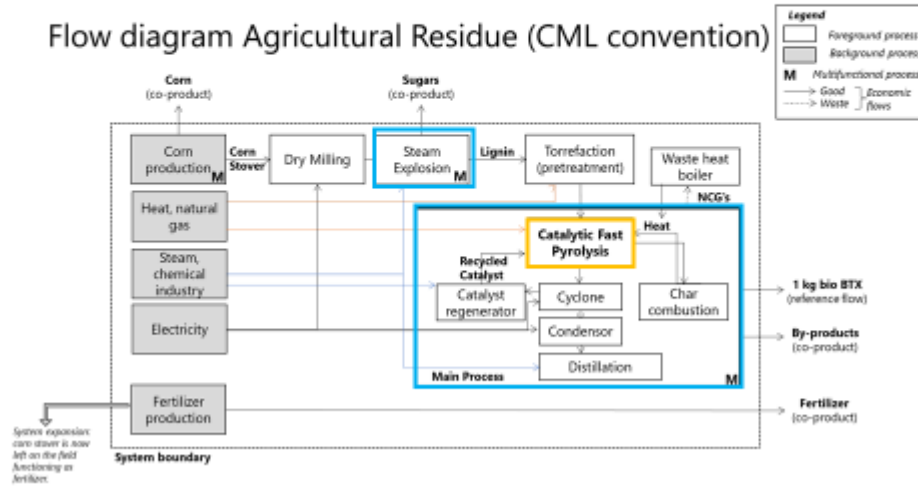
Technological development



Framework from van der Hulst et al. (2020)

Flow Diagram

Flow diagram Agricultural Residue (CML convention)



Phase I | TRL 1 2 3 4 5 6

Phase II

Table 1: Formulas and provides in scale-up calculations

Scale-up calculation	Formula	Reference
Calculation milling energy	$E_{milling} = 0.0161 \text{ kWh} \cdot m$	Picasso et al., 2015
Calculation steam consumption	$m_s = \frac{P}{h_{fg}}, P = \frac{m \cdot C_p \cdot \Delta T}{t}$	Engineering ToolBox, 2008
Calculation stirring energy	$E_{stir} = \frac{P_{stir} \cdot t}{3600}$	Picasso et al., 2015
Calculation heating energy	$Q_{heat} = \frac{m_{heat} \cdot C_p \cdot \Delta T}{3600} = \frac{m_{heat} \cdot C_p \cdot (T_{out} - T_{in}) + \frac{m_{heat} \cdot C_p \cdot (T_{out} - T_{in})}{t} \cdot t}{3600}$	Picasso et al., 2015
Calculation drying energy	$Q_{dry} = \frac{m_{dry} \cdot C_p \cdot \Delta T}{3600} + \frac{m_{dry} \cdot (T_{dry} - T_{in}) \cdot AR_{dry}}{3600}$	Picasso et al., 2015



Lignin isolation:

