

A prospective LCA of mycelium-based composites

Environmental impact assessment of future adoption of mycelium-based materials for non-structural aircraft components

Javier Alberto Urgiles Ortiz



MSc. Industrial Ecology

A prospective LCA of mycelium-based composites

Environmental impact assessment of future adoption
of mycelium-based materials for
non-structural aircraft components

by

Javier Alberto Urgiles Ortiz

to obtain the degree of Master of Science
at Delft University of Technology & Leiden University,
to be defended publicly at 09:30 on July 10, 2024.

| | | |
|---------------------|--|-------------------------------|
| Student number: | 6109829 s3962687 | TU Delft Leiden University |
| Supervisors: | Dr. Bernhard Steubing Dr. Kunal Masania | Leiden University TU Delft |
| Project duration: | February 2024 - July 2024 | |
| Additional support: | Dr. Camille Carre MSc. Mrinal Chaudhury | Airbus TU Delft |

Cover: AI generated image

Executive summary

As aviation accounts for 13.4% of the transport sector's emissions and 3.6% of all human greenhouse gas (GHG) emissions, the need for a sustainable bio-based industry arises. Meeting the growing demand for air travel requires a shift towards more sustainable alternatives, particularly in reducing fuel demand and emissions. Innovations such as weight reduction through bio-sourced materials, notably mycelium-based composites (MBCs), are promising. MBCs are known for their biodegradability, low energy consumption, and versatile applications, including packaging, furniture, fashion, and building materials, but also thermally and acoustically insulating properties that enable their use in the aerospace industry. This thesis focuses on adopting MBCs for non-structural purposes in aircraft cabin interiors. Despite their technological potential, early-stage development and limited data constrain the assessment of MBCs' environmental effects. The project aims to what are the future environmental impacts of producing MBCs at industrial production levels for aircraft interior applications, and how do they compare to conventional alternative materials.

To address this question, the project employed a Prospective Life Cycle Assessment (pLCA), offering a systematic assessment of the environmental impacts despite incomplete information. This study is conducted through two LCA phases designed to comprehensively evaluate the environmental impact of integrating MBCs. The first phase, "intratechnology comparison" focused on understanding the environmental implications of scaling up MBCs production from the laboratory to an industrial level. This phase also assessed the environmental impact of the MBCs material itself. The second phase, "intertechnology comparison" evaluated the environmental impact of an aircraft interior partition composed of MBCs and Scalmalloy compared to a conventional Nomex core sandwich partition. This comparative approach provided insights into the potential environmental benefits of using MBCs in aviation.

The process was divided in: (1) analyzing the current production of MBCs at the laboratory scale to establish the basis for modeling the emerging technology, (2) scaling up the technology to industrial production scenarios, (3) performing a pLCA to comprehensively assess the environmental impact of MBCs, considering uncertainties inherent in the early-stage development of this technology.

Key findings from this study highlight the potential of MBCs. The upscaled production of MBCs is expected to have lower emissions than lab-scale production. Current manufacture remains energy-intensive. In their direct application as non-structural components in aircraft cabin interiors, MBCs showcase advantages over conventional materials due to their lightweight nature, which benefits the use phase. However, the upscaled manufacturing process does not necessarily surpass those of conventional materials, such as the Nomex core sandwich partition, indicating hotspots that need to be addressed.

Additional scenario assessments, recyclability and energy carriers for use phase and manufacturing, were considered. The recyclability of MBCs may offer additional environmental benefits, but careful energy management is crucial to maximize these advantages. The energy carriers for the production significantly impact the environmental impact. Additionally, the lightweight nature of MBCs remains an advantage even with the transition to more decarbonized fuels.

The findings emphasize the importance of using LCA from the early design phase and iteratively as technology develops to achieve optimal results. The pLCA of MBCs offers valuable insights into their environmental impact and guides research and development efforts, helping to make informed decisions about their use in aircraft cabin interiors and further applications.

Keywords: Mycelium based composites, Prospective Life Cycle Assessment, Emerging technology, Future scenario, Upscaling, Aircraft interior

Preface

My journey as an Industrial Ecology student under the Erasmus Mundus CIRCLE program culminates in this thesis. A lifelong fascination with the intersection of innovation, sustainability, and technology fueled my excitement for this research on early adoption of biosourced materials for aviation, applying Life Cycle Assessment (LCA) methodologies.

The LDE Centre for Sustainability deserves my deepest thanks. Their program provided an interdisciplinary experience that has significantly impacted my understanding of sustainability. My thanks also go to Airbus Central Research & Development, Materials Domain, for serving as the study case holder, through the Circulaerospace thesis lab.

I would like to express my gratitude to my thesis supervisors, Dr. Bernhard Steubing and Dr. Kunal Masania, for their invaluable feedback. I am also grateful to Camille Carre and Mrinal Chaudhury for their constant support throughout this research.

Huge shoutout to the CIRCLE program who made studying in such incredible universities in the Netherlands and Austria a reality! And to all the wonderful people I met throughout these years, thank you for enriching the journey.

To my incredible friends, staying connected with all of you was not always easy, juggling calls at odd hours, navigating time zone differences, and even missing one special meeting or two. Thank you for remaining a constant source of strength and laughter, even across the miles. And to the amazing new friends I have made here: you have become a wonderful new chapter.

To my dearest family, my biggest supporters. You have always believed in me, pushing me to reach for more and trust my own capabilities. Despite the distance, your unfailing support has been a constant source to keep me motivated.

Mission accomplished, but the journey is not over!
Now, let's keep the momentum going!

Javier Alberto Urgiles Ortiz
Leiden, July 2024

Contents

| | |
|---|------|
| Executive summary | iii |
| Preface | v |
| List of Figures | ix |
| List of Tables | x |
| List of unit process data | xi |
| Nomenclature | xiii |
| 1. Introduction | 1 |
| 1.1. Problem definition | 1 |
| 1.2. Case study component | 2 |
| 1.3. Literature review | 3 |
| 1.3.1. The journey of a new material: from lab to aircraft | 3 |
| 1.3.2. Life Cycle Assessment for early-stage technologies | 3 |
| 1.3.3. A review of Life Cycle Assessment studies of MBCs | 4 |
| 1.3.4. Areas needing further study | 5 |
| 1.4. Research question | 6 |
| 2. Methods | 7 |
| 2.1. Goal and scope definition | 7 |
| 2.1.1. Goal | 7 |
| 2.1.2. Scope | 8 |
| 2.1.3. Functional unit and reference flows | 9 |
| 2.1.4. Description of product alternatives | 9 |
| 2.1.4.1. Mycelium based composite material | 9 |
| 2.1.4.2. Mycelium based partition | 9 |
| 2.1.4.3. Conventional sandwich partition | 10 |
| 2.2. Life Cycle Inventories | 10 |
| 2.2.1. Economy-environment system boundary | 10 |
| 2.2.2. Multifunctionality | 10 |
| 2.2.3. Cut-offs | 11 |
| 2.2.4. Flow charts | 11 |
| 2.2.5. Data | 16 |
| 2.2.5.1. Mycelium based composite material | 16 |
| 2.2.5.2. Mycelium based partition | 16 |
| 2.2.5.3. Conventional sandwich partition | 17 |
| 2.2.6. Scenarios description | 17 |
| 2.2.6.1. Background processes through PREMISE | 17 |
| 2.2.6.2. Foreground processes | 17 |
| 2.2.6.3. Energy carriers for manufacturing | 18 |
| 2.2.6.4. Recycling processes | 18 |
| 2.2.7. Upscaling of technology | 18 |
| 2.2.8. Sensitivity analysis | 22 |
| 2.2.8.1. Impact categories | 22 |
| 2.2.8.2. Energy carries for use phase | 22 |
| 2.2.8.3. End-of-life of MBCs partition | 22 |
| 3. Results | 23 |
| 3.1. Status quo and future impact of MBCs production | 23 |
| 3.1.1. Characterization results | 23 |
| 3.1.2. Contribution analysis | 24 |
| 3.1.3. Recyclability of MBCs, cradle-to-gate assessment | 25 |
| 3.2. Comparison across different product applications | 26 |
| 3.2.1. Characterization results | 26 |
| 3.2.2. Contribution analysis | 27 |
| 3.2.3. Contribution analysis of product applications, including use phase | 27 |

| | | |
|------------|--|----|
| 3.2.4. | Contribution analysis of product applications, excluding use phase | 27 |
| 3.2.5. | Recyclability of MBCs, cradle-to-grave, circular production | 28 |
| 3.3. | Sensitivity analysis | 29 |
| 3.3.1. | Impact assessment methodology choice | 29 |
| 3.3.2. | Energy carriers, manufacturing | 31 |
| 3.3.3. | Energy carrier, use phase | 32 |
| 3.3.4. | End-of-Life, Scalmalloy recyclability | 33 |
| 4. | Discussion | 35 |
| 4.1. | Key findings | 35 |
| 4.2. | From lab to industry | 35 |
| 4.3. | The pathway to aircraft applications | 36 |
| 4.4. | Further considerations | 37 |
| 4.5. | Limitations and further research | 38 |
| 5. | Conclusion | 41 |
| References | | 45 |
| Appendix | | 49 |
| A. | Conceptual framework for prospective lifecycle assessment | 51 |
| B. | Extended five steps approach for technology upscaling | 52 |
| | Step 1 – Current maturity definition | 52 |
| | Step 2 - Lab-scale data for current technology definition | 53 |
| | Step 3 – Selection of reference technology at industrial scale | 54 |
| | Step 4 – Analysis of potential changes | 55 |
| | Step 5 – Analysis of variability and uncertainty | 55 |
| C. | Unit process data | 56 |
| | C1. MBCs production lab scale | 56 |
| | C2. MBCs production upscaled | 62 |
| | C3. MBCs & Scalmalloy partition | 68 |
| | C4. Nomex core, conventional | 72 |
| | C5. Additional foreground processes for scenario running | 77 |
| D. | Extended results, baseline analysis | 80 |
| | D.1. Contribution analysis of laboratory vs. industrial production of 1 kg of MBCs | 80 |
| | D2. Extended contribution analysis of product applications, including use phase | 82 |
| | D3. Product applications, excluding use phase | 83 |
| E. | Extended results, recyclability | 84 |
| | E.1. MBCs production, material only, employing recycled MBCs material (outsourced) | 84 |
| | E.2. MBCs & Scalmalloy partition production, interior partition, employing recycled MBCs material, including use phase emissions (circular production) | 84 |
| | E.3. MBCs & Scalmalloy partition production, interior partition, employing recycled MBCs material, excluding use phase emissions (circular production) | 85 |
| | E.4. MBCs & Scalmalloy partition production, alternatives of EoL of Scalmalloy | 85 |
| F. | Sensitivity analysis, additional information | 86 |
| | F.1. Impact assessment methodology choice, MBCs, material only | 86 |
| | F.2. Impact assessment methodology choice, partition alternatives | 86 |
| | F.3. Energy carries, manufacturing, MBCs, material only | 86 |
| | F.4. Energy carries, manufacturing, partitions | 89 |
| | F.5. Energy carries, use phase, fuel | 90 |

List of Figures

| | |
|--|----|
| Figure 1. Concept Design for MBCs bionic partition. Modified based on: Chaudhury (2023) | 2 |
| Figure 2. Pathway to integrating new materials in aviation, inspired by: (Chaudhury, 2023; Smart Certification for Sustainable Aviation, n.d.) | 3 |
| Figure 3. LCA framework integrated with distribution of cost, knowledge and design freedom during the stages of technology development. Source: (Villares et al., 2017) | 4 |
| Figure 4. LCA methodology diagram built upon Sander-Titgemeyer et al. (2023) and Langkau et al. (2023) | 7 |
| Figure 5. Material model for (a) mycelium based, (b) conventional aircraft partition, inspired by: Chaudhury (2023) and Vidal et al. (2018) | 9 |
| Figure 6. Cradle-to-gate lab scale production for the production of 1 kg of MBCs, inspired on Volk (2024), and adjusted with reference to Alaux et al (2023) | 12 |
| Figure 7. Cradle-to-gate upscaled production for the production of 1 kg of MBCs, based on Alaux et al (2023) mushroom farm setting. Full details on the parameters considered are available on upscaling of technology section. | 13 |
| Figure 8. Cradle-to-grave mycelium based partition, based on Chaudhury (2023) design, and upscaled production of MBCs derived from Volk (2024), and Alaux et al (2023) | 14 |
| Figure 9. Cradle-to-grave conventional partition, honeycomb core, based on Vidal et al. (2018) production processes and Chaudhury (2023) dimensioning of design | 15 |
| Figure 10. Flowchart of five-step-scaling procedure and amount of methodologies performing each step. Adapted from: Erakca et al. (2024). TRL: Technology Readiness Level, MRL: Manufacturing Readiness Level, MPL: Market Penetration Level | 19 |
| Figure 11. Graphical representation for upscaling and pLCA of of Mycelium-Based Composites (MBCs) across different levels of technology development. Inspired by: Alaux et al. (2023); Thonemann et al. (2020) | 19 |
| Figure 12. Cradle-to-gate environmental impact evolution, comparison between lab scale and upscaled production of 1 kg of MBCs across the EF v3.1 impact categories. *Please note technology is not ready until 2035, therefore status quo comparison is neglectable for comparison purposes. ** Baseline scenario | 24 |
| Figure 13. Increased recycled input (cradle-to-gate) for the production of 1 kg of MBCs, baseline upscaled production for 2035, using EF v3.1 impact categories. | 25 |
| Figure 14. Cradle-to-grave impact breakdown of aircraft interior panels: MBCs & Scalmalloy vs. Nomex core (conventional alternative), excluding (left) and including (right) in-flight associated emissions during partition lifetime, baseline scenario 2035, using EF v3.1 impact categories. | 27 |
| Figure 15. Contribution analysis for MBCs & Scalmalloy aircraft partition, excluding use phase, for impact categories: (a) ecotoxicity, (b) acidification, (c) climate change. Baseline scenario 2035, using EF v3.1 | 28 |
| Figure 16. Comparative assessment of recyclability potential and environmental impacts of MBCs and Nomex core partitions across different recyclability scenarios, using EF v3.1 impact categories | 29 |
| Figure 17. Sensitivity analysis employing different characterization models: EF 3.1 and ReCiPe for the comparison on the production of 1 kg of MBCs in laboratory and industrial scale. Only comparable impact categories were selected and scaled to the laboratory production baseline | 30 |
| Figure 18. Sensitivity analysis employing different impact assessment models: EF 3.1 and ReCiPe for the comparison between interior aircraft partitions. Only comparable impact categories were selected and scaled to the highest impact. Baseline 2035. | 30 |
| Figure 19. Sensitivity analysis during manufacturing, baseline 2035, using different energy carriers for: (a) of 1 kg of MBCs, (b) MBCs & Scalmalloy interior partition, (c) Nomex core partition, using EF v3.1 impact categories. | 31 |
| Figure 20. Sensitivity analysis based on using energy carriers: (a) kerosene, (b) biokerosene, (hydrogen) during the use phase on aircraft per partition over a period of six year, average lifespan of partition before replacement. | 32 |
| Figure 21. Sensitivity analysis for the EoL of Scalmalloy component over an MBCs & Scalmalloy partition: influence of incineration vs. recycling. Baseline 2035, using EF v3.1 impact categories | 33 |

List of Tables

| | |
|--|----|
| Table 1. Overview of LCA studies for mycelium based materials..... | 5 |
| Table 2. Sources for data of laboratory production for MBCs production..... | 16 |
| Table 3. Dimensions and material properties of partition design, derived from Chaudhury (2023) | 17 |
| Table 4. Dimensions and material properties of partition design, adjusted from Chaudhury (2023) and Vidal et al. (2018) | 17 |
| Table 5. Key points from online session with Airbus experts..... | 20 |
| Table 6. Key aspects for systematic upscaling approach. Adapted from: van der Hulst et al. (2020) . | 20 |
| Table 7. Considerations for upscaling MBCs technology for its use in non-structural aircraft partitions | 21 |
| Table 8. Energy carriers selected for assessment..... | 18 |
| Table 9. Comparison between upscaled and lab production of 1 kg MBCs, characterization results for the baseline scenario, cradle to gate, using the EF v3.1 impact categories..... | 23 |
| Table 10. Characterization results for the comparison between interior partitions alternatives, baseline scenario 2035, using EF v3.1 impact categories. | 26 |

List of unit process data

| | |
|--|----|
| Model 1. Agar petri dish preparation | 56 |
| Model 2. Agar, seaweed | 56 |
| Model 3. Broth preparation, mycelium | 57 |
| Model 4. Composite incubation and growing | 57 |
| Model 5. Drying of composite..... | 58 |
| Model 6. Malt extract | 58 |
| Model 7. Medium incubation on bioreactor | 59 |
| Model 8. Moisture of substrate..... | 59 |
| Model 9. Mycelium composite molding, single use PP mold | 60 |
| Model 10. Mycelium liquid preparation, for incubation | 60 |
| Model 11. Mycelium seed extraction..... | 61 |
| Model 12. Sterilization of substrate | 61 |
| Model 13. Substrate milling | 62 |
| Model 14. Upscaled composite incubation and growing | 62 |
| Model 15. Dextrose extract, broth | 63 |
| Model 16. Upscaled drying of composite | 63 |
| Model 17. MBCs recycling, outsourced, applicable in upscaled production | 64 |
| Model 18. Upscaled Medium incubation on bioreactor | 64 |
| Model 19. Upscaled Medium preparation for incubation..... | 65 |
| Model 20. Upscaled Moisture of substrate..... | 65 |
| Model 21. Upscaled Mycelium composite molding, customized mold | 66 |
| Model 22. Upscaled Mycelium seed extraction | 66 |
| Model 23. Upscaled Sterilization of substrate | 67 |
| Model 24. Upscaled Substrate milling | 67 |
| Model 25. Cutting of composite, laser cutting..... | 68 |
| Model 26. MBCs recycling for internal reuse, circular production | 68 |
| Model 27. One-step manufacture, MBC partition..... | 69 |
| Model 28. Provision of non-structural support, mycelium based mixed Scalmalloy partition | 69 |
| Model 29. Scalmalloy production..... | 70 |
| Model 30. Use on aircraft lifespan, partition, mycelium based mixed Scalmalloy..... | 70 |
| Model 31. Use of partition, over its lifespan (6 years), interior panel, MBCs and Scalmalloy (exc. in-flight emissions)..... | 71 |
| Model 32. Use of partition, cut for mycelium based components, (exc. in-flight emissions) | 71 |
| Model 33. Use of partition, cut for Scalmalloy (exc. in-flight emissions)..... | 72 |
| Model 34. Application of decorative film in sandwich panel | 72 |
| Model 35. Aramid paper/phenolic honeycomb, expanded phenolic-coated aramid paper honeycomb..... | 73 |
| Model 36. Manufacture of fireproof fiber fabric..... | 73 |
| Model 37. One-step manufacture of sandwich panel | 74 |
| Model 38. Production of reinforced polymer prepreg | 74 |
| Model 39. Provision of non-structural support, conventional sandwich partition..... | 75 |
| Model 40. Thermoset, phenolic glass fiber | 75 |
| Model 41. Use of partition over lifespan, interior panel, Nomex core (excl. in-flight emissions)..... | 76 |
| Model 42. Use on aircraft, partition, conventional sandwich partition (for 6 years) | 76 |
| Model 43. Energy carrier, use phase | 77 |
| Model 44. Mass-induced energy demand, transport of nonstructural mass | 77 |
| Model 45. Use of biokerosene | 78 |
| Model 46. Use of fossil kerosene | 78 |

| | |
|---|----|
| Model 47. Use of hydrogen fuel cell..... | 78 |
| Model 48. Energy carrier, manufacturing | 79 |

Nomenclature

| Abbreviation | Definition |
|---------------------|--|
| EoL | End of Life |
| GHG | Greenhouse gas |
| IAM | Integrated assessment model |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MBCs | Mycelium based composites |
| MPL | Market Penetration Level |
| MRL | Manufacturing Readiness Level |
| NDC | Nationally Determined Contributions |
| pLCA | Prospective Life Cycle Assessment |
| premise | PRospective EnvironMental Impact asSEment |
| REMIND | REgional Model of Investment and Development |
| TRL | Technology Readiness Level |

1

Introduction

In this chapter, the case study is introduced, addressing current uncertainties and new frontiers surrounding bio-based materials replacing traditional components in aircraft for a more sustainable aerospace industry. Then, an overview of the thesis outline is provided.

1.1. Problem definition

Currently, aviation is responsible for 13.4% of the transport sector emissions, representing 3.6 % of all human greenhouse gas (GHG) emissions (EASA & EEA, 2019; Rahn et al., 2022). While the demand for airline travel keeps growing, shifting to a more sustainable bio-based industry is important considering the vast fuel demand and the consequent emissions (Barke et al., 2020). Meeting the growing demand for airline travel requires a shift towards more eco-friendly alternatives, particularly in addressing the vast fuel demand and consequent emissions, as well as the waste generated by industry mostly treated through landfill and incineration. In such process, weight reduction in aviation has a significant impact on fuel efficiency, operational costs, and environmental impact (Sacchi et al., 2023; Tsai et al., 2014). The aviation sector therefore is increasingly prioritizing the search for lighter materials as a strategic approach to minimize aircraft weight (Airbus, 2021a). Therefore innovations result essential as part of multi-pronged approaches to decarbonization which combine technological advancements, operational improvements, and more sustainable material sources (Airbus, 2023).

Bio-sourced materials, such as mycelium-based composites (MBCs), have demonstrated a significant potential to replace the conventional petroleum-based materials used for the manufacture of aircraft interiors (Barke et al., 2020; Cerimi et al., 2019; Ramon et al., 2018). These bio sourced composites are created by the mycelium, a collective network of vegetative microfilaments called hyphae, which are capable of transforming waste products into substrates for their growth (Yang et al., 2021). Interest in their research and commercialization has been generated because of their zero waste nature, low energy consumption, and broad range of applications including packaging, furniture, fashion and building materials (Alemu et al., 2022; Bitting et al., 2022; Bonenberg et al., 2023; Yang et al., 2021). The applicability of MBCs in the aviation sector has been encouraged considering the material thermal and acoustical properties, suitable for non-structural purposes (Bitting et al., 2022).

The focus of this thesis project is on the adoption of MBCs for non-structural purposes in aircraft cabin interiors. In fact, interior components are a potential section for environmental impact reduction as they represent 10% of the weight of an empty aircraft (Chaudhury, 2023). Currently, the composites used in aircraft interiors, though regulated by the REACH directive due to potential toxicity concerns, require high energy for production and present significant challenges for reuse or recycling, often leading to incineration at end-of-life (Zhang et al., 2020). This focus on non-structural components using MBCs is particularly relevant due to their more frequent replacement. Unlike the structural parts of the airframe of a commercial aircraft which spend 30-plus years in operational service (Airbus, 2021b), interior components are typically replaced five times over that period (Chaudhury, 2023). This shorter replacement cycle presents an opportunity to explore the adoption of new technologies like MBCs. By

targeting frequently replaced cabin elements, we can introduce and evaluate MBCs within a shorter timeframe, paving the way for their wider acceptance in the aviation industry.

The aviation sector, being a critical focus area for sustainable practices, necessitates a thorough analysis of environmental implications of MBCs. Being an emerging technology, mycelium-based composites (MBCs) are still under development (Travaglini et al., 2019). Therefore, extensive Research, Development, and Innovation (RDI) efforts are underway to refine their properties for practical use. While MBCs hold immense technology potential, for MBCs to contribute meaningfully to sustainable aviation, a comprehensive analysis and assessment of the potential environmental impact throughout their lifecycle is required to make informed decisions about their feasibility for further adoption. This poses a substantial challenge in conducting conventional Life Cycle Assessments (LCA), as LCA is predominantly applied to existing products and services that have sufficient data on the different processes and supplies, which is gathered after significant technological development. Whereas in the early stages of development, knowledge about the product is still uncertain, as data is still being gathered and improvements are yet uncertain (Cooper et al., 2009). Therefore, conducting a Prospective Life Cycle Assessment (pLCA) appears as a valuable approach. This assessment would involve the construction of potential scenarios (Alaux et al., 2023; Langkau et al., 2023) simulating the environmental impact of MBCs at a larger production scale, building upon current lab-based production methods, specifically applied in aircraft interior panels as a sustainable alternative to traditional petroleum-based materials.

1.2. Case study component

This thesis project is based on a case provided by the Airbus, under the Interdisciplinary Thesis Lab 2023-2024: Circulaerospace. The study case proposes analyzing how bio-sourced materials can replace traditional petroleum-based products in aerospace applications. A significant challenge to their widespread adoption in the aerospace sector lies in the limited data and knowledge regarding the processing of these low-maturity bio-sourced materials. In this way, commissioned by Airbus Central Research & Development (Materials Domain), this project aims to address these challenges within the framework of Case Study #3: Aerospace Meets Biotech. Specifically, the challenge proposes to investigate how to best assess the environmental performance of these low-maturity-level materials using life cycle assessment (LCA) (LDE CfS Industries-Hub, 2023).

As a precedent, this study follows the groundwork laid by Chaudhury (2023) "Designing Circular Applications of Mycelium-Based Materials for Aircraft Cabins" which identified promising applications for these bio-materials in secondary structures and aircraft interiors. One of them is a novel concept for a passenger cabin partitions (see Figure 1).

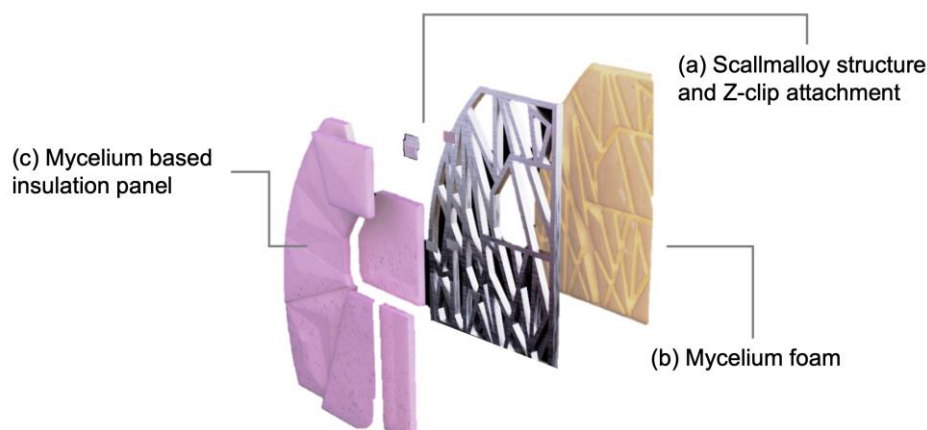


Figure 1. Concept Design for MBCs bionic partition. Modified based on: Chaudhury (2023)

It must be noted that this design has not yet been fully developed, and it remains as concept on which this thesis will be constructed around. An including an initial comparative life cycle assessment with common petroleum-based alternatives. As a next step, this thesis aims to explore methods for scaling up the current lab-scale production and conduct a more in-depth life cycle assessment specifically focusing on the manufacturing of MBCs for aircraft interior panels., and applying it to its application as partition panels. Further details of the dimensions and materials of alternatives are shown on section 2.1.4.

1.3. Literature review

1.3.1. The journey of a new material: from lab to aircraft

The modern aviation industry's rapid growth has driven the development of next-generation aircraft materials. Advancements in material development and manufacturing techniques are driving the use of innovative materials like composites in aircraft, leading to continued progress (Parveez et al., 2022). While new materials offer exciting possibilities for lighter airplanes, cost reduction, and the extension of the service life of the components in the aircraft structures, getting them certified for use takes a long time, extending it up to decades. The traditional testing process for new aviation materials is yet considered a bottleneck. While it ensures safety through extensive testing, the sheer number of tests (especially for new designs and materials) hinders innovation in the industry (Pascoe, 2024; *Smart Certification for Sustainable Aviation*, n.d.). The following image presents the main stages of bringing a new material into use for aerospace applications.

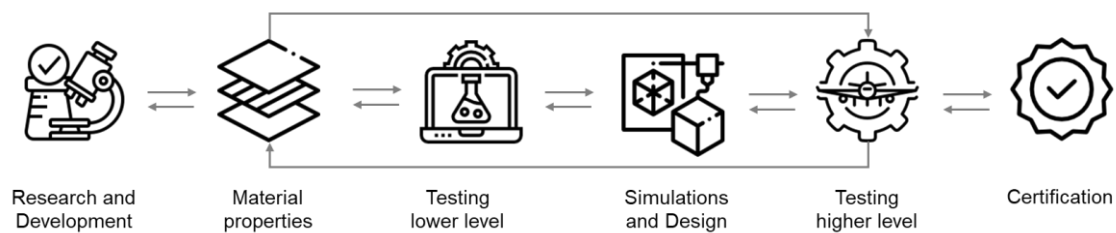


Figure 2. Pathway to integrating new materials in aviation, inspired by: (Chaudhury, 2023; *Smart Certification for Sustainable Aviation*, n.d.)

The lengthy approval process for new materials in aerospace presents a double-edged sword. On the one hand, the extensive testing generates a wealth of data, allowing for incremental improvements on existing technologies. This data-driven approach fosters innovation within established material families. However, the same process can restrain disruptive technologies. Since the path to certification is long and extensive with uncertainty, both technically and commercially, companies are often hesitant to invest in new materials. This can hinder the industry's ability to make significant leaps forward. So, in the pursuit of a more sustainable aviation industry, evaluating the environmental impact of new materials becomes especially crucial. During this process, Life Cycle Assessments (LCA) can be integrated and performed at the design stages when exploring new materials such as mycelium-based materials (MBCs) for aircraft cabin applications. This analysis, conducted early in the development process, aims to assess the environmental performance of the material and determine its potential advantages and drawbacks.

1.3.2. Life Cycle Assessment for early-stage technologies

Similar to the development of aircraft materials, which undergo lengthy certification processes to ensure they meet specific safety and performance criteria (including material properties, fatigue resistance, flammability, etc.), Life Cycle Assessment (LCA) also benefits from continuous development. As the methodology and data collection techniques for LCA improve, the resulting assessments become more reliable. However, early choices in a technology's development significantly influence its environmental

impact (Villares et al., 2017), and that is why incorporating LCA for new materials can significantly guide research, development, and innovation (RDI) efforts identifying potential environmental impacts early on (Pacana et al., 2023; van der Giesen et al., 2020). When used early in development, the outcome do not only anticipate and avoid significant environmental burdens, but given the freedom to make significant changes is higher, this allows fostering innovation to try more disruptive changes, discard and opt for new paths, and save costs before it becomes more difficult to make adjustments while technologies have reached established high levels of development (Cooper et al., 2009; van der Giesen et al., 2020). Figure 4 illustrates a typical technology development pathway, emphasizing the role of life cycle assessments (LCA) throughout the process (Villares et al., 2017).

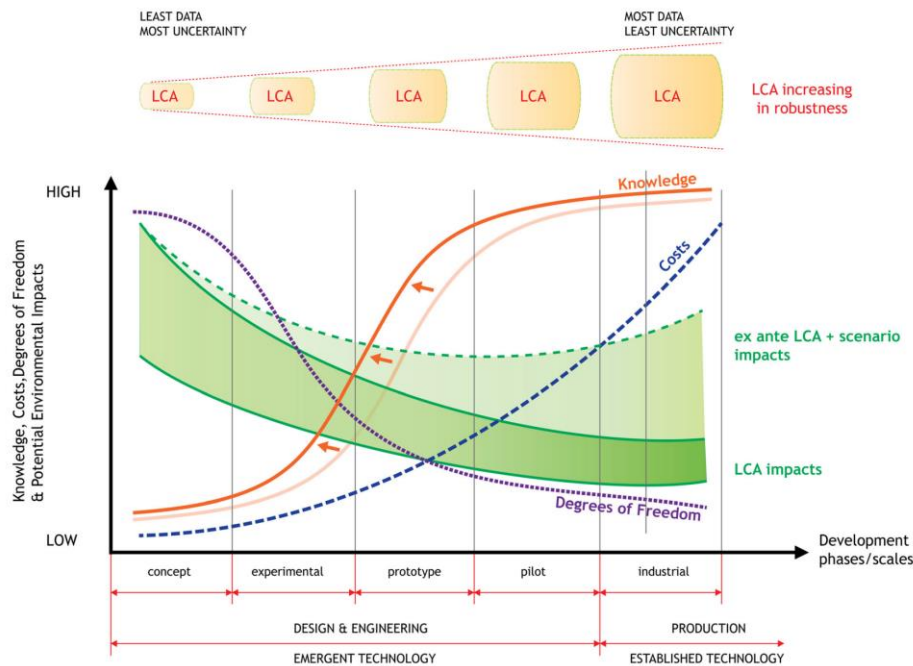


Figure 3. LCA framework integrated with distribution of cost, knowledge and design freedom during the stages of technology development. Source: (Villares et al., 2017)

Most life cycle assessments evaluate products on the basis of a well-defined technology for which historical data has been gathered. In contrast, a prospective LCA (pLCA) evaluates a technology at a low technology readiness level (TRL) and looks into potential future developments (Alaux et al., 2023). Hence, effective methods are needed to assess a technology's potential environmental impact during these initial stages (van der Giesen et al., 2020). Thus, in a pLCA the studied technology is in an early phase of development (e.g., small-scale production), but the technology is modeled at a future, more-developed phase (e.g., large-scale production) (Arvidsson et al., 2023; Florin et al., 2023). Therefore, this methodology is suitable for assessing MBCs as it is possible to fill data gaps by providing a systematic assessment of environmental impact in the absence of complete information (Ayala, 2023; Cucurachi et al., 2022).

