



UNIVERSITY OF INSUBRIA

DEPARTMENT OF SCIENCE AND HIGH TECHNOLOGY

Ph.D. in Environmental Sciences

**ENVIRONMENTAL SUSTAINABILITY OF
HIGH-PERFORMANCE THERMOPLASTIC
MATERIALS**

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ABSTRACT

Thermoplastic compounds are utilised in various industries due to their exceptional mechanical properties. However, polymers are often produced from non-renewable sources, such as petroleum, through energy-intensive processes. Therefore, understanding their environmental impact is crucial for proposing effective mitigation solutions. This research evaluates the environmental performance of seven high-performance thermoplastic compounds added with different flame retardants. The analysis was conducted using Life Cycle Assessment (LCA) methodology and following the PCR 2010:16 Plastics in primary forms v4.0.0. The software used was SimaPro v10.1 with Ecoinvent database v3.10. The Functional Units considered are 1 kg and 1 L of compound. Furthermore, several mitigation scenarios were evaluated, such as the introduction of mechanically recycled polymers and the use of different energy mixes. The results show significant variations in impact depending on the polymer, flame retardant, and its density. In particular, polyamide-based polymers tend to have a higher impact. Regarding mitigation scenarios, the introduction of recycled polymers at different rates brings the most significant benefits compared to other mitigation systems. The results of this study will be useful to both the scientific community and technical stakeholders involved in the production and design of sustainable thermoplastic compounds.

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ABBREVIATIONS

AU	Allocation Unit
BPS-at	Brominated polystyrene
CFs	Characterization Factors
CR	Chemical Recycling
DALY	Disability Adjusted Life Years
DEPAL	Aluminium diethylphosphinate
EoL	End-of-life
EPD	Environmental Product Declaration
FU	Functional Unit
GF	Glass fiber
GHG	Greenhouse Gases
GLO	Global
GWP	Global Warming Potential
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MR	Mechanical Recycling
PA	Polyamide
PA6	Polyamide 6
PA66	Polyamide 6,6
PBB	Polybrominated Biphenyls

PBDE	Polybrominated Diphenyl Ethers
PBT	Polybutadiene terephthalate
PCR	Product Category Rules
PFAR	Per and Polyfluoroalkyl Substances
Pt	Point
PP	Polypropylene
PPS	Polyphenylene sulfide
ReR	Europe
RoW	Rest of World
SB	System Boundaries
U	Unit

1 CHAPTER 1: INTRODUCTION

1.1 Research context

Global plastic production has grown exponentially over the past seventy years [1]. Since 1950, when annual production was estimated at just 21 million tonnes, global production has now exceeded 400 million tonnes [2]. In Europe, 50 tonnes of plastic were produced in 2022, leading to an annual production of over 45 tonnes of plastic waste in 2023 [3]. These numbers show that the impacts of plastic production and plastic waste management have become one of the most pressing environmental challenges worldwide [4]. Despite policies and strategies aimed at encouraging the use of low-impact raw materials, recycling, and reuse, such as the European Union's Circular Economy Package, which requires all packaging to be reusable or recyclable, significant obstacles remain [5]. These include the lack of robust markets for recycled plastic, differences in collection systems across countries, and concerns about the quality and safety of recycled materials [6-7]. An estimated 85% of plastics produced are thermoplastics [8].

Thermoplastics are prized for their excellent formability, low density, and versatility, making them essential in countless industrial and consumer applications: Polyamides (PA), polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC) are examples of commonly used thermoplastics [9-11]. Among these, engineering thermoplastics play a significant role in sectors requiring high mechanical, thermal, and chemical performance, such as the automotive, aerospace, construction, and electronics industries [12]. To meet stringent technical requirements, engineering thermoplastics are often modified with additives, fillers, and flame retardants, which can further complicate their environmental impact [13].

At every stage of their life cycle, from raw material extraction and processing to manufacturing, use, and final disposal, engineering thermoplastics contribute significantly to resource depletion, greenhouse gas emissions, and pollution [14]. Furthermore, improper waste management can cause persistent plastic pollution, including the generation of microplastics that pose risks to ecosystems and human health [15].

Flame retardants, while critical to product safety, may also be of concern due to the potential release of hazardous substances [16].

To mitigate these impacts, increasing attention has been paid to the integration of biobased polymers synthesised from renewable resources, which offer improved biodegradability and sustainability [17]. However, biobased alternatives are not always viable for high-performance engineering applications, where technical requirements remain stringent [18]. Mechanical recycling, in this context, offers a practical solution to reduce the demand for virgin materials while maintaining the properties necessary for engineering uses [19]. In this scenario, Life Cycle Assessment (LCA) has established itself as a fundamental methodology for quantifying the environmental impacts associated with products, processes or services throughout their entire life cycle, from cradle to grave [20-21].

The research project focused on evaluating the environmental impacts generated throughout the life cycle of the production process for high-performance thermoplastic materials, encompassing the origin of raw materials used in production, as well as marketing. The assessment was carried out using the Life Cycle Assessment approach, as outlined in UNI EN ISO 14040 and 14044 [22-23].

The activity is carried out in collaboration between LATI's Research and Development (R&D) department and the Department of Theoretical and Applied Sciences (DiSTA) of the University of Insubria. In particular, LATI is co-financing a PNRR Ph.D. scholarship in environmental engineering.

LATI Industria Termoplastici S.p.A. is among the most important European manufacturers of technical thermoplastics for engineering purposes. Founded in 1945 by Cosimo Conterno, today the company is run by Michela Conterno, daughter of his son Francesco Conterno who led the group for decades [24]. The company's first activity was to use the materials made available to the Italian population by the Marshall Plan to recycle and produce cellulose acetate compounds. For example, they used underwear made of cellulose acetate, plastic army masks or other items. Then, they launched a range of glass fibre-reinforced products. The demand from the electrical household appliance sector begets the realization of flame-retardant compounds. This is how LATI decided step by step to invest in developing unique high-performance products. Innovation (especially towards eco-sustainable and eco-compatible products) and internationalization are the keywords of the company's strategy.

1.2 Activities timetable

The research activities were carried out over a period of three years, for a total of six semesters. The first semester covered the period from 1st October 2022 to 31st March 2023; the second semester from 1st April 2023 to 30th September 2023; the third semester from 1st October 2023 to 31st March 2024; the fourth semester from 1st April 2024 to 30th September 2024; the fifth semester from 1st October 2024 to 31st March 2025 and finally, the sixth semester from 1st April 2025 to 31st September 2025.

The research activities were conducted over a period of 36 months, with 18 months at the University of Insubria (University site), 6 months at the LATI company (Company site), and 12 months at foreign Universities (Abroad). Table 1 summarises the activities carried out for each semester. The complete list of publications and conferences held during the doctoral activities is reported in Chapter 10.

Table 1. Activity Summary Timetable.

Semester	Activities
1st year	
1 st	<u>University site</u> : Environmental and socio-economic analysis of a pilot briquetting plant in La Paz (Bolivia) using the Life Cycle Thinking (LCT) methodology, resulting in two scientific publications. Literature review of LCA applied to thermoplastics for engineering purposes. <u>Company site</u> : Analysis of the production process, inventory analysis with data collection, and process modelling in SimaPro software for LCA evaluation.
2 nd	<u>Company site</u> : Completion of data collection for the products analysed. Data processing, development and improvement of the SimaPro model, and obtaining initial results.
2nd year	
3 rd	<u>University site</u> : Completion of comparative LCA of three thermoplastic compounds. Obtaining baseline scenario results, interpretation phase, and development of mitigation scenarios (e.g. use of green energy, photovoltaic installation). Initial analyses on recycled raw materials and drafting of a scientific paper. <u>Abroad</u> : Research abroad at the Department of Chemistry, Aristotle University of Thessaloniki (Greece) for 3 months. Assessment of the environmental sustainability of an arsenic-

contaminated water treatment plant in Malgara (Greece) using LCA methodology. Results were included in a scientific publication.

4th University site: Analysis of mitigation scenarios involving the use of mechanically recycled raw materials. Comparison of benefits for three different compounds. Submission of a scientific paper presenting the research findings.

3rd year

5th University site: Comparative analysis of a PA6-based thermoplastic compound, evaluating versions with polymer from chemical recycling, mechanical recycling, and recycled glass fibre. Abroad: Research abroad at the Department of Mechanical and Materials Engineering at Universitat Politècnica de València (Spain) for 3 months. Assessment of the environmental and economic sustainability of five polymers for 3D printing. The study identified optimal options in terms of environmental impact and costs, and proposed mitigation strategies. Analyses were conducted using LCA and Life Cycle Costing (LCC) methodologies. Findings were included in a scientific paper.

6th University site: Evaluation of the environmental profile of three high-performance thermoplastic compounds with different polymers. Abroad: Research abroad at the Department of Civil and Environmental Engineering at Brunel University of London (United Kingdom) for 6 months. The first part includes the evaluation of the state-of-the-art of LCA methodology applied to modular and prefabricated buildings. Results were included in a scientific publication. The second part deals with the comparison of the environmental impacts of recycling processes of waste fibers for cement composites such as carbon fiber, glass fiber and basalt fiber. The analysis was carried out using the LCA methodology. The findings were reported in a scientific article.

1.3 Life Cycle Assessment methodology

The environmental analysis is carried out through the Life Cycle Assessment (LCA) methodology. LCA is a systematic and rigorous methodology employed to quantify the environmental impacts associated with the entire life cycle of a product, service, or process. This comprehensive approach spans from the extraction of raw materials through production, distribution, use, and eventual disposal. LCA proves to be an essential tool for assessing sustainability and facilitating informed decision-making, as it enables the identification of environmental impacts and areas for potential improvement.

The international standards ISO 14040 and ISO 14044 provide a robust framework for conducting LCAs, ensuring consistency, reliability, and comparability of results across various studies and sectors [22-23, 25]. Adherence to these standards assists organisations in conforming to best practices in LCA, making it an invaluable resource for sustainable development and environmental management. According to the mentioned ISO standards and as reported in Figure 1, the phases of LCA are four:

Goal and scope definition: defining the assumptions and the limits of the study is the preliminary step of the analysis. The scope of research, Functional Unit and System Boundaries are defined in this step, as well as the identification of the necessary data.

Life Cycle Inventory Analysis: this is the collection phase of all necessary data to meet the scopes of the LCA study; in this step, the mass and energy balances and the result of this phase is the Life Cycle Inventory are required.

Life Cycle Impact Assessment: this step converts the Life Cycle Inventory into the related environmental impacts and effects on natural resource use, the natural environment and human health.

Interpretation: this is the final step of an LCA analysis; the results are critically examined, and possible changes may be made to reduce the environmental impact.

This study has been supported by the guidelines, i.e. Product Category Rules (PCR), for Environmental Product Declaration (EPD) for plastic-based products. Thus, the PCR 2010:16 Plastics v4.0.0 (revised on 1st July 2024) were also used to frame the overall structure of the study [26].

According to ISO 14040 and ISO 14044 standards [1-2], this technical report employs a structured and systematic approach for conducting an LCA. By adhering to ISO 14040 and ISO 14044 standards, this report ensures the LCA methodology's reliability, consistency, and transparency, making it a valuable resource for stakeholders seeking to assess and mitigate the environmental impacts of their products, services, or processes. The analysis was carried out with SimaPro v10.1 [27] and Ecoinvent database v3.10 [27].

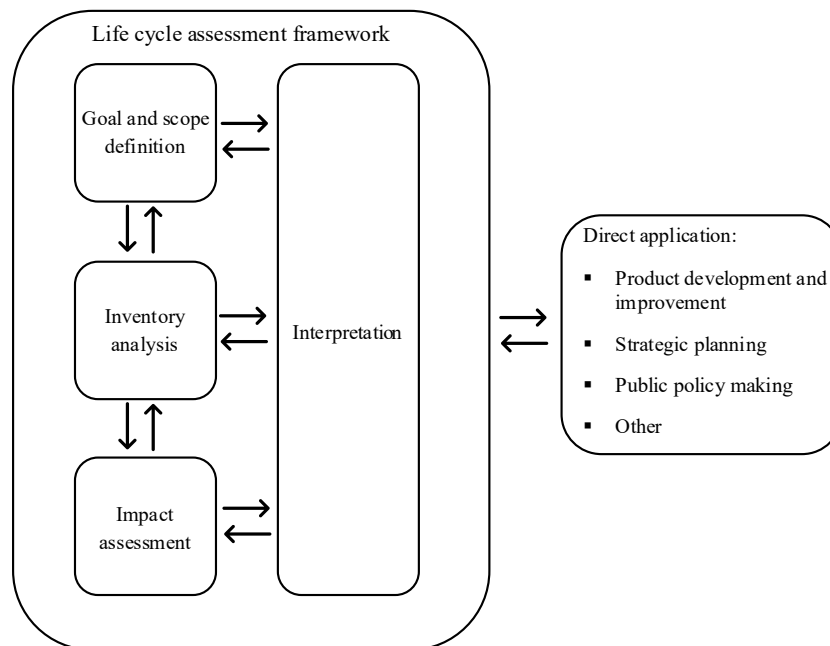


Figure 1. Life Cycle Assessment framework (adapted from [22]).

1.4 References

- [1] Okoffo, E.D., Erica Donner, McGrath, S.P., Tscharke, B.J., O'Brien, J.W., O'Brien, S., Ribeiro, F., Burrows, S.D., Toapanta, T., Rauert, C., Samanipour, S., Mueller, J.F., Thomas, K.W. (2021). Plastics in biosolids from 1950 to 2016: A function of global plastic production and consumption. *Water Research*, 201, 117367. doi:10.1016/j.watres.2021.117367.
- [2] Nayanathara Thathsarani Pilapitiya, P.G.C., Ratnayake, A.S., 2024. The world of plastic waste: A review. *Cleaner Materials*. <https://doi.org/10.1016/j.clema.2024.100220>.
- [3] Real, L.E.P. (2023). *Plastics Statistics: Production, Recycling, and Market Data*. In: *Recycled Materials for Construction Applications*. Springer, Cham. doi.org/10.1007/978-3-031-14872-9_5.
- [4] Macheca, A. D., Mutuma, B., Adalima, J. L., Midheme, E., Lucas, L. H. M., Ochanda, V. K., & Mhlanga, S. D. (2024). Perspectives on Plastic Waste Management: Challenges and Possible Solutions to Ensure Its Sustainable Use. *Recycling*, 9(5), 77. doi: 10.3390/recycling9050077.
- [5] Chioatto, E., Sospiro, P. (2023). Transition from waste management to circular economy: the European Union roadmap. *Environment, Development and Sustainability* 25, 249–276. doi:10.1007/s10668-021-02050-3.
- [6] Mhatre, P., Panchal, R., Singh, A., Bibyan, S. (2021). A systematic literature review on the circular economy initiatives in the European Union, *Sustainable Production and Consumption*, 26, 187-202, doi:10.1016/j.spc.2020.09.008.
- [7] Mazur-Wierzbicka, E. (2021). Circular economy: advancement of European Union countries. *Environmental Sciences Europe* 33, 111. doi:10.1186/s12302-021-00549-0.
- [8] Wang, C., Yi, L., Chen W.Q., Zhu, B., Qu, S., Xu, M.(2021). Critical review of global plastics stock and flow data. *Journal of Industrial Ecology* 25, 1300-1317. doi:10.1111/jiec.13125.
- [9] Ozturk, F., Cobanoglu, M., Ece, R.E. (2023). Recent advancements in thermoplastic composite materials in aerospace industry. *Journal of Thermoplastic Composite Materials* 37(9), 3084-3116. doi:10.1177/08927057231222820.

- [10] Sakaue, K. (2023). Viscoelastic and Viscoplastic Behavior of Polymer and Composite. doi: 10.1007/978-3-031-22401-0_9.
- [11] Mărieș, G. R. E., and Abrudan, A. M. (2018). Thermoplastic polymers in product design. in IOP Conference Series: Materials Science and Engineering doi: 10.1088/1757-899X/393/1/012118.
- [12] Baltrocchi, A.P.D., Carnevale Miino, M., Maggi, L., Rada, E.C., Torretta, V. (2025). A comprehensive critical review of Life Cycle Assessment applied to thermoplastic polymers for mechanical and electronic engineering. *Environmental Technology Reviews* 14, 458–470. doi:10.1080/21622515.2025.2491632.
- [13] Sabet, M. (2024). Advancements in halogen-free polymers: exploring flame retardancy, mechanical properties, sustainability, and applications. *Polymer-Plastics Technology and Materials*, 63(13), 1794–1818. doi:10.1080/25740881.2024.2359633.
- [14] Maga, D., Aryan, V., Beard, A. (2024). Toward Sustainable Fire Safety: Life Cycle Assessment of Phosphinate-Based and Brominated Flame Retardants in E-Mobility and Electronic Devices. *ACS Sustainable Chemistry & Engineering* 12, 3652–3658. doi:10.1021/acssuschemeng.3c07096.
- [15] Carnevale Miino, M., Galafassi, S., Zullo, R., Torretta, V., Rada, E. C. (2024). Microplastics removal in wastewater treatment plants: A review of the different approaches to limit their release in the environment. *Science of the Total Environment*, 930, 172675. doi:10.1016/j.scitotenv.2024.172675.
- [16] de Boer, J., Harrad, S., Sharkey, M. (2024). The European Regulatory Strategy for flame retardants—The right direction but still a risk of getting lost. *Chemosphere*, 347, 140638. doi:10.1016/j.chemosphere.2023.140638.
- [17] Okolie, O., Kumar, A., Edwards, C., Lawton, L. A., Oke, A., McDonald, S., Thakur, V. K., & Njuguna, J. (2023). Bio-Based Sustainable Polymers and Materials: From Processing to Biodegradation. *Journal of Composites Science*, 7(6), 213. doi:10.3390/jcs7060213.

- [18] Cywar, R.M., Rorrer, N.A., Hoyt, C.B., Beckham, G.T., Chen, E.Y. (2022). Bio-based polymers with performance-advantaged properties. *Nature Reviews Materials* 7, 83-103. doi:10.1038/s41578-021-00363-3.
- [19] Baltrocchi, A.P.D., Lotti, D., Carnevale Miino, M., Maggi, L., Rada, E.C., Torretta, V., (2025). Environmental impact of three different engineering thermoplastics: How much does it change when using recycled polyamide? *Journal of Cleaner Production* 514, 145769. doi:10.1016/j.jclepro.2025.145769.
- [20] Ferronato, N., Baltrocchi, A. P. D., Romagnoli, F., Mendoza, I. J. C., Portillo, M. A. G., Torretta, V. (2023). Environmental Life Cycle Assessment of biomass and cardboard waste-based briquettes production and consumption in Andean areas. *Energy for Sustainable Development*, 72, 139-150. doi:10.1016/j.esd.2022.12.005.
- [21] Baltrocchi, A.P.D., Carnevale Miino, M., Katsoyiannis, I.A., Tolkou, A.K., Maggi, L., Rada, E.C., Torretta, V. (2024). Assessment of environmental sustainability of drinking water treatments fo arsenic removal. *Resources, Conservation and Recycling*. 211, 107878. doi:10.1016/j.resconrec.2024.107878.
- [22] ISO 14040:2021. (2021). Environmental Management-Life Cycle Assessment-Principles and framework. Geneva, Switzerland. <https://www.iso.org/standard/37456.html>.
- [23] ISO 14044:2021. (2021). Environmental Management-Life Cycle Assessment-Requirements and guidelines. Geneva, Switzerland. <https://www.iso.org/standard/38498.html>.
- [24] LATI | History: Who is LATI? (2025). Available online: <https://www.lati.com/en/about-lati/history/>. (Accessed 30.07.2025).
- [25] ISO 14025:2020. (2020). Environmental labels and declarations-Type III Environmental Declarations Principles and procedures. Geneva, Switzerland. <https://www.iso.org/standard/38131.html>.
- [26] Product Category Rules (PCR) 2010:16 Plastics in primary forms v3.0.2. (2022). <https://api.environdec.com/api/v1/EPDLibrary/Files/482e9ef6-90be-4c59-c57e-08dc95fad0b1/Data>.

[27] PRé Consultants. Software SimaPro v10.1 (2024). <https://simapro.com/wp-content/uploads/2025/02/SimaPro101WhatIsNew.pdf>.

[28] Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M. (2005). The ecoinvent database: overview and methodological framework (7 pp). *International Journal of Life Cycle Assessment* 10, 3-9. doi:10.1065/lca2004.10.181.1.