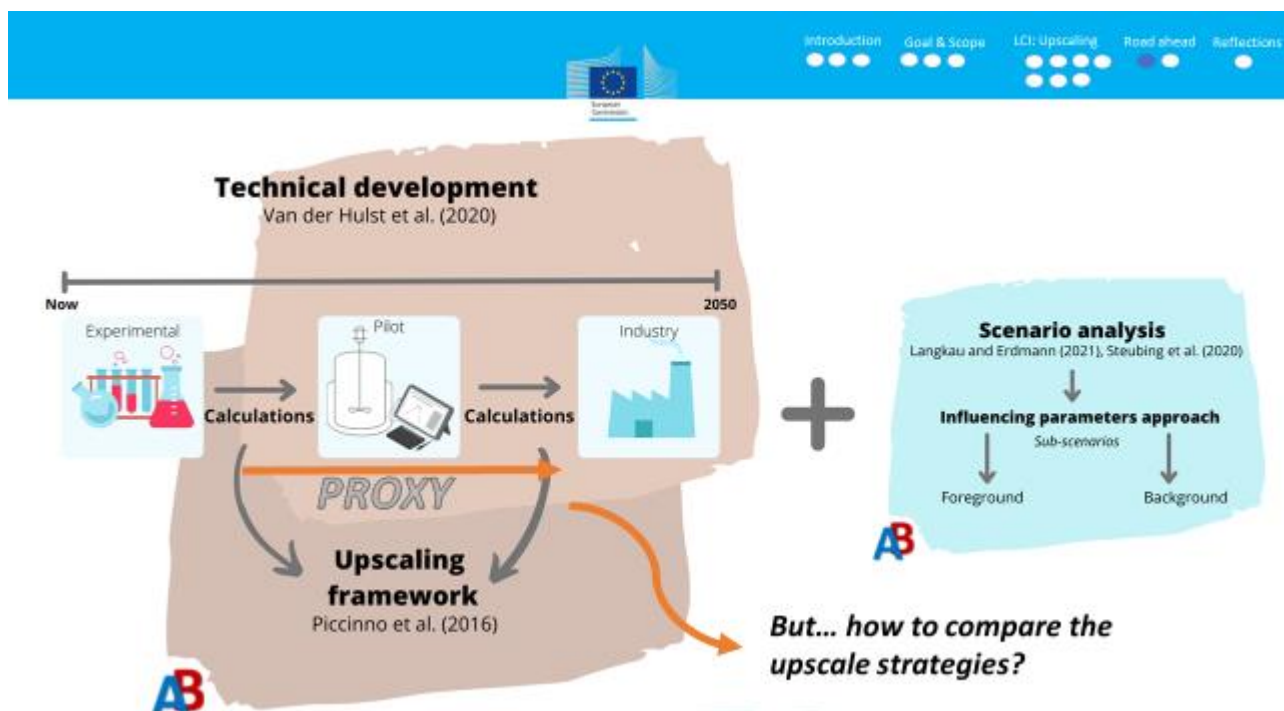
- 1) Solvent extraction (benzene/ethanol, 24h)
- 2) Powder milling (72h)
- 3) Extraction (dioxane/water, 24h)
- 4) Precipitation in diethyl ether,
- 5) Vacuum drying (40°C, 12h).



A: Heating energy & steam consumption
B,C: Heating energy & Calculation stirring energy

Lignin isolation:

- A: Steam explosion in reactor (200°C, 3min, 2 wt% H2SO4, 3MPa)
B, C: Solvent extraction in reactor (100°C, 20min, dioxane/water, 20% solvent reduction)



Introduction Goal & Scope LCI: Upscaling Road ahead Reflections

Road ahead

Real pilot-scale data

BioBTX

About BioBTX

BioBTX B.V. was founded to develop efficient and ethical bioprocesses for the production of sustainable BTX. We do this out of a love for the planet we've been given and out of a passion about changing the way we look at waste. We are persistent and audacious. We don't believe in can'ts, but in can and will do.

We are a company passionate about innovation and taking our part in the fight against climate change. We use the waste around us - 100% from plastic production - to create BioBTX as an opportunity to reduce impact on the environment.

Reflections

- Good guidance in regard to modelling choices
 - Streamlining prospective LCAs makes them more comparable
- Upscaling guidelines are useful, but an extra step would be helpful on how to model generally the technological development of a product
 - E.g. the framework of van der Hulst et al. (2020)
- Upscaling remains very uncertain when there is little information available
 - Uncertainty assessments are therefore very important
- Scenario development: prioritizing parameters in the first place proved difficult (at step A)
 - Engagement of stakeholders
- Good information on state-of-the art biogenic carbon literature and modelling, but practical guidelines on how to actually treat it would further benefit the framework.