1.3.3. A review of Life Cycle Assessment studies of MBCs

Research on the environmental impact of MBCs, through life cycle assessment (LCA), is limited and has so far been focused to laboratory settings (Alaux et al., 2023; Chaudhury, 2023; Robertson et al., 2020; Stelzer et al., 2021; Volk et al., 2024; Williams et al., 2022). The wide range of potential applications, diverse material origins and production processes, inherent to a still in development technology (Bitting et al., 2022), all contribute to the variability in LCA results across existing studies, see Table 2. A consistent topic around them is the need to scale up MBC production for a more accurate environmental impact assessment (Chaudhury, 2023; Robertson et al., 2020; Stelzer et al., 2021; Volk et al., 2024; Williams et al., 2022).

Table 1. Overview of LCA studies for mycelium based materials

| Application | Scope | TRL* | Functional unit | Sources |
|----------------------------|------------------|---|--|------------------------|
| Aviation (interior panels) | Cradle-to-cradle | Conceptual, lab-scale | 1 bionic partition (41.6 kg) | Chaudhury (2023) |
| Construction (panels) | Cradle to-grave | Lab-scale, and upscaled to industrial mushroom farms production | 1 block of insulation material (10 × 10 × 10-cm); 1 m ² thermal resistance, value of 1 m ² K/W | Alaux et al. (2023) |
| Construction (panels) | Cradle-to-gate | Lab-scale | 1 kg of MBCs (hemp/ sawdust substrate) | Volk et al. (2024) |
| Construction (brick) | Cradle-to-gate | Lab scale | Normalformat, (24×11.5×7.1 cm) | Stelzer et al. (2021) |
| Leather | Cradle-to-gate | Large scale production** | 1 m ² of mycelium based leather | Williams et al. (2022) |

* TRL= Technology Readiness Level, **Product does not correspond to composites application, but it has a high TRL

Most studies on mycelium-based composites (MBCs) have so far centered on their application in construction, particularly walls. In fact, when compared to traditional products like rockwool and extruded polystyrene, MBCs have substantially less of an environmental impact (Volk et al., 2024). This provides a good foundation for further development of this research focused on using MBCs for interior panels in aircraft. To the best of knowledge, only one study has investigated upscaling this technology, as of this writing. The study by Alaux et al. (2023) scaled MBCs for industrial building applications considering a industrial mushroom farms setting and developing scenarios for different energy and transport mixes. Furthermore, no life cycle assessment (LCA) studies have been found specifically for the use of MBCs in aviation, aside from the one this study is building upon (Chaudhury, 2023). The comparative fast tracking LCA of MBCs (lab scale) and conventional aircraft partitions revealed lower environmental impacts derived from fuel savings given a 40% weight reduction of the cabin interior (Chaudhury, 2023). These initial studies set valuable insights for assessing MBCs in aviation applications at advanced TRLs.

One crucial step before scaling up production for the aerospace sector is establishing and validating a robust lab-scale process. While MBCs may appear suitable based on initial lab results, uncertainties in data and limitations in production cycles can significantly impact their environmental footprint and economic viability when scaled (Thonemann et al., 2020). Likewise, a challenge for this study is identifying the differences between laboratory systems and industrial processes to establish data validity. MBCs as in any other low TRL technology, numerous design elements remain unresolved, and they have not undergone testing in real operating environment (Blanco et al., 2020). Scaling up MBC production can introduce unforeseen challenges. This includes the generation of additional waste products like heat and wastewater, which may not be apparent at the lab scale. Additionally, specialized lab equipment might not translate well to industrial processes, potentially leading to underestimates of the true environmental impact (Thonemann et al., 2020).

1.3.4. Areas needing further study

This review of existing literature several key points to be further explored. Some relevant highlights for this study include:

Promising potential: While primarily studied in construction, MBCs show promise for sustainable applications in aircraft interiors, potentially offering significant environmental benefits compared to traditional materials.

Limited upscaling research: There is a scarcity of research on large-scale MBC production, particularly for aviation applications. This includes challenges like optimizing energy consumption and ensuring data validity when scaling from lab to industrial settings.

Data uncertainty: Relying solely on lab-generated data may not be sufficient for a robust LCA. Integrating expert and stakeholder knowledge can strengthen the accuracy of the assessment.

1.4. Research question

Building upon the problem statement presented and the findings from the literature review, this study aims to assess the environmental impact of using mycelium-based composites (MBCs) as an alternative to polymer-based materials for aircraft interior panels. This research question (RQ) is formulated as follows:

RQ: What are the future environmental impacts of producing mycelium based composites (MBCs) in industrial production levels for aircraft interior applications and how do they compare to alternative materials?

To address the main research question, several key sub-research questions (SRQs) are formulated.

1. How does the production processes of MBCs differ between laboratory scale and industrial scale?
2. What are the future environmental impacts of MBCs on an industrial production level?
3. When used for non-structural aircraft cabin interior applications how do these MBCs materials compare to other of competing materials?
4. Considering the environmental impacts of an MBCs aircraft partition, how can these be reduced in their future industrial production?

2

Methods

A prospective LCA (pLCA) is built upon the LCA principles, requirements and framework, which were applied according to the guidelines provided by the International Organization for Standardization (ISO, 2006a, 2006b), and used in this study to calculate the environmental impacts of aircraft interior panels throughout different stages of their life cycle. The Handbook of Life Cycle Assessment (Guinée et al., 2002) was followed as guideline through this study. The interrelated, iterative steps of an LCA research are goal and scope definition, lifecycle inventory analysis (LCI), lifecycle impact assessment (LCIA), and interpretation (Guinée et al., 2002).

LCA is an iterative process, as illustrated in the figure below. Therefore the interpretation of the outcome of each phase can lead to adjustments to previous phases. However, to ensure clear communication, this thesis will only present the finalized versions of the goal and scope definition, life cycle inventory (LCI), and life cycle impact assessment (LCIA) phases in their respective sections. A detailed description of the framework employed to refine various LCA steps and decisions improvements and iterations is provided in Annex A.

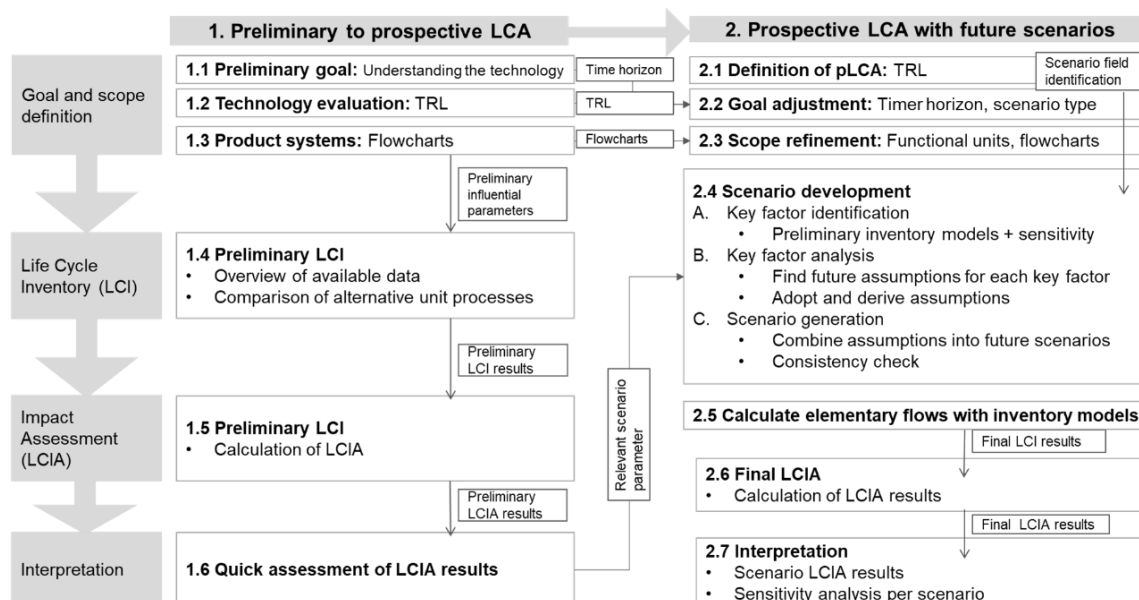


Figure 4. LCA methodology diagram built upon Sander-Titgemeyer et al. (2023) and Langkau et al. (2023)

2.1. Goal and scope definition

2.1.1. Goal

The goal for this Life Cycle Assessment (LCA) aims to estimate the environmental impact of using mycelium-based composites (MBCs) in future aircraft interior panels, as stated in the research question section. By identifying the stages with the highest environmental impact, we can target areas for

improvement. Additionally, this LCA will compare the environmental performance of MBCs panels to conventional options used in the market. The results are intended to provide a reference point for informed decisions regarding sustainable interior materials for aircraft. Since MBCs are an emerging technology, the LCA outcomes can help forecast and understand their environmental impact despite limited data. This understanding can then be used to assess their desirability for use in aircraft.

This study is conducted as part of the Master's thesis for the degree in Industrial Ecology (CIRCLE Program) at Leiden University and TU Delft. The case of study was commissioned by Airbus through the Leiden-Delft-Erasmus Centre for Sustainability. To ensure the robustness of the framework and assumptions used in this study, valuable insights were provided by experts from Airbus. The thesis supervisors, Dr. Bernhard Steubing and Dr. Kunal Masania, as well as the designer of the mycelium based partition panel, Mrinal Chaudhury, provided guidance throughout this study.

2.1.2. Scope

The present study aims to calculate the environmental impacts of the future adoption of mycelium based composites (MBCs) for aircraft interior applications. The study was conducted in a five months period. The approach chosen includes two different assessments at material (intratechnology) and product level (intertechnology).

The first correspond to the comparison between the current laboratory and upscaled industrial level production of MBCs. This assessment follows a cradle-to-gate assessment to identify stages for in-house improvement. The second, at product level, is cradle-to-grave. A comparative LCA is carried out to assess the environmental burden of the conceptual design of a mycelium based aircraft interior partition, considering the upscaled MBCs production, against a current conventional option made out of Nomex honeycomb core material. This approach considers the use phase, which accounts for the fuel consumption associated with the panels throughout their lifespan in the aircraft. The following stages are included: extraction and processing of materials, transportation, manufacturing and end of life

Regarding the geographical scope, it reflects European manufacturing, assuming best available technology, with most materials sourced from the region. As limited primary data was available, inputs unless specified for Europe dataset are considered from global markets. This is given supply chains can source materials from different regions of the globe. The usage and disposal phases are also modeled using European data.

For the temporal scope, it was ensured to access to the most recent data and that process make reference to the most recent technology. Therefore, as foreground processes are referencing to studies carried out in the last 2 years. In addition, since studies suggest MBCs require 10 more years of development to achieve the highest TRL (Alaux et al., 2023), upscaling is projected for 2035. In addition, the aviation industry's goal to reach zero-emissions by 2050 is considered a second potential timeline, by this year widespread adoption of MBCs is assumed to be expected.

This analysis follows the midpoint environmental impact categories recommended by the European Commission. These categories are based on the Environmental Footprint (EF v3.1) characterization model (European Commission, 2017). This choice ensures consistency with both European standards and Airbus' internal practices, allowing future comparisons and promoting better communication of the results.

While this LCA relies mostly on secondary data for most aspects of the product system models, the overall approach provides valuable academic insights into the environmental impact of mycelium-based composites (MBCs) for aircraft interior panels. It is important to acknowledge that due to the reliance on secondary data and the low TRL of the mycelium based aircraft design, the results cannot be used for public comparative assertions or environmental claims. However, this study can still serve as a

reference point for future research and development efforts aiming to optimize the environmental performance of MBCs for the aviation industry.

2.1.3. Functional unit and reference flows

As mentioned, this study includes two different assessments at material (intratechnology) and product level (intertechnology). For the former, since MBCs represent the same product at both lab and industrial scale, comparing them by mass provides a standardized basis. So a functional unit of mass is chosen as this approach ensures a direct comparison. Utilizing mass (1 kg) as functional unit aligns with recommended practices in other studies in order to facilitate data comparison and avoids introducing unnecessary complexities due to factors like volume or surface area, which can fluctuate based on specific materials inputs and properties (Volk et al., 2024).

On the other hand, when assessing MBCs under specific applications, a more detailed functional unit is required. In this case, it is considered (a) mycelium based partition, and (b) conventional Nomex core alternative. Figure 4 depicts both material models.

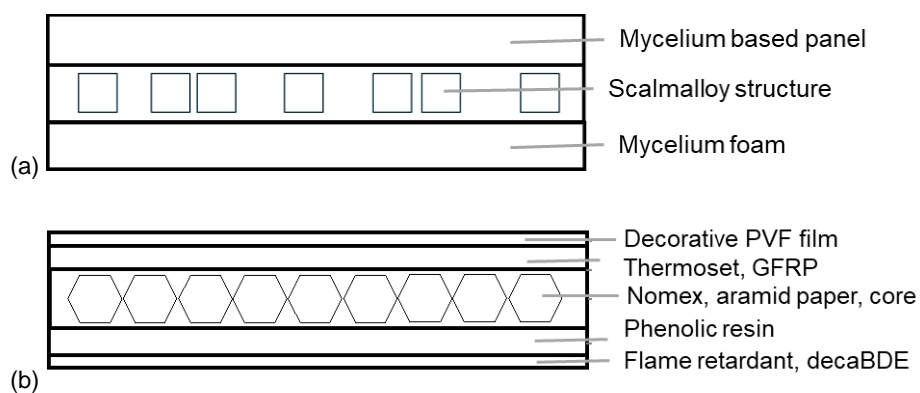


Figure 5. Material model for (a) mycelium based, (b) conventional aircraft partition, inspired by: Chaudhury (2023) and Vidal et al. (2018)

In this case, the functional unit is established by focusing on their specific role within the airplane. The partitions have the function of providing support for non-structural components of an aircraft interior, while dividing the aircraft interior into distinct zones. And, while a full aircraft might function for 20-30 years, conventional aircraft partitions are replaced more frequently, typically 4-5 times during that period (Chaudhury, 2023). The MBCs partition lifespan is not yet defined, therefore it is assumed the same for both alternatives. Therefore, the functional unit (FU) for the assessment at product level is the use of one aircraft interior partition providing six years of non-structural support. An additional assessment per partition, excluding the use phase was conducted in parallel.

2.1.4. Description of product alternatives

2.1.4.1. Mycelium based composite material

The research adopted the inventory outlined by Volk et al. (2024) to model a mycelium composite panel, specifically using the *Ganoderma lucidum* fungi species. The substrate used is sawdust, considering the results to produce insulation biocomposited (Alaux et al., 2023; Miralbes et al., 2021; Schritt et al., 2021; Volk et al., 2024). Detailed assumptions under the product are provided in the data collection section.

2.1.4.2. Mycelium based partition

It is composed of a skeletal framework, designed by Bastian Schaefer of Airbus and Autodesk, built on Scalmetalloy, a bionic aluminum alloy (Al-Mg-Sc) (Awd et al., 2018), biocomposite filler material which is cultivated from mycelium within the mold created by the bionic skeleton, and surface coverage and acoustic insulation using customizable textured mycelium based panels. The design reduces the

number of materials to two (Chaudhury, 2023) and is meant to eliminate non-recyclable and petroleum-based materials entirely, relying mostly on bio-based composites derived from mycelium.

The partition utilizes a tile-based assembly approach, enabling easy installation and disassembly. This facilitates repairs by allowing for the replacement of individual tiles in case of localized damage, minimizing overall waste. Additionally, the bionic skeleton offers attachment points for crew amenities like seating, monitors, and utilities, ensuring functional parity with conventional partitions (Chaudhury, 2023). Material properties, weights and dimensions are available in the data section 2.2.5.

2.1.4.3. Conventional sandwich partition

The second alternative has a sandwich structure and it is composed of a core, outer skins, and a decorative film (Vidal et al., 2018). The core, made from aramid fiber paper (Nomex®) in a honeycomb structure, is lightweight and strong. A resin, typically phenolic resin, binds fiberglass within the outer skins to form a reinforced composite for added strength. The decorative film, likely made of polyvinyl fluoride (PVF), provides a finished surface layer. Finally, a flame retardant, decabromodiphenyl ether (decaBDE), is used for safety reasons, although more sustainable alternatives may exist in the market. Further details on section 2.2.5.

2.2. Life Cycle Inventories

2.2.1. Economy-environment system boundary

A cradle-to-gate LCA approach is used for the material assessment, focusing on the environmental impacts associated with the production of MBCs. This analysis aims to identify potential areas for environmental improvement within the current manufacturing process and explore options for future optimization. The system boundary encompasses all stages involved in preparing the materials for cultivation (including the environmental impacts associated with material acquisition and pre-processing), growing the mycelium, and processing the final composite material. Energy use within the laboratory settings was accounted for each process. Finally, end-of-life (EoL) considerations, include the disposal of the material generated within the in-house production of MBCs. The use phase is not assessed in this material approach, but their disposal is analyzed through incineration with energy recovery and recycling as substrate for MBCs cultivation.

The cradle-to-grave LCA takes a more high-level approach to the assembly process for both the MBCs and conventional options, compared to the in-depth detail provided for MBC material production. While not a step-by-step breakdown, the assembly analysis remains representative of the actual process. Existing databases offer established data on the environmental footprint of acquiring and processing materials used in both options, eliminating the need for a deep dive into those aspects.

For the MBC option, the LCA considers the MBC production previously mentioned, including and incorporating the Scalmalloy skeleton. The environmental impact of Scalmalloy is modeled based on its material composition and average production energy consumption. Finally, the assembly process for the MBC component is analyzed at a broader level due to the design's simplicity and lack of current customization needs. Similarly, the conventional option focuses on the overall energy requirements and main joining methods used for their different core, outer layer and decorative film components. Similarly, the assembly process for the conventional component is examined at a high level to ensure a fair comparison between the two approaches. Additionally the included use phase accounts for the fuel consumption associated with the panels throughout their lifespan in the aircraft.

2.2.2. Multifunctionality

Multifunctionality is a critical aspect to address in Life Cycle Inventory (LCI), especially for processes involving coproduction and waste treatment (e.g., closed-loop systems). This is because these processes generate multiple products or handle waste alongside the main product.

However, in this study, the chosen background process data from the Ecoinvent system model, specifically the "allocation, cut-off by classification", already incorporates most multifunctionality aspects within its models. Therefore, additional allocation within this study might not be necessary. Regarding foreground processes, the production modeled here is linear, with each process resulting in a single product (monoproduction). Only one of the scenario assessments, during the cradle-to-grave production of MBCs partitions, incorporates recycling. In this specific case, allocation based on mass was employed to divide the multifunctional process into monofunctional ones (Guinée et al., 2002). This approach was chosen due to the lack of readily available and specific monetary values for MBCs in the literature. Monetary allocation, though common, is less suitable here.

2.2.3. Cut-offs

Several aspects are excluded from the assessment due to data limitations and to ensure comparability among the different system products.

Industrial facilities: The assessment did not include industrial facilities such as buildings, and machinery. While these elements could significantly impact certain life cycle stages and impact categories, due to a lack of specific data, their contributions were not accounted for in this study.

Personalization and Maintenance: Activities related to the obtention of desired shapes of the elements evaluates, as well as assembly, disassembly, and servicing components were excluded due to a lack of available inventory data.

Transport: Due to the generalized location of manufacturing sites (assuming European manufacturing), representing transport accurately posed challenges. Although estimates were made for the transport of primary materials based on the market background processes, transport for assembly and to end-of-life treatment was excluded (process-specific burdens options were preferred). In similar fashion, several of these aspects were excluded from the assessment of the structural components of an aircraft, developed by Arblaster (2023).

Use: The use phase was only accounted for the product assessment. It excludes associated airport infrastructure construction, as well as activities that may fluctuate the lifespan of the product such as maintenance, repair, replacement, and refurbishment of the partitions themselves. This exclusion is due to a lack of existing research and data limitations in these areas. Use phase non-structural component on of aircraft was based on the work of Arblaster (2023).

2.2.4. Flow charts

The flowcharts are presented in Figures 6-9. Please note not all economic flows are displayed. For a detailed disclose see the unit process data, available in Appendix D.

Figure 6. Cradle-to-gate lab scale production for the production of 1 kg of MBCs, inspired on Volk (2024), and adjusted with reference to Alaux et al (2023)

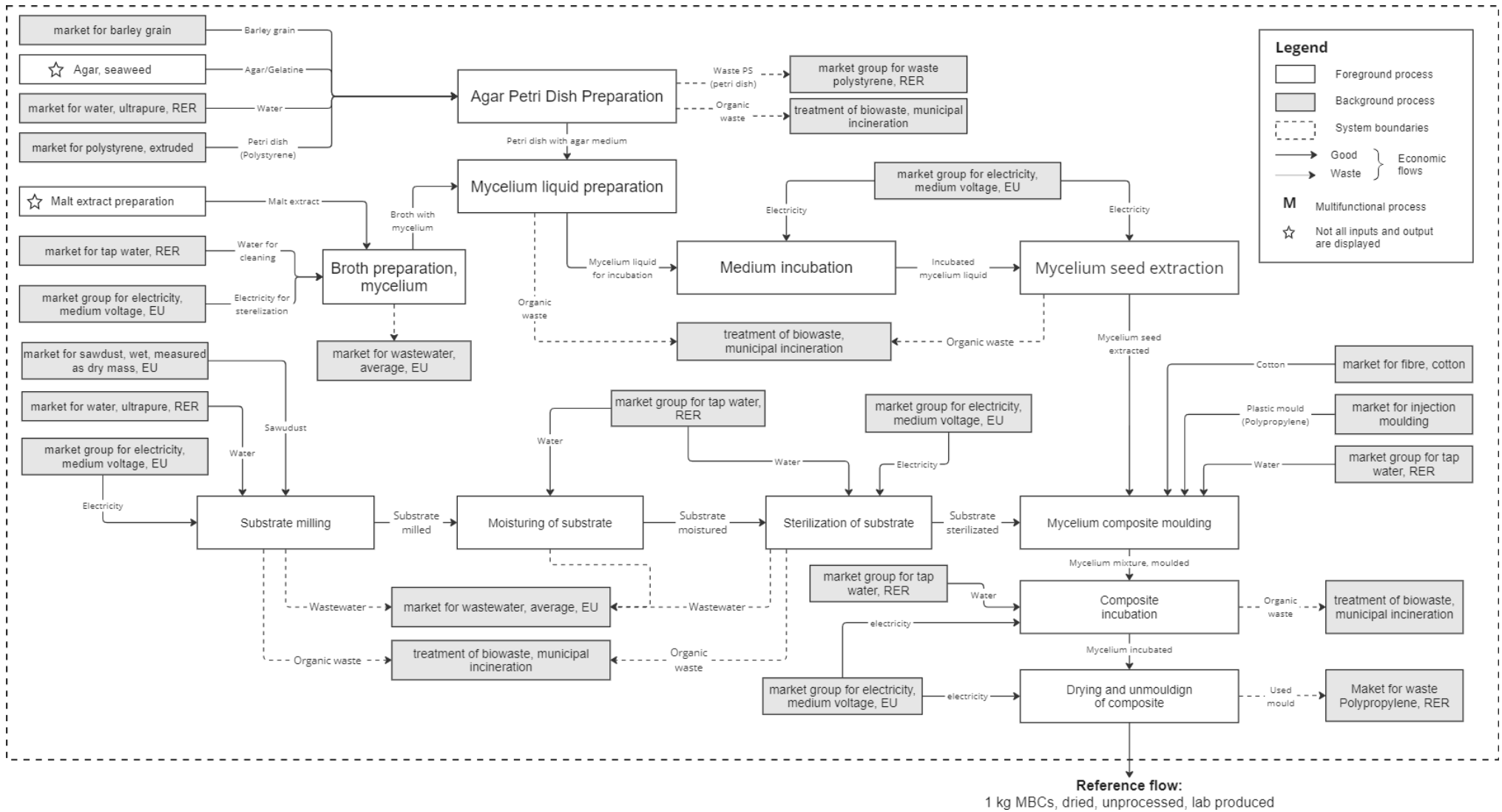


Figure 7. Cradle-to-gate upscaled production for the production of 1 kg of MBCs, based on Alaux et al (2023) mushroom farm setting. Full details on the parameters considered are available on upscaling of technology section.

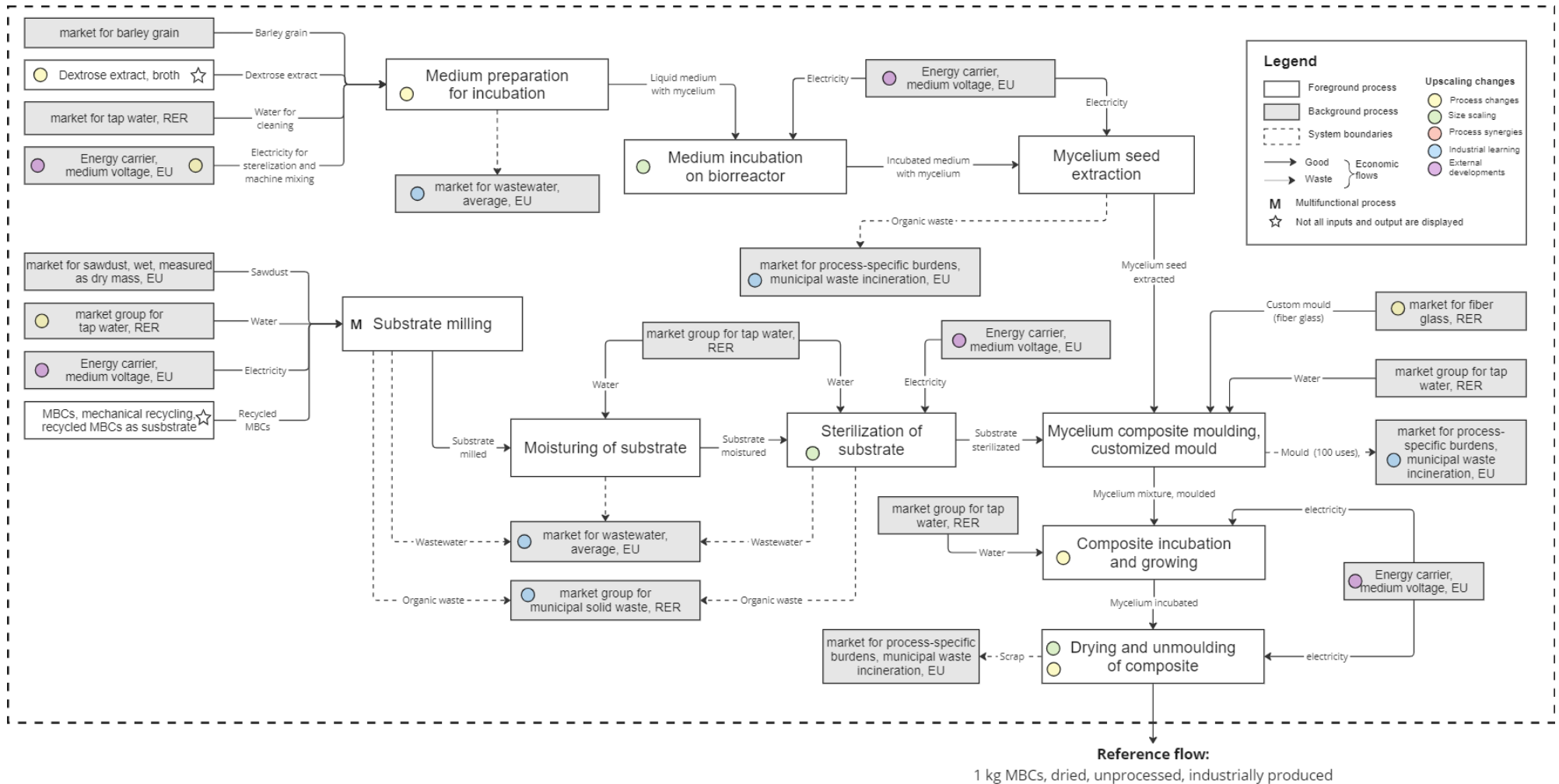


Figure 8. Cradle-to-grave mycelium based partition, based on Chaudhury (2023) design, and upscaled production of MBCs derived from Volk (2024), and Alaux et al (2023)

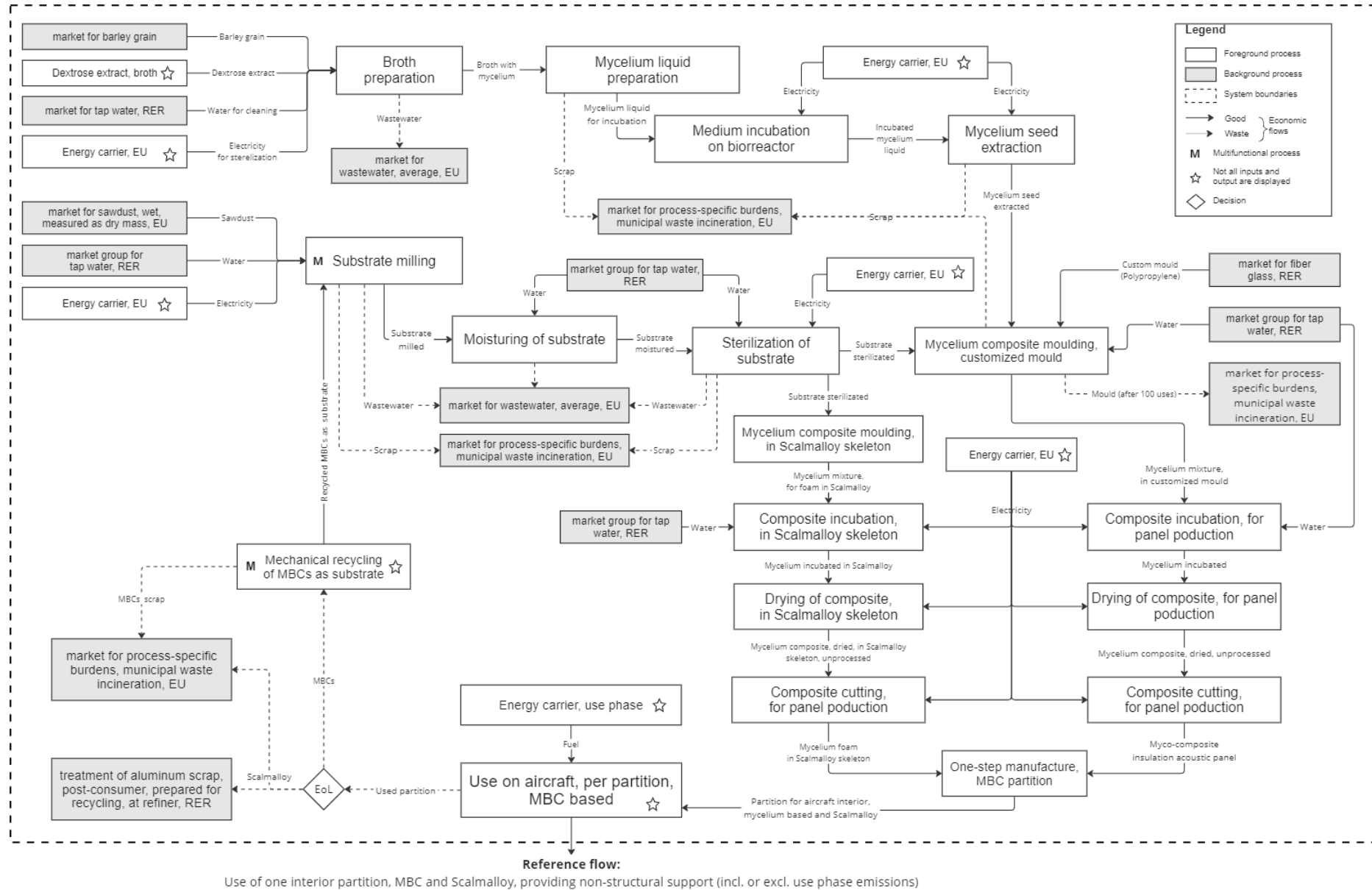
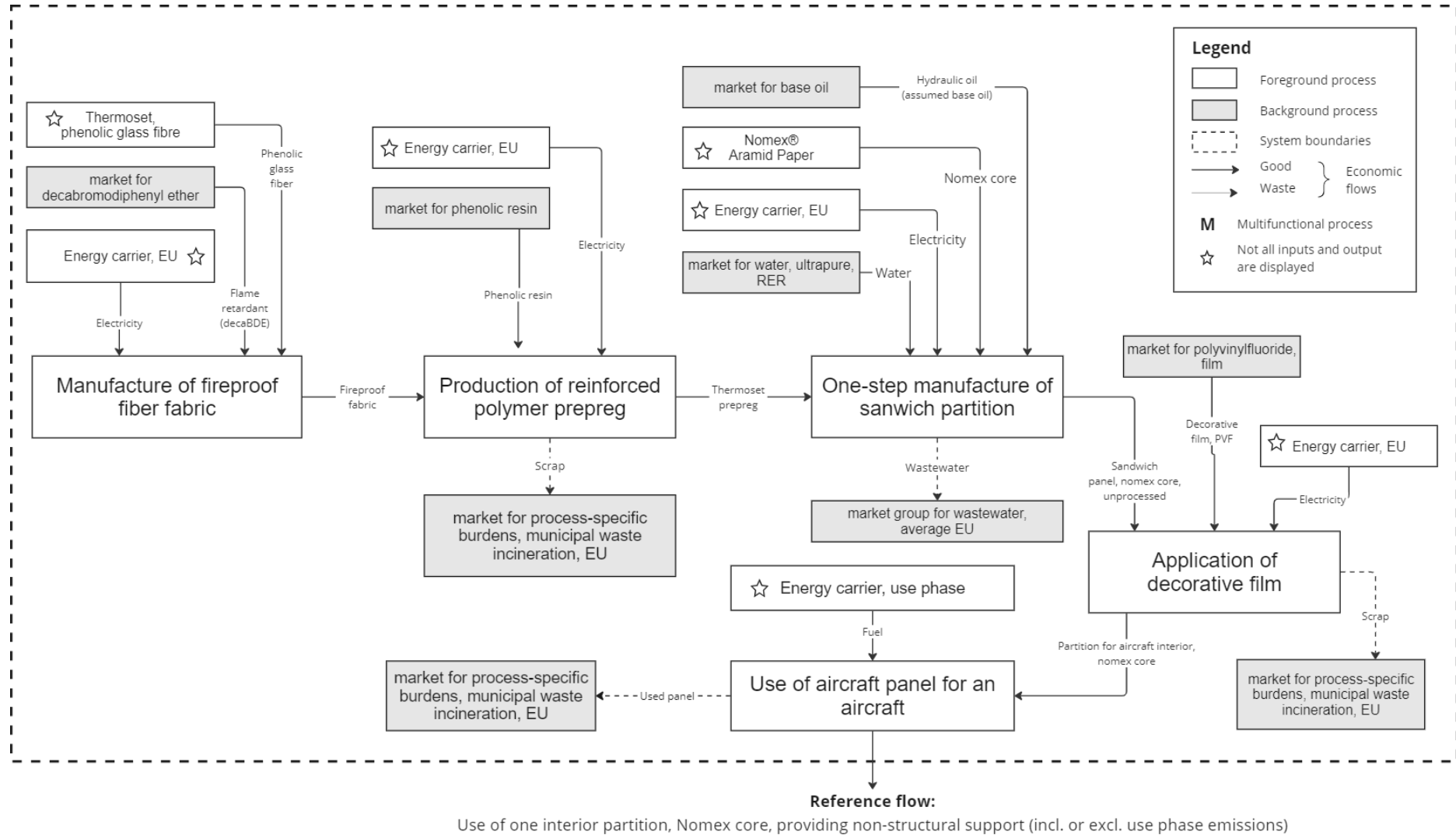


Figure 9. Cradle-to-grave conventional partition, honeycomb core, based on Vidal et al. (2018) production processes and Chaudhury (2023) dimensioning of design



2.2.5. Data

To conduct this LCA, representative data for various processes within the system boundaries was gathered over a 3.5-month period. Since manufacturer data was not directly available, alternative sources were used presented below. Background process were taken from the Ecoinvent database (v3.9.1), “allocation, cut-off by classification” system model, which include the supply of raw material, electricity, wastewater and waste treatment. Further foreground processes are based on literature review including previous LCA inventories, patents analysis, adjustments to background models. Additional materials databases such as Agribalyse (v3.0.1) and Granta EduPack (2023 R2) were reviewed. All of them were modeled using Ecoinvent data, proxies and cut-off methods (reported if employed). Modeling was carried out using the Activity Browser software (v2.8).