2 CHAPTER 2: LITERATURE REVIEW

A more extensive and detailed discussion of the existing literature on this topic has been published in a dedicated review article [1]; the present chapter therefore provides a concise synthesis.

2.1 Introduction

In recent years, several reviews have studied the LCA approach applied to thermoplastic production. The research of Molina-Besch (2022) [2] analysed the use and End of Life (EoL) LCA model of bioplastics; Bishop et al. (2021) [3] studied a methodology for assessing the environmental impacts of bioplastics versus petroleum-based plastics; the review of Ramesh and Vinodh (2020) [4] focused on the environmental impacts of petroleum-based polymers compared with the biopolymers; Spierling et al. (2018) [5] evaluated the sustainability of bioplastic production. Finally, the study of Hottle et al (2013) [6] compared the environmental impacts of three biopolymers and five petroleum-derived polymers. Materials, purpose, and findings of previous reviews are reported in Table 2. The aim of the study of Baltrocchi et al. (2025) [1] is to evaluate the state of the art of the LCA methodology applied to thermoplastics for engineering purposes.

Table 2. The features of LCA thermoplastics review articles (adapted from [1]).

Study	Ref.	Materials	Aim	Results
Molina-Besch (2022)	[2]	Bio-based biodegradable plastics	Analyse and evaluate how the use of biodegradable bioplastics is modelled in LCA.	The evaluation showed that the use phase is neglected compared to the other phases.
Bishop et al. (2021)	[3]	Bioplastics and petrochemical plastics	Propose a methodology for assessing the environmental impacts through LCA analysis of bioplastics compared to petrochemical plastics.	A series of indications are proposed to conduct the LCA.

Ramesh and Vinodh (2020)	[4]	Bio-based and petroleum-derived polymers	and Comparison of impacts from LCA analysis between petroleum-derived polymers and biopolymers.	Biopolymers have lower environmental impacts than petroleum-based polymers.
Spierling et al. (2018)	[5]	Bio-based plastics	Sustainability assessment of the production of bioplastics.	Biobased plastics could bring relevant benefits in terms of GHG emissions.
Hottle et al. (2013)	[6]	Bio-based and petroleum-derived polymers	and Comparison of the impacts from LCA analysis of producing three biopolymers with five petroleum-derived polymers.	Biopolymers show similar impacts to petroleum-derived polymers.

2.2 Materials and methods

The literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [7]. Furthermore, the Scopus® database was used for the analysis with the following keywords: ((carbon AND footprint) OR LCA OR “Life cycle assessment”) AND (Thermoplastics OR “Biobased plastics” OR polymers OR polymers) AND compound in the “article title, abstract, keywords” field). The first step identified 138 results. The first screening process selected only research articles and documents from English language journals published between 2008 and 2012. A total of 103 documents passed the first screening process. The second screening process, based on the titles and abstracts, selected documents that (i) analysed thermoplastic materials; (ii) conducted an LCA analysis; and (iii) were not limited to the study of packaging materials, single-use products, and other non-engineering uses. Finally, based on the selected criteria, 7 articles were identified as relevant. The diagram of the criteria of selection is reported in Figure 2.

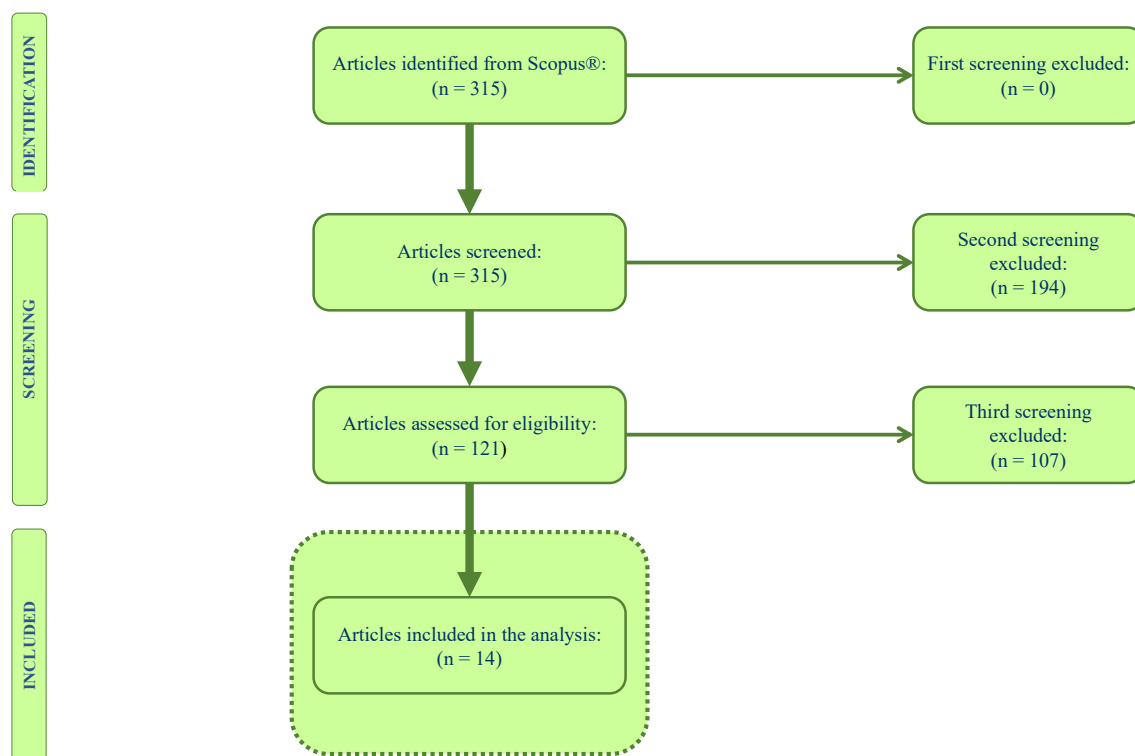


Figure 2. Diagram of criteria of selection (adapted from [1]).

2.3 Results

The analysis shows that the studies were published between 2015 and 2022, with a notable increase in contributions in 2022. The articles are primarily concentrated in Europe, with additional studies from North America and Australia, and span seven different scientific journals. The primary focus of the studies is the comparison of virgin or petroleum-derived materials with their bio-based or recycled counterparts. A total of 17 raw materials were evaluated, with PA, PP, and HDPE being the most frequently studied polymers. The results indicate that the use of recycled and bio-based materials generally yields environmental benefits, including reduced greenhouse gas emissions and a lower overall impact. However, these advantages often come with some challenges, such as potential performance limitations, economic feasibility issues, and industrial complications. The main details are reported in Table 3.

Table 3. The publications feature details of materials, aims and findings (adapted from [6]).

Study	Ref.	Materials	Aims	Main findings
Tinz et al. (2022)	[8]	AB, PA66 with GF30, PC, POM	Calculate the impacts derived from the mechanical recycling of post-industrial plastic waste.	The results per kg of regrind show values from 0.146 to 0.152 kg CO ₂ eq.
Seile et al. (2022)	[9]	PLA and PA with GF	Evaluation of the production of different PLA compositions compared to PA66 and GF30.	Bio-based compounds offer benefits in terms of GWP, but PA66 with GF30 presents less impact in other categories.
He et al. (2022)	[10]	PA	Evaluation of automotive parts.	The material produced with recycled PA has fewer impacts compared to petroleum-based PA66.
Galve et al. (2022)	[11]	PA6, virgin and recycled PP	Comparison of the environmental impacts of components made of different materials	The recycled PP reduces the environmental impact by around 30 % compared to other materials.
Nguyen et al. (2020)	[12]	HDPE and bio-HDPE	GWP evaluation of different piping systems.	HDPE pipes have higher environmental emissions compared to the bio-based solution.
Korol et al. (2016)	[13]	PP and GF with natural fibre ranged from 10 to 30 %	Compare the impacts of plastic pallets.	It is impossible to define the most environmentally friendly materials.
Delogu et al. (2015)	[14]	PA and GF30 - PP and GF35	Evaluate the environmental performance of automotive parts made in PP and PA.	Replacing PP with PA brings significant reductions in the impacts.

Regarding the LCA analysis, the studies employed different software, primarily SimaPro and GaBi, and varied in their FUs and SBs. Furthermore, most articles assessed only the GWP, without examining the complete environmental profile.

In conclusion, the study shows that the scientific literature presents many gaps in studies applying the LCA methodology to thermoplastic materials for engineering use.

2.4 References

- [1] Baltrocchi, A.P.D., Carnevale Miino, M., Maggi, L., Rada, E.C., Torretta, V. (2025). A comprehensive critical review of Life Cycle Assessment applied to thermoplastic polymers for mechanical and electronic engineering. *Environmental Technology Reviews* 14, 458–470. doi:10.1080/21622515.2025.2491632.
- [2] Molina-Besch, K. (2022). Use phase and end-of-life modeling of biobased biodegradable plastics in life cycle assessment: a review. *Clean Technologies and Environmental Policy* 24, 3253–3272. doi: 10.1007/s10098-022-02373-3.
- [3] Bishop, G., Styles, D., and Lens, P. N. L. (2021). Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions. *Resources, Conservation and Recycling* 168. doi: 10.1016/j.resconrec.2021.105451.
- [4] Ramesh, P., and Vinodh, S. (2020). State of art review on Life Cycle Assessment of polymers. *International Journal of Sustainable Engineering* 13, 411–422. doi: 10.1080/19397038.2020.1802623.
- [5] Spierling, S., Knüpfner, E., Behnsen, H., Mudersbach, M., Krieg, H., Springer, S., et al. (2018). Bio-based plastics - A review of environmental, social and economic impact assessments. *Journal of Cleaner Production* 185, 476–491. doi: 10.1016/j.jclepro.2018.03.014.
- [6] Hottle, T. A., Bilec, M. M., and Landis, A. E. (2013). Sustainability assessments of bio-based polymers. *Polymer Degradation and Stability* 98, 1898–1907. doi: 10.1016/j.polymdegradstab.2013.06.016.
- [7] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery* 88, 105906. doi: 10.1016/j.ijssu.2021.105906.
- [8] Tinz, J., de Ancos, T., and Rohn, H. (2022). Carbon Footprint of Mechanical Recycling of Post-Industrial Plastic Waste: Study of ABS, PA66GF30, PC and POM Regrinds. *Waste* 1, 127–139. doi: 10.3390/waste1010010.

- [9] Seile, A., Spurina, E., and Sinka, M. (2022). Reducing Global Warming Potential Impact of Bio-Based Composites Based of LCA. *Fibers* 10. doi: 10.3390/fib10090079.
- [10] He, D., Kim, H. C., De Kleine, R., Soo, V. K., Kiziltas, A., Compston, P., et al. (2022). Life cycle energy and greenhouse gas emissions implications of polyamide 12 recycling from selective laser sintering for an injection-molded automotive component. *Journal of Industrial Ecology* 26, 1378–1388. doi: 10.1111/jiec.13277.
- [11] Galve, J. E., Elduque, D., Pina, C., and Javierre, C. (2022). Life Cycle Assessment of a Plastic Part Injected with Recycled Polypropylene: A Comparison with Alternative Virgin Materials. *International Journal of Precision Engineering and Manufacturing - Green Technology* 9, 919–932. doi: 10.1007/s40684-021-00363-2.
- [12] Nguyen, L. K., Na, S., Hsuan, Y. G., and Spatari, S. (2020). Uncertainty in the life cycle greenhouse gas emissions and costs of HDPE pipe alternatives. *Resources, Conservation and Recycling* 154. doi: 10.1016/j.resconrec.2019.104602.
- [13] Korol, J., Burchart-Korol, D., and Pichlak, M. (2016). Expansion of environmental impact assessment for eco-efficiency evaluation of biocomposites for industrial application. *Journal of Cleaner Production* 113, 144–152. doi: 10.1016/j.jclepro.2015.11.101.
- [14] Delogu, M., Del Pero, F., Romoli, F., and Pierini, M. (2015). Life cycle assessment of a plastic air intake manifold. *International Journal of Life Cycle Assessment* 20, 1429–1443. doi: 10.1007/s11367-015-0946-z.

3 CHAPTER 3: MATERIALS

This chapter describes the composition and the properties of the compounds.

3.1 LATAMID 66 H2 G/25-V0CT1

LATAMID 66 H2 G/25-V0CT1, in short “V0CT1”, is a self-extinguishing glass-reinforced thermoplastic compound based on PA66. The main application is the production of injection moulded parts for electrical, electronics and appliances sector. Table 4 reports the V0CT1 raw material composition and their percentage contribution. This compound has several key features that make it ideal for specific applications. Firstly, it exhibits a significant improvement in its thermal stability. Additionally, the compound incorporates GF, further enhancing its mechanical properties. This imparts the material with increased strength and stiffness. This compound is rated as UL94 V-0 class, meaning it self-extinguishes when removing the flame source. The flame retardants are brominated polystyrene (BPS-at) combined with antimony trioxide and zinc borate. It is free from Polybrominated Biphenyls (PBB) and Polybrominated Diphenyl Ethers (PBDE), substances that can pose environmental and health risks. Furthermore, this product is Per-and Poly-fluoroalkyl Substances (PFAS) free, contributing to environmental preservation. Physical, mechanical, thermal and electrical properties are shown from Table 5 to Table 9. The data is available in the technical data sheets on the LATI website [1].

Table 4. V0CT1 representative composition used in this research project.

Raw material	Percentage (%)
Polyamide 6,6	43-46
Glass fibre	25-28
Brominated polystyrene in combination with antimony trioxide	21-24
Other	<15

Table 5. VOCT1 - Physical properties.

Physical properties	Standard	Value measure units
Density	ISO 1183	1.55 g cm ⁻³
Linear shrinkage at moulding		
Longitudinal (2.0 mm/60 MPa)	ISO 294-4	0.35 ÷ 0.60 %
Transversal (2.0 mm/60 MPa)	ISO 294-4	0.70 ÷ 1.00 %
Moisture absorption		
saturation, in air	ISO 62-4	1.55 %

Table 6. V0CT1 - Mechanical properties.

Mechanical properties	Standard	Value measure units
CHARPY impact strength		
Unnotched, at +23 °C	ISO 179-1eU	45.0 kJ m ⁻²
Notched, at +23 °C	ISO 179-1eA	7.0 kJ m ⁻²
Tensile elongation		
At break (5 mm/min), 23 °C	ISO 527	2.1 %
At break (5 mm/min), 60 °C	ISO 527	2.9 %
At break (5 mm/min), 90 °C	ISO 527	3.8 %
At break (5 mm/min), 120 °C	ISO 527	4.8 %
At break (5 mm/min), 150 °C	ISO 527	5.3 %
Tensile strength		
At break (5 mm/min), 23 °C	ISO 527	110 MPa
At break (5 mm/min), 60 °C	ISO 527	95 MPa
At break (5 mm/min), 90 °C	ISO 527	75 MPa
At break (5 mm/min), 120 °C	ISO 527	65 MPa
At break (5 mm/min), 150 °C	ISO 527	60 MPa
Elastic modulus		
Tensile (1 mm/min), 23 °C	ISO 527	8,000 MPa
Tensile (1 mm/min), 60 °C	ISO 527	6,500 MPa
Tensile (1 mm/min), 90 °C	ISO 527	5,000 MPa
Tensile (1 mm/min), 120 °C	ISO 527	4,500 MPa
Tensile (1 mm/min), 150 °C	ISO 527	3,000 MPa

Table 7. V0CT1 - Thermal properties.

Thermal properties	Standard	Value measure units
Coefficient of linear thermal expansion (CLTE)		
30 °C to 100 °C (longitudinal)	ISO 11359	25E-6 K ⁻¹
30 °C to 100 °C (transversal)	ISO 11359	55E-6 K ⁻¹
VICAT – Softening point		
50 N (heating rate 120 °C h ⁻¹)	ISO 306	245 °C
HDT – Heat Deflection Temperature		
0.45 MPa	ISO 75	255 °C
1.81 MPa	ISO 75	240 °C

Table 8. V0CT1 - Flame resistance properties.

Thermal properties	Standard	Value measure units
Oxygen Index	ASTM D 2863	31 %
Flammability rating		
3 mm thickness	UL 94	V-0.5 VA
1.75 mm thickness	UL 94	V-0
0.75 mm thickness	UL 94	V-0
0.4 mm thickness	UL 94	V-0
GWFI – Glow Wire Flammability Index		
2 mm thickness	IEC 60695-2-12	960 °C
1 mm thickness	IEC 60695-2-12	960 °C
GWIT – Glow Wire Ignition Test		
2 mm thickness	IEC 60695-2-12	900 °C
1 mm thickness	IEC 60695-2-12	900 °C

Table 9. V0CT1 - Electrical properties.

Electrical properties	Standard	Value measure units
CTI - Comparative Tracking Index		
Solution A (without surfactant)	IEC 60112	400 V
Electrical resistivity		
Surface, dry	ASTM D 257	1E12 Ω
Dielectric strength (short period)		
2 mm thickness, 23 °C, dry	ASTM D 149	21 kV mm ⁻¹

3.2 LATAMID 66 H2 G/25-V0HF1

LATAMID 66 H2 G/25-V0HF1, in short “V0HF1”, is a halogen-free glass-reinforced thermoplastic compound based on PA66. The main application is the production of injection moulded parts for electrical, electronics and appliances sector. Table 10 reports the V0HF1 raw material composition and their percentage contribution. This compound has several key features that make it ideal for specific applications. Firstly, it exhibits a significant improvement in its thermal stability. Additionally, the compound incorporates GF, further enhancing its mechanical properties. This imparts the material with increased strength and stiffness and it is rated as UL94 V-0 class. The flame retardant is a mixture including Aluminium Diethylphosphinate (DEPAL). It is free of halogens-based flame retardants and red phosphorous. This compound is also PFAS free, anticipating environmental restrictions. Physical, mechanical, thermal and electrical properties are shown from Table 11 to Table 15. The data is available in the technical data sheets on the LATI website [2].

Table 10. V0HF1 representative composition used for this research project.

Raw material	Percentage (%)
Polyamide 6,6	43-46
Glass fibre	25-28
DEPAL	21-24
Other	<15

Table 11. V0HF1 - Physical properties.

Physical properties	Standard	Value measure units
Density	ISO 1183	1.40 g cm ⁻³
Linear shrinkage at moulding		
Longitudinal (2.0 mm/60 MPa)	ISO 294-4	0.40 ÷ 0.65 %
Transversal (2.0 mm/60 MPa)	ISO 294-4	0.90 ÷ 1.20 %
Moisture absorption		
saturation, in air	ISO 62-4	1.55 %

Table 12. V0HF1 - Mechanical properties.

Mechanical properties	Standard	Value measure units
CHARPY impact strength		
Unnotched, at +23 °C	ISO 179-1eU	65.0 kJ m ⁻²
Notched, at +23 °C	ISO 179-1eA	9.0 kJ m ⁻²
Tensile elongation		
At break (5 mm/min), 23 °C	ISO 527	3.0 %
At break (5 mm/min), 60 °C	ISO 527	4.3 %
At break (5 mm/min), 90 °C	ISO 527	6.2 %
At break (5 mm/min), 120 °C	ISO 527	7.8 %
At break (5 mm/min), 150 °C	ISO 527	9.0 %
Tensile strength		
At break (5 mm/min), 23 °C	ISO 527	130 MPa
At break (5 mm/min), 60 °C	ISO 527	100 MPa
At break (5 mm/min), 90 °C	ISO 527	80 MPa
At break (5 mm/min), 120 °C	ISO 527	70 MPa
At break (5 mm/min), 150 °C	ISO 527	60 MPa
Elastic modulus		
Tensile (1 mm/min), 23 °C	ISO 527	8,500 MPa
Tensile (1 mm/min), 60 °C	ISO 527	6,000 MPa
Tensile (1 mm/min), 90 °C	ISO 527	4,000 MPa
Tensile (1 mm/min), 120 °C	ISO 527	3,500 MPa
Tensile (1 mm/min), 150 °C	ISO 527	2,500 MPa

Table 13. V0HF1 - Thermal properties.