Annex 6: A case study on the production of protein from CO₂ - Presentation of Octavio Wurmböck, Leiden University

Turning biogenic carbon into high value protein

Octavio Wurmböck | Graz, Austria



Universiteit
Leiden
The Netherlands

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1

Meat replacement from MP



Source: <https://www.labiotech.eu/startup-scout/solar-foods-space-mission-finland/>



Source: <https://www.cnet.com/health/nutrition/air-protein-launches-air-based-meat/>

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2

Literature gap

Origin of issue	Issue					
CO ₂	not allocated; no differentiated between biogenic & fossil CO ₂					
Heat	not allocated/identified as a hotspot					
Ammonia	identified as a hotspot					
Renewable energy	continuous energy production not considered					
Surrounding parameters	not considered (e.g. cost of production)					
Material efficiency	not considered					

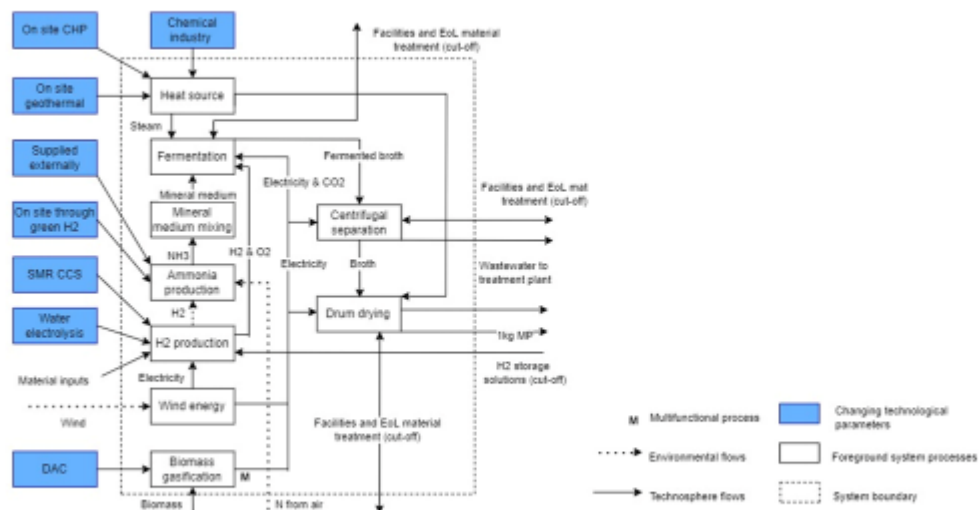
Main Research Question

What are the environmental impacts of producing 1kg of MP protein at manufacturing scale during constant energy and H₂ supply, and how do these results compare to the production of 1kg of soybean meal?

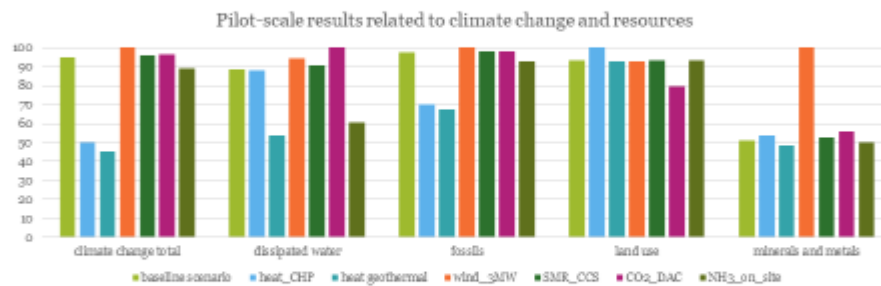
Research approach, 4 phases

- 1) Baseline/pilot-scale LCA; optimising technological setup
- 2) Parameter analysis
- 3) Development of narrative and qualitative scenarios
- 4) Ex-ante LCA of three MP production systems compared to soybean meal