To simulate future scenarios, including the upscaled production, the PROspective EnvironMental Impact asSEment (*premise*) Python library (v.1.4.2) was used, which transforms the Ecoinvent database following an integrated assessment model (IAM) depending on the temporal scope (Luderer et al., 2019; Sacchi et al., 2022). In this case, the REMIND NCD model was chosen (REgional Model of Investment and Development, Nationally Determined Contributions), which aligns to commitments of countries to limit global warming well below 2°C, ideally to 1.5°C, as outlined in the Paris Agreement.

In parallel with data collection, expert consultation was conducted to ensure model accuracy. This involved: (a) validating primary data: contacting the authors of previous studies provided a firsthand understanding of their assumptions, (b) processes validation: discussing the model's processes to ensure technical alignment, (c) upscaling discussions: engaging with experts from Airbus on potential assumptions for upscaling the technology.

2.2.5.1. Mycelium based composite material

For the Mycelium-Based Composites (MBCs), primary data came from three prior studies, based on European production shown on Table 5. Due to the evolving nature of mycelium-based technology, approaches to contact the respective authors were held to understand their methodologies and specific approaches.

Table 2. Sources for data of laboratory production for MBCs production

| Source | Location | Validation | Description |
|---------------------|-------------|------------|---|
| Chaudhury (2023) | Netherlands | Direct | Direct contact, semi-structured interviews |
| Alaux et al. (2023) | Austria | Direct | Direct contact, semi-structured interview |
| Volk et al. (2024) | Germany | Indirect | Validation with industrial designer at TU Delft |

This model incorporated data from Volk et al. (2024) regarding laboratory protocols (including culture medium, fungal isolation techniques, incubation conditions, and sterilization procedures). It also considered the processes of fungal mixing, growth, and resource provision. Adjustments include the use of single-use molds for fabrication and utilizing an average European electricity mix and wastewater treatment approach, instead of the Germany-specific details from the original research. Energy consumption data were primarily sourced from the German study, but additional data from Alaux (2023) et al. was included to better reflect the specific procedures required for Chaudhury (2023) to achieve the desired mycocomposite partition. The waste outflows of the foreground process were connected to suitable waste treatment process. Further details on lab-scale definition are provided in the Annex B, Step 2.

2.2.5.2. Mycelium based partition

Data for the conventional partition assembly was derived from Chaudhury (2023). In addition to the above mentioned MBCs, Scalmalloy was modeled based on a average composition of a reported typical composition of product (Koutny et al., 2018). Energy requirements were derived from proxies aluminum alloys from the Edu GranPack material database. Process and mechanical properties were

analyzed to understand its differences with available alloys (Schmidtke et al., 2011; Zhu et al., 2021). The dimensions and material properties are presented on Table 3.

Table 3. Dimensions and material properties of partition design, derived from Chaudhury (2023)

| Material components | Area [m ²] | Thickness [m] | Volume [m ³] | Density [kg/m ³] | Weight [kg] |
|-----------------------|---------------------------|------------------|-----------------------------|---------------------------------|----------------|
| Scallmalloy structure | 0.44 | 0.025 | 0.011 | 2670 | 29.37 |
| Mycelium foam filler | 2.8 | 0.025 | 0.07 | 50 | 3.5 |
| Mycelium based panel | 3.24 | 0.025 | 0.081 | 100 | 8.1 |
| Total weight | | | | | 40.97 |

2.2.5.3. Conventional sandwich partition

The process was established based on Vidal et al. (2018). In order to adjust their production streamline, to an equally comparable to the one flowchart, revision of the patented technology (Gonzalez-Garcia et al., 2015; Martin et al., 2012) was needed. The materials, energy requirements, as well as waste streams were dimensioned to the conventional alternative used in Chaudhury (2023). In this way, the study to ensure this partition fulfills the same function as the MBCs panel. The materials in Table 4 are suitable for creating a partition with the same functionality (and same surface area in m²) as the mycelium-based one.

Table 4. Dimensions and material properties of partition design, adjusted from Chaudhury (2023) and Vidal et al. (2018)

| Material components | Area [m ²] | Thickness [m] | Volume [m ³] | Density [kg/m ³] | Weight [kg] |
|-------------------------|---------------------------|------------------|-----------------------------|---------------------------------|----------------|
| Nomex honeycomb core | 3.24 | 0.025 | 0.011 | 48 | 3.89 |
| Phenolic resin matrix | 3.24 | 0.005 | 0.016 | 1280 | 20.74 |
| Reinforcement composite | 3.24 | 0.006 | 0.019 | 1850 | 35.96 |
| Decorative film, PVF | 3.24 | 0.0005 | 0.0016 | 1700 | 1.38 |
| Flame retardant | 3.24 | 0.004 | 0.013 | 700 | 0.97 |
| Total weight | | | | | 62.94 |

2.2.6. Scenarios description

2.2.6.1. Background processes through PREMISE

This pLCA built its assessment using the REMIND (REgional Model of Investment and Development) integrated assessment model (IAM) to evaluate the Nationally Determined Contributions (NDC) scenario based on current national policies (Luderer, n.d.; Luderer et al., 2019). This scenario offers a realistic view of global climate action, highlighting that while existing commitments mark progress, achieving the Paris Agreement's 1.5°C target requires greater ambition and stringent policy implementation. Key technical elements include updates to electricity and fuel systems, incorporation of direct air capture and carbon sequestration, utilization, and storage technologies (Arblaster, 2023), and most important, the creation of multiple prospective background databases with five-year time steps (2020, base year) to account future implications around technologies based on different policies.

2.2.6.2. Foreground processes

To upscale the foreground processes, all modeling inputs (Ecoinvent choices) were ensured to correspond with their equivalents projected by the REMIND NDC model. Subsequently, adjustments in the models were made to each process based on the information provided in Table 7. For instance, this included modifications to materials and energy inputs necessitated by new materials for the new operational conditions of the processes. Additionally, waste streams were adjusted to reflect an overall the determined waste reduction, and the types waste streams were changed to correspond with the material substitutions. Furthermore, foreground models were built for the different scenarios encompassing energy carriers (manufacturing and flight fuel), EoL options, and use cases (including and excluding in-flight emissions). This enabled easy iterations and minor modification of the interconnected processes based on specific scenario.

2.2.6.3. Energy carriers for manufacturing

This scenario explores the use of alternative energy carriers within the manufacturing phase. This assessment is carried out at intra and intertechnology level. Therefore, the use on aircraft is excluded of this assessment. Both comparisons are carried replacing the energy source of the baseline production, European mixed energy matrix, medium voltage electricity. However, while the baseline operates at medium voltage, the energy production at the sources for energy (selected sources on Table 9) occurs at high voltage. The scenario acknowledges this discrepancy and reflects the high energy requirements in the model. The scenario depicts characterization of results modeled from 2020 to 2050 to portray patterns in electricity consumption depending on the choice of the energy carriers.

The changes considered in this study are limited to the internal manufacturing process, reflecting process burdens only. External factors like upstream supply chains, such as the production of Scalmalloy (even though, foreground modeled), are not included in the analysis. This is because the focus is on the areas where the manufacturer has no direct influence over the energy employed. Finally, given limitations in the databases, the lack of a generalized European process on Ecoinvent for each energy source, the study focuses on a specific country: the Netherlands (for this scenario only).

Table 5. Energy carriers selected for assessment

| Energy carrier | Voltage | Location | Specification |
|--------------------------------------|---------|-------------------|------------------------|
| market group for electricity | medium | Europe without CH | baseline |
| electricity production, hard coal | high | Netherlands | - |
| electricity production, hydro | high | Netherlands | run-of-river |
| electricity production, natural gas | high | Netherlands | 10MW |
| electricity production, nuclear | high | Netherlands | pressure water reactor |
| electricity production, oil | high | Netherlands | - |
| electricity production, wind | high | Netherlands | 1-3MW turbine, onshore |
| heat and power co-generation, biogas | high | Netherlands | gas engine |

2.2.6.4. Recycling processes

The scenario analyzes the potential for recovering mycelium composite waste streams, based on the easy disassembly design of the partition. Mechanical recycling processes is modeled across a range of scenarios based on the material recovery. Recovery rates are estimated at 0% (complete incineration), 30% (inefficient process), 70% (high performance), and 100% (optimal recovery). The recovered resources, enters the production line to replace the need of virgin substrate.

The recycling process focuses on the product application level, specifically interior partitions, after they reach their end-of-life (cradle-to-gate). The model explores the possibility of recycling the partitions back into the manufacturing process through mechanical recycling, based on a process applicable for carbon fiber composite material from Arblaster (2023). This approach assumes similar functionality for the recycled material but neglects potential property differences between MBCs and recycled carbon fiber. Note, the model does not assess alternative treatments for the Scalmalloy, so incineration is considered its end-of-life option.

For the material assessment, a preliminary evaluation considered replacing the substrate with recycled material. However, due to the study's scope (cradle-to-gate), the model assumes outsourced recycled substrate production, resulting in a linear, non-circular production process. This adds energy consumption (declared as a limitation).

2.2.7. Upscaling of technology

This study adopted a 5-step LCA approach for emerging technologies (Erakca et al., 2024; Tsoy et al., 2020) to evaluate the environmental impact of upscaling MBCs technology from lab-scale to industrial production. Step 1, technology maturity definition, was defined based on literature review and patent development analysis. Whereas, step 2, has been already discussed in the previous section. Full details are provided on Annex B.

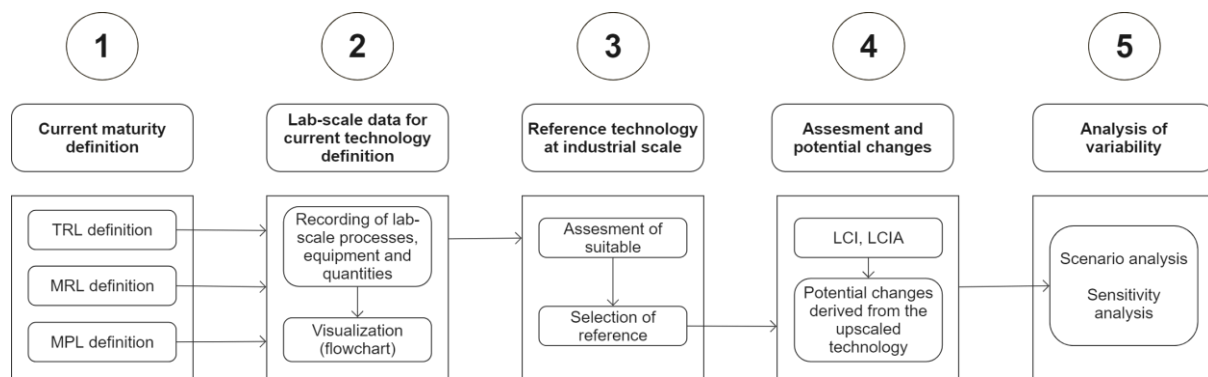


Figure 10. Flowchart of five-step-scaling procedure and amount of methodologies performing each step. Adapted from: Erakca et al. (2024). TRL: Technology Readiness Level, MRL: Manufacturing Readiness Level, MPL: Market Penetration Level

A key point to consider is the timeframe for the comparison. A comparative pLCA requires both scaling the emerging technology to a more advanced stage (high TRL) and modeling all technologies (including existing high-maturity level on the status quo, eg. conventional aircraft interior panels) for comparison at the same point in the future (Thonemann et al., 2020). The following illustration further explains these consideration for this case study.

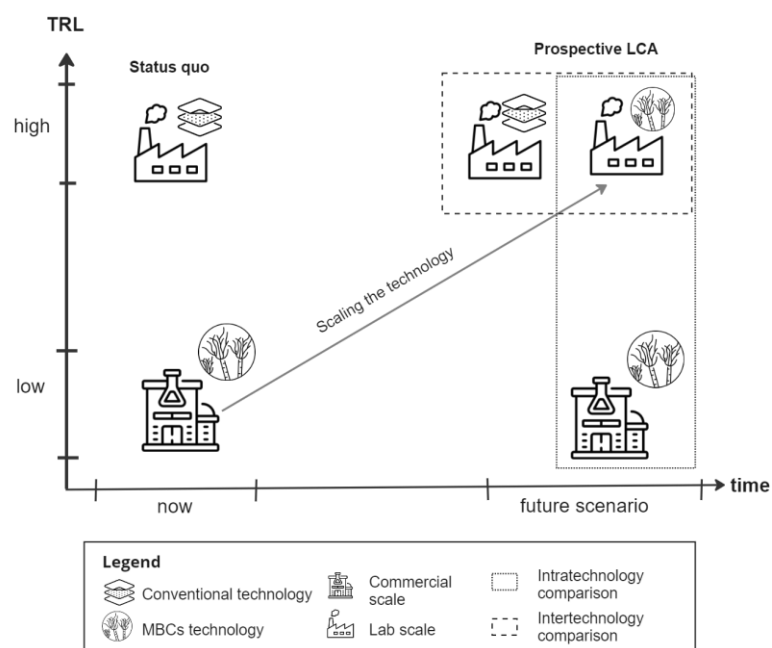


Figure 11. Graphical representation for upscaling and pLCA of Mycelium-Based Composites (MBCs) across different levels of technology development. Inspired by: Alaux et al. (2023); Thonemann et al. (2020)

As a next step for this prospective LCA, a presumed future scenario of what the technology may develop in the future has to be established. The decision tree tool developed by Erakca et al. (2024) was used to identify the most appropriate scaling method for our Life Cycle Assessment (LCA), an approximation technology approach was selected. Full details are Annex B (Step 3).

It is well known that integrating expert and stakeholder knowledge through the developments of the pLCA strengthens the accuracy of the outcomes (Langkau et al., 2023). As first, approach, this process involved consultation with experts in order to identifying a technology reference and gather insights from the dynamics of the industry sector (Erakca et al., 2024; Tsoy et al., 2020). Therefore, a session with experts from Airbus, hold in May 2024, revealed initial insights and limitations of this approach.

Table 6. Key points from online session with Airbus experts

| Parameter | Key takeaways |
|----------------------|---|
| Participants | <ul style="list-style-type: none"> - Polymer Scientist with a specialization in developing biobased materials - LCA specialist with background in Environmental Engineer - Expert in the integration of environmental impact assessment into design |
| Participation | Participation limited to one online workshop |
| Reference technology | A suitable reference technology was not readily identifiable. Instead, suggestions to explore concepts for how a interior partition production may look like acknowledging that the system may be complex and variable. A reasonable yet simplified model should be provided. |
| Use phase | Due to limitations on information disclosure, it is recommended to analyze the product excluding the use phase. If necessary, general estimates around mass-based energy should be used, as specific use depends on the aircraft model (limited disclosure for the thesis). This analysis can be carried out later if needed by the commissioner. |
| Recyclability | MBCs present a promising recyclable solution for interior partitions. However, achieving optimal recyclability necessitates compatibility with customer preferences, which may imply the use of additional surface treatments like films. |
| Conceptual framework | Use of Integrated assessment model (IAM) is a suitable practice of interest for pLCA The proposed timeframe and pLCA approach seem suitable for the given task |

To assess large-scale MBCs' environmental impact, the upscaling scenario was defined based on key considered factors. The framework established by van der Hulst et al. (2020) was followed to collect key aspects to ensure the assessment reflects a realistic industrial scenario.

Table 7. Key aspects for systematic upscaling approach. Adapted from: van der Hulst et al. (2020)

| Key aspects | Description | Approach chosen for study |
|-------------------------------------|--|---|
| Definition of the development stage | Identify the level of technological maturity of the current technology, and the needed for an assertive comparison | Maturity level targeting |
| Process changes | Changes to processing methods due to the availability or necessity of other equipment and materials, typically improving product performance, cheaper and safer production | Deduction from existing industrial processes (functions, dimensions, or similarities) |
| Size scaling | Changes in the physical dimensions of the product (product scaling) and/or the increase in equipment dimensions to accommodate larger products, larger production volumes, or both (equipment scaling) | Changes in resource use and production outcomes due to selected technologies |
| Process synergies | Minimization or valorization of final waste streams through recovery and recycling options for materials and energy | Deduction on flow charts, based on existing industrial production |
| Industrial learning | Learning and experience mechanisms in industrial scale production, typically difficult to disentangle and studied collectively as a single development factor | Deduction on flow charts, derived from optimization (specific for this study) |
| External developments | Future developments in external systems that influence the production of the studied technology or its upstream or downstream processes | Combining LCA with integrated assessment models (IAMs), REMIND NCD model. |

Upscaling significantly modifies both MBC production processes and their background processes to accommodate larger volumes and increased efficiency. The full list of key aspects for upscaling are provided on Table 7. For instance, one crucial field for technology upscaling is energy. The significance of optimizing and exploring options for energy consumption at various stages of the process has been emphasized in both lower and upscaled higher TRL studies (Alaux et al., 2023; Volk et al., 2024). This is especially relevant as electricity consumption has been targeted as the principal source of greenhouse gas emissions in prior literature. As a reference point, the considerations established by Alaux et al. (2023) for electricity of the main sources of consumption: drying and sterilization.

The transition from lab-scale to industrial production of mycelium-based composites requires a significant shifts. While a traditional agar plates for medium growth might be used for initial growth, at large scale this becomes unfeasible. Therefore, large scale bioreactor growing is adopted as alternative. Within this process, replacing agar with a cost-effective alternative like liquid broth easier and cheaper to produce in large volumes. For this case, dextrose (glucose as proxie) may provide enough source for the mycelium (Hur et al., 2008). Whereas, sawdust remains the chosen substrate. However, to

address the variability of fungal species, substrate and additives to produce MBCs can impact product composition and final quality (Volk et al., 2024). Therefore, we will focus on sawdust from circular production streams, as literature suggest MBCs are biodegradable and therefore serve as potential substrate for new mycelium growth (Alemu et al., 2022; Ghazvinian & Gursoy, 2022).

Moreover, single-use molds are not suitable for large-scale production. Therefore, it is considered for this study to replace them with high-quality, reusable molds made from materials like glass fiber-reinforced plastic (Alaux et al., 2023). Other alternatives may include, aluminum ABS (aluminum automotive body sheet), cast aluminum, among other, not selected in this study. Despite the material choice, they can be used repeatedly, minimizing waste (assuming 100 uses before disposal). This enables more precise shaping of the final product, reducing the need for post-processing. In fact, lab-grown MBCs are often limited to simple shapes achieved through pressing (Karana et al., 2018). In this way, the introduction of laser cutting in larger-scale production opens up the creation of complex shapes (Alaux et al., 2023), expanding the design potential of mycelium-based products, required for the applications in aircraft interiors.

It is essential to take into account advancements in both the MBCs technology (main foreground system) and the broader technological context (background system) to prevent temporal discrepancies between the technology and the technological context (Steubing & de Koning, 2021; Thonemann et al., 2020). Thus, all models review implication due to the energy generation, raw materials, manufacturing, or waste treatment decisions for getting an accurate LCI database reflecting these scenarios (Lai et al., 2022; Steubing & de Koning, 2021).

Table 8. Considerations for upscaling MBCs technology for its use in non-structural aircraft partitions

| Phase | Modeled changes | Lab scale (<i>Status quo</i>) | Industrial scale (2035) |
|------------------------------|--|---|--|
| Development stage | Stage definition | TRL 3, MRL 2, MPL 0% | TRL 9, MRL 10, MPL 5% |
| Process changes | Medium alternatives | Use of agar as a growth medium | Use of liquid broth media, rich on glucose, such as dextrose, for cost-effectiveness and scalability |
| | Water source | Ultrapure water for inoculation and mediums | Extended use of average tap water |
| | Substrate mixing | Mixing is performed by hand | Electricity due to machine mixing |
| | Molding techniques | Use of single-use plastic molds, in combination with cotton fiber. | Use of high-quality, reusable molds (glass fiber-reinforced) specific shapes |
| | Growing conditions | Basic environmental controls | Advanced environmental control systems |
| | Cutting | Not required, simple shapes provided through pressing | Laser cutting for more complex shapes |
| Size scaling | Product scaling | Prototypes products | Interior aircraft partitions |
| | Cultivation of Fungi | Static cultivation in small containers | Shift from lab-scale cultivation to mushroom farm settings |
| | Equipment scaling | Small autoclaves, cultivation in small containers | Large industrial autoclaves, extensive fermentation tanks |
| | Sterilization | Autoclave with high relative energy consumption | Industrial autoclave with lower energy consumption |
| | Drying Techniques | Basic convective or small scale oven air drying | Higher energy intensity drying |
| Process synergies | Minimization of waste streams | Waste quantities are small. Basic waste management practices | Integrated waste management systems within facilities. Circular production synergies |
| Industrial learning | Extensive production experience, leads to overall efficiency | NA | Assuming limited waste generation per process, below 5%. Other variations remain uncertain due to variability in processes |
| External developments | Decarbonization of the electricity | Electricity grid mix for Europe | Projected European electricity grid mix emissions considering |
| | Policy and Regulation | Initial efforts towards policy compliance and certification for material adoption | Full compliance with decarbonization policies, comprehensive certification, alignment with 2050 emission targets |

*TRL: technology readiness level, MRL: manufacturing readiness level, MPL: market penetration level

2.2.8. Sensitivity analysis

Sensitivity analysis were performed in order to assess the influence of significant assumptions on the results of this study. This analysis focused on three key assumptions: the method used to assess impacts (impact assessment family), the energy sources considered during the use phase, and the end-of-life (EoL) treatment options.

2.2.8.1. Impact categories

This analysis went beyond the suggested approach using the Environmental Footprint (EF) method version 3.1 (EV 3.1). It compares the results to equivalent impact categories from the ReCiPe method.

2.2.8.2. Energy carries for use phase

Recognizing the significant emissions generated by the partition throughout its life cycle, including the use phase, a sensitivity analysis was conducted to explore the impact of two additional energy sources. The baseline considers the combustion of kerosene fuel. As additional energy carries, biokerosene and hydrogen cells were chose, which are available in the NDC background processes.

This model influences the concept of mass-energy balance and is disclosed on its life cycle inventory. The selected models are energy derived from the combustion of biokerosene, as well as the energy conversion from hydrogen cells. Both derived from the premise database.

2.2.8.3. End-of-life of MBCs partition

The initial analysis assumed a uniform end-of-life (EoL) treatment, incineration, for all materials in the partition. While this aligns with common practices for current composites, it disregards potential material recovery opportunities. Recognizing the significant contribution of the Scalmalloy component to the partition's environmental impact, a sensitivity analysis will be conducted. This analysis will explore the impact of switching the Scalmalloy's EoL treatment to outsourced recycling. The chosen EoL treatment for the Scalmalloy references 'treatment of aluminum scrap, post-consumer, prepared for recycling, at refiner (RER)' as a proxy alternative, neglecting other element present on the alloy composition. However, it's important to note that this analysis prioritizes the study of MBCs. Therefore, a deeper exploration of scalmalloy recycling or its specific properties falls outside the current scope.

3

Results

In this section each chapter comprehensively analyze the key impact categories relevant to the specific assessment. These categories are chosen based the significant distinctions between them, and the direct connection to the material application or use case. This includes considering whether the assessment is carried out at material (MBCs), application (partition) or comparison (with conventional petroleum alternatives), as well as either including or nor the use phase.

3.1. Status quo and future impact of MBCs production

3.1.1. Characterization results

In this section, the characterization results and contribution analysis of the baseline scenario are presented. These results provide the background for other findings including across different. The lifecycle impacts are presented considering encompass only a cradle-to-gate production of material.

Table 9. Comparison between upscaled and lab production of 1 kg MBCs, characterization results for the baseline scenario, cradle to gate, using the EF v3.1 impact categories

| Impact category | Unit | MBCs, lab produced | | | MBCs, industrially produced | | |
|---|-------------------------|--------------------|-----------|-----------|-----------------------------|-----------|-----------|
| | | 2020* | 2035** | 2050 | 2020* | 2035** | 2050 |
| Acidification | mol H+-eq | 2.282E-03 | 4.818E-04 | 4.450E-04 | 1.726E-03 | 3.387E-04 | 3.216E-04 |
| Climate change | kg CO2-eq | 4.958E-01 | 4.708E-02 | 3.222E-02 | 3.896E-01 | 4.174E-02 | 3.054E-02 |
| Ecotoxicity: freshwater | CTUe | 1.130E+00 | 6.598E-01 | 6.994E-01 | 5.998E-01 | 2.377E-01 | 2.844E-01 |
| Energy resources: non-renewable | MJ, net calorific value | 1.147E+01 | 3.003E+00 | 8.595E-01 | 8.916E+00 | 2.335E+00 | 6.674E-01 |
| Eutrophication: freshwater | kg P-eq | 5.290E-04 | 1.009E-05 | 1.347E-05 | 4.103E-04 | 6.961E-06 | 1.053E-05 |
| Eutrophication: marine | kg N-eq | 5.579E-04 | 2.099E-04 | 1.797E-04 | 2.819E-04 | 1.158E-05 | -1.09E-05 |
| Eutrophication: terrestrial | mol N-eq | 4.065E-03 | 1.456E-03 | 1.109E-03 | 3.054E-03 | 1.029E-03 | 7.702E-04 |
| Human toxicity: carcinogenic | CTUh | 1.803E-10 | 1.545E-10 | 1.849E-10 | 1.759E-10 | 1.565E-10 | 1.834E-10 |
| Human toxicity: non-carcinogenic | CTUh | 4.941E-09 | 2.030E-09 | 2.441E-09 | 4.068E-09 | 1.822E-09 | 2.226E-09 |
| Ionizing radiation: human health | kBq U235-eq | 3.182E-01 | 1.323E-01 | 2.020E-02 | 2.478E-01 | 1.029E-01 | 1.555E-02 |
| Land use | dimensionless | 1.012E+01 | 1.116E+01 | 1.144E+01 | 9.453E+00 | 1.027E+01 | 1.050E+01 |
| Material resources: metals/minerals | kg Sb-eq | 1.262E-06 | 2.135E-06 | 3.403E-06 | 9.824E-07 | 1.676E-06 | 2.859E-06 |
| Ozone depletion | kg CFC-11-eq | 8.117E-09 | 3.446E-09 | 3.688E-09 | 6.312E-09 | 2.686E-09 | 3.007E-09 |
| Particulate matter formation | disease incidence | 1.130E-08 | 7.009E-09 | 6.139E-09 | 8.917E-09 | 5.656E-09 | 5.141E-09 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 1.066E-03 | 3.032E-04 | 2.272E-04 | 8.906E-04 | 2.990E-04 | 2.427E-04 |
| Water use | m3 world eq. deprived | 4.447E-01 | 3.577E-01 | 3.200E-01 | 1.501E-01 | 8.254E-02 | 5.395E-02 |

* Current status quo, applicable for lab only, upscaled technology is not ready at that given year

** Baseline, 2035 correspond to the year when the technology will reach a higher TRL

The LCA revealed non-renewable energy consumption and land use as the most significant burdens across both lab-scale and industrial MBC production for 2035. High dependence on the existing electricity grid, regardless of scale, translates to a continued reliance on non-renewable resources (lab: 3.003 MJ, industrial: 2.34 MJ). Land use concerns persist due to the use of virgin materials like sawdust. While less prominent, ecotoxicity in freshwater (lab: 0.66 CTUe, industrial: 0.24 CTUe) and climate change impacts (lab: 0.047 kg CO₂-eq, industrial: 0.0417 kg CO₂-eq) require attention. These findings underscore the need for advancements in renewable energy integration, exploration of sustainable substrate alternatives, and the development of lower-impact production processes.

The comparison on Figure 12 examines the percentage of changes in the different impact categories from lab-produced MBCs to industrially produced MBCs. The analysis highlights how each impact category improves or worsens as production scales up. The upscaled technology for current state (2020, status quo for the NDC model) is projected to have lower emissions. If technology was already available, lab-produced MBCs would have a higher impact in most categories. However, the technology will need still 10 more years for reaching the development level required (Alaux et al., 2023). By the year 2035, the transition from lab to industrial production of mycelium-based materials reveals several different trends. Industrially produced MBCs present a significant lower impact in eutrophication (all types), ecotoxicity, and water use. Whereas their emission derived from climate change, even though lower are expected to increase in the future timeframe.

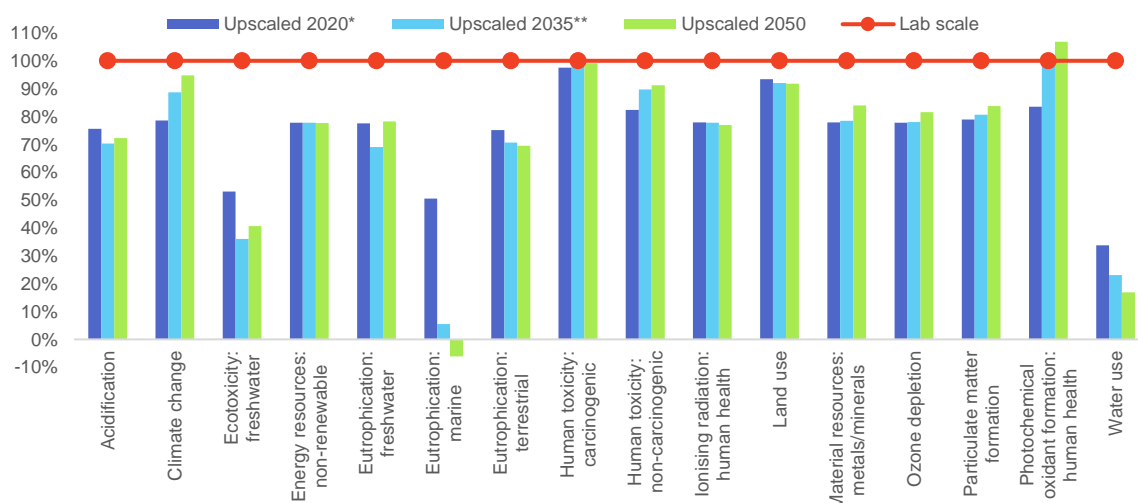


Figure 12. Cradle-to-gate environmental impact evolution, comparison between lab scale and upscaled production of 1 kg of MBCs across the EF v3.1 impact categories. *Please note technology is not ready until 2035, therefore status quo comparison is neglectable for comparison purposes. ** Baseline scenario.

3.1.2. Contribution analysis

A contribution analysis is provided in Annex D (see D.1) to understand the highest impacts associated with the transition from lab-produced to industrially produced MBCs. This analysis verifies that land use impact is primarily associated with the substrate used in MBCs production. Since the quantities and type of substrate remain unchanged between lab and industrial scales, the contribution of land use to the overall environmental impact remains relatively constant. This highlights the need to explore MBC recyclability during production.

Similarly, the analysis confirms that the continued dependence on the existing electricity grid, regardless of scale, translates to a persistent reliance on the same energy carrier. This explains why the impact of energy resources: non-renewable also shows minimal change between lab and industrial production. Furthermore, the occurrence of multiple energy sources within the climate change impact category underscores the significant contribution of electricity consumption to its environmental impact.

It is important to note the energy-intensive nature of the MBC production process, and therefore, it enhances scenarios assessment across other energy alternative carries.

The analysis in Figure 12 also showed reduced impacts for categories like eutrophication: marine, water use and ecotoxicity: freshwater. These reductions are attributed to the replacement of cotton use during customized molding with MBCs. The contribution analysis identifies cotton usage in lab-scale production as a major cause. In lab settings, cotton serves as a barrier alongside single-use plastic molds during the growth process. The shift to customized fiber glass molds with extended lifetimes in industrial production eliminates the need for cotton and single-use plastics. This reduces water consumption associated with cotton irrigation and eliminates the risk of harmful substances entering the environment from processing or discarded plastic molds. Consequently, the environmental impact of MBCs production is demonstrably minimized in these categories. However, the impact value observed in these categories were relatively small compared to others previously mentioned.