Thermal properties	Standard	Value measure units
Coefficient of linear thermal expansion (CLTE)		
30 °C to 100 °C (longitudinal)	ISO 11359	30E-6 K ⁻¹
30 °C to 100 °C (transversal)	ISO 11359	60E-6 K ⁻¹
VICAT – Softening point		
50 N (heating rate 120 °C h ⁻¹)	ISO 306	245 °C
HDT – Heat Deflection Temperature		
0.45 MPa	ISO 75	255 °C
1.81 MPa	ISO 75	240 °C

Table 14. V0HF1 - Flame resistance properties.

Thermal properties	Standard	Value measure units
Oxygen Index	ASTM D 2863	34 %
Flammability rating		
3 mm thickness	UL 94	V-0.5 VA
1.75 mm thickness	UL 94	V-0.5 VA
0.75 mm thickness	UL 94	V-0
GWFI – Glow Wire Flammability Index		
2 mm thickness	IEC 60695-2-12	960 °C
1 mm thickness	IEC 60695-2-12	960 °C
GWIT – Glow Wire Ignition Test		
2 mm thickness	IEC 60695-2-12	775 °C
1 mm thickness	IEC 60695-2-12	775 °C

Table 15. V0HF1 - Electrical properties.

Electrical properties	Standard	Value measure units
CTI - Comparative Tracking Index		
Solution A (without surfactant)	IEC 60112	600 V
Electrical resistivity		
Surface, dry	ASTM D 257	1E12 Ω
Dielectric strength (short period)		
2 mm thickness, 23 °C, dry	ASTM D 149	21 kV mm ⁻¹
2 mm thickness, 23 °C, conditioned	ASTM D 149	9 kV mm ⁻¹

3.3 LATAMID 66 H2 G/25-V0KB3

LATAMID 66 H2 G/25-V0KB3, in short “V0KB3”, is a self-extinguishing glass-reinforced thermoplastic compound based on PA66. The main application is the production of injection moulded parts for electrical, electronics and appliances sector. Table 16 reports the V0KB3 raw material composition and their percentage contribution. This compound has several key features that make it ideal for specific applications. Firstly, it exhibits a significant improvement in its thermal stability. Additionally, the compound incorporates GF, further enhancing its mechanical properties. This imparts the material with increased strength and stiffness and it is rated as UL94 V-0 class. The flame retardant is red phosphorous and it is free of PFAS. Physical, mechanical, thermal, and electrical properties are shown from Table 17 to Table 21. The data is available in the technical data sheets on the LATI website [3].

Table 16. V0KB3 representative composition used for this research project.

Raw material	Percentage (%)
Polyamide 6,6	49-52
Glass fibre	25-28
Red phosphorus masterbatch	10-12
Other	<15

Table 17. V0KB3 - Physical properties.

Physical properties	Standard	Value measure units
Density	ISO 1183	1.34 g cm ⁻³
Linear shrinkage at moulding		
Longitudinal (2.0 mm/60 MPa)	ISO 294-4	0.30 ÷ 0.60 %
Transversal (2.0 mm/60 MPa)	ISO 294-4	0.85 ÷ 1.10 %
Moisture absorption		
saturation, in air	ISO 62-4	1.80 %

Table 18. V0KB3 - Mechanical properties.

Mechanical properties	Standard	Value measure units
CHARPY impact strength		
Unnotched, at +23°C	ISO 179-1eU	60.0 kJ m ⁻²
Unnotched, at -30°C	ISO 179-1eU	40.0 kJ m ⁻²
Notched, at +23°C	ISO 179-1eA	8.0 kJ m ⁻²
Notched, at -30°C	ISO 179-1eA	5.0 kJ m ⁻²
Tensile elongation		
At break (5 mm/min), 23 °C	ISO 527	218 %
Tensile strength		
At break (5 mm/min), 23 °C	ISO 527	125 MPa
Elastic modulus		
Tensile (1 mm/min), 23 °C	ISO 527	8,000 MPa

Table 19. V0KB3 - Thermal properties.

Thermal properties	Standard	Value measure units
Coefficient of linear thermal expansion (CLTE)		
30 °C to 100 °C (longitudinal)	ISO 11359	30E-6 K ⁻¹
30 °C to 100 °C (transversal)	ISO 11359	60E-6 K ⁻¹
VICAT – Softening point		
50 N (heating rate 120 °C h ⁻¹)	ISO 306	240 °C
HDT – Heat Deflection Temperature		
0.45 MPa	ISO 75	260 °C
1.81 MPa	ISO 75	230 °C

Table 20. V0KB3 - Flame resistance properties.

Thermal properties	Standard	Value measure units
Oxygen Index	ASTM D 2863	28 %
Flammability rating		
3 mm thickness	UL 94	V-0
1.75 mm thickness	UL 94	V-0
0.75 mm thickness	UL 94	HB
GWFI – Glow Wire Flammability Index		
2 mm thickness	IEC 60695-2-12	960 °C
1 mm thickness	IEC 60695-2-12	960 °C

Table 21. V0KB3 - Electrical properties.

Electrical properties	Standard	Value measure units
CTI - Comparative Tracking Index		
Solution A (without surfactant)	IEC 60112	600 V
Electrical resistivity		
Surface, dry	ASTM D 257	1E12 Ω
Dielectric strength (short period)		
2 mm thickness, 23 °C, dry	ASTM D 149	21 kV mm ⁻¹
2 mm thickness, 23 °C, conditioned	ASTM D 149	12 kV mm ⁻¹

3.4 LATAMID 6 H2 G/20-V2HF

LATAMID 6 H2 G/20-V2HF, in short “V2HF”, is a self-extinguishing glass-reinforced thermoplastic compound based on Polyamide 6 (PA6). The main application is the production of injection moulded parts for electrical, electronics and appliances sector. Table 22 reports the V2HF raw material composition and their percentage contribution. This compound has several key features that make it ideal for specific applications. It exhibits a significant improvement in its thermal stability and it has a good dimensional stability. Additionally, the compound incorporates GF, further enhancing its mechanical properties. This imparts the material with increased strength and stiffness. This compound is rated as UL94 V-2 class. The flame retardant is melamine cyanurate and it is halogen and PFAS free. Physical, mechanical, thermal, and electrical properties are shown from Table 23 to Table 27. The data is available in the technical data sheets on the LATI website [4].

Table 22. V2HF representative composition used for this research project.

Raw material	Percentage (%)
Polyamide 6	67-70
Glass fibre	17-20
Melamine cyanurate	7-10
Other	<10

Table 23. V2HF - Physical properties.

Physical properties	Standard	Value measure units
Density	ISO 1183	1.32 g cm ⁻³
Linear shrinkage at moulding		
Longitudinal (2.0 mm/60MPa)	ISO 294-4	0.70 ÷ 1.00 %
Transversal (2.0 mm/60MPa)	ISO 294-4	0.70 ÷ 1.00 %
Moisture absorption		
saturation, in air	ISO 62-4	2.20 %

Table 24. V2HF - Mechanical properties.

Mechanical properties	Standard	Value measure units
CHARPY impact strength		
Unnotched, at +23°C	ISO 179-1eU	35.0 kJ m ⁻²
Notched, at +23°C	ISO 179-1eA	3.4 kJ m ⁻²
Tensile elongation		
At break (5 mm/min), 23°C	ISO 527	3.2 %
Tensile strength		
At break (5 mm/min), 23°C	ISO 527	65 MPa
Elastic modulus		
Tensile (1 mm/min), 23°C	ISO 527	4,500 MPa

Table 25. V2HF - Thermal properties.

Thermal properties	Standard	Value measure units
Coefficient of linear thermal expansion (CLTE)		
30 °C to 100 °C (longitudinal)	ISO 11359	60E-6 K ⁻¹
30 °C to 100 °C (transversal)	ISO 11359	70E-6 K ⁻¹
VICAT – Softening point		
50 N (heating rate 120 °C h ⁻¹)	ISO 306	200 °C
HDT – Heat Deflection Temperature		
0.45 MPa	ISO 75	200 °C
1.81 MPa	ISO 75	165 °C

Table 26. V2HF - Flame resistance properties.

Thermal properties	Standard	Value measure units
Oxygen Index	ASTM D 2863	28 %
Flammability rating		
3 mm thickness	UL 94	V-2
1.75 mm thickness	UL 94	V-2
0.75 mm thickness	UL 94	V-2
GWFI – Glow Wire Flammability Index		
2 mm thickness	IEC 60695-2-12	725 °C
1.5 mm thickness	IEC 60695-2-12	725 °C
1 mm thickness	IEC 60695-2-12	725 °C

Table 27. V2HF - Electrical properties.

Electrical properties	Standard	Value measure units
CTI - Comparative Tracking Index		
Solution A (without surfactant)	IEC 60112	550 V
Electrical resistivity		
Surface, dry	ASTM D 257	1E12 Ω
Dielectric strength (short period)		
2 mm thickness, 23 °C, dry	ASTM D 149	21 kV mm ⁻¹

3.5 LATENE 7H2W-V0

LATENE 7H2W-V0, in short for the purpose of this work “LATENE”, is a self-extinguishing thermoplastic compound based on Polypropylene (PP). The main application is the production of injection moulded parts for electrical, electronics and appliances sector. LATENE must not be used to produce parts operating in hot (>70 °C), very humid conditions in contact with hot water or in contact with overheated steam. Table 28 reports the LATENE raw material composition and their percentage contribution. This compound has several key features that make it ideal for specific applications. It exhibits a significant improvement in its thermal stability and it is rated as UL94 V-0 class. The flame retardant is ammonium polyphosphate and it is free of halogens-based flame retardants, red phosphorous and PFAS. Physical, mechanical, thermal, and electrical properties are shown from Table 29 to Table 33. The data is available in the technical data sheets on the LATI website [5].

Table 28. LATENE representative composition used for this research project.

Raw material	Percentage (%)
Polypropylene	71-74
Ammonium polyphosphate	23-26
Other	<6

Table 29. LATENE - Physical properties.

Physical properties	Standard	Value measure units
Density	ISO 1183	1.04 g cm ⁻³
Linear shrinkage at moulding		
Longitudinal (2.0 mm/60 MPa)	ISO 294-4	1.20 ÷ 1.70 %
Transversal (2.0 mm/60 MPa)	ISO 294-4	1.20 ÷ 1.70 %
Moisture absorption		
saturation, in air	ISO 62-4	0.07 %

Table 30. LATENE - Mechanical properties.

Mechanical properties	Standard	Value measure units
CHARPY impact strength		
Unnotched, at +23 °C	ISO 179-1eU	20.0 kJ m ⁻²
Unnotched, at -30 °C	ISO 179-1eU	10.0 kJ m ⁻²
Notched, at +23 °C	ISO 179-1eA	1.8 kJ m ⁻²
Notched, at -30 °C	ISO 179-1eA	0.8 kJ m ⁻²
Tensile elongation		
At yield (5 mm/min), 23 °C	ISO 527	5.0 %
At yield (5 mm/min), 60 °C	ISO 527	5.0 %
At yield (5 mm/min), 90 °C	ISO 527	6.5 %
At break (5 mm/min), 23 °C	ISO 527	25.0 %
At break (5 mm/min), 60 °C	ISO 527	50,0 %
At break (5 mm/min), 90 °C	ISO 527	>50 %
Tensile strength		
At yield (5 mm/min), 23 °C	ISO 527	20 MPa
At yield (5 mm/min), 60 °C	ISO 527	12 MPa
At yield (5 mm/min), 90 °C	ISO 527	8 MPa
At break (5 mm/min), 23 °C	ISO 527	15 MPa
At break (5 mm/min), 60 °C	ISO 527	10 MPa
At break (5 mm/min), 90 °C	ISO 527	NB MPa
Elastic modulus		
Tensile (1 mm/min), 23 °C	ISO 527	1,800 MPa
Tensile (1 mm/min), 60 °C	ISO 527	950 MPa
Tensile (1 mm/min), 90 °C	ISO 527	450 MPa

Table 31. LATENE - Thermal properties.

Thermal properties	Standard	Value measure units
Coefficient of linear thermal expansion (CLTE)		
30 °C to 100 °C (longitudinal)	ISO 11359	120E-6 K ⁻¹
30 °C to 100 °C (transversal)	ISO 11359	120E-6 K ⁻¹
VICAT – Softening point		
50 N (heating rate 120 °C h ⁻¹)	ISO 306	95 °C
HDT – Heat Deflection Temperature		
0.45 MPa	ISO 75	105 °C
1.81 MPa	ISO 75	60 °C

Table 32. LATENE - Flame resistance properties.

Thermal properties	Standard	Value measure units
Oxygen Index	ASTM D 2863	33 %
Flammability rating		
3 mm thickness	UL 94	V-0
1.75 mm thickness	UL 94	V-0
0.75 mm thickness	UL 94	V-2
GWFI – Glow Wire Flammability Index		
2 mm thickness	IEC 60695-2-12	960 °C
1 mm thickness	IEC 60695-2-12	960 °C
GWFI – Glow Wire Ignition Index		
2 mm thickness	IEC 60695-2-13	825 °C
1 mm thickness	IEC 60695-2-13	825 °C

Table 33. LATENE - Electrical properties.

Electrical properties	Standard	Value measure units
CTI - Comparative Tracking Index		
Solution A (without surfactant)	IEC 60112	600 V
Electrical resistivity		
Surface, dry	ASTM D 257	1E12 Ω
Dielectric strength (short period)		
2 mm thickness, 23 °C, dry	ASTM D 149	27 kV mm ⁻¹

3.6 LARTON G/40

LARTON G/40, in short for the purpose of this work “LARTON”, is a thermoplastic compound based on Polyphenylene sulfide (PPS). LARTON is used as structural material. In addition, it has excellent high temperature resistance and high chemical resistance. This compound is ideal for metal replacement in static applications: for example it can replace brass in the hydraulic sector. Table 34 reports the LARTON raw material composition and their percentage contribution. Physical, mechanical, thermal, and electrical properties are shown from Table 35 to Table 39. The data is available in the technical data sheets on the LATI website [6].

Table 34. LARTON representative composition used for this research project.

Raw material	Percentage (%)
Polyphenylene sulfide	56-59
Glass fibre	37-40
PE masterbatch	<7

Table 35. LARTON - Physical properties.

Physical properties	Standard	Value measure units
Density	ISO 1183	1.66 g cm ⁻³
Linear shrinkage at moulding		
Longitudinal (2.0 mm/60 MPa)	ISO 294-4	0.20 ÷ 0.35 %
Transversal (2.0 mm/60 MPa)	ISO 294-4	0.60 ÷ 0.85 %
Moisture absorption		
saturation, in air	ISO 62-4	0.02 %

Table 36. LARTON - Mechanical properties.

Mechanical properties	Standard	Value measure units
CHARPY impact strength		
Unnotched, at +23 °C	ISO 179-1eU	30.0 kJ m ⁻²
Unnotched, at -20 °C	ISO 179-1eU	28.0 kJ m ⁻²
Notched, at +23 °C	ISO 179-1eA	10.0 kJ m ⁻²
Notched, at -20 °C	ISO 179-1eA	9.0 kJ m ⁻²
Tensile elongation		
At break (5 mm/min), 23 °C	ISO 527	1.5 %
At break (5 mm/min), 60 °C	ISO 527	1.6 %
At break (5 mm/min), 90 °C	ISO 527	2.3 %
At break (5 mm/min), 120 °C	ISO 527	3.2 %
At break (5 mm/min), 150 °C	ISO 527	3.4 %
Tensile strength		
At break (5 mm/min), 23 °C	ISO 527	175 MPa
At break (5 mm/min), 60 °C	ISO 527	165 MPa
At break (5 mm/min), 90 °C	ISO 527	145 MPa
At break (5 mm/min), 120 °C	ISO 527	95 MPa
At break (5 mm/min), 150 °C	ISO 527	95 MPa
Elastic modulus		
Tensile (1 mm/min), 23 °C	ISO 527	15,000 MPa
Tensile (1 mm/min), 60 °C	ISO 527	14,500 MPa
Tensile (1 mm/min), 90 °C	ISO 527	11,000 MPa
Tensile (1 mm/min), 120 °C	ISO 527	7,500 MPa
Tensile (1 mm/min), 150 °C	ISO 527	6,100 MPa

Table 37. LARTON - Thermal properties.

Thermal properties	Standard	Value measure units
Coefficient of linear thermal expansion (CLTE)		
30 °C to 100 °C (longitudinal)	ISO 11359	15E-6 K ⁻¹
30 °C to 100 °C (transversal)	ISO 11359	35E-6 K ⁻¹
VICAT – Softening point		
50 N (heating rate 120 °C h ⁻¹)	ISO 306	260 °C
HDT – Heat Deflection Temperature		
0.45 MPa	ISO 75	280 °C
1.81 MPa	ISO 75	270 °C
Thermal conductivity		
In plane	ASTM E 14561-92	0.4 W (m K) ⁻¹
Through plane	ASTM E 14561-92	0.3 W (m K) ⁻¹

Table 38. LARTON - Flame resistance properties.

Thermal properties	Standard	Value measure units
Oxygen Index	ASTM D 2863	44 %
Flammability rating		
3 mm thickness	UL 94	V-0
1.75 mm thickness	UL 94	V-0
0.75 mm thickness	UL 94	V-0
GWFI – Glow Wire Flammability Index		
2 mm thickness	IEC 60695-2-12	960 °C
1 mm thickness	IEC 60695-2-12	960 °C
GWFI – Glow Wire Ignition Test		
2 mm thickness	IEC 60695-2-13	775 °C
1 mm thickness	IEC 60695-2-13	775 °C

Table 39. LARTON - Electrical properties.

Electrical properties	Standard	Value measure units
CTI - Comparative Tracking Index		
Solution A (without surfactant)	IEC 60112	125 V
Electrical resistivity		
Surface, dry	ASTM D 257	1E12 Ω
Dielectric strength (short period)		
2 mm thickness, 23 °C, dry	ASTM D 149	18 kV mm ⁻¹

3.7 LATER 4 G/30-V0

LATER 4 G/30-V0, in short for the purpose of this work “LATER”, is a thermoplastic compound based on Polybutadiene terephthalate (PBT). The main application is the production of injection moulded parts for self-extinguishing materials in electrical, electronics and home appliances sector. Table 40 reports the LATER raw material composition and their percentage contribution. Although it does not absorb moisture like Polyamide (PA), this material suffers hydrolysis in the presence of water vapor or water at high temperatures. However, it has good chemical resistance. Additionally, the compound incorporates GF, further enhancing its mechanical properties and it is rated as UL94 V-0 class. It is added with brominated flame retardants and it is free of PBB and PFAS. Physical, mechanical, thermal and electrical properties are shown from Table 41 to Table 45. The data is available in the technical data sheets on the LATI website [7].

Table 40. LATER representative composition used for this research project.

Raw material	Percentage (%)
Polybutadiene	50-53
Glass fibre	27-30
Tetrabromobisphenol A (TBBPA)	7-10
Antimony trioxide	1-3
Other	<15

Table 41. LATER - Physical properties.

Physical properties	Standard	Value measure units
Density	ISO 1183	1.61 g cm ⁻³
Linear shrinkage at moulding		
Longitudinal (2.0 mm/60 MPa)	ISO 294-4	0.20 ÷ 0.45 %
Transversal (2.0 mm/60 MPa)	ISO 294-4	0.70 ÷ 1.00 %
Moisture absorption		
saturation, in air	ISO 62-4	0.14 %

Table 42. LATER - Mechanical properties.

Mechanical properties	Standard	Value measure units
CHARPY impact strength		
Unnotched, at +23 °C	ISO 179-1eU	55.0 kJ m ⁻²
Unnotched, at -20 °C	ISO 179-1eU	35.0 kJ m ⁻²
Notched, at +23 °C	ISO 179-1eA	10.0 kJ m ⁻²
Notched, at -20 °C	ISO 179-1eA	10.0 kJ m ⁻²
Tensile elongation		
At break (5 mm/min), 23 °C	ISO 527	2.2 %
At break (5 mm/min), 60 °C	ISO 527	4.0 %
At break (5 mm/min), 90 °C	ISO 527	5.0 %
At break (5 mm/min), 120 °C	ISO 527	5.5 %
At break (5 mm/min), 150 °C	ISO 527	5.7 %
Tensile strength		
At break (5 mm/min), 23 °C	ISO 527	130 MPa
At break (5 mm/min), 60 °C	ISO 527	90 MPa
At break (5 mm/min), 90 °C	ISO 527	70 MPa
At break (5 mm/min), 120 °C	ISO 527	55 MPa
At break (5 mm/min), 150 °C	ISO 527	45 MPa
Elastic modulus		
Tensile (1 mm/min), 23 °C	ISO 527	9,500 MPa
Tensile (1 mm/min), 60 °C	ISO 527	6,400 MPa
Tensile (1 mm/min), 90 °C	ISO 527	4,600 MPa
Tensile (1 mm/min), 120 °C	ISO 527	3,500 MPa
Tensile (1 mm/min), 150 °C	ISO 527	2,800 MPa

Table 43. LATER - Thermal properties.