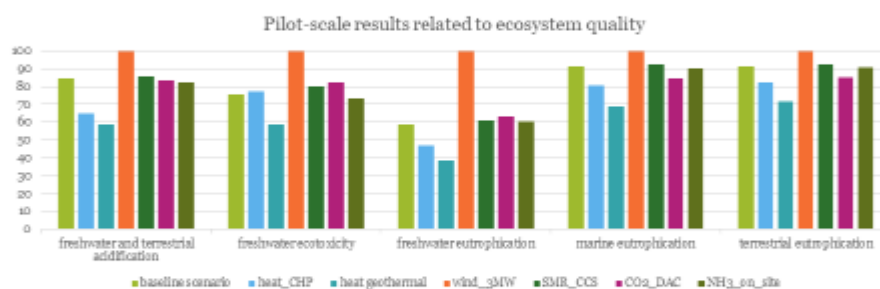
Phase 1: optimising technological setup



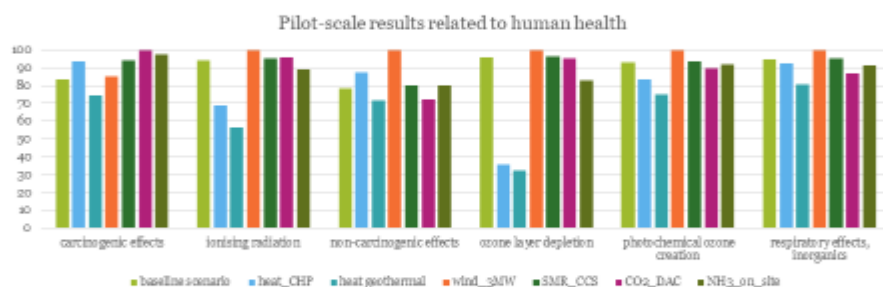
Pilot-scale characterisation:



Pilot-scale characterisation:



Pilot-scale charaterisation:



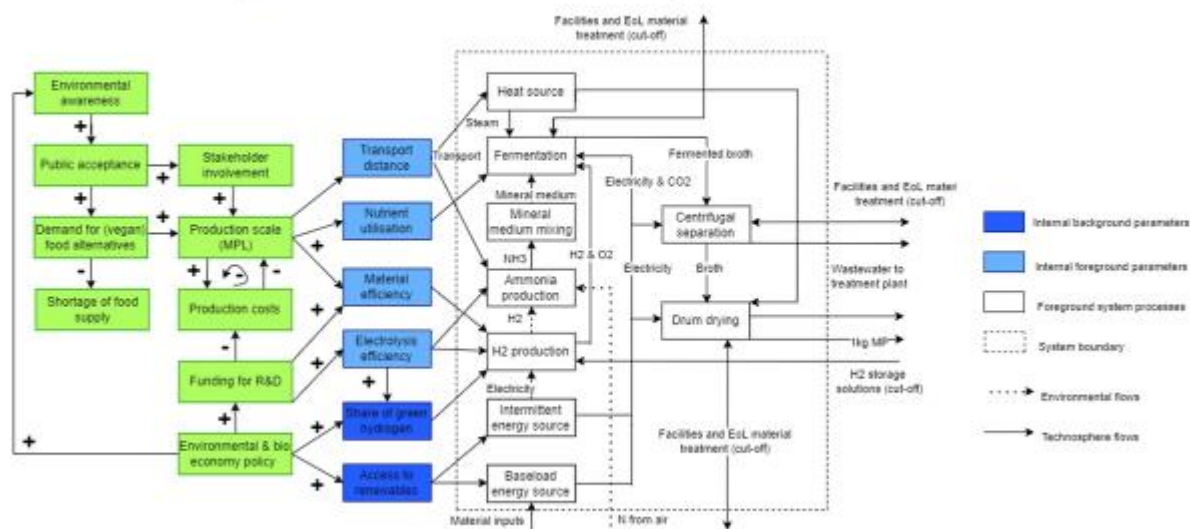
Pilot-scale charaterisation:

Parameters to be tested	Baseline-scenario	Alternative-scenario
Source of steam	Supplied through chemical industry	Produced on site
Source of NH ₃	Supplied through chemical industry	Green Nh ₃ produced on site
Wind turbine	1MW	3MW
H ₂ source	Alkaline electrolysis	SMR CCS
CO ₂ source	Point source - biomass combustion	DAC