3.1.3. Recyclability of MBCs, cradle-to-gate assessment

This scenario analysis considers the production of MBCs (upscaled scenario 2035) using recycled substrates, considering outsourced provision of the recycled substrate. As seen in Figure 13, land use impact progressively improves with increasing use of recycled inputs, reflecting a significant reduction in land required. On the other hand, the recycling efficiency rate presents an interesting complexity. In the 30% recycled material scenario, lower recycling efficiency leads to a higher overall environmental impact compared to virgin sawdust across all categories except land use. This highlights the crucial role of optimizing the recycling process. As the efficiency improves (represented by higher percentages of recycled material being successfully incorporated), the environmental impact progressively decreases. It is important to note a limitation within the current recycling model used in the assessment. The model conceptualizes outsourced recycling, which adds energy consumption to the system. This explains the increases in across the scenarios that considered recycled material. A more precise model could potentially address the overestimation issue and provide a clearer picture of the environmental benefits associated with using recycled substrates in MBC production. The detailed results for each scenario are available in Appendix E (numeral 1).

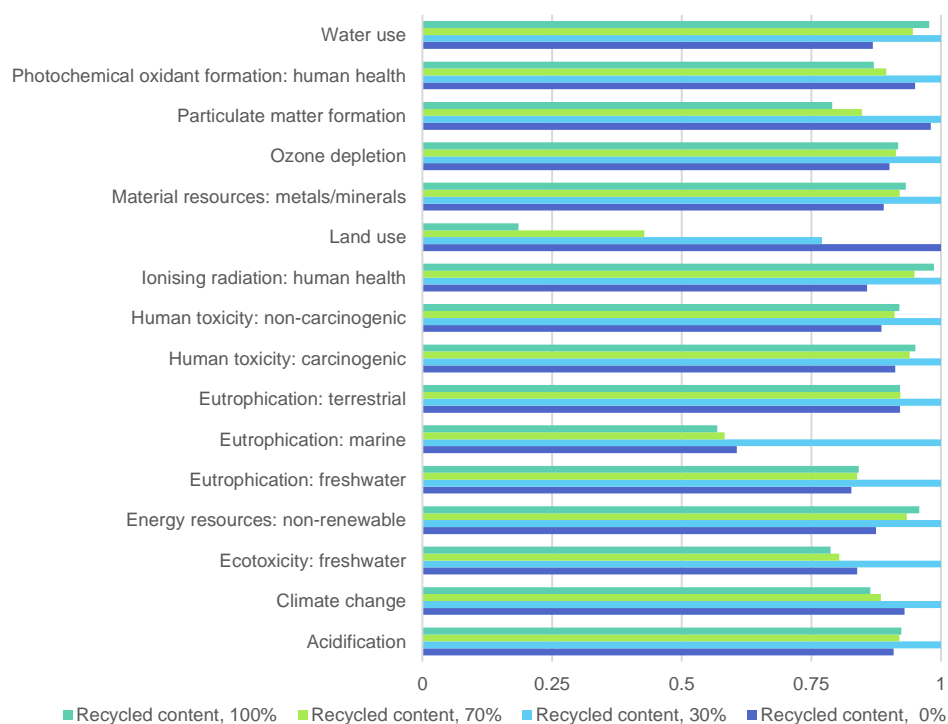


Figure 13. Increased recycled input (cradle-to-gate) for the production of 1 kg of MBCs, baseline upscaled production for 2035, using EF v3.1 impact categories.

3.2. Comparison across different product applications

This section analyzes the potential application of MBCs for aircraft interiors. It shifts the focus from the previous section's mass-based functional unit to consider the product's use phase within an intertechnology comparison. Employing a cradle-to-grave approach, the results target the baseline 2035, when MBC technology is expected to be fully commercially available. A key aspect of this assessment involves differentiating between emissions associated with the in-flight use phase and those excluded from it. This distinction is crucial given the significant contribution of fuel consumption to the environmental impact of this non-structural aircraft component.

3.2.1. Characterization results

The characterization results in Table 10 for the partition composed of MBCs and Scalmalloy reveals a promising environmental profile, with potential long-term benefits outweighing the initial environmental impact of manufacturing. In the production phase, when examining the environmental impacts of MBCs & Scalmalloy and Nomex Core, excluding the use phase, it is clear that MBCs & scalmalloy exhibit higher impacts across several key categories. Specifically, MBCs & Scalmalloy demonstrate significant burdens in climate change (743 kg CO₂-eq), non-renewable energy consumption (9880 MJ), freshwater ecotoxicity (8720 CTUe), acidification (4.46 mol H⁺-eq), and photochemical oxidant formation (2.54 kg NMVOC-eq). In comparison, Nomex Core shows lower impacts in these categories, with notable values in energy resources (6220 MJ) and climate change (256 kg CO₂-eq).

Including the use phase, the environmental impacts shift towards the Nomex core partition, which shows significantly higher overall impacts across most categories. Nomex Core exhibits high non-renewable energy consumption (345000 MJ), climate change impacts (5500 kg CO₂-eq), freshwater ecotoxicity (150000 CTUe), marked acidification (25.0 mol H⁺-eq), and elevated photochemical oxidant formation (51.2 kg NMVOC-eq). In contrast, MBCs & Scalmalloy partition shows increased impacts when the use phase is included, yet it remains lower than those of Nomex Core, with 230000 MJ for non-renewable energy, 4150 kg CO₂-eq for climate change, 105000 CTUe for freshwater ecotoxicity, 19.9 mol H⁺-eq for acidification, and 35.1 kg NMVOC-eq for photochemical oxidant formation.

Table 10. Characterization results for the comparison between interior partitions alternatives, baseline scenario 2035, using EF v3.1 impact categories.

| Impact category | Unit | Excluding use | | Including use | |
|---|-----------------------------------|-------------------|------------|-------------------|------------|
| | | MBCs & Scalmalloy | Nomex core | MBCs & Scalmalloy | Nomex core |
| Acidification | mol H ⁺ -eq | 4.46E+00 | 1.32E+00 | 1.99E+01 | 2.50E+01 |
| Climate change | kg CO ₂ -eq | 7.43E+02 | 2.56E+02 | 4.15E+03 | 5.50E+03 |
| Ecotoxicity: freshwater | CTUe | 8.72E+03 | 3.01E+03 | 1.05E+05 | 1.50E+05 |
| Energy resources: non-renewable | MJ, net calorific value | 9.88E+03 | 6.22E+03 | 2.30E+05 | 3.45E+05 |
| Eutrophication: freshwater | kg P-eq | 4.56E-01 | 3.91E-02 | 5.43E-01 | 1.74E-01 |
| Eutrophication: marine | kg N-eq | 7.98E-01 | 2.70E-01 | 3.89E+00 | 5.03E+00 |
| Eutrophication: terrestrial | mol N-eq | 8.17E+00 | 2.73E+00 | 3.49E+01 | 4.38E+01 |
| Human toxicity: carcinogenic | CTUh | 6.68E-07 | 8.11E-07 | 2.13E-06 | 3.06E-06 |
| Human toxicity: non-carcinogenic | CTUh | 1.06E-05 | 5.28E-06 | 3.54E-05 | 4.35E-05 |
| Ionizing radiation: human health | kBq U235-eq | 7.52E+01 | 7.16E+01 | 1.26E+02 | 1.49E+02 |
| Land use | dimensionless | 3.09E+03 | 1.74E+03 | 1.56E+04 | 2.11E+04 |
| Material resources: metals/minerals | kg Sb-eq | 7.65E-03 | 7.40E-03 | 1.14E-02 | 1.31E-02 |
| Ozone depletion | kg CFC-11-eq | 1.19E-05 | 6.75E-06 | 3.72E-04 | 5.59E-04 |
| Particulate matter formation | disease incidence | 6.03E-05 | 1.40E-05 | 1.89E-04 | 2.12E-04 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 2.54E+00 | 1.11E+00 | 3.51E+01 | 5.12E+01 |
| Water use | m ³ world eq. deprived | 1.77E+02 | 2.28E+02 | 4.19E+02 | 5.99E+02 |

The comparative analysis presented in Figure 14 showcases that while MBCs & Scalmaalloy partitions have higher environmental impacts when considering its manufacturing compared to Nomex Core, the situation reverses when the use phase is considered (in-flight associated impacts). This advantage is connected from the inherent lightweight advantages of the mycelium based design.

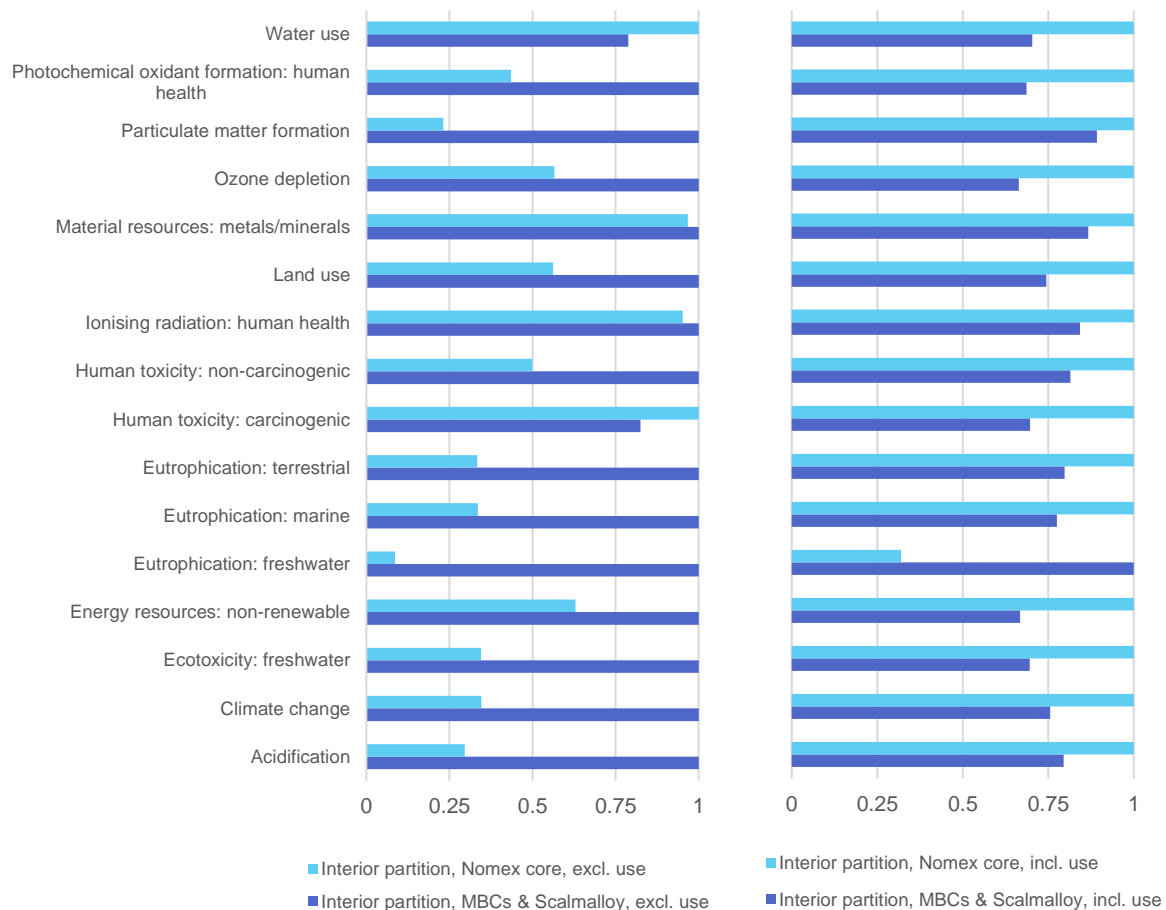


Figure 14. Cradle-to-grave impact breakdown of aircraft interior panels: MBCs & Scalmaalloy vs. Nomex core (conventional alternative), excluding (left) and including (right) in-flight associated emissions during partition lifetime, baseline scenario 2035, using EF v3.1 impact categories.

3.2.2. Contribution analysis

For further details on the environmental impact breakdown, refer to Annex D. This annex provides a contribution analysis for key impact categories, highlighting the main contributors.

3.2.3. Contribution analysis of product applications, including use phase

As expected, across all categories and for both alternatives analyzed, fuel consumption, specifically baseline kerosene combustion, emerges as the dominant contributor driving the environmental burden. For full disclosure refer to Annex D.2.

3.2.4. Contribution analysis of product applications, excluding use phase

To further isolate the environmental impact of the partitions, excluding the use phase, a separate contribution analysis was conducted. Figure 15 delves into specific activities within the manufacturing stage. For the MBCs partition, the results reveal a concerning trend. Scandium and the furnace operation associated with Scalmaalloy production emerge as significant contributors to the environmental impact. This finding prompts a reassessment of the decision to utilize Scalmaalloy in the current design, especially considering its currently higher environmental impacts compared to the Nomex core during manufacturing. This analysis underscores the need for further exploration of

alternative materials and potentially more sustainable production methods for the Scalmalloy component. The significant contribution of scandium is particularly noteworthy, given its relative scarcity. However, the fact that this process was foreground modeled adds another layer of complexity, as uncertainties might exist due to the limitations of this modeling approach. For full details on both alternatives refer to Annex D.3.

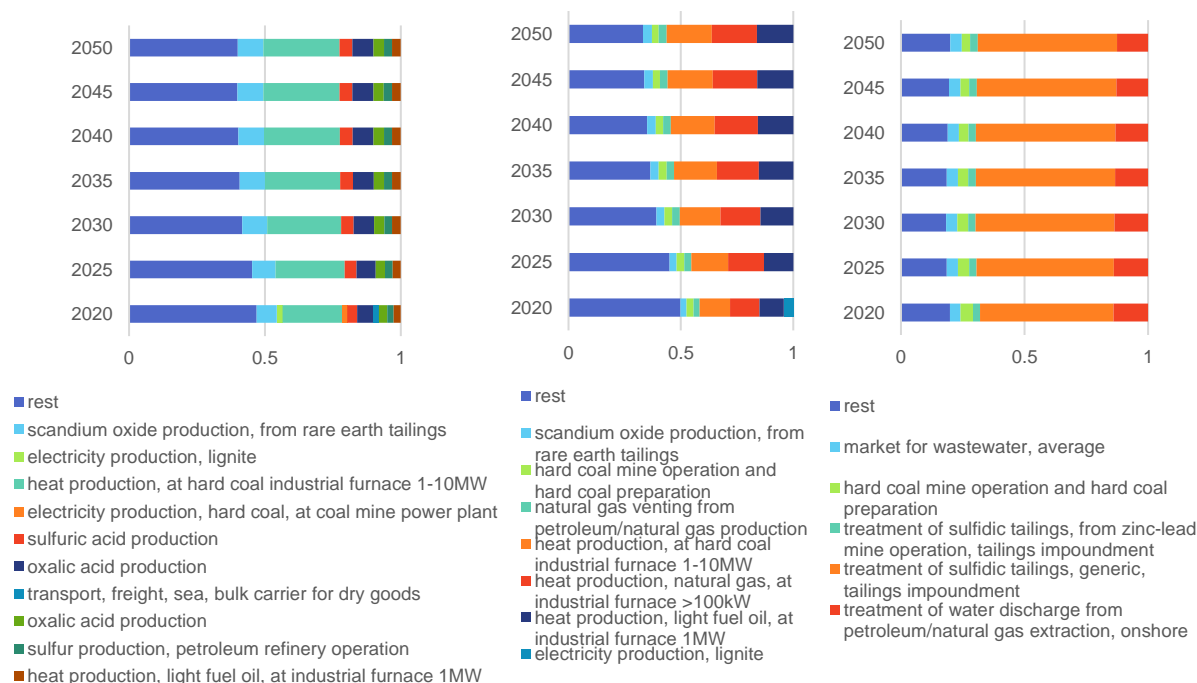


Figure 15. Contribution analysis for MBCs & Scalmalloy aircraft partition, excluding use phase, for impact categories: (a) ecotoxicity, (b) acidification, (c) climate change. Baseline scenario 2035, using EF v3.1.

3.2.5. Recyclability of MBCs, cradle-to-grave, circular production

The assessment focuses on the recyclability potential of MBCs derived from the MBCs & Scalmalloy partition, which constitutes 28% of its weight. Figure 16 showcases how when considering the use phase, changes are not significant due to the substantial importance of in-flight use. However, when focusing solely on the manufacturing phase and EoL, the recycling procedure's efficiency heavily influences the overall impact, with minor variations observed in the overall impact patterns.

While recycling boasts advantages in terms of land use, it is important to acknowledge its trade-offs. The process (as modeled in this study) can be energy-intensive, potentially contributing more to climate change compared to incineration (based on background data). Additionally, recycling may introduce a minor but noteworthy increase in human toxicity (carcinogenic effects).

Despite these considerations, the overall environmental impact patterns remain largely consistent. Nomex core still demonstrates a better performance most EF 3.1 impact categories, when excluding in-flight emissions, except for water use and carcinogenic effects, previously indicated in the baseline assessment.

For a detailed breakdown of the different environmental impact categories for each recycling scenario, refer to Annexes E (numerals 2 and 3).

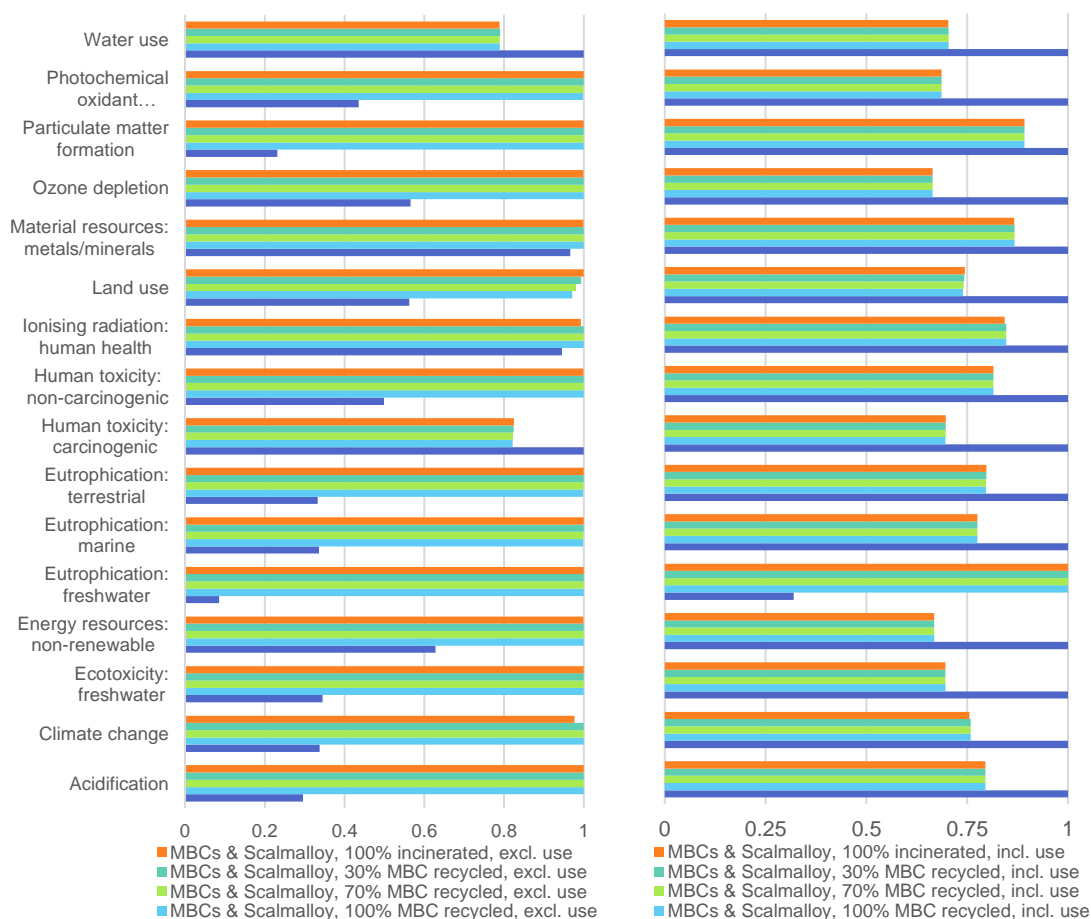


Figure 16. Comparative assessment of recyclability potential and environmental impacts of MBCs and Nomex core partitions across different recyclability scenarios, using EF v3.1 impact categories.

3.3. Sensitivity analysis

3.3.1. Impact assessment methodology choice

In this sensitivity analysis, the ReCiPe methodology was used to contrast the findings with those obtained using the Environmental Footprint (EF) v3.1 method. The analysis focuses on two aspects: 1) the environmental impact of lab-scale vs. upscaled MBCs production, and 2) the environmental impact of different partition alternatives. It is important to note that the analysis is limited to a 2035 baseline scenario. Detailed values for each impact category assessed through ReCiPe in Annex F.1.

In first place, the sensitivity analysis indicates that scaling up MBCs production from lab to industrial scale generally results in lower environmental impacts across most categories. However, the choice of impact assessment methodology (EF 3.1 vs. ReCiPe) can influence the magnitude of these impacts. In special, ecotoxicity: freshwater, eutrophication: marine, and water use are categories of concern as seen in Figure 17. Given the variability across the impact assessment method, it is underscored the necessity to carefully interpret these results, considering the different environmental flows accounted for by the characterization factors.

The low variability in the other impact categories suggests that the environmental impacts are relatively stable across different assessment methodologies. The average range of variation is small (highest 22.23% for ionizing radiation: human health), indicating that these categories can be reliably assessed without significant concern for method-induced discrepancies. This consistency provides confidence in the assessment results for climate change, human toxicity (carcinogenic), ionizing radiation, land use, and ozone depletion impacts.

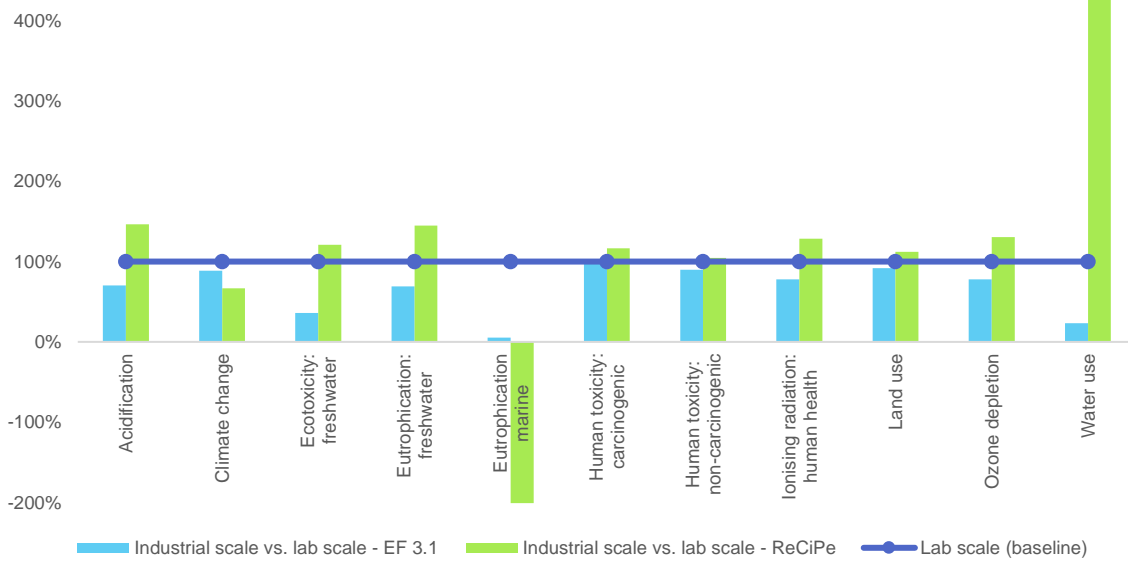


Figure 17. Sensitivity analysis employing different characterization models: EF 3.1 and ReCiPe for the comparison on the production of 1 kg of MBCs in laboratory and industrial scale. Only comparable impact categories were selected and scaled to the laboratory production baseline.

The sensitivity analysis carried out for the comparison of environmental impacts between Nomex core and MBCs & Scalmalloy partitions, excluding and including the use phase, reveals that water use, and eutrophication: marine show significant variations, as well as human toxicity: non-carcinogenic (not of concern in the previous in material assessment) are sensitive to the method selected. Whereas climate change, ionizing radiation: human health, and ozone depletion are more reliable categories with consistent performance across both assessment methodologies. See Annex F.2. for more details.

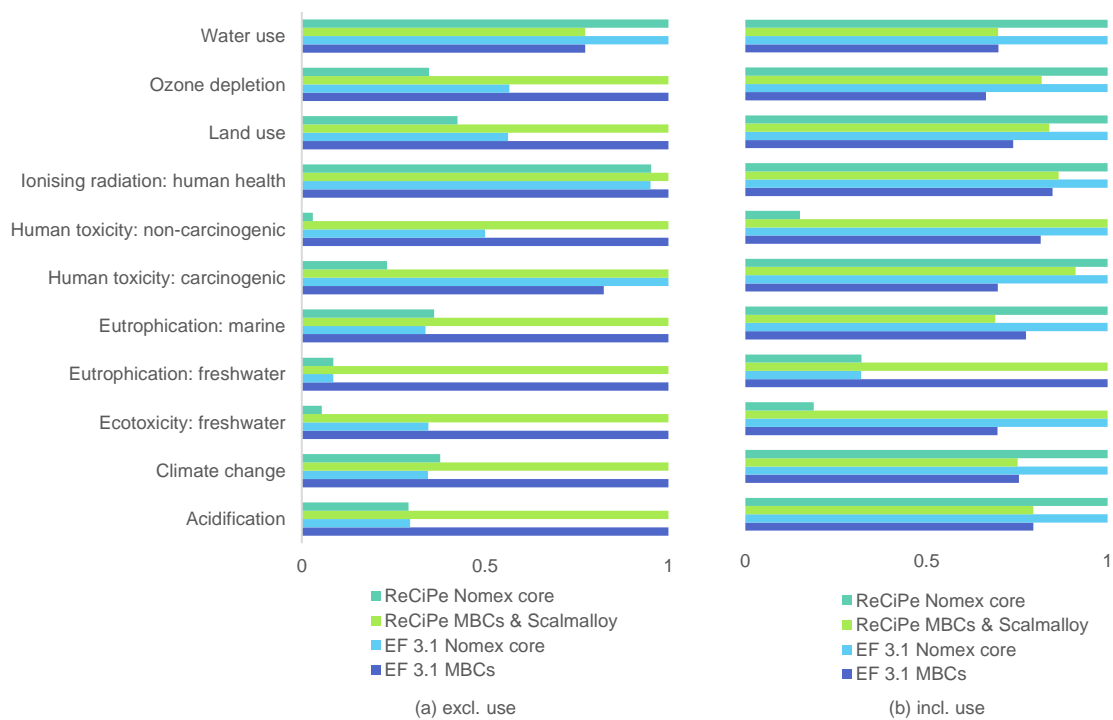


Figure 18. Sensitivity analysis employing different impact assessment models: EF 3.1 and ReCiPe for the comparison between interior aircraft partitions. Only comparable impact categories were selected and scaled to the highest impact. Baseline 2035.

3.3.2. Energy carriers, manufacturing

Prior sections have identified MBCs production as an energy-intensive process. This section delves into the energy consumption of upscaled production of MBCs material, and partition alternatives. The selection of energy source plays a crucial role in the environmental impact. A switch to a cleaner energy source would have a ripple effect, positively impacting various environmental categories as shown in Figure 19. Regardless of the production method, the energy used directly affects the final outcome. Its origin will directly influence the impact category this is related to. Among all impact categories, the use of renewable sources have a lower impact. Few exceptions include ionizing radiation which is higher when using nuclear power; as well as, water use which ranks higher when using hydro power because the energy inherently derived from this source.

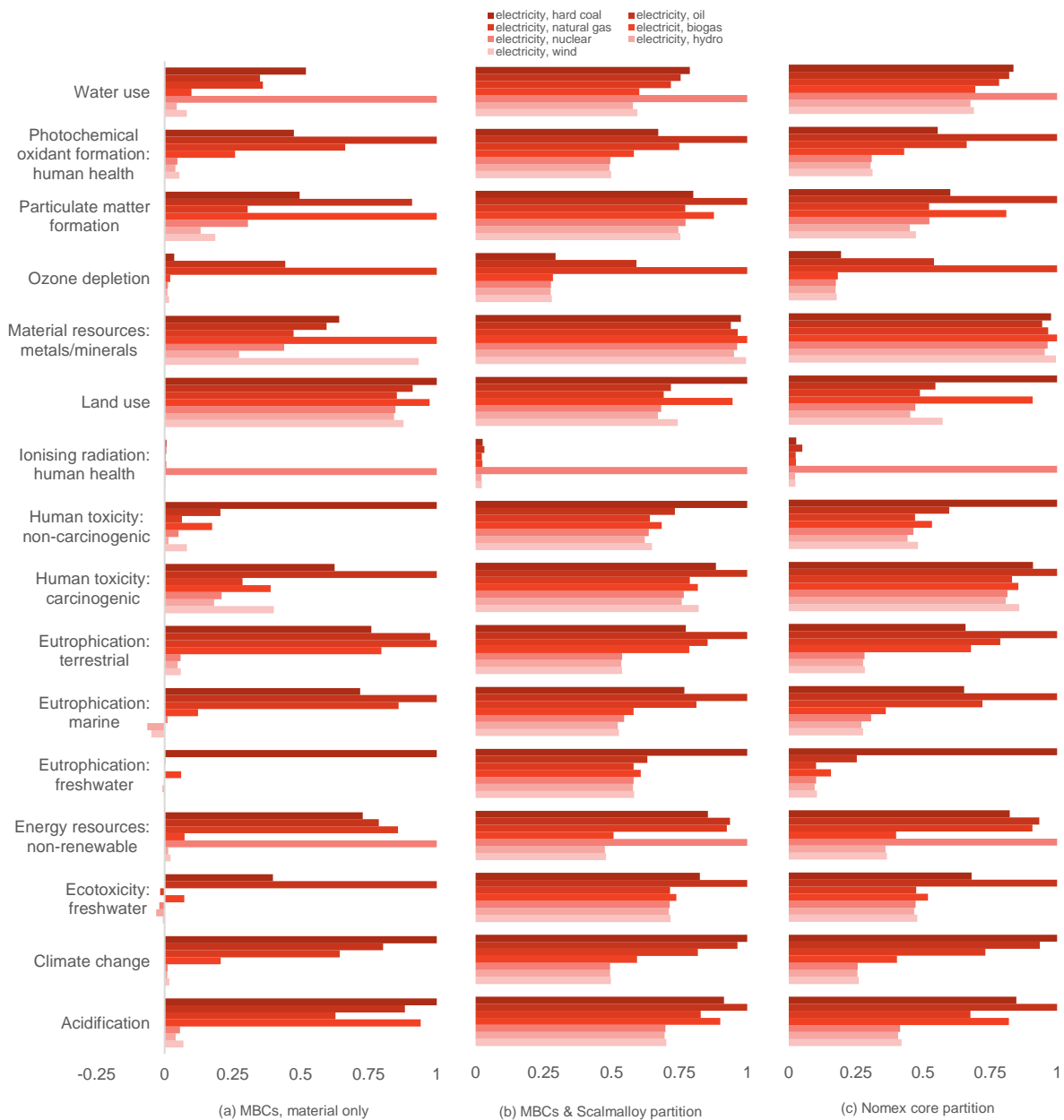


Figure 19. Sensitivity analysis during manufacturing, baseline 2035, using different energy carriers for: (a) of 1 kg of MBCs, (b) MBCs & Scalmalloy interior partition, (c) Nomex core partition, using EF v3.1 impact categories.

The analysis of MBCs material only (a) reveals that some environmental impact categories increase equally across different electricity sources, indicating a direct relationship with energy consumption. The 2035 scenario that continues reliance on hard coal, oil, or natural gas emphasizes this point, highlighting how these old-conventional sources significantly elevate the environmental impact across

all categories. Conversely, a shift towards renewable energy sources offers substantial reductions. Negative values for ecotoxicity in freshwater and marine environments, are anticipated for the future assessment, which might be attributable to background IAMs associated to advancements in technologies, which may include, for instance, the incorporation of carbon sequestration techniques. A further breakdown is available in Annex F.3 though a contribution analysis focused on climate change and energy: non-renewable resources.

The comparison between MBCs & Scalmaalloy (b) and Nomex core (c) partitions using different energy carriers (see Annex F.4) reveals similar patterns across the variability among the impact categories of: climate change, ionizing radiation: human health, ozone depletion, photochemical oxidant formation: human health, and particulate matter formation. It is assumed that these are primarily influenced by the energy source. Thus, it suggests that improving the energy source, such as shifting to renewable energy, can significantly reduce environmental impacts in these categories. On the other hand, categories with high variability, such as water use, human toxicity (non-carcinogenic and carcinogenic), material resources: metals/minerals, and ecotoxicity: freshwater, suggest that contributions are associated with other parts or inputs of the production system. For these, a broader approach to reducing environmental impact may be needed, not just the energy source.

3.3.3. Energy carrier, use phase

In the sensitivity analysis, it is explored the influence of transitioning to greener fuels, specifically biokerosene and hydrogen, compared to kerosene, on the environmental performance of MBCs & Scalmaalloy and Nomex core partition. As seen in Figure 20 and further detailed in Annex F.5, the main driver remains within the use phase remains linked to the weight of both partitions (MBCs & Scalmaalloy partitions are lighter, thus perform better in most impact categories).