Thermal properties	Standard	Value measure units
Coefficient of linear thermal expansion (CLTE)		
30 °C to 100 °C (longitudinal)	ISO 11359	30E-6 K ⁻¹
30 °C to 100 °C (transversal)	ISO 11359	65E-6 K ⁻¹
VICAT – Softening point		
50 N (heating rate 120 °C h ⁻¹)	ISO 306	205 °C
HDT – Heat Deflection Temperature		
0.45 MPa	ISO 75	220 °C
1.81 MPa	ISO 75	205 °C
Thermal conductivity		
In plane	ASTM E 14561-92	0.2 W (m K) ⁻¹
Through plane	ASTM E 14561-92	0.2 W (m K) ⁻¹

Table 44. LATER - Flame resistance properties.

Thermal properties	Standard	Value measure units
Oxygen Index	ASTM D 2863	31 %
Flammability rating		
3 mm thickness	UL 94	V-0
1.75 mm thickness	UL 94	V-0
0.75 mm thickness	UL 94	V-0
GWFI – Glow Wire Flammability Index		
2 mm thickness	IEC 60695-2-12	960 °C
1 mm thickness	IEC 60695-2-12	960 °C

Table 45. LATER - Electrical properties.

Electrical properties	Standard	Value measure units
CTI - Comparative Tracking Index		
Solution A (without surfactant)	IEC 60112	250 V
Electrical resistivity		
Surface, dry	ASTM D 257	1E12 Ω
Dielectric strength (short period)		
2 mm thickness, 23 °C, dry	ASTM D 149	22 kV mm ⁻¹

3.8 References

[1] LATI technical datasheet of LATAMID 66 H2 G/25-V0CT1 (2024). Available online: https://lambda.lati.com/Download/FogliTecnici/UK/LATAMID_66_H2_G_25-V0CT1__UK.PDF.

(Accessed 22.08.2024).

[2] LATI technical datasheet of LATAMID 66 H2 G/25-V0HF1 (2024). Available online: https://lambda.lati.com/Download/FogliTecnici/UK/LATAMID_66_H2_G_25-V0HF1__UK.PDF.

(Accessed 22.08.2024).

[3] LATI technical datasheet of LATAMID 66 H2 G/25-V0KB3 (2024). Available online: https://lambda.lati.com/Download/FogliTecnici/UK/LATAMID_66_H2_G_25-V0KB3__UK.PDF.

(Accessed 22.08.2024).

[4] LATI technical datasheet of LATAMID 6 H2 G/20-V2HF (2024). Available online: https://lambda.lati.com/Download/FogliTecnici/UK/LATAMID_6_H2_G_20-V2HF__UK.PDF.

(Accessed 22.08.2024).

[5] LATI technical datasheet of LATENE 7H2W-V0 (2025). Available online: https://lambda.lati.com/Download/FogliTecnici/UK/LATENE_7H2W-V0__UK.PDF. (Accessed

17.07.2025).

[6] LATI technical datasheet of LARTON G/40 (2025). Available online: https://lambda.lati.com/Download/FogliTecnici/UK/LARTON_G_40__UK.PDF. (Accessed

17.07.2025).

[7] LATI technical datasheet of LATER 4 G/30-V0 (2025). Available online: https://lambda.lati.com/Download/FogliTecnici/UK/LATER_4_G_30-V0__UK.PDF. (Accessed

17.07.2025).

4 CHAPTER 4: METHODS

This study aims to analyse the environmental impacts of six compounds life-cycle from cradle to gate. In detail, the assessment considers the production of raw materials and the factory compounding processes. Furthermore, the transport of the materials, the supply of energy, the use of packaging, emissions into the atmosphere and the final disposal of waste are considered. These results can be used to improve their environmental performance in the future.

4.1 Database and LCA software

The LCA software was SimaPro v10.1 [1]. Ecoinvent v3.10 [2] was used to conduct the quantitative evaluation in this analysis. This database provided the background system's life cycle inventory data for raw and processed materials.

4.2 Functional Unit

The Functional Unit (FU) is 1 kg of product in the form of granules, including its packaging (the weight of the packaging is not included in this 1 kg). This FU fulfils the requirements stated in the PCR 2010:16 Plastics in primary forms v4.0.0 [3]. However, final transport (downstream phase) was also evaluated in addition to the stages reported by PC. Furthermore, other FU that refers to 1 L of final product is considered.

4.3 System Boundaries and life cycle phases studied

The life cycle of products should be divided into three different life cycle steps: upstream, core and downstream (Figure 2). The use and End-of-life of the product have not been considered. The System Boundary (SB) can be seen in Figure 3.

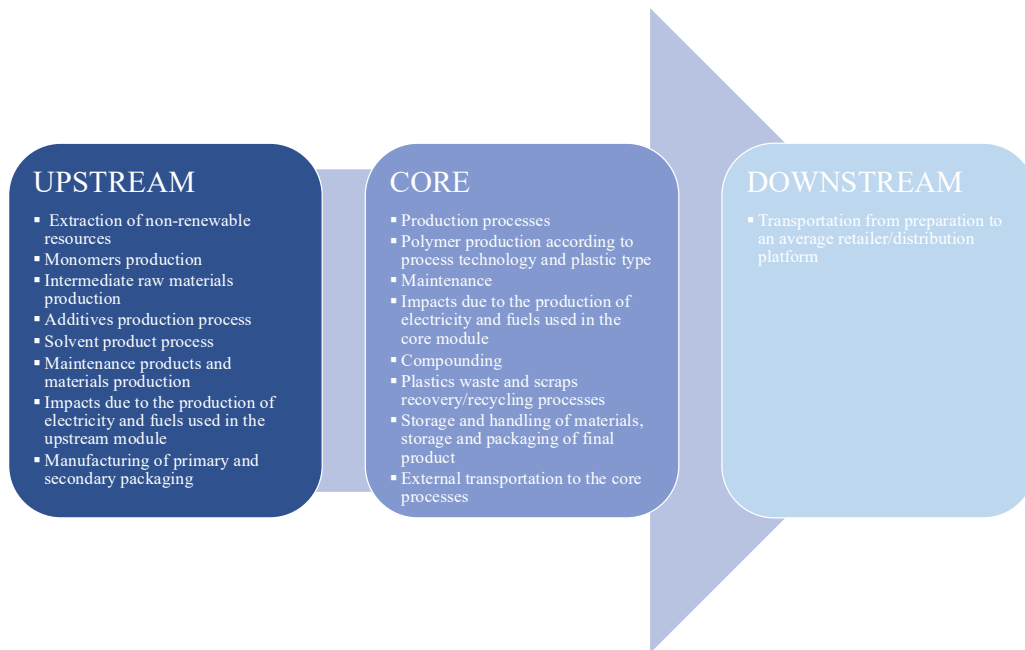


Figure 3. System boundaries diagram according to PCR 2010:16 [3].

Upstream processes. This phase encompasses the process production of raw materials and packaging.

Core processes. This phase encompasses all the production processes carried out within the LATI facilities, such as warehousing, material handling and preparation, extrusion and auxiliary production services. This phase also includes the treatment of waste generated within the facility and using electricity, water, and natural gas inside the factory. Furthermore, it includes the transport of the raw materials to the LATI factory.

Downstream processes. The final phase includes the transportation of the compound from the facility to a distribution platform located in Limito di Pioltello, Milan, Italy.

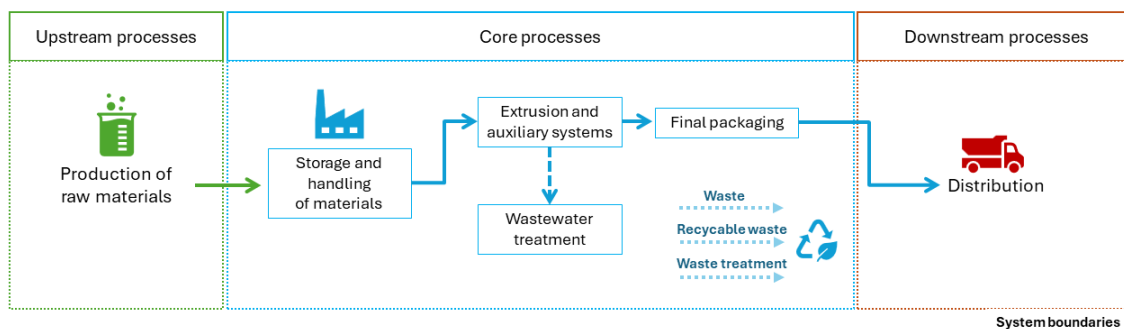


Figure 4. System boundaries scheme.

4.4 Assumptions and cut-offs

In accordance with the PCR 2010:16 [3], all primary raw materials and processes have been considered. Generally, less than 1 % of total material and energy flows were excluded. The data relating to background processes for raw materials, transport activities and energy expenditure in manufacturing LATI product components are found or modified from the Ecoinvent unit processes. The inventory data corresponds to the year 2023 for V0CT1, V0HF1, V0KB2 and V2HF, while to the year 2024 for LATENE, LARTON and LATER. The average scraps generated during the manufacturing of 1 kg of the compound considered in this study has been considered excluding V0HF1 since were <1 %. Regarding V0CT1, V0HF1, V0KB3 the electricity allocated to the facility does not include the portion consumed by the extruders; this has been quantified at the average value of 0.358 kWh per kg of material produced (ref. 2023). Electricity refers to the Italian national mix (see Table 46). Concerning LATENE, LARTON and LATER, the electricity is sourced partly under a 100% wind-powered Guarantee of Origin certificate (modelled as 100% wind source) and partly from photovoltaic panels installed on the factory roof, with a portion of the photovoltaic energy exported to the grid. It is assumed that the waste is treated and disposed in final disposal. The following flows are not included in the SB:

- Emissions related to infrastructure processes are excluded since the related flows are assumed negligible compared to the production of the building product when compared at these systems' lifetime levels.
- Manufacture of equipment used in production, buildings, or any other capital goods.
- Transportation of personnel to the plant.
- Transportation of personnel within the plant.
- Research and development activities.

4.5 Data Requirements

The inventory data necessary for the LCA encompassed the type and production details of the raw materials constituting the evaluated product, specifically:

- Transport of raw materials and packaging;
- The energy requirement of the core phase;
- Average weights of individual products;
- Type of waste from the core phase.

Global or European market processes were employed to manufacture the available products, as Italian datasets were lacking. A comprehensive list of inventory data is provided in chapter 4.

4.6 Data Representativeness

The study is conducted in Italy, and thus, data concerning energy requirements and waste disposal reflect the Italian context. Considering their European sourcing nature, European datasets (RER) were employed for the manufacturing processes. The primary data was gathered internally. All production data corresponds to values for the year 2023 and 2024, excluding the electricity used in the extruder, which refers to the specific electricity consumption of an example production batch.

The primary data used in the analysis were collected at LATI's facility in Gornate Olona (VA). They were obtained through technical meetings and questionnaires with expert operators. In addition, site inspections were conducted with the production site personnel where it was impossible to find primary data, and secondary data from databases or scientific literature were used. Secondary data from Ecoinvent databases were used for modelling the production of raw materials and packaging, which are processes beyond the company's control. The processes within the Ecoinvent database reflect the data from version 3.10, released in 2024 [2].

4.7 Sensitivity Analysis

The sensitivity analysis was evaluated for V0CT1, V0HF1, V0KB3 and V2HF. Alternative scenarios were defined to understand how technological solutions could enhance the environmental performance of the investigated technological system. Specifically, an analysis of the core phase was conducted,

introducing a different source of electricity with a higher share of renewable sources (Scenario 1 and Scenario 2). The baseline scenario assumed an energy mix reported by the Ecoinvent database for the Italian Medium Voltage Energy mix. Scenario 3 evaluated the replacement of oil-based PA66 with mechanical recycled polymer in different percentages.

Scenario 1. This scenario, named “Green Energy” integrates the utilization of renewable sources in the core phase of electricity with two different mixes. Mix 1 incorporates energy derived from geothermal, hydro, wind power, biogas, and biomass sources, while Mix 2 exclusively relies on energy from hydro sources. Table 46 presents the breakdown of the electricity sources for the present scenario (based on the Italian mix in 2020 [4]), for Mix 1, and for Mix 2.

Table 46. Scenario 1: Energy origin of real situation and two green scenarios.

Energy origin	Italian country mix		Green Energy	
	Baseline scenario (ref.	Green scenario	Green scenario	
	2020 [15]) [%]	MIX 1 [%]	MIX 2 [%]	
Geothermal	2	6	0	
Hydro	18	56	100	
Wind power	6	21	0	
Biogas	4	13	0	
Biomass	1	4	0	
	Renewable	31	100	100
	TOT %			
Imported from abroad	17	0	0	
Coal	10	0	0	
Natural gas	38	0	0	
Oil	4	0	0	
	Non-renewable	69	0	0
	TOT %			

Scenario 2. In this scenario, called “Photovoltaic” (PV), the electricity used in the core phase was replaced at varying percentages with energy sourced from solar panels ideally installed on the company’s roof or other designated areas. This process is derived directly from the Ecoinvent database, specifically described as *“Electricity, low voltage {IT} | electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, U”* [2] (see Annex II). This dataset represents the generation of grid-connected low voltage electricity with a 3 kWp building-integrated photovoltaic (PV) module in Italy. The 3 kWp module has been chosen as the standard module for building-integrated PV electricity generation. The module is a multi-Si panel installed on a slanted roof. The percentages for supplying the electricity demand using solar PV panels were 25%, 50%, 75%, and 100%.

Scenario 3. In this scenario, named “Recycling”, the oil-based PA66 was substituted with a mechanical recycled PA. The processes *“LATI – mechanical recycling simulation | Cut-off, U”* was created by modifying the process present in the database *“Polyethylene, high density, granulate, recycled {Europe without Switzerland} | polyethylene production, high density, granulate, recycled | Cut-off, U”*. In detail, the input process *“Waste polyethylene, for recycling, sorted {Europe without Switzerland} | market for waste polyethylene, for recycling, sorted | Cut-off, U”* has been replaced with *“plastic flake, consumer electronics, for recycling {GLO} | market for plastic flake, consumer electronics, for recycling | Cut-off, U”*. Mechanical recycled polymer replacement rates are available in Table 47 and Figure 4.

Table 47. Scenario 3: Mechanical recycled polymer replacement rates.

Name	Mechanical recycled polymer	Virgin oil-based polymer
Grade A	100 %	0 %
Grade B	90 %	10 %
Grade C	70 %	30 %
Grade D	50 %	50 %
Grade E	30 %	70 %
Grade G	10 %	90 %

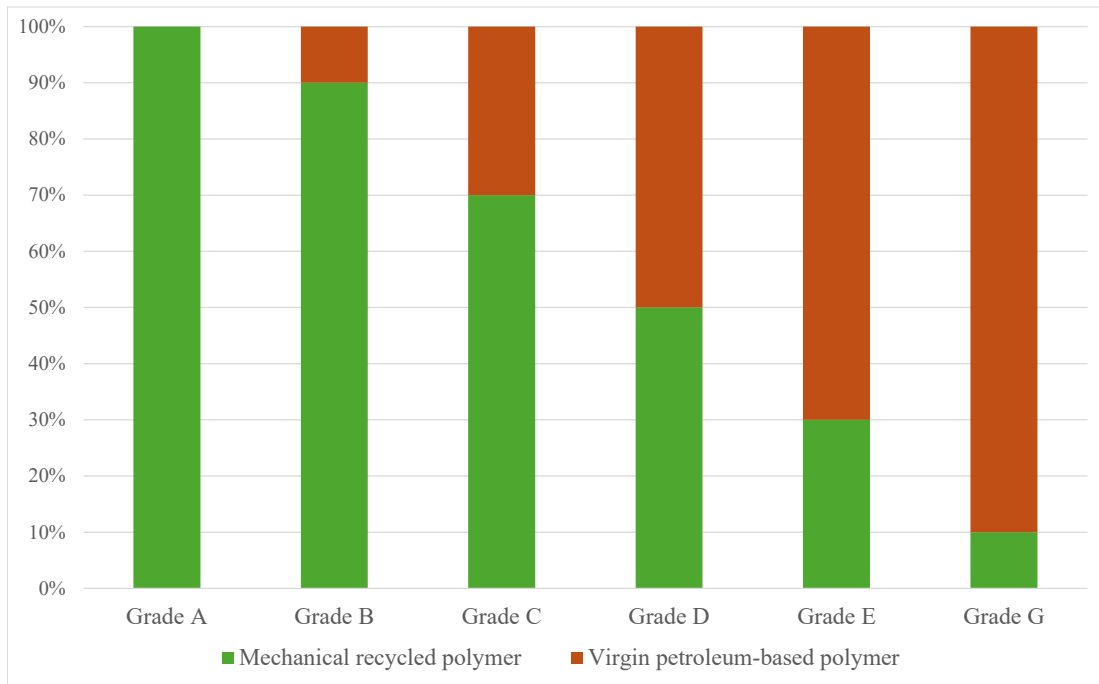


Figure 5. Scenario 3: Recycled polymer replacement rates.

Scenario 4. This scenario, named “*MR vs CR*”, was evaluated for V2HF. In particular, PA from mechanically recycling (MR) was compared with PA from chemically recycling (CR) at the rates reported in Table 47. Regarding MR was used the methodology described in Scenario 3, while for CR the data are taken from the EPD for ECONYL[®] polymer (EPD Certification No. S-P-00500) [5]. The comparison was made in terms of CO₂ eq, given that the environmental impact categories were calculated with different impact assessment methods. Table 48 reports the quantities of CO₂ eq per 1 kg of virgin oil-based PA and recycled PA.

Table 48. Scenario 4: Emissions of 1 kg of virgin oil-based PA and recycled PA.

PA origin	Impact (kg CO ₂ eq)	Reference
Virgin oil-based	9.28	Nylon 6 {RER} nylon 6 production Cut-off, U
Mechanical Recycling	0.49	LATI - mechanical recycling simulation Cut-off, U
Chemical Recycling	0.95	EPD for ECONYL [®] polymer

4.8 Life Cycle Impact Assessment

LCIA facilitates the conversion of emissions and resource extractions into a concise set of environmental impact scores, aiding in the interpretation of LCA studies [6]. This transformation is achieved through characterization factors, which reveal the environmental impact per unit of the stressor (e.g., per kilogram of resource used or emission released). Two primary methods for deriving characterization factors are at the midpoint or endpoint.

Characterization factors at the midpoint level are positioned along the impact pathway, typically beyond where the environmental mechanism becomes uniform for all environmental flows assigned to that impact category [7]. They quantify the environmental impacts of specific pollutants or stressors associated with a product or process, facilitating a more detailed analysis of its environmental footprint. Conversely, characterization factors at the endpoint level in Life Cycle Assessment (LCA) provide a holistic perspective by aggregating and expressing the overall environmental impacts of specific endpoints, such as human health, ecosystem quality, and resource depletion.

These two approaches are complementary: midpoint characterization maintains a stronger connection to environmental flows with relatively low uncertainty, while endpoint characterization offers superior insights into the environmental significance of these flows, albeit with higher uncertainty compared to the midpoint characterization factors [6].

The calculation method “ReCiPe 2016 v1.07 endpoint, Hierarchist perspective, Normalization World (2010) H method” has been utilized for environmental impacts to obtain the results. The results for endpoint and midpoint are reported with the unit Ecopoint (Pt) [8].

An Ecopoint is the unit of measure for the environmental impact of a unit, product, or material. The Ecopoint score is relative to the impact of an EU citizen over one year: 1000 Ecopoints represent the environmental impact of 1 EU citizen over one year. The more Ecopoints a unit or design receives, the worse the unit’s environmental impact.

An overview of the link between the midpoint impact categories and the three endpoint categories is shown in Figure 5.

Furthermore, according to the PCR 2010:16, the environmental impacts have also been calculated with the impact assessment method “EN 15804+A2 (adapted)” [9]. The impact categories and indicators are shown in Table 49.