Phase 2: parameter analysis - PESTEL

- **Political:** policy support, lobbying of established stakeholders, power of the established suppliers, subsidies for agricultural production, health targets, access to renewable energy supply
- **Economic:** price development, consequences on employment, funding grants for R&D for biobased food products, economies of scale, health care costs
- **Sociological:** stakeholder involvement, food consumption habits, acceptance of novel production method, general disaffirmation of GMO food in the EU, education on environmental issues and solutions, environmental awareness, sustainable consumption habits, advertisement, ethical sourcing of materials/elements, independence of soil and weather conditions, resource efficiency, water saving, resource availability, food availability, local food production
- **Technological:** technological development, technical efficiency, flexibility of food production, comparatively easy to scale up the production system, grid stability,
- **Environmental:** climate change impacts highly dependent on source of energy, land and water availability, less strain on soils, resource availability, good local connection
- **Legal:** food regulation, legislation to mitigate climate change and air pollution, EU food and safety laws

Phase 2: parameter analysis - CLD



Phase 3: Building of scenarios / CCA

		Demand for vegan alternatives		Environmental awareness		Funding for R&D		Bioeconomy policy support		Production costs		Production scale MPL	
		High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Demand for vegan alternatives	High												
	Low												
Environmental awareness	High	3	1										
	Low	1	3										
Funding for R&D	High	3	1	5	1								
	Low	1	5	1	5								
Bioeconomy policy support	High	2	1	3	1	3	1						
	Low	1	5	1	5	1	5						
Production costs	High	1	5	0	0	1	3	1	3				
	Low	2	1	0	0	3	1	3	1				
Production scale MPL	High	3	1	0	0	0	0	0	0	1	3		
	Low	1	5	0	0	0	0	0	0	3	1		
Public acceptance	High	2	1	3	1	2	1	2	1	0	0	3	1
	Low	1	5	1	5	1	2	1	2	0	0	1	3
Shortage of food supply	High	1	5	1	5	0	0	1	3	3	1	1	1
	Low	2	1	3	1	0	0	3	1	1	3	3	3
Stakeholder involvement	High	2	1	3	1	2	1	2	1	1	3	2	1
	Low	1	5	1	5	1	3	1	3	3	1	1	2
Access to renewables	High	2	1	3	1	2	1	2	1	2	1	3	1
	Low	1	2	1	3	1	2	1	3	1	2	1	3
Electrolysis efficiency	High	0	0	0	0	3	1	3	1	1	3	3	1
	Low	0	0	0	0	1	3	1	3	3	1	1	3
Material efficiency	High	0	0	0	0	3	1	3	1	1	3	3	1
	Low	0	0	0	0	1	3	1	3	3	1	1	3
Nutrient utilisation	High	0	0	0	0	3	1	3	1	1	3	3	1
	Low	0	0	0	0	3	1	3	1	3	1	1	3
Use of green hydrogen	High	0	0	0	0	3	1	3	1	3	1	3	1
	Low	0	0	0	0	1	3	1	3	3	1	1	3

Phase 3: Building of scenarios / CCA

[illegible]

Phase 3: Story line

Demand for vegan alternatives	Environmental awareness	Funding for R&D	Bioeconomy policy support	Production costs	Production scale MPL
Vegan alternatives remain niche products	Environmental awareness is low and remains conceptual	Funding is low and insufficient	Low policy support; climate targets are not reached	Production costs are high; funding is needed as product not market competitive	MPL of 10 might not be reached; production scale remains at a low MPL below 5
Vegan alternatives penetrate the market on a large scale	Environmental awareness is supported through concrete individual choices	Funding is sufficient for technological and market development	Sufficient policy support; climate targets are likely reached	Production costs are market competitive, yet remain high; no funding needed	MPL between 5-50; product is commercially produced
Vegan alternatives become dominant over animal products	Environmental awareness is institutionalised on a broad scale	Funding is enough to support lobbying and institutionalisation	Policy support beyond climate targets, tackling food security & resource use globally	Production costs outperform animal alternatives	MPL of 50-100; full economies of scale are reached