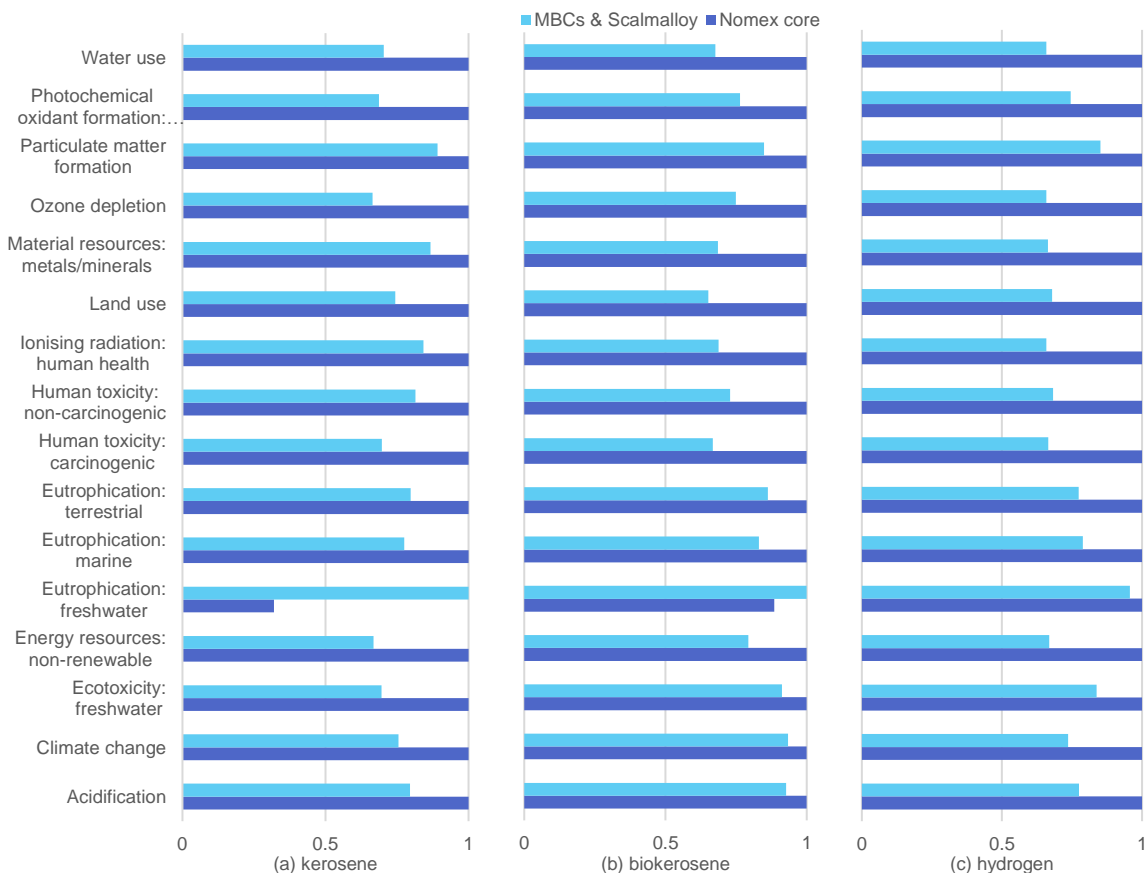


Figure 20. Sensitivity analysis based on using energy carriers: (a) kerosene, (b) biokerosene, (hydrogen) during the use phase on aircraft per partition over a period of six year, average lifespan of partition before replacement.

3.3.4. End-of-Life, Scalmetalloy recyclability

The results of this analysis resemble the results presented in section 3.1.3 and 3.2.3. for recyclability. Once again, when considering the use phase, the differences between EoL scenarios become almost unnoticeable. This reinforces that the use phase dominates the overall environmental impacts, making the variations due to different EoL treatments relatively minor. When excluding the use phase, recycling scenarios show minor increases in environmental impacts compared to incineration.

Recycling of Scalmetalloy (outsourced) shows slightly higher impacts across most categories compared to incineration. This can be attributed to the additional energy required for outsourced recycling processes, including transportation and processing. Additionally, when considering then 100% recycled scenario (both MBCs and Scalmetalloy) ranks as the highest. In this case, this highlights the need of a more specific and optimized recycling process that could potentially reduce these impacts significantly.

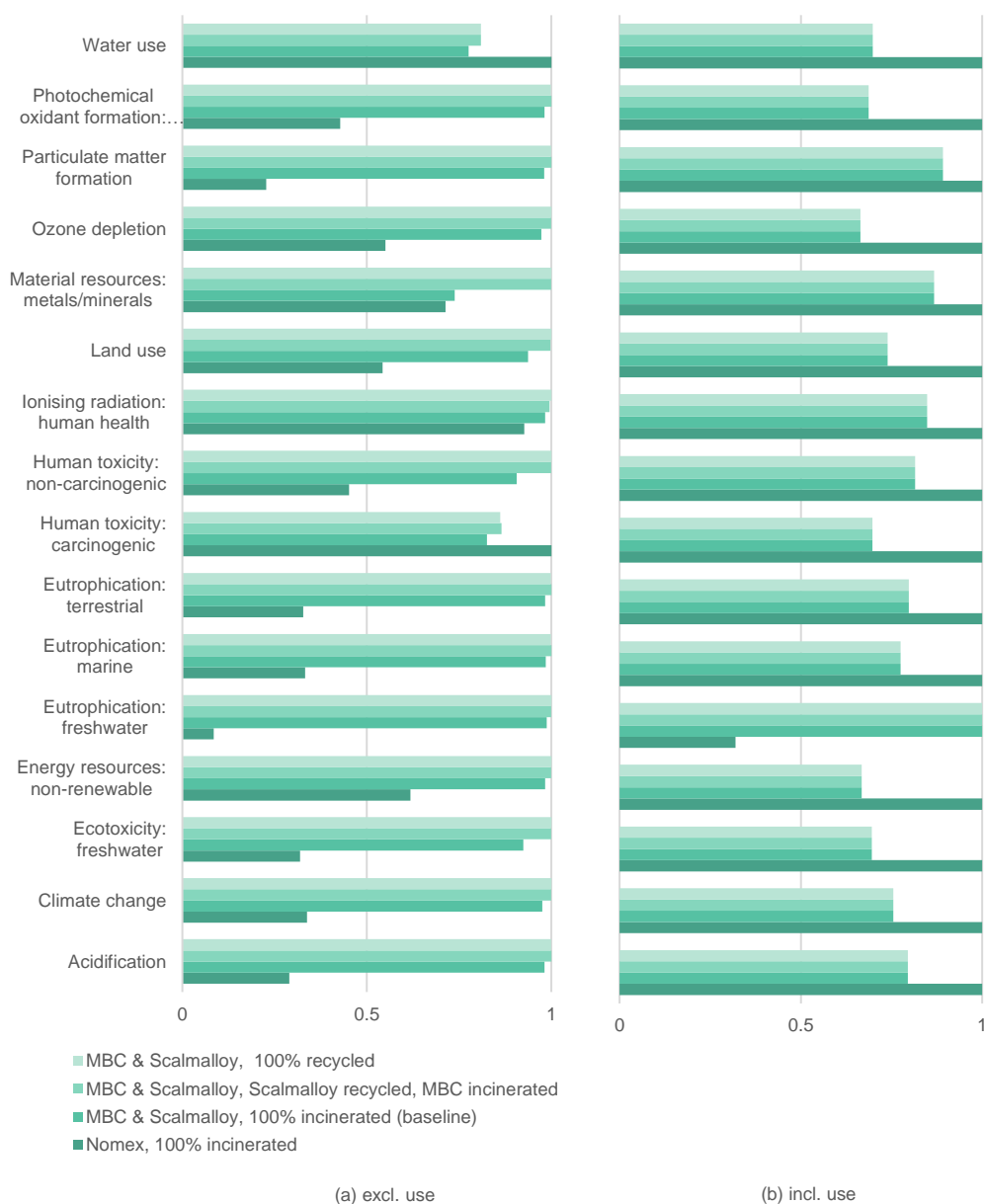


Figure 21. Sensitivity analysis for the EoL of Scalmetalloy component over an MBCs & Scalmetalloy partition: influence of incineration vs. recycling. Baseline 2035, using EF v3.1 impact categories

For a detailed breakdown of the different environmental impact categories for each recycling scenario, in this sensitivity analysis, refer to Annex E.4.

4

Discussion

4.1. Key findings

A key finding of this study is the high energy dependence of mycelium based composites (MBCs) production, even after estimated process optimization at the upscaled level. In order to achieve a significant reduction in the environmental impact of MBC production, energy optimization among processes, and further exploration of the energy matrix used in MBCs production are crucial. The study has shown energy consumption has a direct influence over the impact categories of climate change, ionizing radiation: human health, ozone depletion, photochemical oxidant formation: human health, and particulate matter formation. Areas with significant energy consumption, such as drying, sterilization, and cutting processes, require targeted optimization efforts. Additionally, optimizing controlled environment conditions for mycelium growth could potentially reduce energy consumption and production time, while maintaining efficiency.

When evaluating non-structural components, aircraft partitions, light weight emerges as the most critical factor. Thus, the promising use of MBCs as the sole material in aircraft partitions is limited given current strength limitations that prevent them from fulfilling their function, providing non-structural support. So, despite, the potential lower environmental impact of MBCs, given its bio-sourced nature, additional that provide structural support, such as Scalmalloy used in this design remain required.

The inherent lightweight nature of MBCs translates to a significant advantage when used as interior aircraft partitions. Lightweight translates to significant fuel savings and reduced in-flight emissions throughout the aircraft's operational life, leading to a potentially lower overall environmental impact compared to conventional materials like the Nomex core sandwich partition considered in this study. However, a crucial consideration emerges when the manufacturing phase is isolated from the lifecycle assessment. In this setting, the comparative LCA revealed a higher environmental footprint for MBCs & Scalmalloy partition compared to the conventional Nomex core one. Hence, while MBCs demonstrate significant promise during the use phase, further optimization of the manufacturing process remains necessary to fully unlock their potential for sustainable aircraft non-structural components.

4.2. From lab to industry

The status quo laboratory production have significant impacts values for fossil energy demand (11.47 MJ), climate change (0.4958 kg CO₂-eq), and land use (10.12). The results show considerable differences from those of previous studies. For climate change are lower to the ones from other studies employing similar substrates: 0.6933 and 0.6417 kg CO₂-eq for hemp and sawdust respectively (Volk et al., 2024), a range of 0.5560 - 0.7413 kg CO₂-eq for Mycobamboo (Carcassi et al., 2022). The energy demand from non renewable sources and land use are higher compared to the state of art 5.2779 MJ (Livne et al., 2022) and 7.71-7.26 MJ as well as 7.672 for landuse (Volk et al., 2024). It must be noted that the mentioned products refer to MBCs used for insulation purposes, similar to the requirements needed for aerospace application. Other MBCs forms such as bricks for stability and thermal regulation have higher values for climate change 1.15 - 3.18 kg CO₂-eq (Stelzer et al., 2021). The cause of the

observed variations remains unidentified due to limitations in the detail and transparency of inventory data provided by the respective studies. Further comparison with additional alternatives were limited given the lack of a similar functional unit (Alaux et al., 2023; Stelzer et al., 2021).

This study projects the upscaled technology to have lower environmental impact across most categories compared to the lab scale. This aligns with the findings of Alaux et al. (2023) except for eutrophication and terrestrial ecotoxicity. These discrepancies likely stem from differences in the impact assessment methods, as these categories are not included (CML 2001) or divided differently in the framework used here (EF 3.1). Limited literature is available for the upscale of technology, and have mainly reported changes for climate change impact category. Alaux et al. (2020) demonstrated a 40% reduction and Stelzer et al. achieving 68%. While our study shows a lower reduction (20%) for climate change, this is due to the more conservative upscaling approach, with significant changes centered in sterilization and drying processes.

The LCA revealed non-renewable energy consumption and land use as the most significant burdens across both lab-scale and industrial MBCs production for 2035. The first one is driven by the energy carrier used in manufacturing, while the second by the substrate employed for MBCs production. These findings underscore the need for advancements in renewable energy integration, exploration of sustainable substrate alternatives in order to achieve lower-impact production processes.

While recycling MBCs offers potential benefits, the additional energy required for these processes necessitates a careful balance between material recovery and environmental costs. The efficiency of the recycling process is influential; low recycling rates can negate the environmental benefits by introducing higher overall impacts. Future research should focus on optimizing recycling techniques to enhance efficiency and reduce energy consumption. This includes exploring advanced recycling methods, integrating renewable energy sources into the recycling process, and developing more precise models that accurately reflect the benefits and drawbacks of recycling MBCs.

The environmental impact of MBC production is significantly influenced by the energy sources used. The reliance on conventional fossil fuels elevates the environmental burden, whereas a shift towards renewable energy sources offers substantial reductions in impacts such as climate change and ecotoxicity.

4.3. The pathway to aircraft applications

The application of MBCs for aircraft interiors presents both significant potential and substantial challenges. While the current design of the MBC partition assessment shows promise, associated due to its lightweight advantage, several aspects of its manufacturing process require refinement to align with the ambitious goals of zero emissions and sustainable aviation.

MBCs based partitions offer a compelling proposition due to their inherent lightweight nature, which translates to significant fuel savings and reduced in-flight emissions over its lifespan within an aircraft operation. However, it is crucial to consider the trade-offs. While a relatively small weight reduction can significantly benefit the use phase, conventional materials are also undergoing continuous development towards lighter designs. If, in the future, both MBCs and conventional materials achieve similar weight levels, the environmental impact of the manufacturing phase will become a more critical factor. Here, MBCs face a challenge, as their current manufacturing processes require further optimization to minimize their environmental footprint. Therefore, ongoing research efforts should prioritize not only maintaining the lightweight advantage of MBCs but also optimizing their manufacturing processes to ensure their long-term sustainability compared to potentially lighter conventional materials.

This study showed an average lower impact in most categories in the range of 20 – 35 % (except for eutrophication of freshwater). In fact, the last one is strongly associated to the material selection for the

skeleton structure. While Scalmalloy is used in the current model, its large impact due to the presence of scandium enforces the need to search for alternative materials.

Additionally, the biodegradability of MBCs presents a long-term environmental advantage, potentially reducing waste and promoting a circular economy. However, this benefit comes with manufacturing considerations. Biodegradable components might require additional processing for proper EoL, potentially increasing energy consumption. Careful selection of an optimal recycling process is crucial to balance biodegradability with minimal manufacturing energy use.

4.4. Further considerations

The modeling assumes similar functionality within a same lifespan for MBCs and conventional alternatives, but the actual properties might differ. This variance needs further investigation to accurately assess its performance and environmental impacts.

The study acknowledges the limitations of its results. Due to the use of various scenarios and assumptions, the findings are specific to the technology investigated and may contain uncertainties. It is emphasized that these projections serve as a starting point for identifying environmental hotspots and potential improvements, not definitive predictions. This work can act as a foundation for further research. The purpose of this thesis was to establish a reference point for guiding future upscaling MBCs. It is crucial to note that this study is conducted solely for academic purposes. Consequently, while the results may serve as a valuable guide, it is imperative to emphasize that they do not directly translate into data applicable for industrial use in the aviation sector. This limitation underscores the academic nature of the study and its focus on providing conceptual insights rather than immediately implementable industry solutions.

For MBCs technology to achieve long-term success in aviation, further material development must ensure it meets the stringent criteria of current aviation materials. This includes rigorous testing for fire resistance, mechanical strength, and durability. Thus, investing in research to enhance biocomposite performance and developing industry standards for their use will be critical to achieving ambitious emission reduction targets in the aviation sector. Along this process, pLCA should be accounted as a tool since the design phase for improvement and informed decision making.

To advance MBCs, comprehensive LCA during design is crucial. This enables informed, sustainable decision-making by stakeholders, especially during this early development stage where significant optimizations are possible. LCA should consider diverse end-of-life scenarios, material substitutions, and innovative manufacturing techniques. An iterative approach for MBCs development will need to integrate LCA results and data from future prototyping is crucial. By constantly refining LCAs and incorporating learnings from prototyping into design choices, manufacturers and designers can minimize environmental impact. This iterative approach will accelerate the development of a sustainable, efficient, and advanced MBC technologies.

To ensure the long-term success of MBCs technology, its development must go beyond simply scaling production from laboratory to industry. Given the early stage of MBCs development, alongside with the use of technology surveillance, it is crucial to track the emergence of alternative technologies that could disrupt its development, and enable its positioning in the market. This includes monitoring advancements in materials science, manufacturing methods, and any evolving regulations that might impact MBCs adoption. Further efforts should also prioritize traceability of the origin of resources.

There is a need for broader industry engagement. Future research necessitates interdisciplinary collaboration so that the upscaled production of MBCs becomes clearer.

4.5. Limitations and further research

Limitations related to data availability have been carefully addressed in this study. As the case holder, Airbus does not directly produce the material, and therefore records on lab-scale technology depend upon primary data available from Chaudhury (2023) and secondary data and literature review. Unlike primary data that can be directly verified and controlled, secondary data relies on the accuracy and integrity of external sources. This study tried to contact the sources of these studies, yet it is challenging to validate the data comprehensively, potentially leading to the inclusion of inaccurate assumptions or biased information.

Both the lab-scale experimentation and scenario development stages actively sought feedback from the case holder and thesis supervisors. To accommodate possible time constraints, the validation process involved sessions with technology experts from Airbus working on scenario development and material research. However, for the critical validation required for the upscaling of the technology, only one session with multiple persons was available. While this limitation may have impacted the precision of the validation process, it represented a necessary compromise to adhere to the timeframe and availability of the experts. In this way, the upscaling of the technology was limited to a conservative estimation of changes and based on previous work of technologies used in the field. However, aviation is a complex industry, requiring considering more complex system dynamics for the upscaling of the technology. Additionally, approaches that involve meetings with different experts on the topic can further refine the estimates and enhance the precision of the technology integration into the aviation system.

Further research efforts are crucial to unlock the full potential of MBCs for sustainable aviation applications. Optimizing production methods remains a priority to ensure consistent material properties that meet the stringent standards of the aerospace industry. Exploring diverse substrates, including recycled materials and alternative bio-based options, is required for further MBCs development. Substrate variations can influence final material properties, but also potentially impact growth time and production processes. Additionally, research into cascading reuse/recycling cycles for bio-sourced composites is necessary to maximize their lifespan. Understanding the long-term behavior of MBCs, particularly their moisture sensitivity, insulation and fire resistance characteristics, durability, and potential biodegradation, is also of importance.

Given the current energy-intensive nature of MBCs manufacturing process, future research efforts could explore the feasibility of implementing a closed-loop system for internal heat recovery. This approach could significantly reduce the overall energy consumption and contribute to a more circular production.

A key area for future research lies in developing a more accurate and MBCs-specific recycling model. The current assessment relies on an adaptation from carbon fiber recycling, which may not fully capture the unique characteristics of MBCs and could potentially overestimate environmental impact. A more precise model tailored to MBCs should consider not only mechanical recycling but also adjust for their biodegradability, providing a clearer picture of the environmental benefits associated with recycled substrates. Additionally, this study focused specially on the MBC material component, excluding the recyclability of the additional structural element, Scalmalloy. Optimizing and understanding the recycling potential of these components should also be a focus of future investigations.

A limitation of this study lies in the modeling of Scalmalloy's environmental impact. Due to the lack of a publicly available, detailed material composition, the model relies on average values gathered from literature and patents. This inherent variability in the material's composition introduces significant uncertainty into the results. Consequently, the environmental impact of Scalmalloy might be misrepresented, potentially affecting its competitiveness compared to conventional materials.

The development of MBCs for aircraft partitions is actively exploring alternative manufacturing techniques for producing MBC partitions (which were not covered in the scope in this study). Further

LCA research should explore these alternative MBCs production methods, evaluating their energy consumption and environmental impact.

Finally, further research should include a cost-benefit analysis of transitioning from conventional materials to biosourced MBCs. This analysis will help in understanding the economic implications and potential financial benefits of adopting MBCs, ensuring that they are not only environmentally sustainable but also economically viable.

5

Conclusion

This study addressed the environmental viability of mycelium based composites (MBCs) as materials for aircraft applications. A key challenge lied in evaluating their impact considering the uncertainties associated with their early-stage development. To tackle this challenge, the thesis employed a Prospective Life Cycle Assessment (pLCA) methodology. By starting with an early-stage design concept for a mycelium-based aircraft partition, the thesis evaluated the potential of an upscaled industrial version, expected to be ready by 2035. This evaluation combined data obtained from previous records on lab experiments, literature review, and various scenario considerations to project future feasibility and performance. This analysis explored the potential of incorporating circular waste streams for MBCs production, as opposed to a linear end-of-life approach, and examined the influence of different energy carriers during manufacturing and use. Overall, the lightweight nature of MBCs remains the primary driver for the environmental performance of these interior components.

Early-stage assessments are critical for identifying potential environmental impacts and opportunities for improvement. The upscaled technology currently projects lower emissions compared to lab-scale production. However, the full potential of this technology will only be realized around 2035, as it requires approximately 10 more years to reach the necessary development level. Future environmental impacts of MBCs at an industrial production level will depend on various factors, including the energy sources used, the efficiency of the production processes, and the choice of material inputs.

The industrial upscaled MBCs production showed reduced impacts for most indicators compared to the laboratory production, but a considerable trade-off was observed with regard to terrestrial ecotoxicity. The main driver for the climate change, and its associated emissions was found to be the electricity use during the manufacturing phase. Indeed, scaling up MBCs production is energy-intensive.

Thus, the increased production volume at the industrial scale may easily add up more energy demand, particularly due to additional processes required to achieve quality standards. As a result, the impacts can increase significantly, contributing impact categories of climate change, ionizing radiation: human health, ozone depletion, photochemical oxidant formation: human health, and particulate matter formation. The categories of terrestrial ecotoxicity, eutrophication of fresh water and water usage show the most significant reductions during upscaling. However, they are sensitive to the selection of impact methodology assessment. The sensitivity analysis revealed less variation for climate change impact, indicating these results reflect a strong foundation for future research.

The production process for MBCs is highly energy-intensive. Despite considerations for industrial learning and energy-efficient machinery during upscaling, the process is still heavily dependent on energy. Potential hotspots in the manufacturing stage are associated with increased energy consumption, therefore high energy-intensive procedures such as sterilization and drying are key areas for improvement. Additionally, as the country of production and its energy matrix are strongly related, transitioning to cleaner energy sources significantly influence of the final environmental impact.

The pLCA identified climate change, non-renewable energy consumption and land use as the most significant burdens for industrial MBC production by 2035. Under the projected IAM model, climate change emissions are expected to increase if there is a reliance on the current energy matrix. Land use remains significant and is dependent on the choice of substrate. Land use can be reduced by decreasing the need for virgin materials and considering recycling. However, trade-offs are evident as recycling adds energy demands and impacts other categories sensitive to energy use. Therefore, more accurate recycling methods are required. These findings highlight the necessity for advancements in renewable energy, sustainable substrate alternatives, and energy efficient production processes.

The results are encouraging for MBCs as a material for non-structural aircraft application when considering its use phase, mainly associated to its lightweight nature. This trend persists across various environmental impact categories, even in scenarios where aviation energy carriers are swiftly decarbonized. However, the manufacturing process at the projected stage does not necessarily surpass those of conventional materials, such as the Nomex core sandwich partition. One must attribute this to the years of development and improvement that conventional materials have undergone. Therefore, to balance this, it is necessary to improve the manufacturing process and not rely solely on the material's lightweight properties, considering ongoing research and development aimed at making conventional composites lighter may diminish or negate the perceived benefits of MBCs. One must not neglect the emerging technology nature of MBCs, they require optimization and process refinement to eventually become better options.

The current design of the mycelium-based partition assessment must be improved, particularly regarding material selection and considerations related to waste streams. To take advantage of the recyclability potential, the current model enable the reuse of the final MBCs part of the overall partition as substrate for the growth of new material, reducing the need for virgin substrate.

Recycling does not inherently mean better environmental performance. The additional energy required for recycling processes highlights the need to balance the benefits of material recovery with the environmental costs, including the efficiency of the recycling process itself. This is crucial for understanding the overall sustainability of upscaling MBC technology. If recycling rates are too low or the recycling process is inefficient, the process may not significantly improve the overall environmental impact. The recycling methods selected in this study for recovering MBCs did not show a significant improvement in reducing the overall environmental impact of the mycelium based partitions.

Exploring less impactful materials than the currently used alloy is another area for improvement. While the alloy remains advantageous due to its compactness, it contains rare elements, mainly scandium, that have higher environmental impacts due to extraction and potential depletion. A more promising approach might be replacing the structural skeleton components with alternative materials. This could involve identifying materials with lower life cycle impacts that still meet the required structural properties or reducing the amount of material used in the structural skeleton through design optimization.

The upscaling of MBCs technology presents both challenges and opportunities. By enhancing early-stage LCA assessments, optimizing recycling processes, adopting renewable energy sources, exploring alternative substrates, and ensuring regulatory compliance, the environmental performance of MBCs can be significantly improved.

The emerging nature of the MBCs technology allows for creative and disruptive approaches. Early assessments for MBCs highlight as key areas for innovation: exploring diverse recycling methods and EoL options, performance in real environmental conditions, extending its lifespan, investigating material combinations and alternative substrates, and developing improved manufacturing techniques.

By filling crucial data gaps, the pLCA serves as a foundation for informed decision-making and future research and development efforts for sustainable aircraft cabin interiors. This project paves the way for the potential adoption of MBCs, fostering a more environmentally friendly future for the aviation industry.

References

- Airbus. (2021a). *Decarbonisation. Towards low-carbon air travel for future generations*. <https://www.airbus.com/en/sustainability/respecting-the-planet/decarbonisation>
- Airbus. (2021b). *Operating life*. <https://www.airbus.com/en/products-services/commercial-aircraft/the-life-cycle-of-an-aircraft/operating-life>
- Airbus. (2023). *Global Market Forecast 2023—2042*. https://www.airbus.com/sites/g/files/jlcbta136/files/2023-06/GMF%202023-2042%20Presentation_0.pdf
- Alaux, N., Vašatko, H., Maierhofer, D., Saade, M. R. M., Stavric, M., & Passer, A. (2023). Environmental potential of fungal insulation: A prospective life cycle assessment of mycelium-based composites. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-023-02243-0>
- Alemu, D., Tafesse, M., & Mondal, A. K. (2022). Mycelium-Based Composite: The Future Sustainable Biomaterial. *International Journal of Biomaterials*, 2022, 8401528. <https://doi.org/10.1155/2022/8401528>
- Arblaster, T. (2023). *Environmental trade-offs of aerostructures: A prospective lifecycle assessment of wing ribs*. <https://repository.tudelft.nl/islandora/object/uuid%3A8e4ca28b-134f-402b-80ea-f3e8f1fc63db>
- Arvidsson, R., Svanström, M., Sandén, B. A., Thonemann, N., Steubing, B., & Cucurachi, S. (2023). Terminology for future-oriented life cycle assessment: Review and recommendations. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-023-02265-8>
- Awd, M., Tenkamp, J., Hirtler, M., Siddique, S., Bambach, M., & Walther, F. (2018). Comparison of Microstructure and Mechanical Properties of Scalmetalloy® Produced by Selective Laser Melting and Laser Metal Deposition. *Materials*, 11(1), Article 1. <https://doi.org/10.3390/ma11010017>
- Ayala, M. (2023). *Novel seaweed-based bioplastic: A prospective Life Cycle Assessment*. <https://doi.org/10.54337/aau561807181>
- Barke, A., Thies, C., Melo, S. P., Cerdas, F., Herrmann, C., & Spengler, T. S. (2020). Socio-economic life cycle assessment of future aircraft systems. *Procedia CIRP*, 90, 262–267. <https://doi.org/10.1016/j.procir.2020.01.096>
- Bitting, S., Derme, T., Lee, J., Van Mele, T., Dillenburger, B., & Block, P. (2022). Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication. *Biomimetics*, 7(2), Article 2. <https://doi.org/10.3390/biomimetics7020044>
- Blanco, C. F., Cucurachi, S., Guinée, J. B., Vijver, M. G., Peijnenburg, W. J. G. M., Trattnig, R., & Heijungs, R. (2020). Assessing the sustainability of emerging technologies: A probabilistic LCA method applied to advanced photovoltaics. *Journal of Cleaner Production*, 259, 120968. <https://doi.org/10.1016/j.jclepro.2020.120968>
- Bonenberg, A., Sydor, M., Cofta, G., Doczekalska, B., & Grygorowicz-Kosakowska, K. (2023). Mycelium-Based Composite Materials: Study of Acceptance. *Materials*, 16(6), Article 6. <https://doi.org/10.3390/ma16062164>
- Carcassi, O. B., Minotti, P., Habert, G., Paoletti, I., Claude, S., & Pittau, F. (2022). Carbon Footprint Assessment of a Novel Bio-Based Composite for Building Insulation. *Sustainability*, 14(3), Article 3. <https://doi.org/10.3390/su14031384>
- Cerimi, K., Akkaya, K. C., Pohl, C., Schmidt, B., & Neubauer, P. (2019). Fungi as source for new bio-based materials: A patent review. *Fungal Biology and Biotechnology*, 6(1), 17. <https://doi.org/10.1186/s40694-019-0080-y>
- Chaudhury, M. C. (2023). *Designing Circular Applications of Mycelium-Based Materials for Aircraft Cabins*. <https://repository.tudelft.nl/islandora/object/uuid%3Ab03f6df7-5fec-4f67-9dd1-f3aee82ed502>
- Cooper, C., Alderliesten, R., La Rocca, G., & Benedictus, R. (2009). *In Search of a Knowledge Based Preliminary Design Method of Complex Aircraft Wings*.
- Cucurachi, S., Steubing, B., Siebler, F., Navarre, N., Caldeira, C., & Sala, S. (2022). *Prospective LCA methodology for Novel and Emerging Technologies for BIO-based products—The PLANET BIO project*. <https://doi.org/10.2760/167543>
- EASA & EEA. (2019). *European aviation environmental report 2019*. Publications Office. <https://data.europa.eu/doi/10.2822/309946>
- Erakca, M., Baumann, M., Helbig, C., & Weil, M. (2024). Systematic review of scale-up methods for prospective life cycle assessment of emerging technologies. *Journal of Cleaner Production*, 451, 142161. <https://doi.org/10.1016/j.jclepro.2024.142161>
- European Commission. (2017). *PEFCR Guidance document,—Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs)* (v6.3). https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf
- Florin, M.-V., et al, & International Risk Governance Center at EPFL (IRGC) (Eds.). (2023). *IRGC (2023) Ensuring the environmental sustainability of emerging technologies—2. Edited volume*. EPFL. <https://doi.org/10.5075/epfl-irgc-298445>
- Gavankar, S., Suh, S., & Keller, A. A. (2015). The Role of Scale and Technology Maturity in Life Cycle Assessment of Emerging Technologies: A Case Study on Carbon Nanotubes. *Journal of Industrial Ecology*, 19(1), 51–60. <https://doi.org/10.1111/jiec.12175>

- Ghazvinian, A., & Gursoy, B. (2022). Basics of building with mycelium-based bio-composites: A review of built projects and related material research. *Journal of Green Building*, 17(1), 37–69. <https://doi.org/10.3992/jgb.17.1.37>
- Gonzalez-Garcia, A., Martin, P. P., Lapena, N., & Wonneberger, M. (2015). *Fire resistant sustainable aircraft interior panels* (United States Patent US20150190987A1). <https://patents.google.com/patent/US20150190987/de>
- Guinée, J., Gorrae, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A., Oers, L., Wegener Sleeswijk, A., Suh, S., Haes, H., Bruijn, H., van Duin, R., & Huijbregts, M. (2002). *Handbook on LCA, operational guide to the ISO standards*.
- Hur, H., Imtiaj, A., Lee, M. W., & Lee, T.-S. (2008). Suitable Conditions for Mycelial Growth of *Phellinus* spp. *Mycobiology*, 36(3), 152–156. <https://doi.org/10.4489/MYCO.2008.36.3.152>
- ISO. (2006a). *Environmental management—Life cycle assessment—Principles and framework*. ISO, 14040.
- ISO. (2006b). *Environmental management—Life cycle assessment—Requirements and guidelines*. ISO, 14044.
- Karana, E., Blauwhoff, D., Hultink, E.-J., & Camere, S. (2018). *When the Material Grows: A Case Study on Designing (with) Mycelium-based Materials*. 12(2).
- Koutny, D., Skulina, D., Pantělejev, L., Paloušek, D., Lenczowski, B., Palm, F., & Nick, A. (2018). Processing of Al-Sc aluminum alloy using SLM technology. *Procedia CIRP*, 74, 44–48. <https://doi.org/10.1016/j.procir.2018.08.027>
- Lai, Y. Y., Karakaya, E., & Björklund, A. (2022). Employing a Socio-Technical System Approach in Prospective Life Cycle Assessment: A Case of Large-Scale Swedish Sustainable Aviation Fuels. *Frontiers in Sustainability*, 3. <https://www.frontiersin.org/articles/10.3389/frsus.2022.912676>
- Langkau, S., Steubing, B., Mutel, C., Ajie, M. P., Erdmann, L., Voglhuber-Slavinsky, A., & Janssen, M. (2023). A stepwise approach for Scenario-based Inventory Modelling for Prospective LCA (SIMPL). *The International Journal of Life Cycle Assessment*, 28(9), 1169–1193. <https://doi.org/10.1007/s11367-023-02175-9>
- LDE Cfs Industries-Hub. (2023). *Interdisciplinary Thesis Lab 2023-2024: Circulaerospace*. https://www.centre-for-sustainability.nl/uploads/cfs/attachments/Thesis%20lab%20booklet_Aerospace%20V2A%201_0.pdf
- Livne, A., Wösten, H. A. B., Pearlmutter, D., & Gal, E. (2022). Fungal Mycelium Bio-Composite Acts as a CO₂-Sink Building Material with Low Embodied Energy. *ACS Sustainable Chemistry & Engineering*, 10(37), 12099–12106. <https://doi.org/10.1021/acssuschemeng.2c01314>
- Luderer, G. (n.d.). *REMIND - REgional Model of INvestments and Development*. Potsdam Institute for Climate Impact Research. Retrieved May 15, 2024, from <https://www.pik-potsdam.de>
- Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., Fricko, O., Hejazi, M., Humpenöder, F., Iyer, G., Mima, S., Mouratiadou, I., Pietzcker, R. C., Popp, A., van den Berg, M., van Vuuren, D., & Hertwich, E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, 10(1), 5229. <https://doi.org/10.1038/s41467-019-13067-8>
- Martin, P. P., Gonzalez-Garcia, A., Lapena, N., Fita-Bravo, S., Martinez-Sanz, V., & Marti-Ferrer, F. (2012). *Green Aircraft Interior Panels* (United States Patent US20120148824A1). <https://patents.google.com/patent/US20120148824A1/en>
- Miralbes, R., Ranz, D., & Zouzias, D. (2021). Study of the Use of Sawdust and Mycelium Composite as a Substitute of EPS. In L. Roucoules, M. Paredes, B. Eynard, P. Morer Camo, & C. Rizzi (Eds.), *Advances on Mechanics, Design Engineering and Manufacturing III* (pp. 67–72). Springer International Publishing. https://doi.org/10.1007/978-3-030-70566-4_12
- Pacana, A., Siwiec, D., Bednarova, L., & Petrovský, J. (2023). Improving the Process of Product Design in a Phase of Life Cycle Assessment (LCA). *Processes*, 11, 2579. <https://doi.org/10.3390/pr11092579>
- Parveez, B., Kittur, M. I., Badruddin, I. A., Kamangar, S., Hussien, M., & Umarfarooq, M. A. (2022). Scientific Advancements in Composite Materials for Aircraft Applications: A Review. *Polymers*, 14(22), Article 22. <https://doi.org/10.3390/polym14225007>
- Pascoe, J. A. (2024). *Certification and circularity: Combining safety and sustainability* [LDE-CFS Thesislab].
- Rahn, A., Wicke, K., & Wende, G. (2022). Using Discrete-Event Simulation for a Holistic Aircraft Life Cycle Assessment. *Sustainability*, 14(17), Article 17. <https://doi.org/10.3390/su141710598>
- Ramon, E., Sguazzo, C., & Moreira, P. M. G. P. (2018). A Review of Recent Research on Bio-Based Epoxy Systems for Engineering Applications and Potentialities in the Aviation Sector. *Aerospace*, 5(4), Article 4. <https://doi.org/10.3390/aerospace5040110>
- Robertson, O., Høgdal, F., Mckay, L., & Lenau, T. (2020). Fungal Future: A review of mycelium biocomposites as an ecological alternative insulation material. *DS 101: Proceedings of NordDesign 2020, Lyngby, Denmark, 12th - 14th August 2020*, 1–13. <https://doi.org/10.35199/NORDDESIGN2020.18>
- Sacchi, R., Becatini, V., Gabrielli, P., Cox, B., Dirnaichner, A., Bauer, C., & Mazzotti, M. (2023). How to make climate-neutral aviation fly. *Nature Communications*, 14(1), Article 1. <https://doi.org/10.1038/s41467-023-39749-y>
- Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2022). PROspective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and Sustainable Energy Reviews*, 160, 112311. <https://doi.org/10.1016/j.rser.2022.112311>