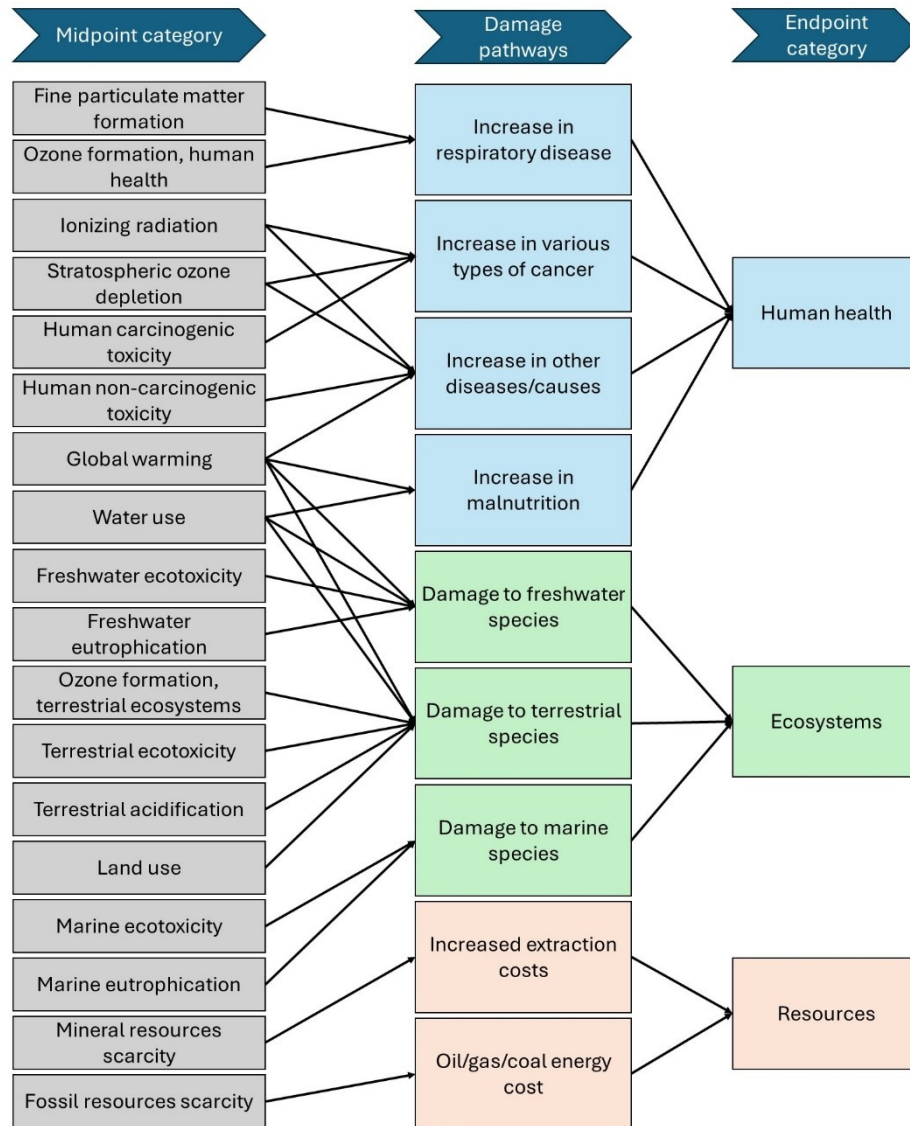


Figure 6. ReCiPe 2016 midpoint categories and their relation to the endpoint (adapted from [10]).

Table 49. Details of the impact categories of the method “EN 15804+A2 (adapted)”.

Impact category	Indicator	Acronym	Unit
Climate change - Total	Global warming potential	GWP - total	kg CO ₂ eq
Climate change - Fossil	Global warming potential fossil fuels	GWP - fossil	kg CO ₂ eq
Climate change - Biogenic	Global warming potential biogenic	GWP - biogenic	kg CO ₂ eq
Climate change - land use and land use change	Global warming potential land use and land use change	GWP - luluc	kg CO ₂ eq
Climate Change	Global warming potential - 100a	GWP100a	kg CO ₂ eq
Ozone depletion	Depletion potential of the stratospheric ozone layer	ODP	kg CFC 11 eq
Acidification	Acidification potential, Accumulated exceedance	AP	mol H ⁺ eq
Eutrophication aquatic Freshwater	Eutrophication potential, fraction of nutrients reaching Freshwater end compartment	EP - freshwater	kg P eq
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching Freshwater end compartment	EP - freshwater	kg N eq
Eutrophication terrestrial	Eutrophication potential, Accumulated exceedance	EP - terrestrial	mol N eq
Photochemical ozone formation	Formation potential of tropospheric ozone	POCP	kg NMVOC eq
Depletion of abiotic resources – minerals and metals	Abiotic depletion potential for non-fossil resources	ADP - minerals&metals	kg Sb eq
Depletion of abiotic resources – fossil fuels	Abiotic depletion potential for fossil resources	ADP-fossil	MJ, net calorific value
Water use	Water (user) deprivation potential, deprivation-weighted water consumption	WDP	m ³ world eq. deprived

Particulate matter emissions	Potential incidence of disease due to PM emissions	PM	Disease incidence
Ionizing radiation, human health	Potential human exposure efficiency relative to U235	IRP	kBq U235 eq.
Eco-toxicity (Freshwater)	Potential comparative toxic unit for ecosystems	ETP - fw	CTUe
Human toxicity, cancer effects	Potential comparative toxic unit for humans	HTP - c	CTUh
Human toxicity, non-cancer effects	Potential comparative toxic unit for humans	HTP - nc	CTUh
Land use related impacts / soil quality	Potential soil quality index	SQP	dimensionless

4.9 References

- [1] PRé Consultants. Software SimaPro v10.1 (2024).
- [2] Ecoinvent v3.10 Database. (2024).
- [3] Product Category Rules (PCR) 2010:16 Plastics in primary forms v4.0.0. (2024).
- [4] IEA World Energy Statistics and Balances. OECD iLibrary, eISSN: 1683-4240, (2020). doi:10.1787/enestats-data-en.
- [5] Environmental Product Declaration (EPD) of ECONYL[®] polymer (EPD Certification No. S-P-00500).
- [6] Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, and van Zelm R.. ReCiPe 2008: A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and endpoint levels. First edition. Report i: Characterisation. the Netherlands: Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. (2009).
- [7] Hauschild, M. Z., and Huijbregts, M. A. J. Introducing life cycle impact assessment. Chapter 1. In Life cycle impact assessment, Hauschild and Huijbregt (eds). Springer. (2015).
- [8] Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F. et al. ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22, 138–147 (2017). doi:10.1007/s11367-016-1246-y.
- [9] Andreasi Bassi, S., Ferrara, N., Amadei, A., Valente, A., Sala, S., Ardente, F. (2023). Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. Publications Office of the European Union, Luxembourg. doi:10.2760/798894.

5 CHAPTER 5: LIFE CYCLE INVENTORY

This chapter presents the evaluated LATI products Life Cycle Inventory (LCI). The input and output data sources and the database used are reported in Annex I. The environmental data related to the production of components of the LATI products, energy consumption, transportation, and waste management have been taken from the Ecoinvent v3.10 database (see Annex II for more details). The study was conducted to collect as much primary data as possible. The data were obtained through technical meetings and questionnaires with expert operators. In addition, site inspections were conducted with the production site personnel where it was impossible to find primary data and secondary data from databases or scientific literature were used. In accordance with LATI, some primary data have been omitted as they are confidential data. All calculations steps and mass balance control calculations are available in Annex III and Annex IV, respectively.

5.1 V0CT1

5.1.1 Upstream processes

Background processes for the upstream phase have been sourced from all materials associated with the V0CT1 product, utilizing the Ecoinvent v3.10 database. The primary components of the V0CT1 product are predominantly PA66 with GF. The flame retardants are brominated polystyrene combined with antimony trioxide (BPS-at) and zinc borate. Ethylene copolymer is manufactured in Italy and transported in big bag packaging by truck. Brominated polystyrene is produced in USA and shipped in big bag packaging by truck and ship. Antimony trioxide is produced in China and transported in big bag packaging by truck and ship. Zinc borate is produced in Italy and transported in big bag packaging by truck. PA66 is produced in Italy and transported using tank trucks. GF is produced in Brazil and shipped in big bag packaging by truck and ship. All final product packaging is manufactured in Italy and transported by truck.

5.1.2 Core processes

This phase includes the electricity, methane and water consumption inside the factory, the extruder maintenance materials, the treatment of waste generated and subsequently disposed.

5.1.3 Downstream processes

The final phase includes the transportation of the final compound from the LATI facilities to a distribution platform located in Limoto di Pioltello, Milan, Italy, 65 km away. The transportation is carried out using a truck with a capacity ranging from 7.5 to 16 metric tons.

5.1.4 Mass balance control

Table 50 reports the input and output mass balance of the V0CT1 process production.

Table 50. V0CT1 mass balance.

Phase	Material	I/O	Quantity	Unit
	Ethylene copolymer production	I	<i>omissis</i>	kg
	Ethylene copolymer packaging	I	0.0000	kg
	Ethylene copolymer pallet	I	0.0000	kg
	Brominated polystyrene production	I	<i>omissis</i>	kg
	Brominated polystyrene packaging	I	0.0005	kg
	Brominated polystyrene pallet	I	0.0000	kg
	Antimony trioxide production	I	<i>omissis</i>	kg
Upstream	Antimony trioxide packaging	I	0.0001	kg
	Antimony trioxide pallet	I	0.0000	kg
	Zinc borate production	I	<i>omissis</i>	kg
	Zinc borate packaging	I	0.0002	kg
	Zinc borate pallet	I	0.0000	kg
	Polyamide 6,6 production	I	<i>omissis</i>	kg
	Glass fibre production	I	<i>omissis</i>	kg
	Glass fibre packaging	I	0.0006	kg

	Glass fibre pallet	I	0.0000	kg
	Final product packaging PE bag	I	0.0036	kg
	Final product packaging ALU bag	I	0.0036	kg
	Final product pallet	I	0.0001	kg
	Final product cap	I	0.0016	kg
	Tap water	I	0.0002	m ³
	Well water	I	0.0004	m ³
	Maintenance materials	I	0.0111	kg
Core	Waste wood	O	0.0000	kg
	Waste plastics	O	0.0184	kg
	Waste scrap steel (maintenance materials)	O	0.0111	kg
	Wastewater treatment	O	0.0006	m ³
	Compound	O	1.0000	kg
Downstream	Final packaging bag	O	0.0072	kg
	Final packaging cap	O	0.0016	kg
	Final packaging pallet	O	0.0001	kg
Mass balance	Total Mass Input		1.0390	kg
	Total Mass Output		1.0390	kg

5.2 V0HF1

5.2.1 Upstream processes

Background processes for the upstream phase have been sourced from all materials associated with the V0HF1 product, utilizing the Ecoinvent v3.10 database. The primary components of the V0HF1 product are predominantly PA66 with GF. The flame retardant is a mixture including aluminium diethylphosphinate (DEPAL) and other components. DEPAL is manufactured in Germany and transported in big bag packaging by truck. Melamine polyphosphate is produced in China and transported in big bag packaging by truck and ship. Zinc borate is produced in Italy and transported in

big bag packaging by truck. PA6 and PA66 are produced in Italy and transported using tank trucks. GF is produced in Brazil and shipped in big bag packaging by both truck and ship. All final product packaging is manufactured in Italy and transported by truck.

5.2.2 Core processes

This phase includes the electricity, methane and water consumption inside the factory, the extruder maintenance materials, the treatment of waste generated and subsequently disposed.

5.2.3 Downstream processes

The final phase includes the transportation of the final compound from the LATI facility to a distribution platform located in Limoto di Pioltello, Milan, Italy, 65 km away. The transportation is carried out using a truck with a capacity ranging from 7.5 to 16 metric tons.

5.2.4 Mass balance control

Table 51 reports the input and output mass balance of the V0HF1 process production.

Table 51. V0HF1 mass balance.

Phase	Material	I/O	Quantity	Unit
Upstream	DEPAL production	I	<i>omissis</i>	kg
	DEPAL packaging	I	0.0003	kg
	DEPAL pallet	I	0.0000	kg
	Melamine polyphosphate production	I	<i>omissis</i>	kg
	Melamine polyphosphate packaging	I	0.0003	kg
	Melamine polyphosphate pallet	I	0.0000	kg
	Polyamide 6 production	I	<i>omissis</i>	kg
	Zinc borate production	I	<i>omissis</i>	kg
	Zinc borate packaging	I	0.0000	kg
	Zinc borate pallet	I	0.0000	kg
	Polyamide 6,6 production	I	<i>omissis</i>	kg

	Glass fibre production	I	<i>omissis</i>	kg
	Glass fibre packaging	I	0.0006	kg
	Glass fibre pallet	I	0.0000	kg
	Final packaging PE bag	I	0.0036	kg
	Final product packaging ALU bag	I	0.0036	kg
	Final product pallet	I	0.0001	kg
	Final product packaging cap	I	0.0016	kg
Core	Tap water	I	0.0002	m ³
	Well water	I	0.0004	m ³
	Maintenance materials	I	0.0111	kg
	Waste wood	O	0.0000	kg
	Waste plastics	O	0.0012	kg
	Waste scrap steel	O	0.0111	kg
	Wastewater treatment	O	0.0006	m ³
Downstream	Compound	O	1.0000	kg
	Final packaging bag	O	0.0072	kg
	Final packaging cap	O	0.0016	kg
	Final packaging pallet	O	0.0001	kg
Mass balance	Total Mass Input		1.0218	kg
	Total Mass Output		1.0218	kg

5.3 V0KB3

5.3.1 Upstream processes

Background processes for the upstream phase have been sourced from all materials associated with the V0KB3 product, utilizing the Ecoinvent v3.10 database. The primary components of the V0KB3 product are predominantly PA66 with GF. The flame retardant is red phosphorus purchased as masterbatch. Red phosphorus masterbatches are produced in Italy and transported in big bag packaging by truck. The Ionomer impact modifier is manufactured in Italy and transported in big bag packaging by truck. PA66

is produced in Italy and transported using tank trucks. GF is produced in Brazil and shipped in big bag packaging by truck and ship. All final product packaging is manufactured in Italy and transported by truck.

5.3.2 Core processes

This phase includes the electricity, methane and water consumption inside the factory, the extruder maintenance materials, the treatment of waste generated and subsequently disposed.

5.3.3 Downstream processes

The final phase includes the transportation of the final compound from the LATI facility to a distribution platform located in Limoto di Pioltello, Milan, Italy, 65 km away. The transportation is carried out using a truck with a capacity ranging from 7.5 to 16 metric tons.

5.3.4 Mass balance control

Table 52 reports the input and output mass balance of the V0KB3 process production.

Table 52. V0KB3 mass balance.

Phase	Material	I/O	Quantity	Unit
	Red phosphorus masterbatches production	I	<i>omissis</i>	kg
	Red phosphorus masterbatches packaging	I	0.0003	kg
	Red phosphorus masterbatches pallet	I	0.0000	kg
	Ionomer (impact modifier) production	I	<i>omissis</i>	kg
	Ionomer (impact modifier) packaging	I	0.0002	kg
Upstream	Ionomer (impact modifier) pallet	I	0.0000	kg
	Polyamide 6,6 production	I	<i>omissis</i>	kg
	Glass fibre production	I	<i>omissis</i>	kg
	Glass fibre packaging	I	0.0000	kg
	Glass fibre pallet	I	0.0000	kg
	Final product packaging PE bag	I	0.0036	kg

	Final product packaging ALU bag	I	0.0036	kg
	Final product pallet	I	0.0001	kg
	Final product cap	I	0.0016	kg
	Tap water	I	0.0002	m ³
	Well water	I	0.0004	m ³
	Maintenance materials	I	0.0111	kg
Core	Waste wood	O	0.0000	kg
	Waste plastics	O	0.0151	kg
	Waste scrap steel	O	0.0111	kg
	Wastewater treatment	O	0.0006	m ³
	Compound	O	1.0000	kg
Downstream	Final packaging bag	O	0.0072	kg
	Final packaging cap	O	0.0016	kg
	Final packaging pallet	O	0.0001	kg
Mass balance	Total Mass Input		1.0351	kg
	Total Mass Output		1.0357	kg

5.4 V2HF

5.4.1 Upstream processes

Background processes for the upstream phase have been sourced from all materials associated with the V2HF product, utilizing the Ecoinvent v3.10 database. The primary components of the V2HF product are predominantly PA6 with GF. The flame retardant is melamine cyanurate. Melamine cyanurate is produced in China and shipped in cardboard packaging by truck and ship. PA6 is produced in Italy and transported using big bag packaging by truck, while GF is produced in Italy and shipped in cardboard packaging by truck. All final product packaging is manufactured in Italy and transported by truck.

5.4.2 Core processes

This phase includes the electricity, methane and water consumption inside the factory, the extruder maintenance materials, the treatment of waste generated and subsequently disposed.

5.4.3 Downstream processes

The final phase includes the transportation of the final compound from the LATI facilities to a distribution platform located in Limite di Pioltello, Milan, Italy, 65 km away. The transportation is carried out using a truck with a capacity ranging from 7.5 to 16 metric tons.

5.4.4 Mass balance control

Table 53 reports the input and output mass balance of the V2HF process production.

Table 53. V2HF mass balance.

Phase	Material	I/O	Quantity	Unit
Upstream	Melamine cyanurate production	I	<i>omissis</i>	kg
	Melamine cyanurate packaging	I	0.0029	kg
	Melamine cyanurate pallet	I	0.0000	kg
	Polyamide 6 production	I	<i>omissis</i>	kg
	Polyamide 6 packaging	I	0.0018	kg
	Polyamide 6 pallet	I	0.0000	kg
	Glass fibre production	I	<i>omissis</i>	kg
	Glass fibre packaging	I	0.0062	kg
	Glass fibre pallet	I	0.0000	kg
	Final product packaging PE bag	I	0.0036	kg
	Final product packaging ALU bag	I	0.0036	kg
	Final product pallet	I	0.0001	kg
	Final product cap	I	0.0016	kg
Core	Tap water	I	0.0002	m ³
	Well water	I	0.0004	m ³

	Maintenance materials	I	0.0002	kg
	Waste wood	O	0.0001	kg
	Waste plastics	O	0.0362	kg
	Waste cardboard	O	0.0091	kg
	Waste scrap steel (maintenance materials)	O	0.0002	kg
	Wastewater treatment	O	0.0006	m ³
Downstream	Compound	O	1.0000	kg
	Final packaging bag	O	0.0072	kg
	Final packaging cap	O	0.0016	kg
	Final packaging pallet	O	0.0001	kg
Mass balance	Total Mass Input		1.0488	kg
	Total Mass Output		1.0550	kg

5.5 LATENE

5.5.1 Upstream processes

Background processes for the upstream phase have been sourced from all materials associated with the LATENE product, utilizing the Ecoinvent v3.10 database. The primary component of the LATENE product is PP. The flame retardants is Ammonium polyphosphate. PP is manufactured in South Africa and Belgium and shipped in big bag packaging by truck and ship. Ammonium polyphosphate is produced in Spain and transported in big bag packaging by truck and ship. All final product packaging is manufactured in Italy and transported by truck.

5.5.2 Core processes

This phase includes the electricity, methane and water consumption inside the factory, the extruder maintenance materials, the treatment of waste generated and subsequently disposed.

5.5.3 Downstream processes

The final phase includes the transportation of the final compound from the LATI facilities to a distribution platform located in Limoto di Pioltello, Milan, Italy, 65 km away. The transportation is carried out using a truck with a capacity ranging from 7.5 to 16 metric tons.

5.5.4 Mass balance control

Table 54 reports the input and output mass balance of the LATENE process production.

Table 54. LATENE mass balance.