Public acceptance	Shortage of food supply	Stakeholder involvement	Access to renewables	Use of green hydrogen
There is low public acceptance and animal products remain the first choice	Remains high due to inefficient resource use	Remains low with dispersed interest, low network formation & learning	Little access as renewable energy production remains centralised	Low due to high cost related to H2 production; grey & blue H2 remain dominant
MP is publicly accepted; MP is at par with animal products	Effects of more efficient resources use start emerging on global level	Network formation starts to emerge, interests start to align	Renewable energy becomes more de-centralised and accessible	Green H2 is largely implemented, yet still needs subsidies to remain competitive
MP have become part of normality and are no longer extraordinary	Production in scarce regions leads to more equal distribution	Solid network formations change institutional structures	Renewable energy is fully accessible	Green H2 is fully implemented due to low production price

Technical parameters relevant for upscaling of MP production
Electrolysis efficiency
Material efficiency
Nutrient utilisation

Worst case scenario: Pilot scale, 2020
 Mid-case scenario: MPL 5-50, 2035
 Best case scenario: MPL 50-100, 2050

Ex-ante LCA of three MP reference systems

Ex-ante LCA on

- 1) Bioenergy using biomass in the UK
 - 2) Geothermal energy in Island
(steam: CHP, CO2: point source biomass combustion)
 - 3) Hydropower in Finland
(steam: CHP, CO2: point source biomass combustion)
-
- a) pilot scale (TRL 5-7)
 - b) 2025 (TRL 9)
 - c) 2040 (MPL 5-50)
 - d) 2055 (MPL 50-100)

Scenario		2025 Bioen. MPL 0-5	2025 Hydro MPL 0-5	2025 Geoth. MPL 0-5	2040 Bioen. MPL 5-50	2040 Hydro MPL 5-50	2040 Geoth. MPL 5-50	2055 Bioen. MPL 50-100	2055 Hydro MPL 50-100	2055 Geoth. MPL 50-100
Parameter	Unit									
deionised water	kg	10	10	10	9.5	9.5	9.5	9	9	9
nickel	kg	11800	11800	11800	6454.6	6454.6	6454.6	1109.2	1109.2	1109.2
steel_unalloyed	kg	170000	170000	170000	116230	116230	116230	55460	55460	55460
potassium hydroxide	kg	0.002	0.002	0.002	0.0015	0.0015	0.0015	0.001	0.001	0.001
AEL_plant_material_inputs	kg	5.10517E-08	5.10517E-08	5.10517E-08	4.08E-08	4.08E-08	4.08E-08	3.40E-08	3.40E-08	3.40E-08
electrolysis efficiency	kWh/kg H ₂	50	50	50	48.5	48.5	48.5	41.9	41.9	41.9
electricity for H ₂ _wind onshore_GB	unit	1	0	0	1	0	0	1	0	0
electricity for H ₂ _wind onshore_FI	unit	0	1	0	0	1	0	0	1	0
electricity for H ₂ _geothermal_IS	unit	0	0	1	0	0	1	0	0	1
electricity except for H ₂ _wind onshore_FI	unit	0	0.35	0	0	0.35	0	0	0.35	0
electricity except of H ₂ _wind onshore_GB	unit	0.35	0	0	0.35	0	0	0.35	0	0
electricity except of H ₂ _geothermal_IS	unit	0	0	1	0	0	1	0	0	1
electricity bioenergy_GB_except for H ₂	unit	0.65	0	0	0.65	0	0	0.65	0	0
electricity hydro_FI_except for H ₂	unit	0	0.65	0	0	0.65	0	0	0.65	0
CO ₂ _point_source	unit	1	1	0	1	1	0	1	1	0
heat_geothermal	unit	0	0	1	0	0	1	0	0	1
heat_CHP	unit	1	1	0	1	1	0	1	1	0
ammonia_on_site	unit	1	1	1	1	1	1	1	1	1
CO ₂ _DAC	unit	0	0	1	0	0	1	0	0	1
electr.(wind) for st of green NH ₃ production	kWh	11000	11000	11000	9000	9000	9000	6500	6500	6500
electr.(var.) for st of green NH ₃ production	kWh	75	75	75	70	70	70	60	60	60
NH ₃ emissions to air	kg	0.08	0.08	0.08	0.075	0.075	0.075	0.07	0.07	0.07
green NH ₃ production capacity	t/year	20000	20000	20000	50000	50000	50000	100000	100000	100000
Nutrient utilisation	%	90	90	90	95	95	95	99	99	99