- Sander-Titgemeyer, A., Risse, M., & Weber-Blaschke, G. (2023). Applying an iterative prospective LCA approach to emerging wood-based technologies: Three German case studies. *The International Journal of Life Cycle Assessment*, 28(5), 495–515. <https://doi.org/10.1007/s11367-023-02139-z>
- Schmidtke, K., Palm, F., Hawkins, A., & Emmelmann, C. (2011). Process and Mechanical Properties: Applicability of a Scandium modified Al-alloy for Laser Additive Manufacturing. *Physics Procedia*, 12, 369–374. <https://doi.org/10.1016/j.phpro.2011.03.047>
- Schritt, H., Vidi, S., & Pleissner, D. (2021). Spent mushroom substrate and sawdust to produce mycelium-based thermal insulation composites. *Journal of Cleaner Production*, 313, 127910. <https://doi.org/10.1016/j.jclepro.2021.127910>
- Smart certification for sustainable aviation. (n.d.). TU Delft. Retrieved April 23, 2024, from <https://www.tudelft.nl/en/stories/articles/smart-certification-for-sustainable-aviation>
- Stelzer, L., Hoberg, F., Bach, V., Schmidt, B., Pfeiffer, S., Meyer, V., & Finkbeiner, M. (2021). Life Cycle Assessment of Fungal-Based Composite Bricks. *Sustainability*, 13(21), Article 21. <https://doi.org/10.3390/su132111573>
- Steubing, B., & de Koning, D. (2021). Making the use of scenarios in LCA easier: The superstructure approach. *The International Journal of Life Cycle Assessment*, 26(11), 2248–2262. <https://doi.org/10.1007/s11367-021-01974-2>
- Thonemann, N., Schulte, A., & Maga, D. (2020). How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. *Sustainability*, 12(3), Article 3. <https://doi.org/10.3390/su12031192>
- Travaglini, S., Parlevliet, P. P., & Dharan, C. K. H. (2019). Bio-Based Mycelium Materials for Aerospace Applications. *Proceedings of the American Society for Composites 43rd Thirty-Fourth Technical Conference*, 0(0), Article 0. <https://doi.org/10.12783/asc34/31327>
- Tsai, W.-H., Chang, Y.-C., Lin, S.-J., Chen, H.-C., & Chu, P.-Y. (2014). A green approach to the weight reduction of aircraft cabins. *Journal of Air Transport Management*, 40, 65–77. <https://doi.org/10.1016/j.jairtraman.2014.06.004>
- Tsoy, N., Steubing, B., Van Der Giesen, C., & Guinée, J. (2020). Upscaling methods used in ex ante life cycle assessment of emerging technologies: A review. *The International Journal of Life Cycle Assessment*, 25(9), 1680–1692. <https://doi.org/10.1007/s11367-020-01796-8>
- van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, 259, 120904. <https://doi.org/10.1016/j.jclepro.2020.120904>
- van der Hulst, M. K., Huijbregts, M. A. J., van Loon, N., Theelen, M., Kootstra, L., Bergesen, J. D., & Hauck, M. (2020). A systematic approach to assess the environmental impact of emerging technologies: A case study for the GHG footprint of CIGS solar photovoltaic laminate. *Journal of Industrial Ecology*, 24(6), 1234–1249. <https://doi.org/10.1111/jiec.13027>
- Vidal, R., Moliner, E., Martin, P. P., Fita, S., Wonneberger, M., Verdejo, E., Vanfleteren, F., Lapeña, N., & González, A. (2018). Life Cycle Assessment of Novel Aircraft Interior Panels Made from Renewable or Recyclable Polymers with Natural Fiber Reinforcements and Non-Halogenated Flame Retardants. *Journal of Industrial Ecology*, 22(1), 132–144. <https://doi.org/10.1111/jiec.12544>
- Villares, M., İşildar, A., van der Giesen, C., & Guinée, J. (2017). Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste. *The International Journal of Life Cycle Assessment*, 22(10), 1618–1633. <https://doi.org/10.1007/s11367-017-1270-6>
- Volk, R., Schröter, M., Saeidi, N., Steffl, S., Javadian, A., Hebel, D. E., & Schultmann, F. (2024). Life cycle assessment of mycelium-based composite materials. *Resources, Conservation and Recycling*, 205, 107579. <https://doi.org/10.1016/j.resconrec.2024.107579>
- Williams, E., Cenian, K., Golsteijn, L., Morris, B., & Scullin, M. L. (2022). Life cycle assessment of MycoWorks' Reishi™: The first low-carbon and biodegradable alternative leather. *Environmental Sciences Europe*, 34(1), 120. <https://doi.org/10.1186/s12302-022-00689-x>
- Yang, L., Park, D., & Qin, Z. (2021). Material Function of Mycelium-Based Bio-Composite: A Review. *Frontiers in Materials*, 8. <https://www.frontiersin.org/articles/10.3389/fmats.2021.737377>
- Zhang, J., Chevali, V. S., Wang, H., & Wang, C.-H. (2020). Current status of carbon fibre and carbon fibre composites recycling. *Composites Part B: Engineering*, 193, 108053. <https://doi.org/10.1016/j.compositesb.2020.108053>
- Zhu, H., Li, R., WANG, M., Liu, Y., YUAN, T., & NIU, P. (2021). Aluminum alloy powder capable of being used for 3d printing, preparation method therefor, and application thereof (European Union Patent EP3851548A1). <https://patents.google.com/patent/EP3851548A1/en?q=EP3851548A1>

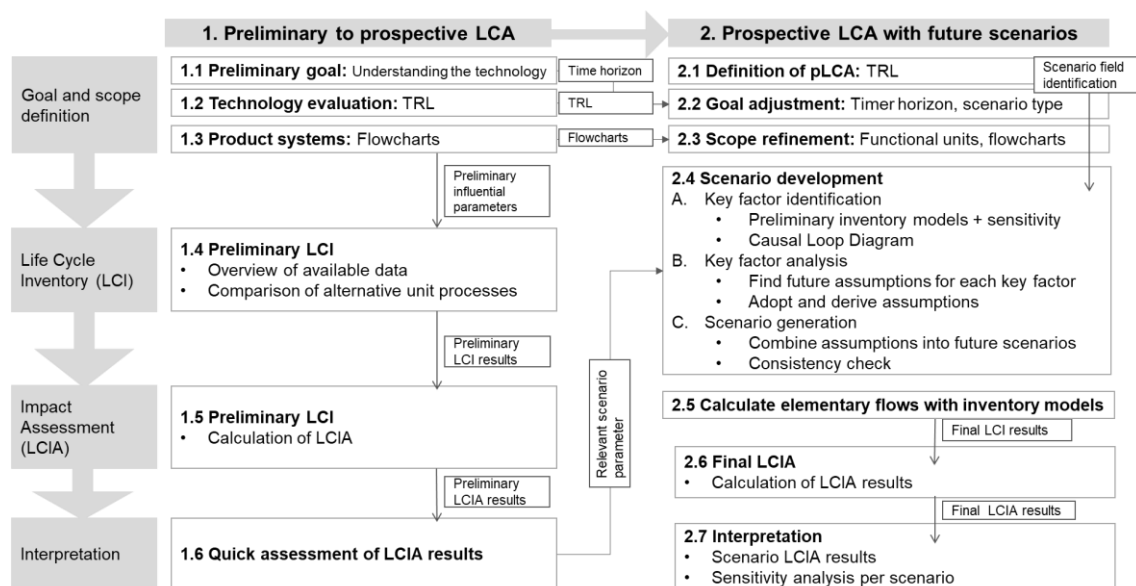
Appendix

A. Conceptual framework for prospective lifecycle assessment

The scenario-based inventory modeling by Langkau et al. (2023) was followed for scenario development for this pLCA. Parallely, the guidelines provided by Cucurachi et al. (Cucurachi et al., 2022) served as basis for pLCA considerations. For the modeling and quantitative assessment ActivityBrowser open source LCA software was used.

First, a preliminary LCA is carried out, conducting an uncertainty analysis to identify factors that may influence potentially future product systems (Sander-Titgemeyer et al., 2023). Findings from this part are integrated into a second phase, the prospective LCA. As shown in Figure 1, the LCA of MBCs at laboratory scale serves to explore the emerging technology (1.1). Then, it is possible to address potential future conditions (1.2–1.3). Insights from these steps serve as a basis for improvements in scope and goal definition (2.1–2.3). Important parameters from 1.4–1.6 are used for scenario modeling (2.4). Then inventory results, impact assessment, and interpretation are carried out (2.5–2.7) (Langkau et al., 2023; Sander-Titgemeyer et al., 2023).

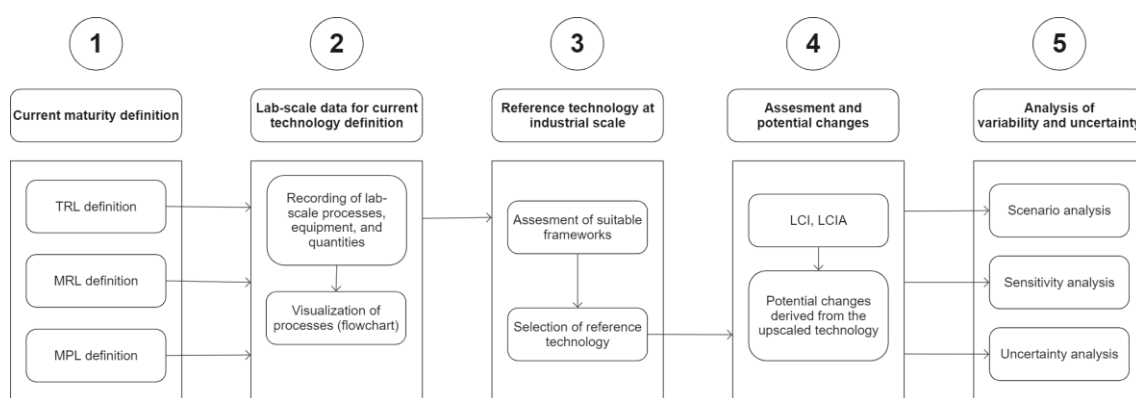
The impacts produced by the scenario-related factors and the LCIA findings of the scenarios will be analyzed. Once hotspots have been identified, this could be linked to the evaluation of the results under strategies for improvement (Sander-Titgemeyer et al., 2023). See below the methodology flow diagram built based on approaches of Langkau et al. (2023) and Sander-Titgemeyer et al. (2023).



B. Extended five steps approach for technology upscaling

In order to evaluate the environmental impact of using bio-based materials (MBCs) for aircraft interiors, the frame by Tsoy et al. (2020) was followed to develop upscaling scenarios, which includes: (a) projected technology scenario definition, (b) preparation of a projected LCA flowchart, and (c) projected data estimation which will be defined based on the data available.

To evaluate the environmental impact a LCA approach was adopted, following the 5-step scale-up methods for prospective LCA of emerging technologies (Erakca et al., 2024; Tsoy et al., 2020). This step-by-step approach provides a framework for assessing the environmental impact of MBCs at a future, larger production scale.

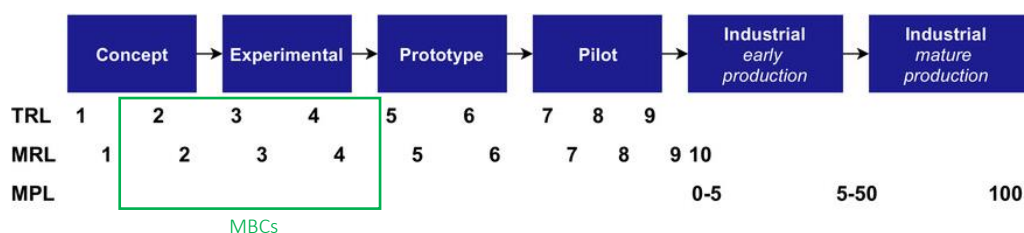


Step 1 – Current maturity definition

Due to the ongoing development and research on MBCs, there is currently a reliance on diverse techniques for producing them (Alaux et al., 2023; Bitting et al., 2022, p. 3; Karana et al., 2018; Robertson et al., 2020; Travaglini et al., 2019; Volk et al., 2024; Williams et al., 2022). Therefore, it is important to note that a more defined version of the lab scale needs to be established.

The first step involves assessing the current stage of development by defining three key metrics: Technology Readiness Level (TRL), Manufacturing Readiness Level (MRL), and Market Penetration Level (MPL). While MBCs have shown promise in various applications, their current TRL varies depending on the intended use.

The following diagram present the interrelationship between TRL, MRL, and MPL. Green box represent the range for mycelium based applications. This was modified based on van der Hulst et al. (2020).

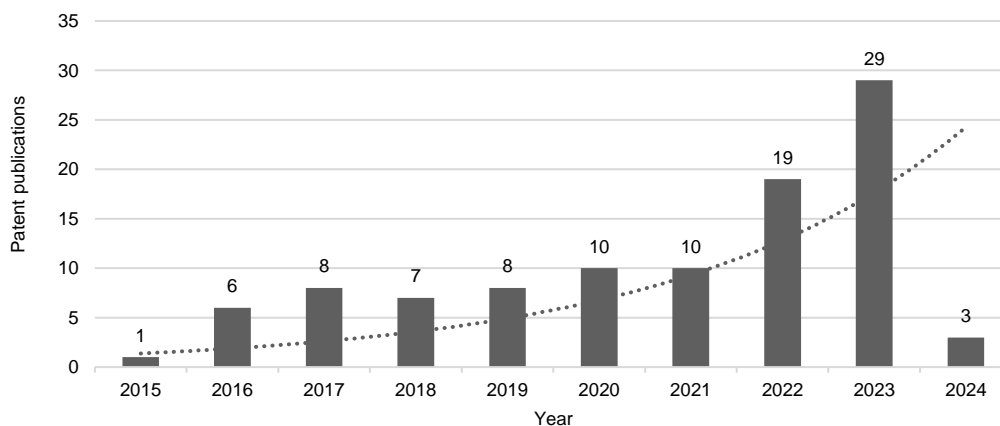


Due to the focus on laboratory-scale production, MBCs for most applications would likely fall between TRL 2-3 (proof of concept). Alaux et al. (2023) suggest a TRL of 4-5 for their use as building insulation, as it has validation in a laboratory environment indicating progress towards pilot-scale production. Similarly, mycelium-based leather is currently at the pilot stage (Williams et al., 2022). However,

applications in the aerospace industry, such as aircraft propellers, remain firmly in the laboratory phase, with pilot projects only expected in the coming years (Chaudhury, 2023). Furthermore, the Manufacturing Readiness Level (MRL) is presumed to be lower than 4 (capable to being produced in a laboratory environment), and it has not yet initiated a Market Penetration Level (MPL). The interconnection between these levels are seen in the following image. The lagging between MRL and MPL compared to the TRL are associated to the time it takes to translate promising research into commercially available products (Gavankar et al., 2015).

Interestingly, a cursory patent database search revealed a significant increase in patent filings for MBCs technologies in the last decade, with a peak since 2022 and a trend suggesting continued growth. This surge in research activity highlights the growing interest in MBCs. However, it's important to remember that translating research and innovation into commercially viable products takes time. Patents primarily focus on novelty and inventive concepts, not necessarily the immediate readiness for market placement. Therefore, a time lag often exists between promising research and the widespread availability of such technologies in the market.

The following is a Historic data of patent publications for mycelium based materials and composites. Please note 2024 is still going, therefore the low number in patent publications for this year.



Obtained from: Patentscope, Date: 30/03/2024

Step 2 - Lab-scale data for current technology definition

Lab-scale data collection is essential for the LCA. However, this relied solely on secondary data sources and did not involve any experimental procedures. The commissioner provided no direct data either. Therefore, a comprehensive literature review was conducted instead to define the current process of MBC production in a laboratory setting, including details on processes, equipment, and material quantities used in current MBC production.

This review focused on identifying the most comprehensive studies on MBC production in a laboratory setting, with an emphasis on geographically relevant research. In this regard, the studies by Alaux et al. (2023) at Graz University of Technology in Austria and Volk et al. (2024) at Karlsruhe Institute of Technology (KIT) in Germany stood out. While both studies involved laboratory measurements, a flowchart was developed for this thesis that incorporates information from the reviewed literature and available databases on materials. This approach might lead to some variations from the original procedures.

While both studies involved laboratory measurements, a flowchart was developed for this thesis that incorporates available databases and materials, potentially leading to some variations from the original procedures. The primary database for this study was Ecoinvent 3.9.1. For foreground processes, and if necessary, modifications to background processes, adjustments to the Ecoinvent models will be made

and thoroughly documented. In cases where direct data is unavailable, proxies and cut-off methods will be employed, and any relevant information obtained from the literature review will be included. In addition, assumptions and limitations are reported in the following chapter. The flowchart for the current technology at lab scale primarily follows the methodology outlined by Volk et al. (2024) for obtaining 1 kg of MBCs material and it is presented. This data then formed the basis for a process flow chart, visually mapping the production steps within the MBC production system.

Step 3 – Selection of reference technology at industrial scale

The decision tree tool developed by Erakca et al. (2024) was used to identify the most appropriate scaling method for our Life Cycle Assessment (LCA). This tool considers several factors relevant to the MBCs technology: its evaluation of "bio-product" and "construction" technology, upscaling of materials, products, or processes, and the scaling range from lab data to an industrial application. The framework also propose evaluation criteria based on four parameters: complexity (the level of expertise required), data intensity (amount of additional data required), duration (time investment needed), and uncertainty (level of inherent uncertainty in the results), first two factors are prioritized based on the limitations identified. The following figure presents the results derived from the tool based on (a) impact results, (b) material and energy flows, using tool developed Erakca et al. (2024).

A. Study specifications

To specify the goal and scope of your study, please select the most suitable option from the dropdown menu.

Data entered completely.

1. Technology type

1.4 Does the technology include chemical component or requires process engineering for its production?

2. Scaling range

3. Scaling of

Outcome

Below is a selection of scaling methods aligned with your specified requirements. Higher ranks indicate reduced appropriateness, while the top-ranked method (ranked 1) demonstrates highest suitability. The 'score' column represents weighted sums, with 1.0 as the optimal choice. Higher scores reflect reduced suitability concerning your precise requirements.

| Rank | Author | Year | Score | Overarching method | Comment | DOI / ISBN |
|------|-------------------------|------|-------|----------------------------|--|---|
| 1 | Erakca et al. | 2023 | 1.9 | Simple extrapolation | Only case study, no methodology | https://doi.org/10.1016/j.jclepro.2022.135510 |
| 2 | Zhou et al. | 2017 | 2.0 | Process engineering | | https://doi.org/10.1021/acs.iecr.7b00360 |
| 3 | Piccinno et al. | 2016 | 2.0 | Process engineering | | https://doi.org/10.1016/j.jclepro.2016.06.164 |
| 4 | Jiménez-González et al. | 2000 | 2.9 | Process engineering | | https://doi.org/10.1007/BF02978615 |
| 5 | Hulst et al. | 2020 | 3.3 | Advanced empirical scaling | | https://doi.org/10.1111/jec.13027 |
| 6 | Bergesen and Suh | 2016 | 3.3 | Advanced empirical scaling | | https://doi.org/10.1016/j.apenergy.2016.02.013 |
| 7 | Simon et al. | 2016 | 3.3 | Approximation | Reference technology and expert consultation are required. | https://doi.org/10.1002/ieam.1788 |
| 8 | Delpierre et al. | 2021 | 3.5 | Approximation | Reference technology and expert consultation are required. | https://doi.org/10.1016/j.jclepro.2021.126886 |

B. Evaluation Criteria

Please weight the criteria listed below according to your requirements. A high weighting indicates that the criterion is important to you. Please ensure that the total weightings add up to 100%.

Weighting balanced.

Low complexity

Low data intensity

Low duration

Low uncertainty

(a)

A. Study specifications

To specify the goal and scope of your study, please select the most suitable option from the dropdown menu.

Data entered completely.

1. Technology type

1.4 Does the technology include chemical component or requires process engineering for its production?

2. Scaling range

3. Scaling of

3.1 Operation conditions of single production processes available?

3.2 Lab or pilot scale energy and material flows available?

Outcome

Below is a selection of scaling methods aligned with your specified requirements. Higher ranks indicate reduced appropriateness, while the top-ranked method (ranked 1) demonstrates highest suitability. The 'score' column represents weighted sums, with 1.0 as the optimal choice. Higher scores reflect reduced suitability concerning your precise requirements.

| Rank | Author | Year | Score | Overarching method | Comment | DOI / ISBN |
|------|-------------------------|------|-------|----------------------|--|---|
| 1 | Erakca et al. | 2023 | 1.9 | Simple extrapolation | Only case study, no methodology | https://doi.org/10.1016/j.jclepro.2022.135510 |
| 2 | Zhou et al. | 2017 | 2.0 | Process engineering | | https://doi.org/10.1021/acs.iecr.7b00360 |
| 3 | Piccinno et al. | 2016 | 2.0 | Process engineering | | https://doi.org/10.1016/j.jclepro.2016.06.164 |
| 4 | Jiménez-González et al. | 2000 | 2.9 | Process engineering | | https://doi.org/10.1007/BF02978615 |
| 5 | Simon et al. | 2016 | 3.3 | Approximation | Reference technology and expert consultation are required. | https://doi.org/10.1002/ieam.1788 |
| 6 | Delpierre et al. | 2021 | 3.5 | Approximation | Reference technology and expert consultation are required. | https://doi.org/10.1016/j.jclepro.2021.126886 |

B. Evaluation Criteria

Please weight the criteria listed below according to your requirements. A high weighting indicates that the criterion is important to you. Please ensure that the total weightings add up to 100%.

Weighting balanced.

Low complexity

Low data intensity

Low duration

Low uncertainty

(b)

Step 4 – Analysis of potential changes

The framework by Erakca et al. (2024) proposes three levels of analysis for considering potential improvements: product, system, and supply chain. Due to limitations in data and the use of conceptual design models, this analysis will prioritize the product level. While a product-centric approach will not directly explore challenges within the system or supply chain, recommendations derived from the product analysis could still point to potential areas for further investigation using these broader frameworks.

Step 5 – Analysis of variability and uncertainty

As part of a prospective LCA this includes: sensitivity, scenario, and uncertainty analysis (dependable of the specific needs of analysis). These techniques are commonly employed in in a LCA framework. By employing these methods, the influence of variations in key assumptions and data points on the overall findings is evaluated. This allows us to refine our understanding of the results, identify areas of high influence, and strengthen the overall robustness of our recommendations (Erakca et al., 2024; Sander-Titgemeyer et al., 2023).

C. Unit process data

Unit process data presented below correspond to the foreground processes modeled, exported from the LCA model. Other background processes could be consulted through the respective data base.

C1. MBCs production lab scale

Model 1. Agar petri dish preparation. Scaled to 1 kg, derived from: Volk et al. (2024)

| Economic flows, in: | | | | |
|---------------------------------|-------------|-----------------------------|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.014409 | kg | Agar, seaweed | Agar, seaweed | RER |
| 0.114932 | kg | barley grain | market for barley grain | GLO |
| 0.055914 | kg | polystyrene, extruded | market for polystyrene, extruded | GLO |
| 0.961513 | kg | water, ultrapure | market for water, ultrapure | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Petri dish with agar medium | Agar petri dish preparation | RER |
| 0.055914347 | kg | biowaste | treatment of biowaste, municipal incineration | Europe without Switzerland |
| 0.090854125 | kg | waste polystyrene | market group for waste polystyrene | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 2. Agar, seaweed. Proxy product, adjusted to RER, derived from: Ecoinvent

| Economic flows, in: | | | | |
|--------------------------------|-------------|---|--|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | lime, algae | lime production, algae | FR |
| Not disclosed | MJ | heat, district or industrial, natural gas | market for heat, district or industrial, natural gas | Europe without Switzerland |
| Not disclosed | kg | tap water | market for tap water | Europe without Switzerland |
| Not disclosed | ton km | transport, freight | market for transport, freight | RER |
| Not disclosed | kWh | electricity, medium voltage | market group for electricity, medium voltage | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Agar, seaweed | Agar, seaweed | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

| Environmental flows, out | | | | |
|---------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 3. Broth preparation, mycelium. Scaled to 1 kg, derived from: Volk et al. (2024)

| Economic flows, in: | | | | |
|----------------------------|-------------|-----------------------------|--|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.196136 | kg | Malt extract | Malt extract | FR |
| 0.852098 | kg | tap water | market for tap water | Europe without Switzerland |
| 0.060292851 | kWh | electricity, medium voltage | market group for electricity, medium voltage | Europe without Switzerland |

| Economic flows, out: | | | | |
|-----------------------------|-------------|---------------------|--------------------------------|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Broth with mycelium | Broth preparation, mycelium | RER |
| 4.82343E-05 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |

| Environmental flows, in | | | | |
|--------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

| Environmental flows, out | | | | |
|---------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 4. Composite incubation and growing. Scaled to 1 kg, derived from: Volk et al. (2024) & Alaux et al. (2023)

| Economic flows, in: | | | | |
|----------------------------|-------------|-------------------------------|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.232768654 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 0.860626176 | kg | Mycelium mixture, molded | Mycelium composite molding, customized mold | RER |
| 0.216963375 | kg | tap water | market for tap water | Europe without Switzerland |

| Economic flows, out: | | | | |
|-----------------------------|-------------|--------------------|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium incubated | Composite incubation and growing | RER |
| 0.077589551 | kg | biowaste | treatment of biowaste, municipal incineration | Europe without Switzerland |

| Environmental flows, in | | | | |
|--------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

| Environmental flows, out | | | | |
|---------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 5. Drying of composite. Scaled to 1 kg, derived from: Volk et al. (2024)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|--|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1.43617 | kg | Mycelium incubated | Composite incubation and growing | GLO |
| 0.68 | kWh | electricity, medium voltage | market group for electricity, medium voltage | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium composite, dried, unprocessed, lab produced | Drying of composite | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 6. Malt extract. Derived from: Volk et al. (2024) & Chaudhury (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|------------------|-----------------------------|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.196136 | kg | barley grain | market for barley grain | FR |
| 0.803864 | kg | water, ultrapure | market for water, ultrapure | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Malt extract | Malt extract | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 7. Medium incubation on lab. Scaled to 1 kg, derived from: Volk et al. (2024) & Chaudhury (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--------------------------------|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 15.92779 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 1.078709 | kg | Liquid medium with mycelium | Medium preparation for incubation | |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Incubated medium with mycelium | Medium incubation on lab | RER |
| 0.07871 | kg | municipal solid waste | market group for municipal solid waste | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |

Model 8. Moisture of substrate. Scaled to 1 kg, derived from: Alaux et al. (2023) & Scaled to 1 kg, derived from: Volk et al. (2024)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---------------------|--------------------------------|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.413994 | kg | Substrate milled | Substrate milling | RER |
| 0.731255 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Substrate moisture | Moisture of substrate | RER |
| 0.000145 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |

Model 9. Mycelium composite molding, single use PP mold. Adjusted from Alaux et al. (2023) & Volk et al. (2024)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--------------------------|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.00278 | kg | Mycelium seed extracted | Mycelium seed extraction | RER |
| 0.99722 | kg | Substrate sterilized | Sterilization of substrate | RER |
| 0.00112 | kg | fiber, cotton | market for fiber, cotton | GLO |
| 0.00384 | kg | injection molding | market for injection molding | GLO |
| 3.13872 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium mixture, molded | Mycelium composite molding, customized mold | RER |
| 0.003139 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| 0.00384 | kg | waste polypropylene | market group for waste polypropylene | Europe without Switzerland |
| 0.001119 | kg | biowaste | treatment of biowaste, municipal incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 10. Mycelium liquid preparation, for incubation. Source: Volk et al. (2024), adjusted to 1 kg

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|---|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.02248 | kg | Petri dish with agar medium | Agar petri dish preparation | RER |
| 0.97752 | kg | Broth with mycelium | Broth preparation, mycelium | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium liquid preparation, for incubation | Mycelium liquid preparation, for incubation | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 11. Mycelium seed extraction. Source: Volk et al. (2024), adjusted to 1 kg

| Economic flows, in: | | | | |
|---------------------------------|-------------|-----------------------------|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.231946 | kWh | electricity, medium voltage | market group for electricity, medium voltage | RER |
| 1.077363 | kg | Incubated mycelium liquid | Medium incubation | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium seed extracted | Mycelium seed extraction | RER |
| 0.077363 | kg | biowaste | treatment of biowaste, municipal incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 12. Sterilization of substrate. Source: Volk et al. (2024)

| Economic flows, in: | | | | |
|---------------------------------|-------------|-----------------------------|--|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.151928 | kWh | electricity, medium voltage | market group for electricity, medium voltage | RER |
| 1 | kg | Substrate moisture | Moisture of substrate | RER |
| 0.053926 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Substrate sterilized | Sterilization of substrate | RER |
| 5.39259E-05 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 13. Substrate milling. Based on: Volk et al. (2024)

| Economic flows, in: | | | | |
|---------------------------------|-------------|------------------------------------|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.375045 | kg | electricity, medium voltage | market group for electricity, medium voltage | RER |
| 1.008065 | kg | sawdust, wet, measured as dry mass | market for sawdust, wet, measured as dry mass | Europe without Switzerland |
| 0.002383 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Substrate milled | Substrate milling | RER |
| 0.008065 | kg | biowaste | treatment of biowaste, municipal incineration | Europe without Switzerland |
| 2.38335E-06 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

C2. MBCs production upscaled

Model 14. Upscaled composite incubation and growing. Adjusted based on Alaux et al. (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.232768654 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 0.820715854 | kg | Mycelium mixture, molded | Mycelium composite molding, customized mold | RER |
| 0.216963375 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium incubated | Composite incubation and growing | RER |
| 0.05 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 15. Dextrose extract, broth. Adjusted based on Malta broth process

| Economic flows, in: | | | | |
|---------------------------------|-------------|------------------|----------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.196136 | kg | glucose | market for glucose | GLO |
| 0.803864 | kWh | tap water | market group for tap water | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Dextrose extract | Dextrose extract, broth | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 16. Upscaled drying of composite. Adjusted based on Alaux et al. (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|----------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1.43617 | kg | Mycelium incubated | Composite incubation and growing | GLO |
| 0.476 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium composite, dried, unprocessed, industrially produced | Drying of composite | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 17. MBCs recycling, outsourced, applicable in upscaled production. Source: Arblaster (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|-------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | MBCS for recycling | Outsourced recycling unit | RER |
| 0.0325 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Kg | Recycled MBCs, outsourced, for substrate | MBCs recycling, outsourced | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 18. Upscaled Medium incubation on bioreactor

| Economic flows, in: | | | | |
|---------------------------------|-------------|--------------------------------|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 15.92779 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 1.07871 | kg | Liquid medium with mycelium | Medium preparation for incubation | |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Incubated medium with mycelium | Medium incubation on bioreactor | RER |
| 0.07871 | kg | municipal solid waste | market group for municipal solid waste | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 19. Upscaled Medium preparation for incubation

| Economic flows, in: | | | | |
|---------------------------------|-------------|-------------------------------|-----------------------------------|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.196136 | kg | Dextrose extract | Dextrose extract, broth | RER |
| 0.060293 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 0.014409 | kg | barley grain | market for barley grain | GLO |
| 0.852098 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Liquid medium with mycelium | Medium preparation for incubation | RER |
| 4.82E-05 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |

Model 20. Upscaled Moisture of substrate

| Economic flows, in: | | | | |
|---------------------------------|-------------|---------------------|--------------------------------|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.413994 | kg | Substrate milled | Substrate milling | RER |
| 0.731255 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Substrate moisture | Moisture of substrate | RER |
| 0.000145 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |

Model 21. Upscaled Mycelium composite molding, customized mold. Adjusted based on Alaux et al. (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|--|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.002783 | kg | Mycelium seed extracted | Mycelium seed extraction | RER |
| 0.997217 | kg | Substrate sterilized | Sterilization of substrate | RER |
| 3.84E-06 | kg | glass fiber reinforced plastic, polyamide, injection molded | market for glass fiber reinforced plastic, polyamide, injection molded | GLO |
| 3.138721472 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium mixture, molded | Mycelium composite molding, customized mold | RER |
| 0.003138721 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| 3.83993E-06 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 22. Upscaled Mycelium seed extraction

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.231946 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 1.077363 | kg | Incubated medium with mycelium | Medium incubation on bioreactor | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium seed extracted | Mycelium seed extraction | RER |
| 0.077363077 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 23. Upscaled Sterilization of substrate. Adjusted based on Alaux et al. (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|-------------------------------|--------------------------------|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.022789 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 1 | kg | Substrate moisture | Moisture of substrate | RER |
| 0.053926 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Substrate sterilized | Sterilization of substrate | RER |
| 5.39259E-05 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 24. Upscaled Substrate milling. Adjusted to incorporate recycled MBCs as substrate

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.375045 | kg | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 0 | | Recycled MBCs, outsourced, for substrate | MBCs recycling, outsourced, efficiency | RER |
| 1.008065 | kg | sawdust, wet, measured as dry mass | market for sawdust, wet, measured as dry mass | Europe without Switzerland |
| 0.002383 | kg | tap water | market for tap water | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Substrate milled | Substrate milling | RER |
| 0.008065 | | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| 2.38335E-06 | m3 | wastewater, average | market for wastewater, average | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Here recycled content and virgin sawdust must be adjusted depending on scenario

C3. MBCs & Scalmalloy partition

Model 25. Cutting of composite, laser cutting. Modeled based on Alaux et al. (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1.05 | kg | Mycelium composite, dried, unprocessed | Drying of composite | RER |
| 0.5896 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Mycelium composite, processed for aerospace, industrially produced | Cutting of composite, laser cutting | RER |
| 0.05 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 26. MBCs recycling for internal reuse, circular production

| Economic flows, in: | | | | |
|---------------------------------|-------------|-------------------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.375045368 | kWh | Energy carrier, manufacturing | | RER |
| 1 | kg | MBCS for recycling | | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.7 | kg | MBCs recycling, if 70 % rate | | RER |
| 0.3 | kg | MBCs recycling, if 30 % rate | | RER |
| 1 | kg | MBCs recycling, if 100 % rate | | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 27. One-step manufacture, MBC partition. Sased on Chaudhury. (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|-------------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 11.6 | Kg | Mycelium composite, processed for aerospace, industrially produced | Cutting of composite, laser cutting | RER |
| 29.37 | kg | Scalmalloy | Scalmalloy production | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | unit | One-step manufacture, MBC partition | One-step manufacture, MBC partition | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 28. Provision of non-structural support, mycelium based mixed Scalmalloy partition. Based on approach of: Arblaster (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | unit | Partition, conventional sandwich, Nomex core | Application of decorative film in sandwich panel | RER |
| 40.97 | kg year | transport of nonstructural mass | mass-induced energy demand | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 6 | year | Provision of non-structural support, conventional sandwich partition | Provision of non-structural support, conventional sandwich partition | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 29. Scalmalloy production. Source: Granta EduPack

| Economic flows, in: | | | | |
|---------------------------------|-------------|--------------------------------|---------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 23.8382 | kWh | Energy, carrier, manufacturing | Energy carrier, manufacturing | RER |
| 0.9539 | kg | aluminum, cast alloy | market for aluminum, cast alloy | GLO |
| 0.029 | kg | magnesium | market for magnesium | GLO |
| 0.011 | kg | scandium oxide | market for scandium oxide | GLO |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Scalmalloy | Scalmalloy production | GLO |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 30. Use on aircraft lifespan, partition, mycelium based mixed Scalmalloy.