Phase	Material	I/O	Quantity	Unit
Upstream	Polypropylene ZA production	I	<i>omissis</i>	kg
	Polypropylene ZA packaging	I	0.0104	kg
	Polypropylene ZA pallet	I	0.0000	kg
	Polypropylene BE production	I	<i>omissis</i>	kg
	Polypropylene BE packaging	I	0.0655	kg
	Polypropylene BE pallet	I	0.0000	kg
	Ammonium polyphosphate production	I	<i>omissis</i>	kg
	Ammonium polyphosphate packaging	I	0.0260	kg
	Ammonium polyphosphate pallet	I	0.0000	kg
	Final product packaging PE bag	I	0.0036	kg
	Final product packaging ALU bag	I	0.0036	kg
	Final product pallet	I	0.0001	kg
	Final product cap	I	0.0016	kg
	Core	Tap water	I	0.0004
Well water		I	0.0002	m ³
Maintenance materials		I	0.0017	kg
Waste wood		O	0.0001	kg
Waste plastics		O	0.1415	kg
Waste scrap steel (maintenance materials)		O	0.0017	kg

	Wastewater treatment	O	0.0006	m ³
Downstream	Compound	O	1.0000	kg
	Final packaging bag	O	0.0072	kg
	Final packaging cap	O	0.0016	kg
	Final packaging pallet	O	0.0001	kg
	Total Mass Input			1.1427
Mass balance	Total Mass Output		1.1527	kg

5.6 LARTON

5.6.1 Upstream processes

Background processes for the upstream phase have been sourced from all materials associated with the LARTON product, utilizing the Ecoinvent v3.10 database. The primary components of the LARTON product are predominantly PPS with GF. GF is manufactured in France and transported in big bag packaging by truck. PPS is produced in China and shipped in big bag packaging by truck and ship. PE masterbatch is produced in United Kingdom and transported in big bag packaging by truck.

5.6.2 Core processes

This phase includes the electricity, methane and water consumption inside the factory, the extruder maintenance materials, the treatment of waste generated and subsequently disposed.

5.6.3 Downstream processes

The final phase includes the transportation of the final compound from the LATI facilities to a distribution platform located in Limito di Pioltello, Milan, Italy, 65 km away. The transportation is carried out using a truck with a capacity ranging from 7.5 to 16 metric tons.

5.6.4 Mass balance control

Table 55 reports the input and output mass balance of the LARTON process production.

Table 55. LARTON mass balance.

Phase	Material	I/O	Quantity	Unit
Upstream	PPS production	I	<i>omissis</i>	kg
	PPS packaging	I	0.0025	kg
	PPS pallet	I	0.0000	kg
	PE masterbatch production	I	<i>omissis</i>	kg
	PE masterbatch packaging	I	0.0001	kg
	PE masterbatch pallet	I	0.0000	kg
	Glass fibre production	I	<i>omissis</i>	kg
	Glass fibre packaging	I	0.0015	kg
	Glass fibre pallet	I	0.0000	kg
	Final product packaging PE bag	I	0.0036	kg
	Final product packaging ALU bag	I	0.0036	kg
	Final product pallet	I	0.0001	kg
	Final product cap	I	0.0016	kg
Core	Tap water	I	0.0004	m ³
	Well water	I	0.0002	m ³
	Maintenance materials	I	0.0014	kg
	Waste wood	O	0.0001	kg
	Waste plastics	O	0.0334	kg
	Waste scrap steel (maintenance materials)	O	0.0017	kg
	Wastewater treatment	O	0.0006	m ³
Downstream	Compound	O	1.0000	kg
	Final packaging bag	O	0.0072	kg
	Final packaging cap	O	0.0016	kg
	Final packaging pallet	O	0.0001	kg
Mass balance	Total Mass Input		1.0446	kg

5.7 LATER

5.7.1 Upstream processes

Background processes for the upstream phase have been sourced from all materials associated with the LATER product, utilizing the Ecoinvent v3.10 database. The primary components of the LATER product are predominantly PBT with GF. The flame retardants are antimony trioxide and TBBPA (Tetrabromobisphenol A). PBT is produced in China and shipped in big bag packaging by truck and ship. Ethylene copolymer is manufactured in Belgium and transported in big bag packaging by truck. Antimony trioxide is produced in China and transported in big bag packaging by truck and ship. GF is produced in Belgium and transported in big bag packaging by truck. PE masterbatch is produced in Germany and transported in big bag packaging by truck. TBBPA is produced in USA and shipped in big bag packaging by truck and ship. All final product packaging is manufactured in Italy and transported by truck. The model of PBT is made through the modification of the existent database: “*Polyethylene terephthalate, granulate, amorphous {RoW} | polyethylene terephthalate production, granulate, amorphous | Cut-off, U*”. In particular the input process “*Ethylene glycol {RoW} | market for ethylene glycol | Cut-off, U*” was replaced with the process “*1,4-butanediol {GLO} | market for 1,4-butanediol | Cut-off, U*”. The new process was named “*Polybutylene terephthalate {RoW} | polybutylene terephthalate production | Cut-off, U*”.

5.7.2 Core processes

This phase includes the electricity, methane and water consumption inside the factory, the extruder maintenance materials, the treatment of waste generated and subsequently disposed.

5.7.3 Downstream processes

The final phase includes the transportation of the final compound from the LATI facilities to a distribution platform located in Limoto di Pioltello, Milan, Italy, 65 km away. The transportation is carried out using a truck with a capacity ranging from 7.5 to 16 metric tons.

5.7.4 Mass balance control

Table 56 reports the input and output mass balance of the LATER process production.

Table 56. LATER mass balance.

Phase	Material	I/O	Quantity	Unit
Upstream	Polybutadiene production	I	<i>omissis</i>	kg
	Polybutadiene packaging	I	0.0018	kg
	Polybutadiene pallet	I	0.0000	kg
	PE masterbatch production	I	<i>omissis</i>	kg
	PE masterbatch packaging	I	0.0000	kg
	PE masterbatch pallet	I	0.0000	kg
	Glass fibre production	I	<i>omissis</i>	kg
	Glass fibre packaging	I	0.0012	kg
	Glass fibre pallet	I	0.0000	kg
	Ethylene copolymer production	I	<i>omissis</i>	kg
	Ethylene copolymer packaging	I	0.0002	kg
	Ethylene copolymer pallet	I	0.0000	kg
	Antimony trioxide production	I	<i>omissis</i>	kg
	Antimony trioxide packaging	I	0.0001	kg
	Antimony trioxide pallet	I	0.0000	kg
	TBBPA production	I	<i>omissis</i>	kg
	TBBPA packaging	I	0.0006	kg
	TBBPA pallet	I	0.0000	kg
	Final product packaging PE bag	I	0.0036	kg

	Final product packaging ALU bag	I	0.0036	kg
	Final product pallet	I	0.0001	kg
	Final product cap	I	0.0016	kg
Core	Tap water	I	0.0004	m ³
	Well water	I	0.0002	m ³
	Maintenance materials	I	0.0017	kg
	Waste wood	O	0.0001	kg
	Waste plastics	O	0.0184	kg
	Waste scrap steel (maintenance materials)	O	0.0017	kg
	Wastewater treatment	O	0.0006	m ³
Downstream	Compound	O	1.0000	kg
	Final packaging bag	O	0.0072	kg
	Final packaging cap	O	0.0016	kg
	Final packaging pallet	O	0.0001	kg
Mass balance	Total Mass Input		1.0248	kg
	Total Mass Output		1.0454	kg

6 CHAPTER 6: RESULTS AND INTERPRETATION

This chapter presents the environmental performance results for the evaluated LATI products. The following sections show the environmental impacts of each product. The detail of the results are reported in Annex V.

6.1 V0CT1

Baseline scenario: the environmental performance of the V0CT1 product baseline scenario is shown in Figure 6 and Figure 7. In total, the entire production process impacts 243.71 mPt. The most impacting process is the upstream phase (226.87 mPt; 93.03 % of the total), followed by the core phase (16.26 mPt; 6.56 %) and downstream (0.58 mPt; 0.23 %). The upstream phase mainly affects human health, with 215.36 mPt. Table 57 presents the indicator results per impact category. The product has a total impact of 6.16 kg CO₂ eq per FU. The upstream contributes 5.72 kg CO₂ eq (92.86 % of the total), followed by the core with 0.42 kg CO₂ eq (6.82 %) and downstream with 0.02 kg CO₂ eq (0.32 %).

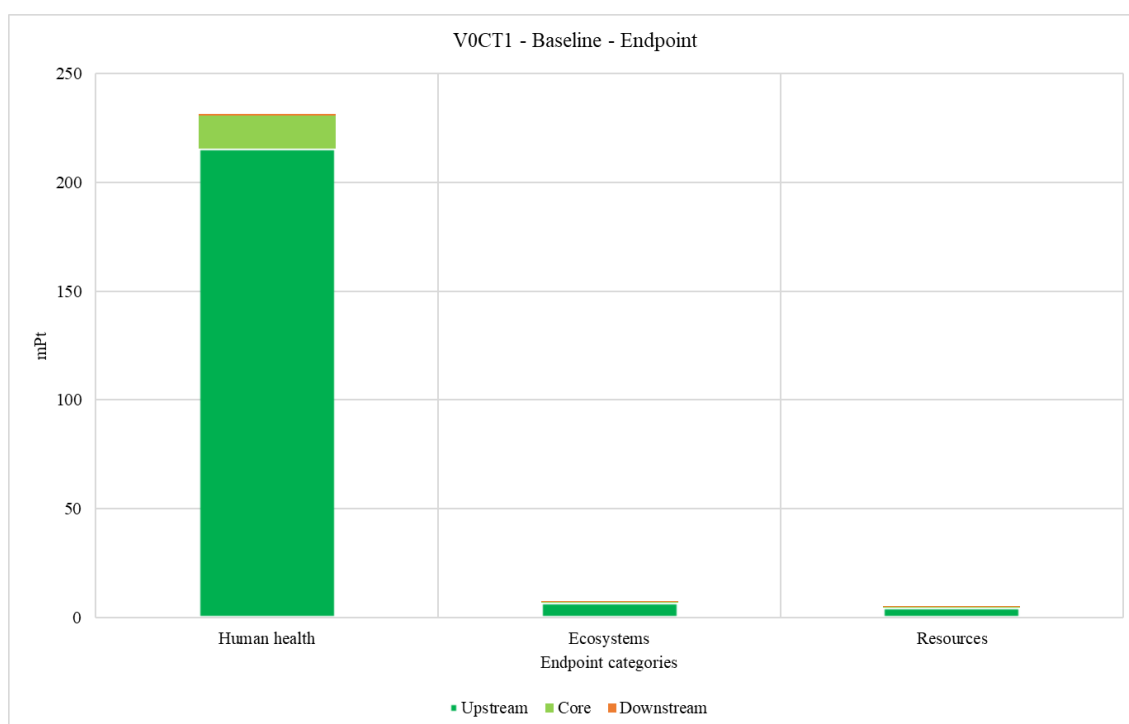


Figure 7. Results - V0CT1 - Baseline - Endpoint categories.

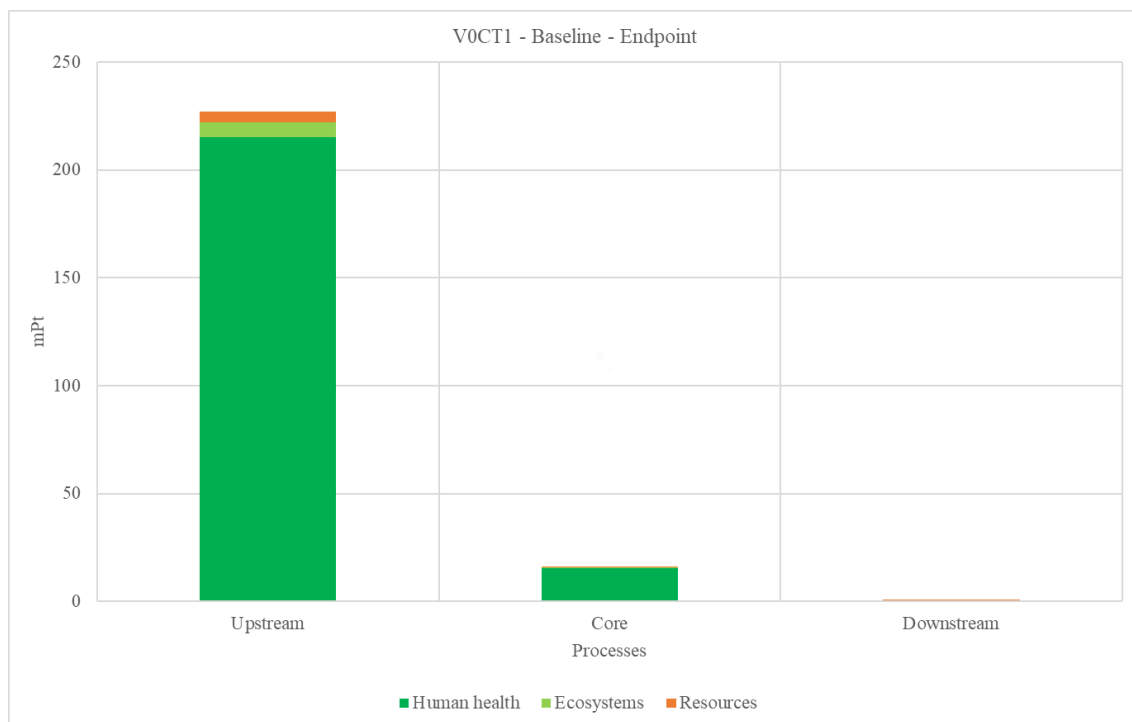


Figure 8. Results - V0CT1 - Baseline - Processes per Endpoint categories.

Table 57. Results - V0CT1 - Baseline - Impact categories.

Impact category	Unit	Total	Upstream	Core	Downstream
Acidification	mol H ⁺ eq	3.2E-02	2.9E-02	2.3E-03	3.1E-05
Climate change	kg CO ₂ eq	6.2E+00	5.7E+00	4.2E-01	1.6E-02
Climate change - Biogenic	kg CO ₂ eq	3.4E-02	1.2E-02	2.3E-02	9.2E-06
Climate change - Fossil	kg CO ₂ eq	6.1E+00	5.7E+00	4.0E-01	1.6E-02
Climate change - Land use and LU change	kg CO ₂ eq	1.3E-03	1.2E-03	8.2E-05	5.0E-06
Ecotoxicity, freshwater - part 1	CTUe	9.2E+00	8.5E+00	6.2E-01	4.6E-02
Ecotoxicity, freshwater - part 2	CTUe	4.6E+00	4.2E+00	3.3E-01	1.2E-02
Ecotoxicity, freshwater - inorganics	CTUe	1.1E+01	1.1E+01	5.7E-01	3.4E-02
Ecotoxicity, freshwater - organics - p.1	CTUe	1.4E+00	1.1E+00	3.0E-01	2.2E-02
Ecotoxicity, freshwater - organics - p.2	CTUe	1.1E+00	1.0E+00	8.3E-02	9.9E-04
Particulate matter	disease inc.	2.9E-07	2.8E-07	1.1E-08	9.8E-10

Eutrophication, marine	kg N eq	9.1E-03	8.6E-03	5.2E-04	7.3E-06
Eutrophication, freshwater	kg P eq	7.0E-04	6.5E-04	4.8E-05	1.0E-06
Eutrophication, terrestrial	mol N eq	6.6E-02	6.0E-02	5.6E-03	7.9E-05
Human toxicity, cancer	CTUh	6.9E-09	5,5E-09	1.2E-09	9.4E-11
Human toxicity, cancer - inorganics	CTUh	7.3E-10	7.0E-10	2.7E-11	1.1E-12
Human toxicity, cancer - organics	CTUh	6.1E-09	4.8E-09	1.2E-09	9.3E-11
Human toxicity, non-cancer	CTUh	6.6E-08	6.4E-08	1.9E-09	1.3E-10
Human toxicity, non-cancer - inorganics	CTUh	5.0E-08	4.8E-08	1.8E-09	1.2E-10
Human toxicity, non-cancer - organics	CTUh	1.6E-08	1.6E-08	1.3E-10	8.4E-12
Ionising radiation	kBq U-235 eq	1.1E-01	8.2E-02	3.2E-02	3.4E-04
Land use	Pt	6.6E+00	5.1E+00	1.3E+00	1.1E-01
Ozone depletion	kg CFC11 eq	3.9E-08	3.1E-08	8.4E-09	3.1E-10
Photochemical ozone formation	kg NMVOC eq	2.0E-02	1.8E-02	2.0E-03	5.2E-05
Resource use, fossils	MJ	2.1E+01	2.0E+01	1.2E+00	1.8E-02
Resource use, minerals and metals	kg Sb eq	7.3E-03	7.3E-03	7.7E-07	5.0E-08
Water use	m ³ depriv.	5.0E+00	4.8E+00	1.8E-01	8.3E-04

Core green scenarios: as regarding the core scenarios comparison analysis (Figure 8), the percentage reduction compared to the core phase of baseline scenario (16.26 mPt) is -66 % for MIX1 (10.76 mPt), -58 % for MIX2 (9.50 mPt), -7 % for 25 % FV (15.26 mPt), -13 % for 50 % FV (14.26 mPt), -19 % for 75 % FV (13.25 mPt) and -25 % for 100 % FV (12.25 mPt). In detail, Figure 8 shows that human health is the endpoint category that benefits most from using renewable energy. Table 58 reports the quantitative values. Regarding climate change, the estimated kg of CO₂ eq emissions are 0.25 kg CO₂ eq, 0.17 kg CO₂ eq, 0.37 kg CO₂ eq, 0.32 kg CO₂ eq, 0.26 kg CO₂ eq and 0.21 kg CO₂ eq for MIX1, MIX2, 25 % FV, 50 % FV, 75 % FV and 100 % FV, respectively.

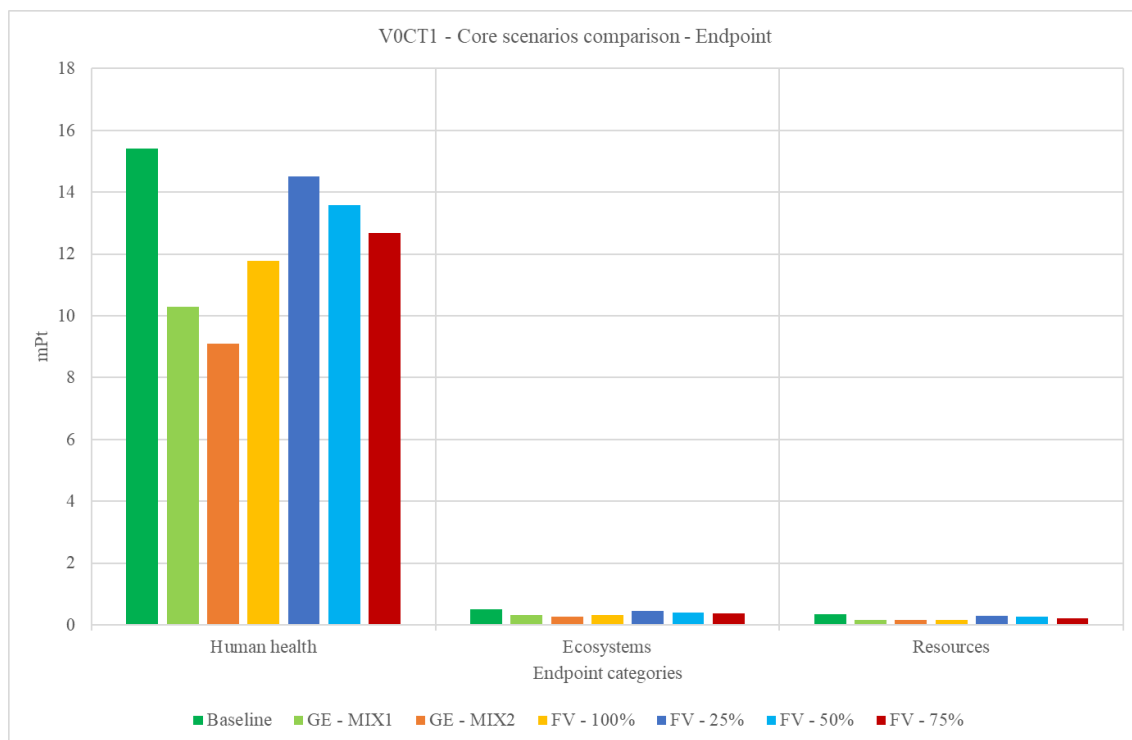


Figure 9. Results - V0CT1 - Green scenarios - Endpoint categories.

Table 58. Results - V0CT1 - Green scenarios - Impact categories.