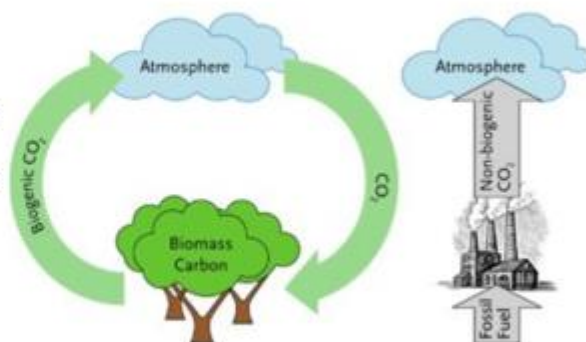
Dis

17

Phase 4: ex-ante LCA biogenic CO₂ sources

Biogenic carbon sources can come from bioenergy plants or other waste streams

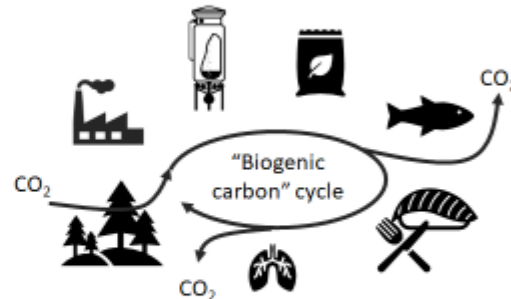
- CO₂ released back into the atmosphere during biomass combustion
- Alternatively, it can be captured and stored (CCS) or utilised (CCU)
- Once the protein is consumed, CO₂ is released again into the atmosphere
- Hence a clean source of CO₂ is needed



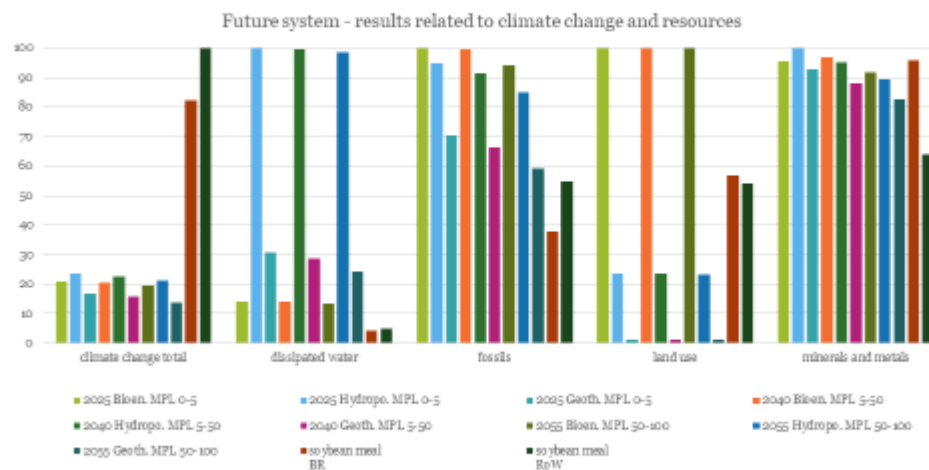
Source: <https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/>