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 6 | year | non-structural support, interior partition, mycelium based mixed Scalmalloy | Provision of non-structural support, mycelium based mixed scalmalloy | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Unit | Use on aircraft lifespan, partition, mycelium based mixed scalmalloy | Use on aircraft lifespan, partition, mycelium based mixed scalmalloy | RER |
| 29.37 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | |
| 11.6 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

This includes the in-flight emissions over a period of 6 years (lifespan of partition)

Model 31. Use of partition, over its lifespan (6 years), interior panel, MBCs and Scalmaalloy (exc. in-flight emissions)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | unit | Used partition, Scalmaalloy segment | Use of partition, cut for Scalmaalloy | RER |
| 1 | unit | Used partition, mycelium based composites segment | Use of partition, cut for mycelium based components | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Unit | Used partition, MBCs & Scalmaalloy (exc. emissions) | Use of partition over lifespan, interior panel, MBCs and Scalmaalloy | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | | |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | | |
| | | | | |

Model 32. Use of partition, cut for mycelium based components, (exc. in-flight emissions)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|---|----------------------------|
| <i>Amount*</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 3.48 | kg | Recycled MBCs for substrate | MBCs recycling | RER |
| 0.2832 | unit | Partition, mycelium based mixed Scalmaalloy | One-step manufacture, MBC partition | RER |
| 8.12 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Unit | Used partition, Scalmaalloy segment | Use of partition, cut for mycelium based components | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | | |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | | |
| | | | | |

* Data presented represent 70% recycling MBCs scenario, must be adjusted for others. Please note this part only corresponds to the MBCs material.

Model 33. Use of partition, cut for Scalmalloy (exc. in-flight emissions)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|---|----------------------------|
| <i>Amount*</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.7168 | unit | Partition, mycelium based mixed Scalmalloy | One-step manufacture, MBC partition | RER |
| 29.37 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Unit | Used partition, scalmalloy segment | Use of partition, cut for Scalmalloy | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

**Data presented represent 70% recycling MBCs scenario, must be adjusted for others. Please note this part only corresponds to the Scalmalloy material.*

C4. Nomex core, conventional

Model 34. Application of decorative film in sandwich panel. Based on Vidal et al. (2018)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 52.26304 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 1 | unit | Conventional sandwich partition, uncoated | One-step manufacture of sandwich panel | RER |
| 4.88 | kg | polyvinyl fluoride, film | market for polyvinyl fluoride, film | GLO |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Unit | Partition, conventional sandwich, Nomex core | Application of decorative film in sandwich panel | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 35. Aramid paper/phenolic honeycomb, expanded phenolic-coated aramid paper honeycomb. Source: Nomex

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0.7 | kg | glass fiber reinforced plastic, polyamide, injection molded | glass fiber reinforced plastic production, polyamide, injection molded | RER |
| 0.3 | kg | epoxy resin, liquid | market for epoxy resin, liquid | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | Nomex Aramid Paper | Aramid paper/phenolic honeycomb, expanded phenolic-coated aramid paper honeycomb | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 36. Manufacture of fireproof fiber fabric. Based on Vidal et al. (2018)

| Economic flows, in: | | | | |
|---------------------------------|-------------|-------------------------------|---------------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 159.0869867 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 35.9 | kg | Phenolic glass fiber | Thermoset, phenolic glass fiber | RER |
| 0.97 | kg | decabromodiphenyl ether | market for decabromodiphenyl ether | GLO |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 36.87 | kg | Fireproof fiber fabric | Manufacture of fireproof fiber fabric | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 37. One-step manufacture of sandwich panel. Based on Vidal et al. (2018)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 3.89 | kWh | Nomex Aramid Paper | Aramid paper/phenolic honeycomb, expanded phenolic-coated aramid paper honeycomb | RER |
| 211.3028125 | kg | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 56.97 | kg | Thermoset prepreg, reinforced polymer | Production of reinforced polymer prepreg | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | unit | Conventional sandwich partition, uncoated | One-step manufacture of sandwich panel | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 38. Production of reinforced polymer prepreg. Based on Vidal et al. (2018)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---------------------------------------|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 245.814636 | kWh | Energy carrier, manufacturing | Energy carrier, manufacturing | RER |
| 36.87 | kg | Fireproof fiber fabric | Manufacture of fireproof fiber fabric | RER |
| 20.1 | kg | phenolic resin | market for phenolic resin | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 56.97 | kg | Thermoset prepreg, reinforced polymer | Production of reinforced polymer prepreg | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 39. Provision of non-structural support, conventional sandwich partition

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|--|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | unit | Partition, conventional sandwich, Nomex core | Application of decorative film in sandwich panel | RER |
| 62.94 | kg year | transport of nonstructural mass | mass-induced energy demand | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 6 | year | Provision of non-structural support, conventional sandwich partition | Provision of non-structural support, conventional sandwich partition | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |

Model 40. Thermoset, phenolic glass fiber. Based on Vidal et al. (2018)

| Economic flows, in: | | | | |
|---------------------------------|-------------|----------------------|---------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 14.36 | kWh | glass fiber | market for glass fiber | GLO |
| 21.54 | kg | phenolic resin | market for phenolic resin | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 35.9 | kg | Phenolic glass fiber | Thermoset, phenolic glass fiber | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| | | | | |

Model 41. Use of partition over lifespan, interior panel, Nomex core (excl. in-flight emissions)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--|---|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kWh | Partition, conventional sandwich, Nomex core | Application of decorative film in sandwich panel | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | unit | Use of partition over lifespan, interior panel, Nomex core | Thermoset, phenolic glass fiber | RER |
| 62.94 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 42. Use on aircraft, partition, conventional sandwich partition (for 6 years)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---|--|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 6 | year | non-structural support, interior partition, conventional sandwich panel | Provision of non-structural support, conventional sandwich partition | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | unit | Use on aircraft, interior partition, conventional sandwich panel | Use on aircraft lifespan, partition, conventional sandwich partition | RER |
| 62.94 | kg | process-specific burdens, municipal waste incineration | market for process-specific burdens, municipal waste incineration | Europe without Switzerland |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

C5. Additional foreground processes for scenario running

Model 43. Energy carrier, use phase

| Economic flows, in: | | | | |
|---------------------------------|-------------|---------------------------------------|----------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0 | kWh | combustion energy, biokerosene | Use of fossil biokerosene | RER |
| 1 | kWh | combustion energy, fossil kerosene | Use of fossil kerosene | RER |
| 0 | kWh | conversion energy, hydrogen fuel cell | Use of use of hydrogen fuel cell | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kWh | Energy carrier, use phase | Energy carrier, use phase | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 44. Mass-induced energy demand, transport of nonstructural mass. Based on approach of Arblaster (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|---------------------------------|----------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | transport of nonstructural mass | mass-induced energy demand | RER |
| 4470* | MJ | Energy carrier, use phase | Energy carrier, use phase | RER |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Kg | transport of nonstructural mass | mass-induced energy demand | GLO |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

4.47e3 MJ is an average quantity required yearly for 1 kg of mass induced.

Model 45. Use of biokerosene. Based on approach of Arblaster (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--------------------------------|---|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Kg | kerosene, synthetic | kerosene production, synthetic, from Fischer Tropsch process, hydrogen from wood gasification, with CCS, energy allocation, at fuelling station | GLO |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 45 | MJ | combustion energy, biokerosene | Use of biokerosene | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 46. Use of fossil kerosene. Based on approach of Arblaster (2023)

| Economic flows, in: | | | | |
|---------------------------------|-------------|--------------------------------|------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | Kg | kerosene | market for kerosene | GLO |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 120 | MJ | combustion energy, biokerosene | Use of fossil kerosene | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |
| Environmental flows, out | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 47. Use of hydrogen fuel cell. Based on approach of Arblaster (2023)

| Economic flows, in: | | | | |
|--------------------------------|-------------|--------------------------------|------------------------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kg | hydrogen, gaseous | market for hydrogen, gaseous | GLO |
| Economic flows, out: | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 45 | MJ | combustion energy, biokerosene | Use of fossil biokerosene | RER |
| Environmental flows, in | | | | |
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

| Environmental flows, out | | | | |
|---------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

Model 48. Energy carrier, manufacturing

| Economic flows, in: | | | | |
|----------------------------|-------------|--|--|----------------------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 0 | kWh | electricity production, hard coal | electricity production, hard coal | NL |
| 0 | kWh | electricity production, hydro, run-of-river | electricity production, hydro, run-of-river | NL |
| 0 | kWh | electricity production, natural gas, 10MW | electricity production, natural gas, 10MW | NL |
| 0 | kWh | electricity production, nuclear, pressure water reactor | electricity production, nuclear, pressure water reactor | NL |
| 0 | kWh | electricity production, oil | electricity production, oil | NL |
| 0 | kWh | electricity production, wind, 1-3MW turbine, onshore | electricity production, wind, 1-3MW turbine, onshore | NL |
| 0 | kWh | electricity, high voltage, renewable energy products, production mix | electricity, high voltage, renewable energy products, production mix | NL |
| 0 | kWh | heat and power co-generation, biogas, gas engine | heat and power co-generation, biogas, gas engine | NL |
| 1 | kWh | market group for electricity, medium voltage | market group for electricity, medium voltage | Europe without Switzerland |

| Economic flows, out: | | | | |
|-----------------------------|-------------|-------------------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Product</i> | <i>Activity</i> | <i>Location</i> |
| 1 | kWh | Energy carrier, manufacturing | | RER |

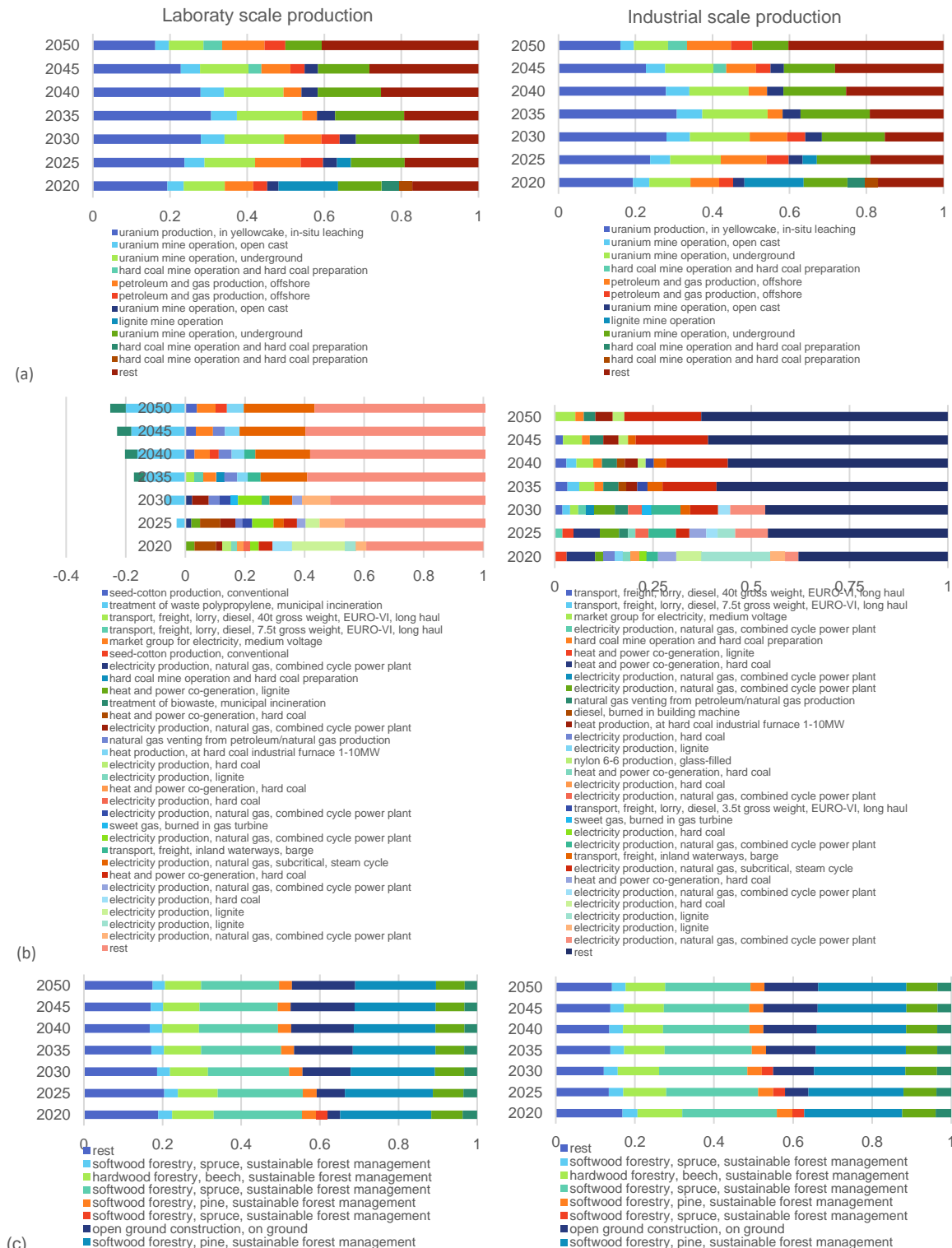
| Environmental flows, in | | | | |
|--------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

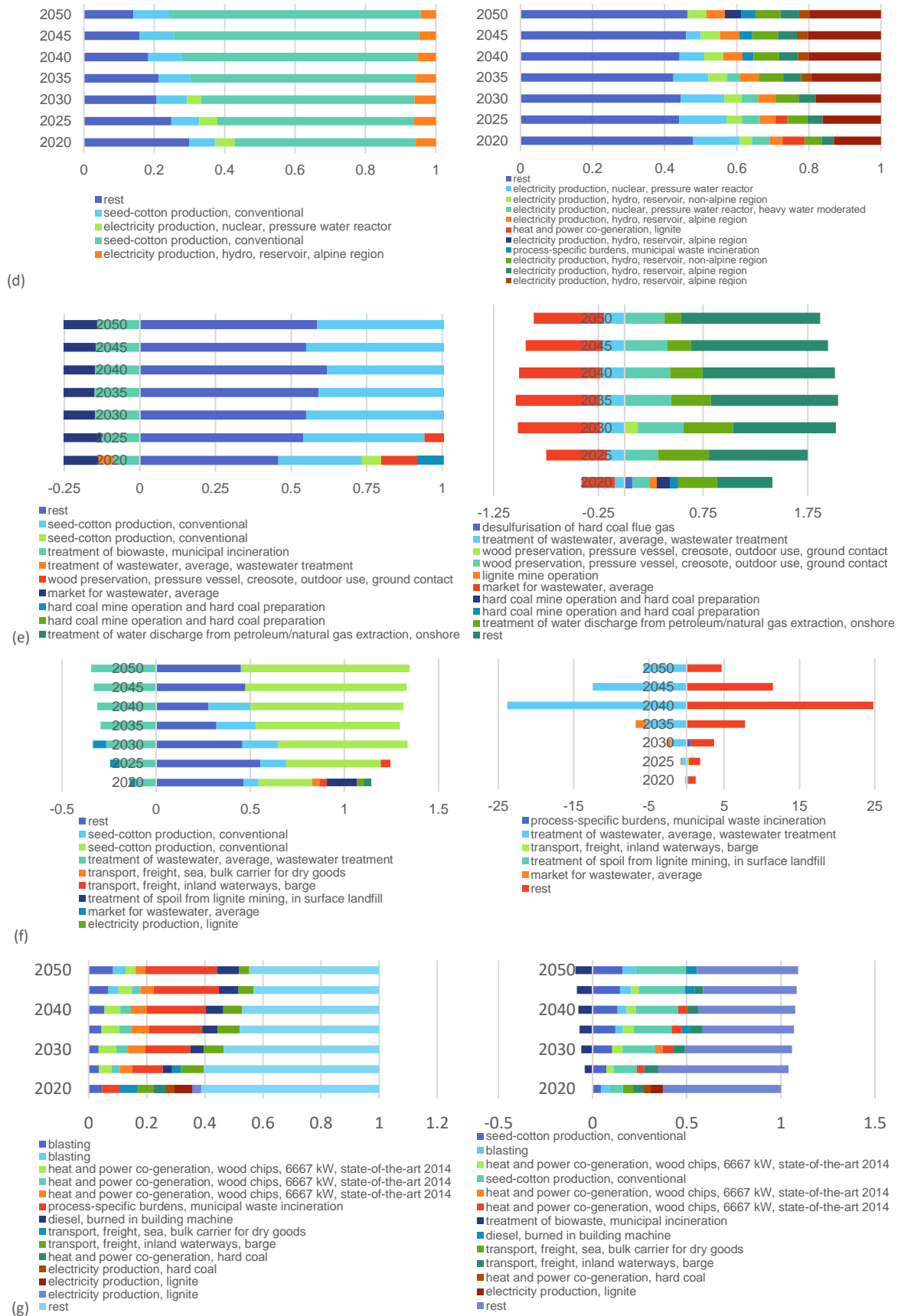
| Environmental flows, out | | | | |
|---------------------------------|-------------|------------------|-----------------|-----------------|
| <i>Amount</i> | <i>Unit</i> | <i>Flow Name</i> | <i>Activity</i> | <i>Location</i> |

D. Extended results, baseline analysis

D.1. Contribution analysis of laboratory vs. industrial production of 1 kg of MBCs

This analysis will focus on key environmental impact categories to identify primary contributors and areas for improvement in the upscaled MBC production process. The following is a contribution analysis for laboratory (left) and industrially produced (right) of 1 kg of MBCs for the impact categories: (a) energy resources: non-renewable, (b) climate change, and (c) land use, (d) water use, (e) ecotoxicity: freshwater, (f) eutrophication: marine, (g) eutrophication: terrestrial, using EF v3.1.

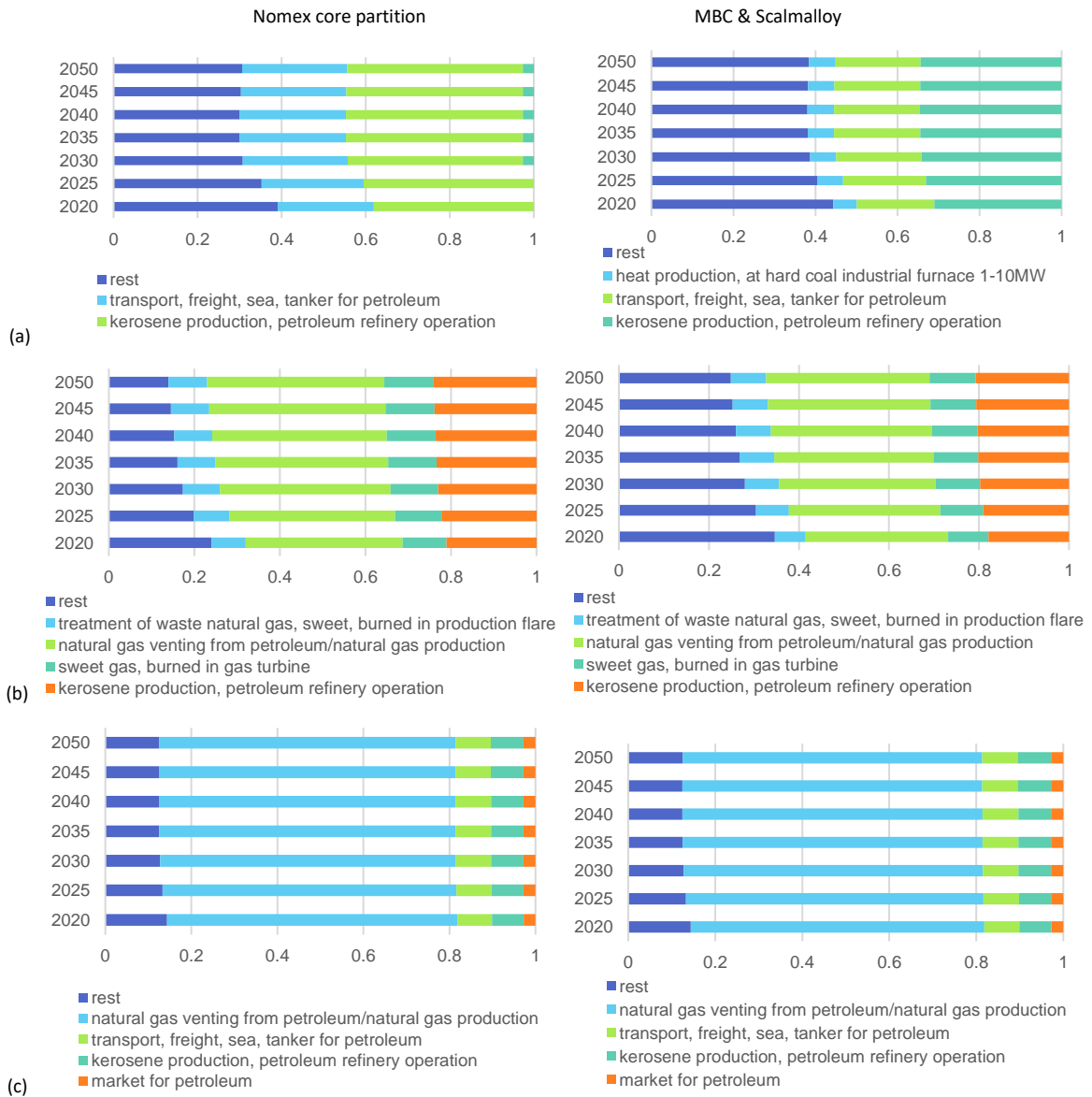




D2. Extended contribution analysis of product applications, including use phase

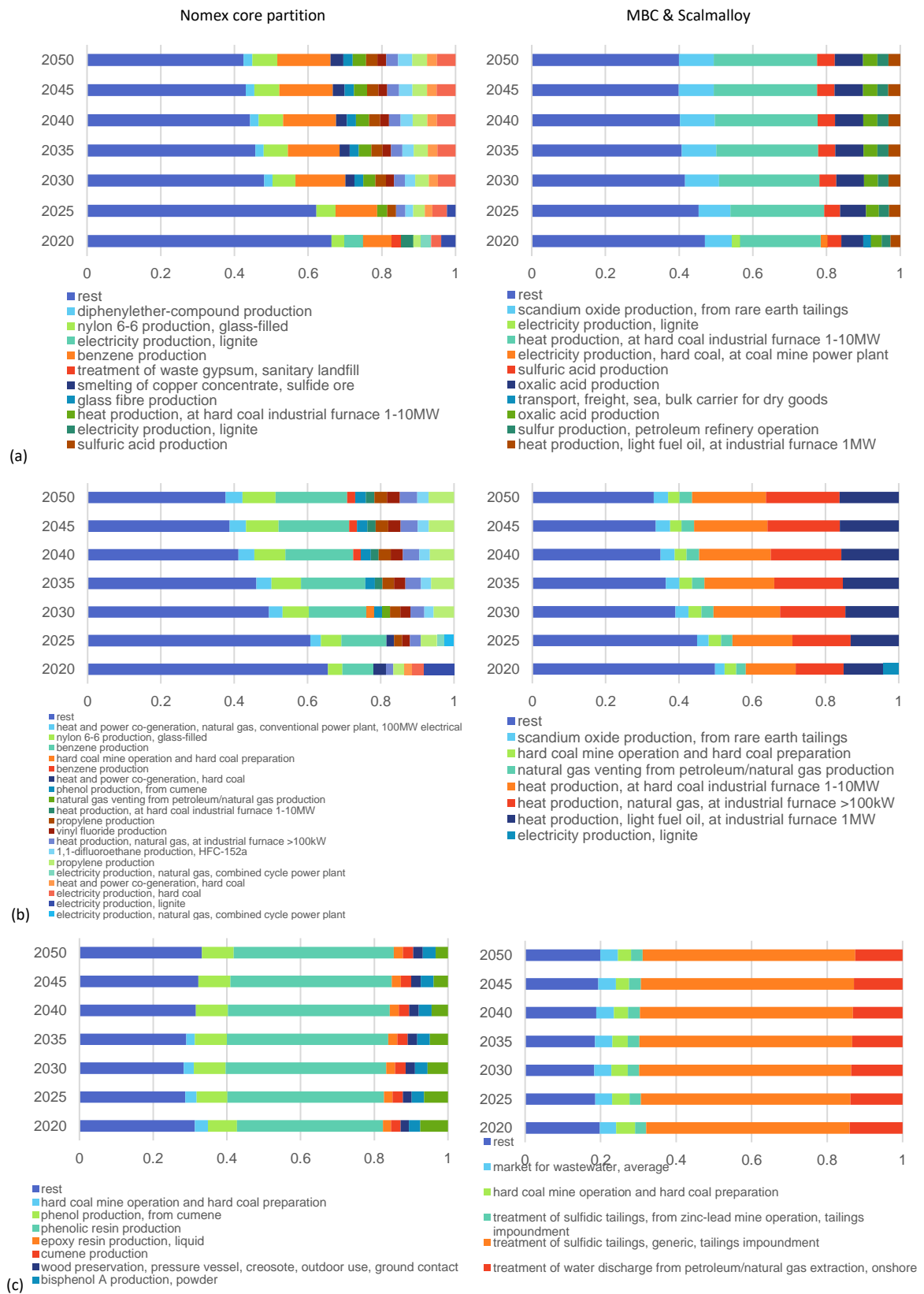
The following contribution analysis underscores the critical role of the use phase in the overall environmental impact of aircraft interior panels. Across all impact categories considered and for both alternatives, fuel consumption (kerosene) emerges as the primary driver of the environmental burden. For insights into the influence of the energy carrier choice on the use phase, please refer to sensitivity analysis in section 3.3.3.

Contribution analysis presented below considering use on aircraft of partition for impact categories: (a) acidification, (b) climate change, (c) photochemical oxidant formation: human health



D3. Product applications, excluding use phase

Contribution analysis considering use on aircraft of partition for impact categories: (a) acidification, (b) climate change, (c) ecotoxicity.