Impact category	Unit	Baseline	GE - MIX1	GE - MIX2	FV - 100%	FV - 25%	FV - 50%	FV - 75%
Acidification	mol H ⁺ eq	2.3E-03	1.7E-03	1.5E-03	1.8E-03	2.2E-03	2.1E-03	2.0E-03
Climate change	kg CO ₂ eq	4.2E-01	2.5E-01	1.7E-01	2.1E-01	3.7E-01	3.2E-01	2.6E-01
Climate change - Biogenic	kg CO ₂ eq	2.3E-02	6.2E-02	6.0E-04	3.1E-04	1.7E-02	1.1E-02	5.9E-03
Climate change - Fossil	kg CO ₂ eq	4.0E-01	1.9E-01	1.7E-01	2.1E-01	3.5E-01	3.0E-01	2.6E-01
Climate change - Land use and LU change	kg CO ₂ eq	8.2E-05	7.9E-05	5.6E-05	1.2E-04	9.2E-05	1.0E-04	1.1E-04
Ecotoxicity, freshwater - part 1	CTUe	6.2E-01	5.2E-01	4.0E-01	6.8E-01	6.3E-01	6.5E-01	6.6E-01
Ecotoxicity, freshwater - part 2	CTUe	3.3E-01	2.6E-01	2.2E-01	3.8E-01	3.4E-01	3.6E-01	3.7E-01
Ecotoxicity, freshwater - inorganics	CTUe	5.7E-01	4.4E-01	3.4E-01	7.8E-01	6.2E-01	6.7E-01	7.2E-01
Ecotoxicity, freshwater - organics - p.1	CTUe	3.0E-01	2.7E-01	2.1E-01	2.6E-01	2.9E-01	2.8E-01	2.7E-01
Ecotoxicity, freshwater - organics - p.2	CTUe	8.3E-02	7.4E-02	7.1E-02	2.0E-02	6.7E-02	5.1E-02	3.6E-02
Particulate matter	disease inc.	1.1E-08	9.0E-09	7.0E-09	9.8E-09	1.0E-08	1.0E-08	1.0E-08

Eutrophication, marine	kg N eq	5.2E-04	4.2E-04	3.8E-04	4.3E-04	4.9E-04	4.7E-04	4.5E-04
Eutrophication, freshwater	kg P eq	4.8E-05	1.9E-05	1.1E-05	3.9E-05	4.5E-05	4.3E-05	4.1E-05
Eutrophication, terrestrial	mol N eq	5.6E-03	4.6E-03	4.1E-03	4.6E-03	5.3E-03	5.1E-03	4.9E-03
Human toxicity, cancer	CTUh	1.2E-09	1.1E-09	8.4E-10	1.1E-09	1.2E-09	1.2E-09	1.2E-09
Human toxicity, cancer - inorganics	CTUh	2.7E-11	2.1E-11	1.7E-11	3.4E-11	2.8E-11	3.0E-11	3.2E-11
Human toxicity, cancer - organics	CTUh	1.2E-09	1.1E-09	8.3E-10	1.1E-09	1.2E-09	1.2E-09	1.1E-09
Human toxicity, non-cancer	CTUh	1.9E-09	1.6E-09	1.2E-09	3.3E-09	2.2E-09	2.6E-09	2.9E-09
Human toxicity, non-cancer - inorganics	CTUh	1.8E-09	1.5E-09	1.1E-09	3.1E-09	2.1E-09	2.4E-09	2.8E-09
Human toxicity, non-cancer - organics	CTUh	1.3E-10	9.5E-11	7.8E-11	1.7E-10	1.4E-10	1.5E-10	1.6E-10
Ionising radiation	kBq U-235 eq	3.2E-02	4.0E-03	2.5E-03	6.2E-03	2.5E-02	1.9E-02	1.3E-02
Land use	Pt	1.3E+00	2.0E+00	6.2E-01	8.4E-01	1.2E+00	1.1E+00	9.6E-01
Ozone depletion	kg CFC11 eq	8.4E-09	3.9E-09	3.4E-09	6.5E-09	7.9E-09	7.5E-09	7.0E-09
Photochemical ozone formation	kg NMVOC eq	2.0E-03	1.5E-03	1.3E-03	1.5E-03	1.9E-03	1.7E-03	1.6E-03
Resource use, fossils	MJ	1.2E+00	2.8E-01	1.5E-01	4.5E-01	9.8E-01	8.0E-01	6.3E-01
Resource use, minerals and metals	kg Sb eq	7.7E-07	7.8E-07	6.4E-07	3.7E-06	1.5E-06	2.3E-06	3.0E-06
Water use	m ³ depriv.	1.8E-01	3.2E-01	8.8E-01	5.6E-02	1.5E-01	1.2E-01	8.8E-02

Upstream recycling scenarios: introducing recycled PA in the upstream phases decreases impacts in all categories. On the total environmental profile, the reduction impacts versus the baseline scenario (226.87 mPt) is -43 % for Grade A (130.84 mPt), -50 % for Grade B (140.44 mPt), -30 % for Grade C (159.65 mPt), -20 % for Grade D (178.86 mPt), -13 % for Grade E (198.06 mPt) and -5 % for Grade G (217.27 mPt) (Figure 9). As far as CO₂ eq emissions are concerned (Table 59), the V0CT1 with recycled polymer as a value of 2.36 kg CO₂ eq for Grade A, 2.69 kg CO₂ eq for Grade B, 3.37 kg CO₂ eq for Grade C, 4.04 kg CO₂ eq for Grade D, 4.71 kg CO₂ eq for Grade E and 5.38 kg CO₂ eq for Grade G.

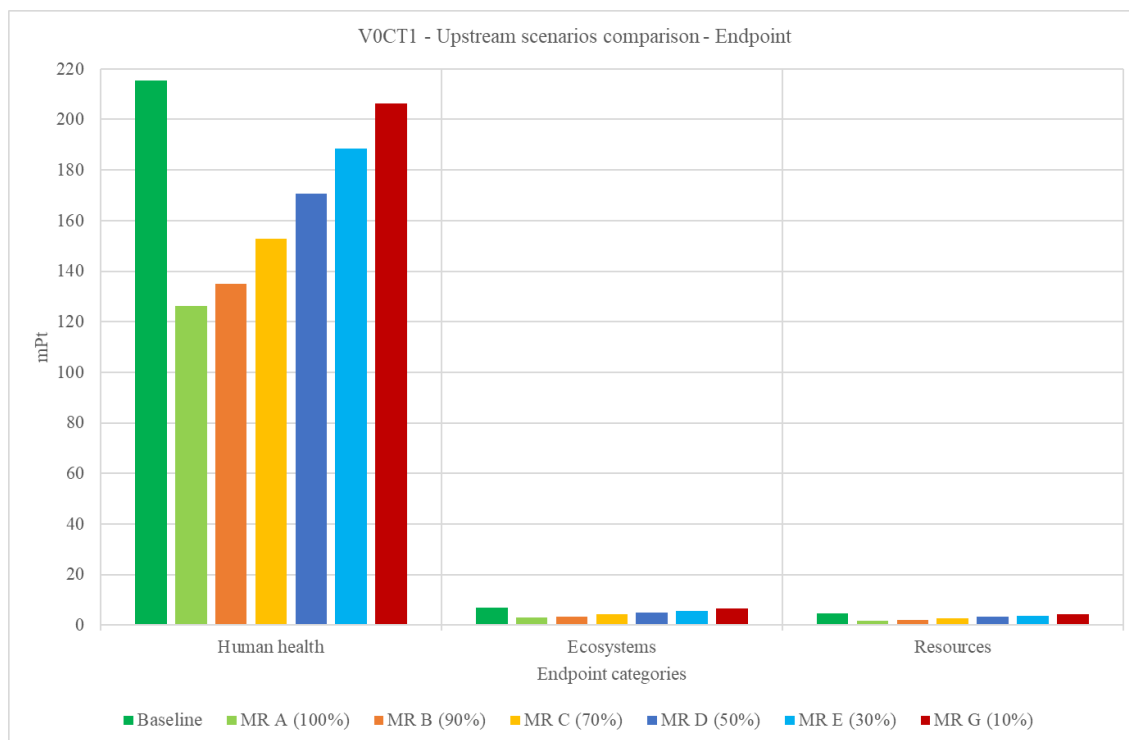


Figure 10. Results - VOCT1 - Recycling scenario - Endpoint categories.

Table 59. Results - VOCT1 - Recycling scenario - Impact categories.

Impact category	Unit	Baseline	A (100%)	B (90%)	C (70%)	D (50%)	E (30%)	G (10%)
Acidification	mol H ⁺ eq	2.9E-02	1.5E-02	1.6E-02	1.9E-02	2.2E-02	2.5E-02	2.8E-02
Climate change	kg CO ₂ eq	5.7E+00	2.4E+00	2.7E+00	3.4E+00	4.0E+00	4.7E+00	5.4E+00
Climate change - Biogenic	kg CO ₂ eq	1.2E-02	2.4E-02	2.3E-02	2.0E-02	1.8E-02	1.5E-02	1.3E-02
Climate change - Fossil	kg CO ₂ eq	5.7E+00	2.3E+00	2.7E+00	3.3E+00	4.0E+00	4.7E+00	5.4E+00
Climate change - Land use and LU change	kg CO ₂ eq	1.2E-03	1.5E-03	1.5E-03	1.5E-03	1.4E-03	1.3E-03	1.3E-03
Ecotoxicity, freshwater - part 1	CTUe	8.5E+00	6.9E+00	7.1E+00	7.4E+00	7.7E+00	8.0E+00	8.3E+00
Ecotoxicity, freshwater - part 2	CTUe	4.2E+00	3.6E+00	3.6E+00	3.8E+00	3.9E+00	4.0E+00	4.2E+00
Ecotoxicity, freshwater - inorganics	CTUe	1.1E+01	9.0E+00	9.1E+00	9.5E+00	9.8E+00	1.0E+01	1.0E+01
Ecotoxicity, freshwater - organics - p.1	CTUe	1.1E+00	1.3E+00	1.2E+00	1.2E+00	1.2E+00	1.1E+00	1.1E+00
Ecotoxicity, freshwater - organics - p.2	CTUe	1.0E+00	2.2E-01	3.0E-01	4.6E-01	6.2E-01	7.8E-01	9.4E-01
Particulate matter	disease inc.	2.8E-07	1.4E-07	1.5E-07	1.8E-07	2.1E-07	2.4E-07	2.6E-07

Eutrophication, marine	kg N eq	8.6E-03	2.9E-03	3.5E-03	4.6E-03	5.7E-03	6.9E-03	8.0E-03
Eutrophication, freshwater	kg P eq	6.5E-04	5.6E-04	5.7E-04	5.9E-04	6.1E-04	6.3E-04	6.5E-04
Eutrophication, terrestrial	mol N eq	6.0E-02	3.3E-02	3.6E-02	4.1E-02	4.7E-02	5.2E-02	5.8E-02
Human toxicity, cancer	CTUh	5.5E-09	6.0E-09	6.0E-09	5.9E-09	5.8E-09	5.7E-09	5.6E-09
Human toxicity, cancer - inorganics	CTUh	7.0E-10	6.5E-10	6.5E-10	6.6E-10	6.8E-10	6.9E-10	7.0E-10
Human toxicity, cancer - organics	CTUh	4.8E-09	5.4E-09	5.3E-09	5.2E-09	5.1E-09	5.0E-09	4.9E-09
Human toxicity, non-cancer	CTUh	6.4E-08	6.6E-08	6.5E-08	6.5E-08	6.5E-08	6.5E-08	6.4E-08
Human toxicity, non-cancer - inorganics	CTUh	4.8E-08	5.0E-08	5.0E-08	5.0E-08	4.9E-08	4.9E-08	4.8E-08
Human toxicity, non-cancer - organics	CTUh	1.6E-08	1.5E-08	1.5E-08	1.6E-08	1.6E-08	1.6E-08	1.6E-08
Ionising radiation	kBq U-235 eq	8.2E-02	1.3E-01	1.2E-01	1.1E-01	1.1E-01	9.6E-02	8.7E-02
Land use	Pt	5.1E+00	6.2E+00	6.1E+00	5.9E+00	5.7E+00	5.5E+00	5.3E+00
Ozone depletion	kg CFC11 eq	3.1E-08	3.3E-08	3.3E-08	3.2E-08	3.2E-08	3.1E-08	3.1E-08
Photochemical ozone formation	kg NMVOC eq	1.8E-02	1.0E-02	1.1E-02	1.3E-02	1.4E-02	1.6E-02	1.8E-02
Resource use, fossils	MJ	2.0E+01	9.9E+00	1.1E+01	1.3E+01	1.5E+01	1.7E+01	1.9E+01
Resource use, minerals and metals	kg Sb eq	7.3E-03	7.3E-03	7.3E-03	7.3E-03	7.3E-03	7.3E-03	7.3E-03
Water use	m ³ depriv.	4.8E+00	5.9E-01	1.0E+00	1.8E+00	2.7E+00	3.5E+00	4.4E+00

Global warming tree: the diagrams depicted in Figure 10 and Figure 11 allow to understand the contribution of processes in climate change. In particular, the emissions are mainly caused by the production of PA66 (59.5 %, 3.59 kg CO₂ eq), brominated polystyrene (16.6 %, 1.00 kg CO₂ eq) and GF (11 %, 0.661 kg CO₂ eq).

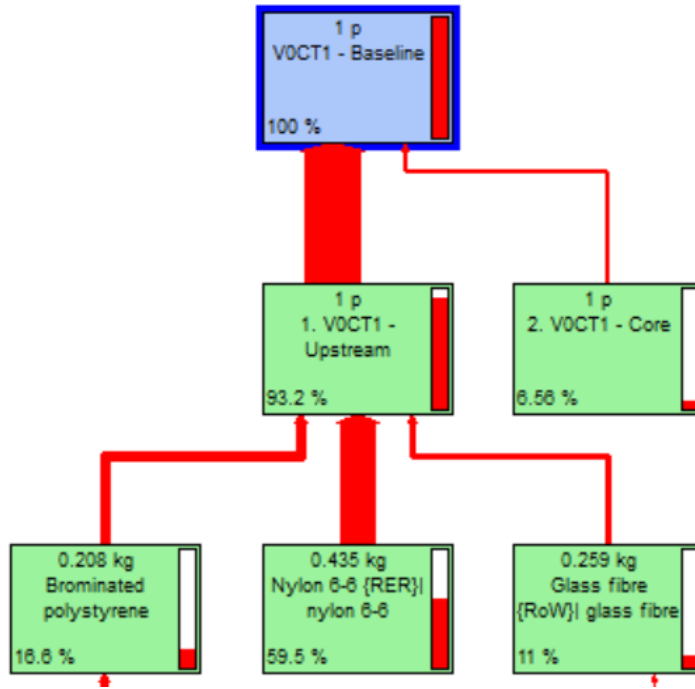


Figure 11. Results - VOCT1 - Baseline - GWP per percentage.

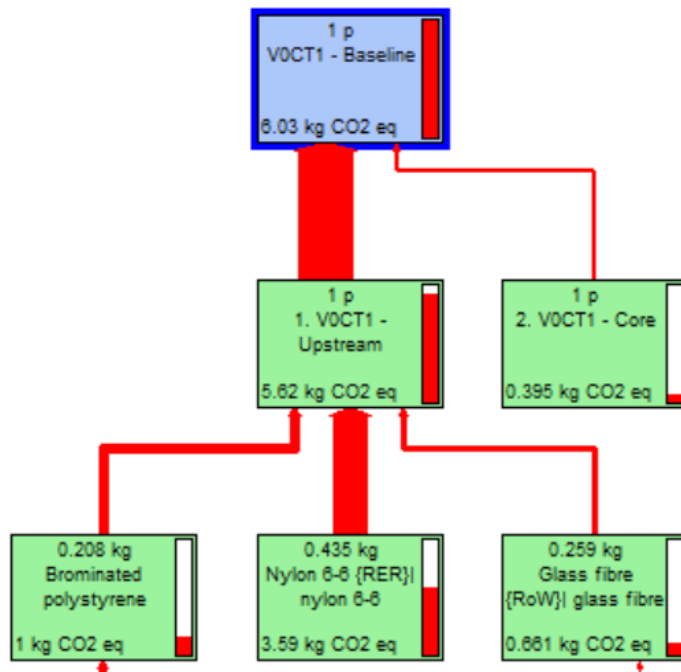


Figure 12. Results - VOCT1 - Baseline - GWP per contribution.

6.2 V0HF1

Baseline scenario: the environmental performance of the V0HF1 product baseline scenario is shown in Figure 12 and Figure 13. In total, the entire production process impacts 266.98 mPt. The most impacting process is the upstream phase (250.76 mPt; 94.01 % of the total), followed by the core phase (15.64 mPt; 5.99 %) and downstream (0.58 mPt; 0.22 %). The upstream phase mainly affects human health, with 238.08 mPt. Table 60 presents the indicator results per impact category. The product has a total impact of 6.76 kg CO₂ eq per FU. The upstream contributes 6.33 kg CO₂ eq (93.64 % of the total), followed by the core with 0.41 kg CO₂ eq (6.07 %) and downstream with 0.02 kg CO₂ eq (0.30 %).

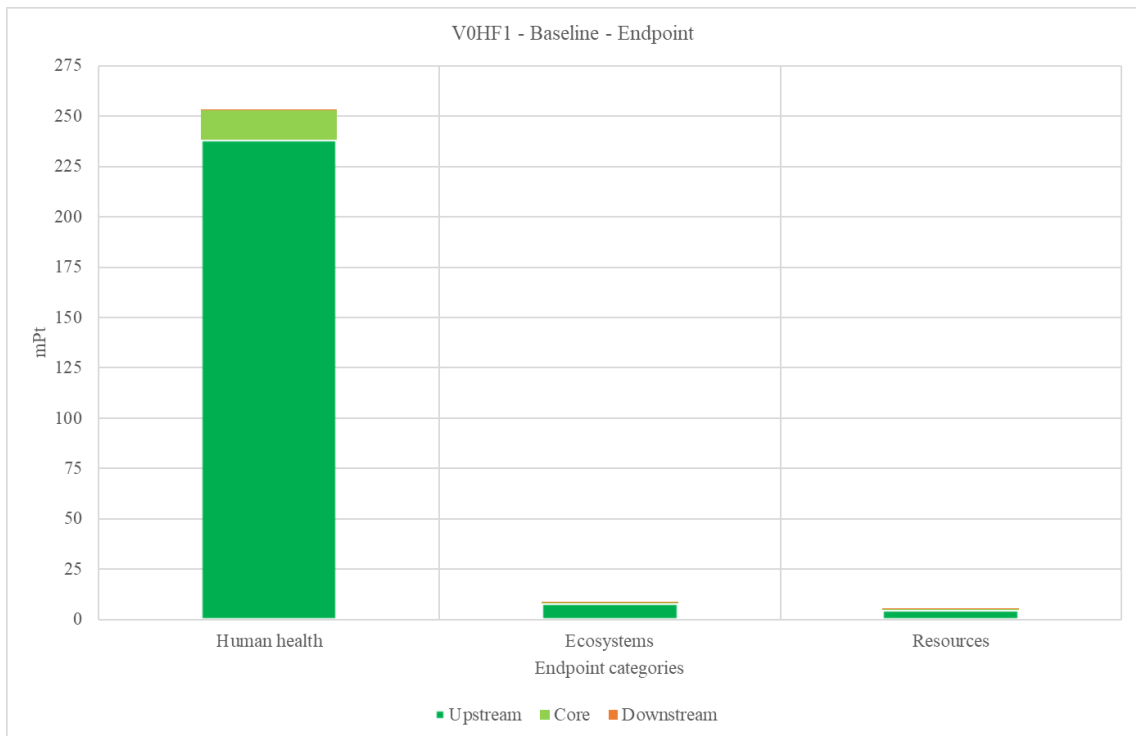


Figure 13. Results - V0HF1 - Baseline - Endpoint categories.