Phase 4: ex-ante LCA biogenic CO₂ sources

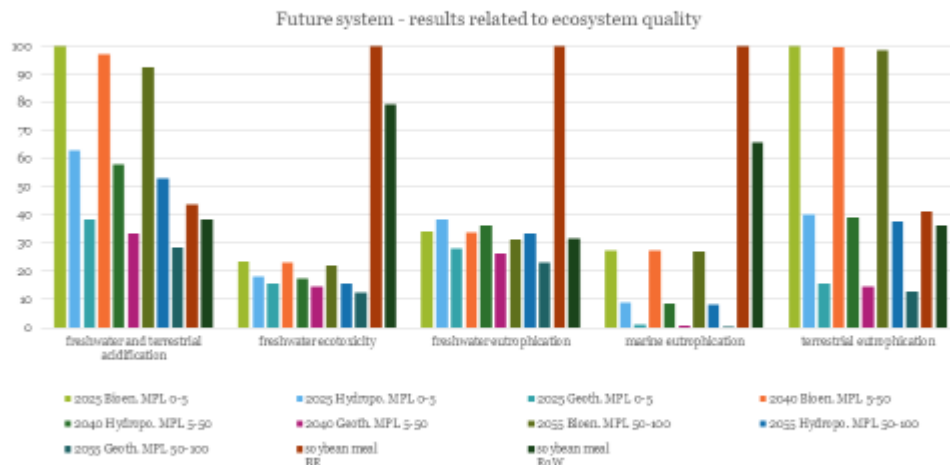
- Carbon assimilated by the body is usually not accounted for in LCA
- One can assume that carbon will eventually end up in the atmosphere
- Therefore source of carbon is very relevant
- Cradle to gate analysis



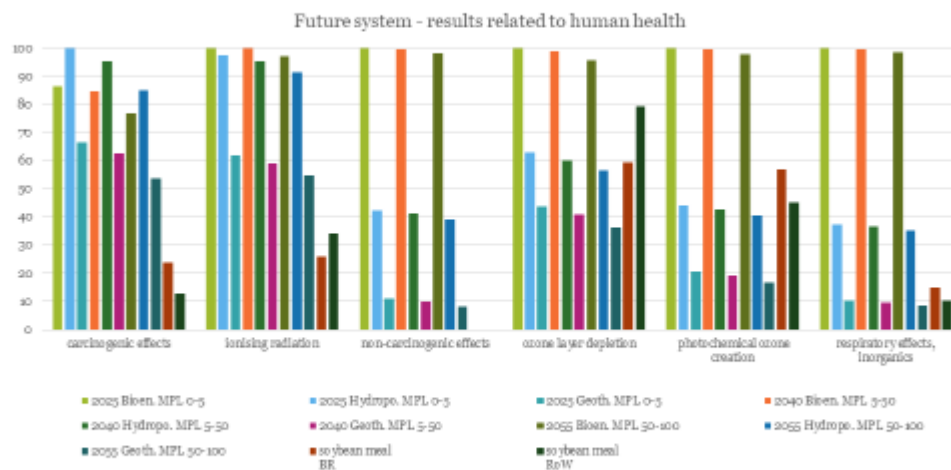
Future system characterisation:



Future system characterisation :



Future system characterisation :



Contribution & hot-spot analysis

Human health related impact categories related to:

- Steel for wind turbines and deep well drilling
- Nuclear waste treatment related to wood pellet production (up to 50% contribution!!)
- Water recycling
- Phosphoric and sulfuric acid production
- Steam from CHP
- Biomass feedstock!
- CO₂ from biomass (if allocated appropriately)

Consistency and completeness check

1) Completeness check:

- Results were in line with previous publications

2) Consistency check:

- Mismatch between foreground and background data as well as temporal mismatch was overcome through contribution analysis of incumbent technology
- Data was consistent between alternatives