E. Extended results, recyclability

E.1. MBCs production, material only, employing recycled MBCs material (outsourced)

| Impact category | Unit | Recycled content | | | |
|---|-------------------------|------------------|----------|----------|----------|
| | | 0% | 30% | 70% | 100% |
| Acidification | mol H+eq | 3.39E-04 | 3.73E-04 | 3.43E-04 | 3.44E-04 |
| Climate change | kg CO2-eq | 4.17E-02 | 4.49E-02 | 3.97E-02 | 3.88E-02 |
| Ecotoxicity: freshwater | CTUe | 2.38E-01 | 2.83E-01 | 2.28E-01 | 2.23E-01 |
| Energy resources: non-renewable | MJ, net calorific value | 2.34E+00 | 2.67E+00 | 2.49E+00 | 2.56E+00 |
| Eutrophication: freshwater | kg P-eq | 6.96E-06 | 8.41E-06 | 7.05E-06 | 7.08E-06 |
| Eutrophication: marine | kg N-eq | 1.16E-05 | 1.91E-05 | 1.11E-05 | 1.09E-05 |
| Eutrophication: terrestrial | mol N-eq | 1.03E-03 | 1.12E-03 | 1.03E-03 | 1.03E-03 |
| Human toxicity: carcinogenic | CTUh | 1.56E-10 | 1.72E-10 | 1.61E-10 | 1.63E-10 |
| Human toxicity: non-carcinogenic | CTUh | 1.82E-09 | 2.06E-09 | 1.87E-09 | 1.89E-09 |
| Ionising radiation: human health | kBq U235-eq | 1.03E-01 | 1.20E-01 | 1.14E-01 | 1.18E-01 |
| Land use | dimensionless | 1.03E+01 | 7.91E+00 | 4.39E+00 | 1.90E+00 |
| Material resources: metals/minerals | kg Sb-eq | 1.68E-06 | 1.88E-06 | 1.73E-06 | 1.76E-06 |
| Ozone depletion | kg CFC-11-eq | 2.69E-09 | 2.98E-09 | 2.72E-09 | 2.74E-09 |
| Particulate matter formation | disease incidence | 5.66E-09 | 5.77E-09 | 4.89E-09 | 4.56E-09 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 2.99E-04 | 3.15E-04 | 2.82E-04 | 2.74E-04 |
| Water use | m3 world eq. deprived | 8.25E-02 | 9.50E-02 | 8.99E-02 | 9.29E-02 |

E.2. MBCs & Scalmalloy partition production, interior partition, employing recycled MBCs material, including use phase emissions (circular production)

| Category | Unit | MBCs & Scalmalloy, 100% MBC recycled, incl. use | MBCs & Scalmalloy, 70% MBC recycled, incl. use | MBCs & Scalmalloy, 30% MBC recycled, incl. use |
|---|-------------------------|---|--|--|
| Acidification | mol H+eq | 1.99E+01 | 1.99E+01 | 1.99E+01 |
| Climate change | kg CO2-eq | 4.17E+03 | 4.17E+03 | 4.17E+03 |
| Ecotoxicity: freshwater | CTUe | 1.05E+05 | 1.05E+05 | 1.05E+05 |
| Energy resources: non-renewable | MJ, net calorific value | 2.30E+05 | 2.30E+05 | 2.30E+05 |
| Eutrophication: freshwater | kg P-eq | 5.43E-01 | 5.43E-01 | 5.43E-01 |
| Eutrophication: marine | kg N-eq | 3.90E+00 | 3.90E+00 | 3.90E+00 |
| Eutrophication: terrestrial | mol N-eq | 3.49E+01 | 3.49E+01 | 3.49E+01 |
| Human toxicity: carcinogenic | CTUh | 2.13E-06 | 2.13E-06 | 2.13E-06 |
| Human toxicity: non-carcinogenic | CTUh | 3.54E-05 | 3.54E-05 | 3.54E-05 |
| Ionizing radiation: human health | kBq U235-eq | 1.26E+02 | 1.26E+02 | 1.26E+02 |
| Land use | dimensionless | 1.56E+04 | 1.56E+04 | 1.57E+04 |
| Material resources: metals/minerals | kg Sb-eq | 1.14E-02 | 1.14E-02 | 1.14E-02 |
| Ozone depletion | kg CFC-11-eq | 3.72E-04 | 3.72E-04 | 3.72E-04 |
| Particulate matter formation | disease incidence | 1.89E-04 | 1.89E-04 | 1.89E-04 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 3.51E+01 | 3.51E+01 | 3.51E+01 |
| Water use | m3 world eq. deprived | 4.22E+02 | 4.22E+02 | 4.22E+02 |

E.3. MBCs & Scalmalloy partition production, interior partition, employing recycled MBCs material, excluding use phase emissions (circular production)

| Category | Unit | MBCs & Scalmalloy, 100% MBC recycled, excl. use | MBCs & Scalmalloy, 70% MBC recycled, excl. use | MBCs & Scalmalloy, 30% MBC recycled, excl. use |
|---|-------------------------|---|--|--|
| Acidification | mol H+-eq | 4.466E+00 | 4.467E+00 | 4.469E+00 |
| Climate change | kg CO2-eq | 7.579E+02 | 7.579E+02 | 7.579E+02 |
| Ecotoxicity: freshwater | CTUe | 8.734E+03 | 8.734E+03 | 8.735E+03 |
| Energy resources: non-renewable | MJ, net calorific value | 9.893E+03 | 9.894E+03 | 9.895E+03 |
| Eutrophication: freshwater | kg P-eq | 4.559E-01 | 4.560E-01 | 4.560E-01 |
| Eutrophication: marine | kg N-eq | 8.022E-01 | 8.027E-01 | 8.033E-01 |
| Eutrophication: terrestrial | mol N-eq | 8.169E+00 | 8.175E+00 | 8.182E+00 |
| Human toxicity: carcinogenic | CTUh | 6.657E-07 | 6.667E-07 | 6.680E-07 |
| Human toxicity: non-carcinogenic | CTUh | 1.058E-05 | 1.058E-05 | 1.058E-05 |
| Ionizing radiation: human health | kBq U235-eq | 7.571E+01 | 7.571E+01 | 7.572E+01 |
| Land use | dimensionless | 3.005E+03 | 3.036E+03 | 3.075E+03 |
| Material resources: metals/minerals | kg Sb-eq | 7.656E-03 | 7.657E-03 | 7.658E-03 |
| Ozone depletion | kg CFC-11-eq | 1.194E-05 | 1.195E-05 | 1.195E-05 |
| Particulate matter formation | disease incidence | 6.029E-05 | 6.030E-05 | 6.032E-05 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 2.542E+00 | 2.543E+00 | 2.545E+00 |
| Water use | m3 world eq. deprived | 1.803E+02 | 1.803E+02 | 1.804E+02 |

E.4. MBCs & Scalmalloy partition production, alternatives of EoL of Scalmalloy

| Impact category | Unit | Excluding use phase | | | | Including use phase | | | |
|---|-------------------------|-------------------------|---|---|---------------------------------|-------------------------|---|---|---------------------------------|
| | | Nomex, 100% incinerated | MBC & Scalmalloy, 100% incinerated (baseline) | MBC & Scalmalloy, MBC incinerated / Scalmalloy recycled | MBC & Scalmalloy, 100% recycled | Nomex, 100% incinerated | MBC & Scalmalloy, 100% incinerated (baseline) | MBC & Scalmalloy, MBC incinerated / Scalmalloy recycled | MBC & Scalmalloy, 100% recycled |
| Acidification | mol H+-eq | 1.32E+00 | 4.47E+00 | 4.55E+00 | 4.55E+00 | 2.50E+01 | 1.99E+01 | 1.99E+01 | 1.99E+01 |
| Climate change | kg CO2-eq | 2.56E+02 | 7.40E+02 | 7.58E+02 | 7.58E+02 | 5.50E+03 | 4.15E+03 | 4.15E+03 | 4.15E+03 |
| Ecotoxicity: freshwater | CTUe | 3.01E+03 | 8.72E+03 | 9.44E+03 | 9.44E+03 | 1.50E+05 | 1.05E+05 | 1.05E+05 | 1.05E+05 |
| Energy resources: non-renewable | MJ, net calorific value | 6.22E+03 | 9.89E+03 | 1.00E+04 | 1.01E+04 | 3.45E+05 | 2.30E+05 | 2.30E+05 | 2.30E+05 |
| Eutrophication: freshwater | kg P-eq | 3.91E-02 | 4.56E-01 | 4.62E-01 | 4.62E-01 | 1.74E-01 | 5.43E-01 | 5.43E-01 | 5.43E-01 |
| Eutrophication: marine | kg N-eq | 2.70E-01 | 7.99E-01 | 8.11E-01 | 8.10E-01 | 5.03E+00 | 3.89E+00 | 3.89E+00 | 3.89E+00 |
| Eutrophication: terrestrial | mol N-eq | 2.73E+00 | 8.18E+00 | 8.32E+00 | 8.31E+00 | 4.38E+01 | 3.49E+01 | 3.49E+01 | 3.49E+01 |
| Human toxicity: carcinogenic | CTUh | 8.11E-07 | 6.69E-07 | 7.01E-07 | 6.99E-07 | 3.06E-06 | 2.13E-06 | 2.13E-06 | 2.13E-06 |
| Human toxicity: non-carcinogenic | CTUh | 5.28E-06 | 1.06E-05 | 1.17E-05 | 1.17E-05 | 4.35E-05 | 3.54E-05 | 3.54E-05 | 3.54E-05 |
| Ionizing radiation: human health | kBq U235-eq | 7.16E+01 | 7.59E+01 | 7.68E+01 | 7.72E+01 | 1.49E+02 | 1.26E+02 | 1.26E+02 | 1.26E+02 |
| Land use | dimensionless | 1.74E+03 | 3.00E+03 | 3.20E+03 | 3.21E+03 | 2.11E+04 | 1.56E+04 | 1.56E+04 | 1.56E+04 |
| Material resources: metals/minerals | kg Sb-eq | 7.40E-03 | 7.66E-03 | 1.04E-02 | 1.04E-02 | 1.31E-02 | 1.14E-02 | 1.14E-02 | 1.14E-02 |
| Ozone depletion | kg CFC-11-eq | 6.75E-06 | 1.19E-05 | 1.23E-05 | 1.23E-05 | 5.59E-04 | 3.72E-04 | 3.72E-04 | 3.72E-04 |
| Particulate matter formation | disease incidence | 1.40E-05 | 6.03E-05 | 6.15E-05 | 6.14E-05 | 2.12E-04 | 1.89E-04 | 1.89E-04 | 1.89E-04 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 1.11E+00 | 2.55E+00 | 2.59E+00 | 2.59E+00 | 5.12E+01 | 3.51E+01 | 3.51E+01 | 3.51E+01 |
| Water use | m3 world eq. deprived | 2.28E+02 | 1.77E+02 | 1.85E+02 | 1.85E+02 | 5.99E+02 | 4.19E+02 | 4.19E+02 | 4.19E+02 |

F. Sensitivity analysis, additional information

F.1. Impact assessment methodology choice, MBCs, material only

Below the characterization results for 1 kg of MBCs, baseline 2035 employing ReCiPe impact assessment family. The respective sensitivity analysis is based upon these results.

| Impact category | Unit, ReCiPe | Lab scale | Industrial scale |
|----------------------------------|--------------------|------------|------------------|
| Acidification | kg SO ₂ | 2.133E-04 | 3.124E-04 |
| Climate change | kg CO ₂ | 1.085E-01 | 7.226E-02 |
| Ecotoxicity: freshwater | CTUe | 1.314E-02 | 1.588E-02 |
| Eutrophication: freshwater | kg P-eq | 7.021E-06 | 1.017E-05 |
| Eutrophication: marine | kg N-eq | -1.953E-05 | 3.920E-05 |
| Human toxicity: carcinogenic | kg 1.4 DCB | 1.473E-02 | 1.713E-02 |
| Human toxicity: non-carcinogenic | kg 1.4 DCB | 1.339E-01 | 1.398E-01 |
| Ionizing radiation: human health | kg CO EQ | 9.525E-02 | 1.225E-01 |
| Land use | m ² | 7.904E-02 | 8.868E-02 |
| Ozone depletion | kg CFC | 2.736E-08 | 3.565E-08 |
| Water use | m ³ | 1.922E-03 | 8.329E-03 |

F.2. Impact assessment methodology choice, partition alternatives

Below the characterization results for the partitions alternatives assessed in this study (baseline 2035, lifespan 6 years) employing ReCiPe impact assessment family. The respective sensitivity analysis is based upon these results.

| Impact category | Unit, ReCiPe | Excluding use phase | | Including use phase | |
|----------------------------------|--------------------|---------------------|------------|---------------------|------------|
| | | MBCs & Scalmetalloy | Nomex core | MBCs & Scalmetalloy | Nomex core |
| Acidification | kg SO ₂ | 3.03E+00 | 8.81E-01 | 1.35E+01 | 1.70E+01 |
| Climate change | kg CO ₂ | 8.22E+02 | 3.10E+02 | 4.58E+03 | 6.10E+03 |
| Ecotoxicity: freshwater | CTUe | 3.56E+02 | 1.94E+01 | 3.91E+02 | 7.39E+01 |
| Eutrophication: freshwater | kg P-eq | 4.56E-01 | 3.91E-02 | 5.44E-01 | 1.74E-01 |
| Eutrophication: marine | kg N-eq | 3.15E-02 | 1.14E-02 | 4.27E-01 | 6.20E-01 |
| Human toxicity: carcinogenic | kg 1.4 DCB | 9.05E+01 | 2.11E+01 | 2.69E+02 | 2.95E+02 |
| Human toxicity: non-carcinogenic | kg 1.4 DCB | 1.06E+04 | 3.22E+02 | 1.16E+04 | 1.74E+03 |
| Ionising radiation: human health | kg CO EQ | 6.92E+01 | 6.60E+01 | 1.06E+02 | 1.22E+02 |
| Land use | m ² | 1.58E+01 | 6.70E+00 | 5.10E+01 | 6.07E+01 |
| Ozone depletion | kg CFC | 3.15E-04 | 1.09E-04 | 1.19E-03 | 1.46E-03 |
| Water use | m ³ | 4.11E+00 | 5.32E+00 | 9.73E+00 | 1.40E+01 |

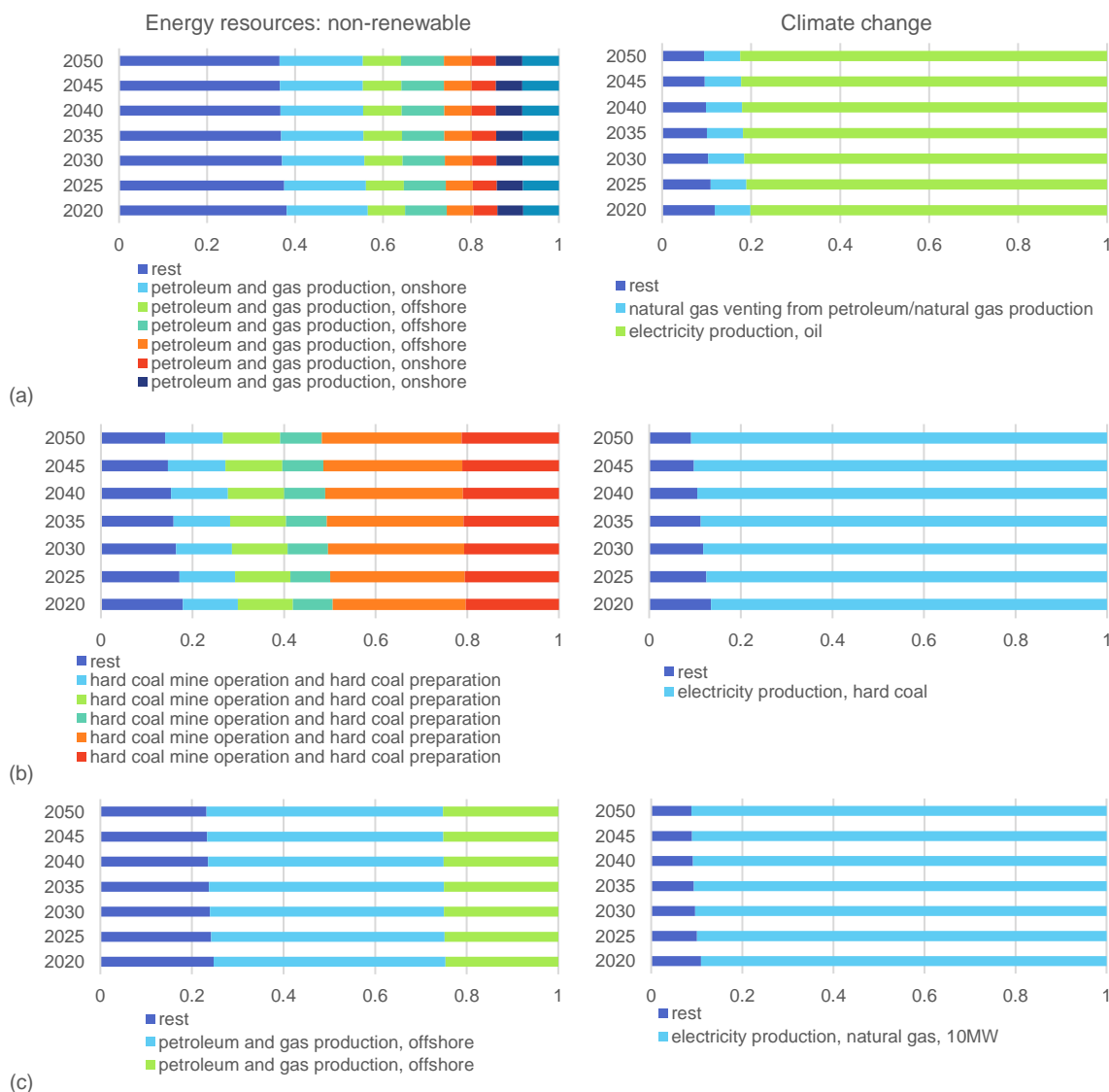
F.3. Energy carriers, manufacturing, MBCs, material only

The characterization results for 1 kg of MBCs, baseline 2035 (upscaled produced) employing seven different types of energy carriers. Note this assessment was conducted employing Dutch background processes. The respective sensitivity analysis is based upon these results.

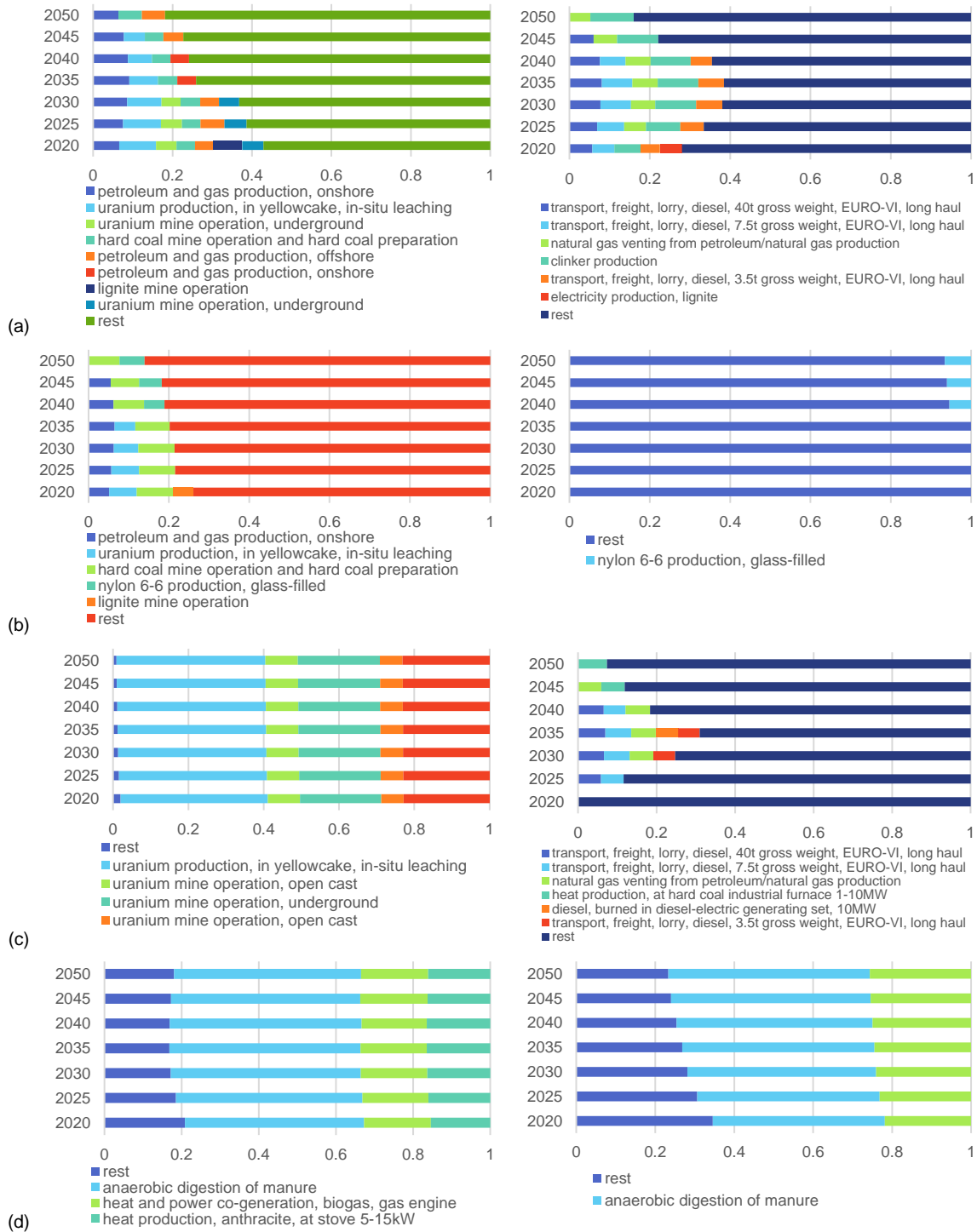
| Impact category | Unit | Energy carriers | | | | | | |
|---------------------------------|-------------------------|-----------------|-----------|-----------|----------|-------------|----------|-----------|
| | | wind | hydro | nuclear | biogas | natural gas | oil | hard coal |
| Acidification | mol H ⁺ -eq | 1.54E-04 | 9.06E-05 | 1.26E-04 | 2.10E-03 | 1.40E-03 | 1.97E-03 | 2.23E-03 |
| Climate change | kg CO ₂ -eq | 2.07E-02 | 1.20E-02 | 1.36E-02 | 2.44E-01 | 7.62E-01 | 9.51E-01 | 1.18E+00 |
| Ecotoxicity: freshwater | CTUe | -3.33E-02 | -1.56E-01 | -9.76E-02 | 3.64E-01 | -8.42E-02 | 5.01E+00 | 1.99E+00 |
| Energy resources: non-renewable | MJ, net calorific value | 3.22E-01 | 1.92E-01 | 1.51E+01 | 1.11E+00 | 1.29E+01 | 1.19E+01 | 1.10E+01 |
| Eutrophication: freshwater | kg P-eq | 9.53E-07 | -3.93E-06 | -1.12E-06 | 3.09E-05 | -1.02E-06 | 1.12E-06 | 5.12E-04 |
| Eutrophication: marine | kg N-eq | -3.56E-05 | -4.62E-05 | 7.71E-06 | 8.89E-05 | 6.20E-04 | 7.21E-04 | 5.18E-04 |
| Eutrophication: terrestrial | mol N-eq | 4.57E-04 | 3.69E-04 | 4.50E-04 | 6.11E-03 | 7.66E-03 | 7.48E-03 | 5.82E-03 |
| Human toxicity: carcinogenic | CTUh | 1.46E-10 | 6.62E-11 | 7.62E-11 | 1.42E-10 | 1.04E-10 | 3.64E-10 | 2.27E-10 |

| | | | | | | | | |
|---|-----------------------|----------|----------|----------|----------|----------|----------|----------|
| Human toxicity: non-carcinogenic | CTUh | 7.51E-10 | 1.28E-10 | 4.70E-10 | 1.61E-09 | 5.85E-10 | 1.89E-09 | 9.22E-09 |
| Ionizing radiation: human health | kBq U235-eq | 2.43E-03 | 1.99E-03 | 8.16E-01 | 4.67E-03 | 2.99E-03 | 4.62E-03 | 5.38E-03 |
| Land use | dimensionless | 9.00E+00 | 8.65E+00 | 8.70E+00 | 9.99E+00 | 8.75E+00 | 9.34E+00 | 1.03E+01 |
| Material resources: metals/minerals | kg Sb-eq | 6.96E-07 | 2.04E-07 | 3.27E-07 | 7.46E-07 | 3.53E-07 | 4.44E-07 | 4.78E-07 |
| Ozone depletion | kg CFC-11-eq | 6.96E-10 | 4.40E-10 | 5.19E-10 | 9.20E-10 | 4.40E-08 | 1.95E-08 | 1.55E-09 |
| Particulate matter formation | disease incidence | 3.49E-09 | 2.47E-09 | 5.73E-09 | 1.87E-08 | 5.71E-09 | 1.70E-08 | 9.28E-09 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 1.74E-04 | 1.28E-04 | 1.51E-04 | 8.30E-04 | 2.13E-03 | 3.21E-03 | 1.53E-03 |
| Water use | m3 world eq. deprived | 1.27E-02 | 7.01E-03 | 1.55E-01 | 1.52E-02 | 5.61E-02 | 5.45E-02 | 8.07E-02 |

A further breakdown provided by the contribution analysis focuses the impact categories of climate change (linked to electricity consumption) and energy: non-renewable resources. The figures below shows the link between non-renewable energy sources, climate change, and MBC production. For non-renewable sources, the impact on climate change is directly proportional to their consumption. The following contribution across is provided for impact categories: Energy resources: non-renewable (left) and climate change (right) of upscaled cradle-to-gate production of 1 kg of MBCs, baseline 2035, across non-renewable energy carries: (a) oil, (b) hard coal, (c) natural gas.



The following contribution across is provided for impact categories: Energy resources: non-renewable (left) and climate change (right) of upscaled cradle-to-gate production of 1 kg of MBCs, baseline 2035, across non-renewable energy carries: (a) hydroelectrical, (b) wind, (c) nuclear, (d) biogas. In contrast, with renewable energy sources, climate change is less influenced by energy consumption. Nuclear energy, however presents an interesting case. While it boasts lower climate change impact compared to traditional fossil fuels, it comes with a significant contribution to the depletion of abiotic non-renewable resources, such as uranium.



F.4. Energy carries, manufacturing, partitions

The characterization results for the manufacturing of one partition, baseline 2035 (upscaled produced) employing seven different types of energy carriers. The analysis is cradle-to-grave, yet ignores the emissions associated to use phase in aircraft. Note this assessment was conducted employing Dutch background processes. The respective sensitivity analysis is based upon these results.

The table present the values corresponding to the conventional Nomex core sandwich partition.

| Impact category | Unit | Energy carrier | | | | | | |
|---|-------------------------|----------------|----------|----------|----------|-------------|----------|-----------|
| | | wind | hydro | nuclear | biogas | natural gas | oil | hard coal |
| Acidification | mol H+-eq | 1.21E+00 | 1.17E+00 | 1.20E+00 | 2.36E+00 | 1.95E+00 | 2.88E+00 | 2.44E+00 |
| Climate change | kg CO2-eq | 2.43E+02 | 2.38E+02 | 2.39E+02 | 3.76E+02 | 6.82E+02 | 8.72E+02 | 9.31E+02 |
| Ecotoxicity: freshwater | CTUe | 2.85E+03 | 2.78E+03 | 2.81E+03 | 3.09E+03 | 2.82E+03 | 5.95E+03 | 4.05E+03 |
| Energy resources: non-renewable | MJ, net calorific value | 5.03E+03 | 4.95E+03 | 1.37E+04 | 5.49E+03 | 1.25E+04 | 1.28E+04 | 1.13E+04 |
| Eutrophication: freshwater | kg P-eq | 3.55E-02 | 3.26E-02 | 3.43E-02 | 5.32E-02 | 3.43E-02 | 8.57E-02 | 3.37E-01 |
| Eutrophication: marine | kg N-eq | 2.42E-01 | 2.35E-01 | 2.67E-01 | 3.15E-01 | 6.29E-01 | 8.71E-01 | 5.69E-01 |
| Eutrophication: terrestrial | mol N-eq | 2.39E+00 | 2.34E+00 | 2.38E+00 | 5.73E+00 | 6.65E+00 | 8.43E+00 | 5.56E+00 |
| Human toxicity: carcinogenic | CTUh | 8.04E-07 | 7.57E-07 | 7.63E-07 | 8.02E-07 | 7.80E-07 | 9.37E-07 | 8.52E-07 |
| Human toxicity: non-carcinogenic | CTUh | 4.65E-06 | 4.28E-06 | 4.48E-06 | 5.16E-06 | 4.55E-06 | 5.77E-06 | 9.65E-06 |
| Ionizing radiation: human health | kBq U235-eq | 1.22E+01 | 1.19E+01 | 4.93E+02 | 1.35E+01 | 1.25E+01 | 2.50E+01 | 1.39E+01 |
| Land use | dimensionless | 9.94E+02 | 7.83E+02 | 8.17E+02 | 1.58E+03 | 8.46E+02 | 9.46E+02 | 1.73E+03 |
| Material resources: metals/minerals | kg Sb-eq | 6.82E-03 | 6.53E-03 | 6.60E-03 | 6.85E-03 | 6.62E-03 | 6.47E-03 | 6.69E-03 |
| Ozone depletion | kg CFC-11-eq | 5.58E-06 | 5.43E-06 | 5.47E-06 | 5.71E-06 | 3.12E-05 | 1.69E-05 | 6.08E-06 |
| Particulate matter formation | disease incidence | 1.27E-05 | 1.21E-05 | 1.40E-05 | 2.17E-05 | 1.40E-05 | 2.68E-05 | 1.61E-05 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 1.04E+00 | 1.01E+00 | 1.02E+00 | 1.42E+00 | 2.19E+00 | 3.31E+00 | 1.84E+00 |
| Water use | m3 world eq. deprived | 1.87E+02 | 1.84E+02 | 2.71E+02 | 1.89E+02 | 2.13E+02 | 2.23E+02 | 2.27E+02 |

Likewise, below the values corresponding to the MBCs & Scalmalloy partition.

| Impact category | Unit | Energy carrier | | | | | | |
|---|-------------------------|----------------|----------|----------|----------|-------------|----------|-----------|
| | | wind | hydro | nuclear | biogas | natural gas | oil | hard coal |
| Acidification | mol H+-eq | 4.35E+00 | 4.31E+00 | 4.33E+00 | 5.58E+00 | 5.14E+00 | 6.19E+00 | 5.66E+00 |
| Climate change | kg CO2-eq | 7.30E+02 | 7.24E+02 | 7.25E+02 | 8.71E+02 | 1.20E+03 | 1.41E+03 | 1.47E+03 |
| Ecotoxicity: freshwater | CTUe | 8.55E+03 | 8.47E+03 | 8.51E+03 | 8.80E+03 | 8.52E+03 | 1.19E+04 | 9.83E+03 |
| Energy resources: non-renewable | MJ, net calorific value | 8.60E+03 | 8.52E+03 | 1.79E+04 | 9.10E+03 | 1.66E+04 | 1.68E+04 | 1.53E+04 |
| Eutrophication: freshwater | kg P-eq | 4.52E-01 | 4.49E-01 | 4.51E-01 | 4.71E-01 | 4.51E-01 | 4.90E-01 | 7.75E-01 |
| Eutrophication: marine | kg N-eq | 7.68E-01 | 7.62E-01 | 7.96E-01 | 8.47E-01 | 1.18E+00 | 1.46E+00 | 1.12E+00 |
| Eutrophication: terrestrial | mol N-eq | 7.81E+00 | 7.75E+00 | 7.81E+00 | 1.14E+01 | 1.24E+01 | 1.45E+01 | 1.12E+01 |
| Human toxicity: carcinogenic | CTUh | 6.61E-07 | 6.11E-07 | 6.17E-07 | 6.58E-07 | 6.35E-07 | 8.05E-07 | 7.12E-07 |
| Human toxicity: non-carcinogenic | CTUh | 9.89E-06 | 9.49E-06 | 9.71E-06 | 1.04E-05 | 9.78E-06 | 1.12E-05 | 1.52E-05 |
| Ionizing radiation: human health | kBq U235-eq | 1.18E+01 | 1.15E+01 | 5.26E+02 | 1.32E+01 | 1.21E+01 | 1.68E+01 | 1.36E+01 |
| Land use | dimensionless | 2.29E+03 | 2.07E+03 | 2.10E+03 | 2.92E+03 | 2.14E+03 | 2.22E+03 | 3.08E+03 |
| Material resources: metals/minerals | kg Sb-eq | 7.03E-03 | 6.72E-03 | 6.80E-03 | 7.06E-03 | 6.81E-03 | 6.64E-03 | 6.89E-03 |
| Ozone depletion | kg CFC-11-eq | 1.07E-05 | 1.05E-05 | 1.06E-05 | 1.08E-05 | 3.81E-05 | 2.25E-05 | 1.12E-05 |
| Particulate matter formation | disease incidence | 5.89E-05 | 5.83E-05 | 6.03E-05 | 6.85E-05 | 6.03E-05 | 7.81E-05 | 6.26E-05 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 2.46E+00 | 2.44E+00 | 2.45E+00 | 2.88E+00 | 3.70E+00 | 4.94E+00 | 3.32E+00 |
| Water use | m3 world eq. deprived | 1.32E+02 | 1.29E+02 | 2.23E+02 | 1.34E+02 | 1.60E+02 | 1.68E+02 | 1.75E+02 |

F.5. Energy carries, use phase, fuel

These characterization results correspond to the assessment of the use one partition, within an aircraft cabin providing non-structural support. It uses the baseline 2035 (combustion energy of kerosene), plus two additional potentially decarbonized energy carriers. The analysis is cradle-to-grave. Note this assessment was conducted employing global background processes. The respective sensitivity analysis is based upon these results.

| Category | Unit | Combustion energy, kerosene | | Combustion energy, biokerosene | | Conversion energy, hydrogen fuel cell | |
|---|-----------------------------------|-----------------------------|-------------------|--------------------------------|-------------------|---------------------------------------|-------------------|
| | | Nomex core | MBCs & Scalmalloy | Nomex core | MBCs & Scalmalloy | Nomex core | MBCs & Scalmalloy |
| Acidification | mol H ⁺ -eq | 2.50E+01 | 1.99E+01 | 1.31E+01 | 1.21E+01 | 2.90E+01 | 2.25E+01 |
| Climate change | kg CO ₂ -eq | 5.50E+03 | 4.15E+03 | 2.03E+03 | 1.89E+03 | 6.73E+03 | 4.96E+03 |
| Ecotoxicity: freshwater | CTUe | 1.50E+05 | 1.05E+05 | 2.58E+04 | 2.36E+04 | 3.62E+04 | 3.03E+04 |
| Energy resources: non-renewable | MJ, net calorific value | 3.45E+05 | 2.30E+05 | 4.11E+04 | 3.26E+04 | 3.28E+05 | 2.19E+05 |
| Eutrophication: freshwater | kg P-eq | 1.74E-01 | 5.43E-01 | 8.98E-01 | 1.02E+00 | 1.41E+00 | 1.35E+00 |
| Eutrophication: marine | kg N-eq | 5.03E+00 | 3.90E+00 | 3.49E+00 | 2.90E+00 | 4.56E+00 | 3.59E+00 |
| Eutrophication: terrestrial | mol N-eq | 4.38E+01 | 3.49E+01 | 3.04E+01 | 2.62E+01 | 5.21E+01 | 4.03E+01 |
| Human toxicity: carcinogenic | CTUh | 3.06E-06 | 2.13E-06 | 8.74E-06 | 5.83E-06 | 9.50E-06 | 6.33E-06 |
| Human toxicity: non-carcinogenic | CTUh | 4.35E-05 | 3.54E-05 | 9.22E-05 | 6.71E-05 | 2.30E-04 | 1.57E-04 |
| Ionizing radiation: human health | kBq U235-eq | 1.49E+02 | 1.26E+02 | 7.63E+02 | 5.25E+02 | 3.84E+03 | 2.53E+03 |
| Land use | dimensionless | 2.11E+04 | 1.57E+04 | 1.63E+06 | 1.06E+06 | 7.09E+04 | 4.81E+04 |
| Material resources: metals/minerals | kg Sb-eq | 1.31E-02 | 1.14E-02 | 8.18E-02 | 5.61E-02 | 2.20E-01 | 1.46E-01 |
| Ozone depletion | kg CFC-11-eq | 5.59E-04 | 3.72E-04 | 7.70E-05 | 5.77E-05 | 9.85E-04 | 6.49E-04 |
| Particulate matter formation | disease incidence | 2.12E-04 | 1.89E-04 | 2.59E-04 | 2.20E-04 | 2.56E-04 | 2.18E-04 |
| Photochemical oxidant formation: human health | kg NMVOC-eq | 5.12E+01 | 3.51E+01 | 1.61E+01 | 1.23E+01 | 1.94E+01 | 1.45E+01 |
| Water use | m ³ world eq. deprived | 5.99E+02 | 4.22E+02 | 1.23E+03 | 8.35E+02 | 4.11E+03 | 2.71E+03 |