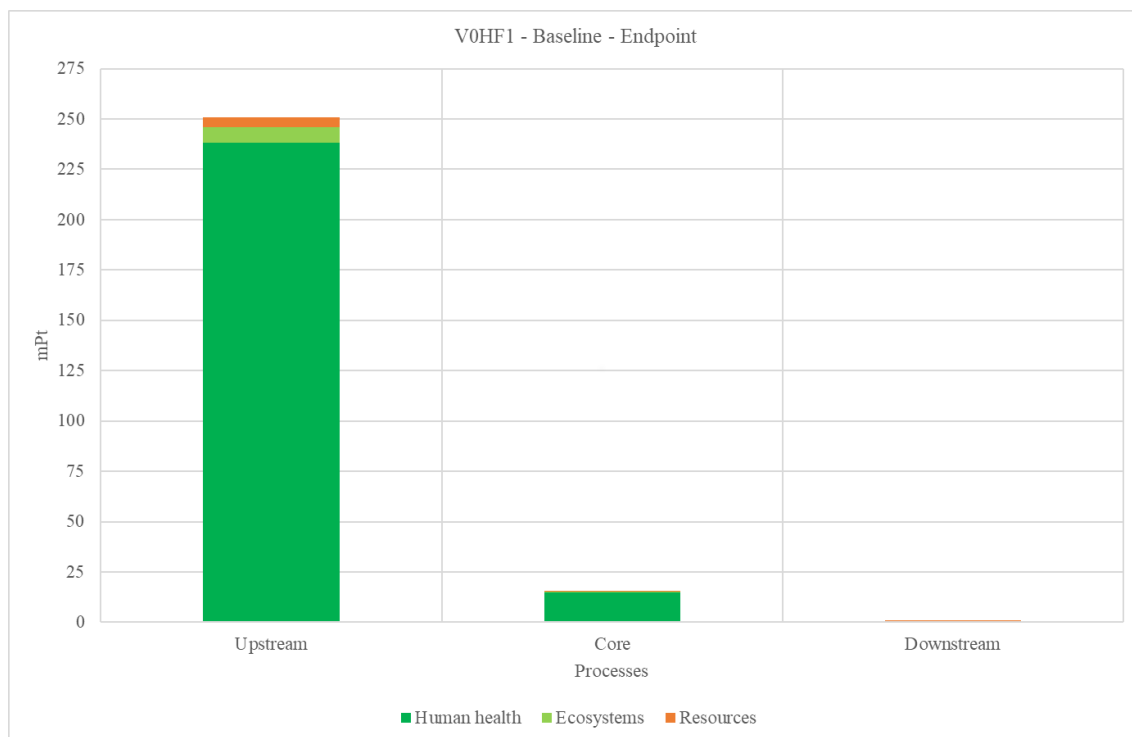


Figure 14. Results - V0HF1 - Baseline - Processes per Endpoint categories.

Table 60. Results - V0HF1 - Baseline - Impact categories.

Impact category	Unit	Total	Upstream	Core	Downstream
Acidification	mol H ⁺ eq	3.4E-02	3.2E-02	2.2E-03	3.1E-05
Climate change	kg CO ₂ eq	6.8E+00	6.3E+00	4.1E-01	1.6E-02
Climate change - Biogenic	kg CO ₂ eq	2.9E-02	6.0E-03	2.3E-02	9.2E-06
Climate change - Fossil	kg CO ₂ eq	6.7E+00	6.3E+00	3.9E-01	1.6E-02
Climate change - Land use and LU change	kg CO ₂ eq	7.3E-03	7.2E-03	7.9E-05	5.0E-06
Ecotoxicity, freshwater - part 1	CTUe	1.2E+01	1.1E+01	5.9E-01	4.6E-02
Ecotoxicity, freshwater - part 2	CTUe	4.6E+00	4.3E+00	3.3E-01	1.2E-02
Ecotoxicity, freshwater - inorganics	CTUe	1.2E+01	1.1E+01	5.6E-01	3.4E-02
Ecotoxicity, freshwater - organics - p.1	CTUe	3.4E+00	3.1E+00	2.8E-01	2.2E-02
Ecotoxicity, freshwater - organics - p.2	CTUe	1.2E+00	1.1E+00	8.2E-02	9.9E-04
Particulate matter	disease inc.	3.2E-07	3.1E-07	1.0E-08	9.8E-10

Eutrophication, marine	kg N eq	9.7E-03	9.2E-03	4.8E-04	7.3E-06
Eutrophication, freshwater	kg P eq	1.0E-03	9.9E-04	4.7E-05	1.0E-06
Eutrophication, terrestrial	mol N eq	6.9E-02	6.3E-02	5.2E-03	7.9E-05
Human toxicity, cancer	CTUh	1.5E-08	1.3E-08	1.2E-09	9.4E-11
Human toxicity, cancer - inorganics	CTUh	7.7E-10	7.4E-10	2.5E-11	1.1E-12
Human toxicity, cancer - organics	CTUh	1.4E-08	1.3E-08	1.1E-09	9.3E-11
Human toxicity, non-cancer	CTUh	5.4E-08	5.2E-08	1.8E-09	1.3E-10
Human toxicity, non-cancer - inorganics	CTUh	5.1E-08	4.9E-08	1.7E-09	1.2E-10
Human toxicity, non-cancer - organics	CTUh	2.9E-09	2.8E-09	1.3E-10	8.4E-12
Ionising radiation	kBq U-235 eq	2.1E-01	1.8E-01	3.2E-02	3.4E-04
Land use	Pt	1.4E+01	1.3E+01	1.3E+00	1.1E-01
Ozone depletion	kg CFC11 eq	3.2E-08	2.3E-08	8.1E-09	3.1E-10
Photochemical ozone formation	kg NMVOC eq	2.2E-02	2.0E-02	1.9E-03	5.2E-05
Resource use, fossils	MJ	2.8E+01	2.7E+01	1.2E+00	1.8E-02
Resource use, minerals and metals	kg Sb eq	1.1E-04	1.1E-04	7.4E-07	5.0E-08
Water use	m ³ depriv.	5.9E+00	5.8E+00	1.8E-01	8.3E-04

Core green scenarios: regarding the core scenarios comparison analysis, the percentage reduction compared to the core phase of the baseline scenario (15.64 mPt) is -35 % for MIX1 (10.15 mPt), -53 % for MIX2 (8.88 mPt), -6 % for 25 % FV (14.64 mPt), -13 % for 50 % FV (13.64 mPt), -20 % for 75 % FV (12.64 mPt) and -36 % for 100 % FV (11.63 mPt). In detail, Figure 14 shows that human health is the endpoint category that benefits most from using renewable energy. Table 61 reports the quantitative values. Regarding climate change, the estimated kg of CO₂ eq emissions are 0.24 kg CO₂ eq, 0.15 kg CO₂ eq, 0.36 kg CO₂ eq, 0.30 kg CO₂ eq, 0.25 kg CO₂ eq and 0.20 kg CO₂ eq for MIX1, MIX2, 25 % FV, 50 % FV, 75 % FV and 100 % FV, respectively.

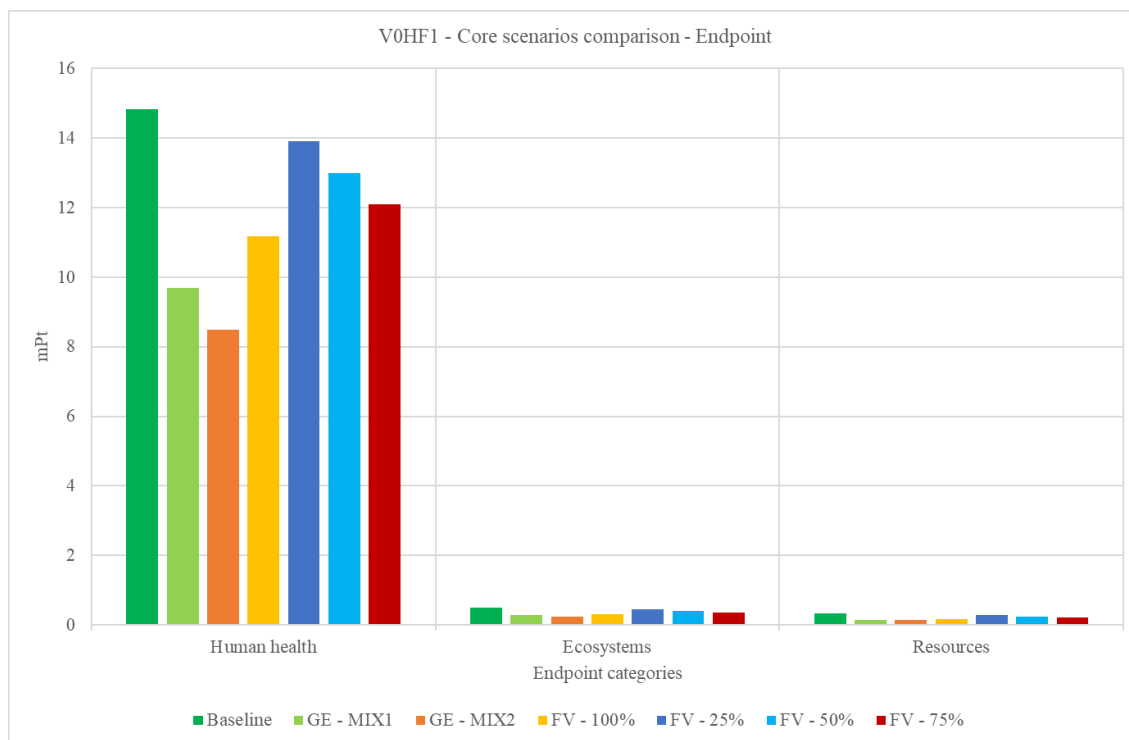


Figure 15. Results - V0HF1 - Green scenarios - Endpoint categories.

Table 61. Results - V0HF1 - Green scenarios - Impact categories.

Impact category	Unit	Baseline	GE - MIX1	GE - MIX2	FV - 100%	FV - 25%	FV - 50%	FV - 75%
Acidification	mol H ⁺ eq	2.2E-03	1.6E-03	1.4E-03	1.7E-03	2.1E-03	1.9E-03	1.8E-03
Climate change	kg CO ₂ eq	4.1E-01	2.4E-01	1.5E-01	2.0E-01	3.6E-01	3.0E-01	2.5E-01
Climate change - Biogenic	kg CO ₂ eq	2.3E-02	6.2E-02	5.9E-04	3.0E-04	1.7E-02	1.1E-02	5.9E-03
Climate change - Fossil	kg CO ₂ eq	3.9E-01	1.8E-01	1.5E-01	1.9E-01	3.4E-01	2.9E-01	2.4E-01
Climate change - Land use and LU change	kg CO ₂ eq	7.9E-05	7.6E-05	5.3E-05	1.2E-04	8.8E-05	9.8E-05	1.1E-04
Ecotoxicity, freshwater - part 1	CTUe	5.9E-01	4.9E-01	3.7E-01	6.4E-01	6.0E-01	6.2E-01	6.3E-01
Ecotoxicity, freshwater - part 2	CTUe	3.3E-01	2.6E-01	2.1E-01	3.8E-01	3.4E-01	3.5E-01	3.7E-01
Ecotoxicity, freshwater - inorganics	CTUe	5.6E-01	4.3E-01	3.2E-01	7.6E-01	6.1E-01	6.6E-01	7.1E-01
Ecotoxicity, freshwater - organics - p.1	CTUe	2.8E-01	2.5E-01	1.9E-01	2.4E-01	2.7E-01	2.6E-01	2.5E-01
Ecotoxicity, freshwater - organics - p.2	CTUe	8.2E-02	7.3E-02	7.0E-02	1.9E-02	6.6E-02	5.1E-02	3.5E-02
Particulate matter	disease inc.	1.0E-08	8.5E-09	6.4E-09	9.3E-09	9.9E-09	9.7E-09	9.5E-09

Eutrophication, marine	kg N eq	4.8E-04	3.8E-04	3.5E-04	4.0E-04	4.6E-04	4.4E-04	4.2E-04
Eutrophication, freshwater	kg P eq	4.7E-05	1.8E-05	1.1E-05	3.8E-05	4.5E-05	4.3E-05	4.0E-05
Eutrophication, terrestrial	mol N eq	5.2E-03	4.3E-03	3.8E-03	4.3E-03	5.0E-03	4.7E-03	4.5E-03
Human toxicity, cancer	CTUh	1.2E-09	1.0E-09	7.6E-10	1.1E-09	1.1E-09	1.1E-09	1.1E-09
Human toxicity, cancer - inorganics	CTUh	2.5E-11	2.0E-11	1.6E-11	3.2E-11	2.7E-11	2.9E-11	3.1E-11
Human toxicity, cancer - organics	CTUh	1.1E-09	9.8E-10	7.4E-10	1.0E-09	1.1E-09	1.1E-09	1.1E-09
Human toxicity, non-cancer	CTUh	1.8E-09	1.5E-09	1.1E-09	3.2E-09	2.2E-09	2.5E-09	2.8E-09
Human toxicity, non-cancer - inorganics	CTUh	1.7E-09	1.4E-09	1.0E-09	3.0E-09	2.0E-09	2.4E-09	2.7E-09
Human toxicity, non-cancer - organics	CTUh	1.3E-10	8.9E-11	7.2E-11	1.6E-10	1.4E-10	1.5E-10	1.6E-10
Ionising radiation	kBq U-235 eq	3.2E-02	3.7E-03	2.1E-03	5.8E-03	2.5E-02	1.9E-02	1.2E-02
Land use	Pt	1.3E+00	2.0E+00	5.6E-01	7.8E-01	1.2E+00	1.0E+00	9.1E-01
Ozone depletion	kg CFC11 eq	8.1E-09	3.6E-09	3.1E-09	6.2E-09	7.6E-09	7.2E-09	6.7E-09
Photochemical ozone formation	kg NMVOC eq	1.9E-03	1.3E-03	1.2E-03	1.4E-03	1.7E-03	1.6E-03	1.5E-03
Resource use, fossils	MJ	1.2E+00	2.8E-01	1.4E-01	4.5E-01	9.7E-01	8.0E-01	6.2E-01
Resource use, minerals and metals	kg Sb eq	7.4E-07	7.6E-07	6.1E-07	3.7E-06	1.5E-06	2.2E-06	3.0E-06
Water use	m ³ depriv.	1.8E-01	3.2E-01	8.8E-01	5.5E-02	1.5E-01	1.2E-01	8.8E-02

Upstream recycling scenarios: introducing recycled PA in the upstream phases decreases impacts in all categories. On the total environmental profile, the reduction impacts versus the baseline scenario (250.76 mPt) is -40 % for Grade A (151.41 mPt), -36 % for Grade B (161.35 mPt), -28 % for Grade C (181.22 mPt), -20 % for Grade D (201.08 mPt), -13 % for Grade E (220.95 mPt) and -4 % for Grade G (240.82 mPt) (Figure 15). As far as CO₂ eq emissions are concerned (Table 62), the V0HF1 with recycled polymer as a value of 2.85 kg CO₂ eq for Grade A, 3.20 kg CO₂ eq for Grade B, 3.89 kg CO₂ eq for Grade C, 4.59 kg CO₂ eq for Grade D, 5.28 kg CO₂ eq for Grade E and 5.98 kg CO₂ eq for Grade G.

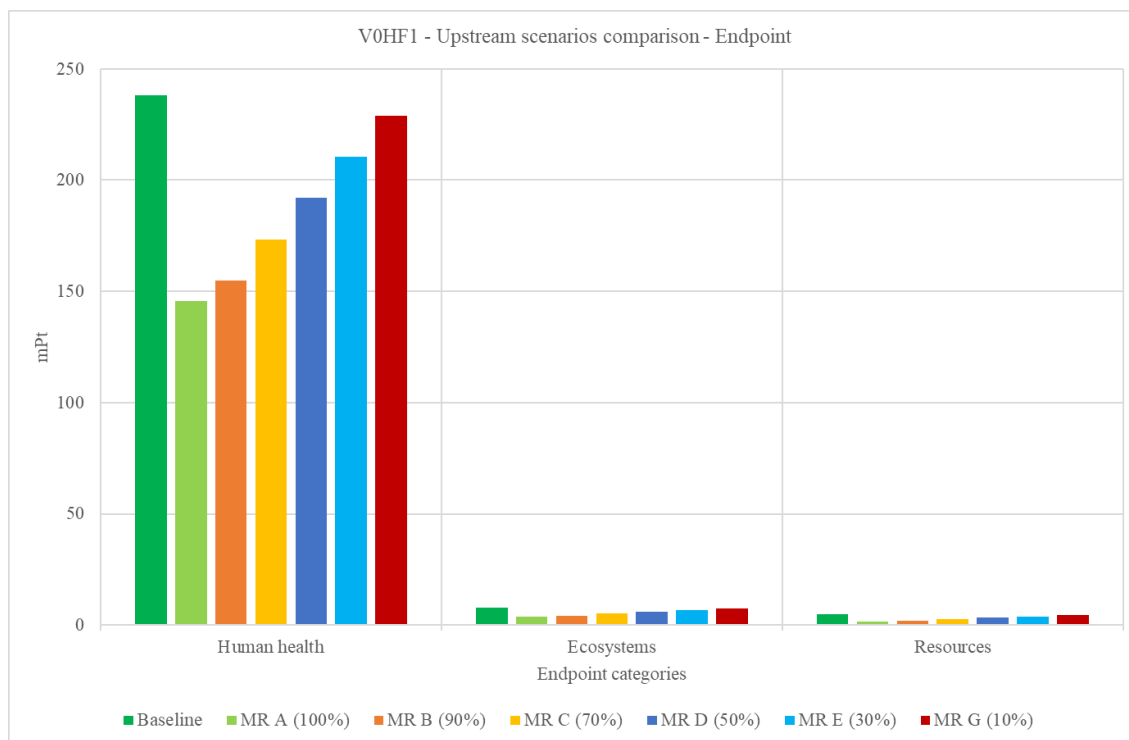


Figure 16. Results - V0HF1 - Recycling scenario - Endpoint categories.

Table 62. Results - V0HF1 - Recycling scenario - Impact categories.

Impact category	Unit	Baseline	A (100%)	B (90%)	C (70%)	D (50%)	E (30%)	G (10%)
Acidification	mol H ⁺ eq	3.2E-02	1.7E-02	1.9E-02	2.2E-02	2.5E-02	2.8E-02	3.1E-02
Climate change	kg CO ₂ eq	6.3E+00	2.9E+00	3.2E+00	3.9E+00	4.6E+00	5.3E+00	6.0E+00
Climate change - Biogenic	kg CO ₂ eq	6.0E-03	1.9E-02	1.8E-02	1.5E-02	1.3E-02	1.0E-02	7.3E-03
Climate change - Fossil	kg CO ₂ eq	6.3E+00	2.8E+00	3.2E+00	3.9E+00	4.6E+00	5.3E+00	6.0E+00
Climate change - Land use and LU change	kg CO ₂ eq	7.2E-03	7.5E-03	7.5E-03	7.4E-03	7.3E-03	7.3E-03	7.2E-03
Ecotoxicity, freshwater - part 1	CTUe	1.1E+01	9.3E+00	9.4E+00	9.8E+00	1.0E+01	1.0E+01	1.1E+01
Ecotoxicity, freshwater - part 2	CTUe	4.3E+00	3.6E+00	3.7E+00	3.8E+00	4.0E+00	4.1E+00	4.2E+00
Ecotoxicity, freshwater - inorganics	CTUe	1.1E+01	9.4E+00	9.5E+00	9.9E+00	1.0E+01	1.1E+01	1.1E+01
Ecotoxicity, freshwater - organics - p.1	CTUe	3.1E+00	3.3E+00	3.2E+00	3.2E+00	3.2E+00	3.1E+00	3.1E+00
Ecotoxicity, freshwater - organics - p.2	CTUe	1.1E+00	3.0E-01	3.8E-01	5.5E-01	7.1E-01	8.8E-01	1.0E+00
Particulate matter	disease inc.	3.1E-07	1.6E-07	1.8E-07	2.1E-07	2.4E-07	2.7E-07	3.0E-07

Eutrophication, marine	kg N eq	9.2E-03	3.3E-03	3.9E-03	5.1E-03	6.2E-03	7.4E-03	8.6E-03
Eutrophication, freshwater	kg P eq	9.9E-04	8.9E-04	9.0E-04	9.2E-04	9.4E-04	9.6E-04	9.8E-04
Eutrophication, terrestrial	mol N eq	6.3E-02	3.6E-02	3.8E-02	4.4E-02	5.0E-02	5.5E-02	6.1E-02
Human toxicity, cancer	CTUh	1.3E-08	1.4E-08	1.4E-08	1.4E-08	1.4E-08	1.3E-08	1.3E-08
Human toxicity, cancer - inorganics	CTUh	7.4E-10	6.8E-10	6.8E-10	7.0E-10	7.1E-10	7.2E-10	7.3E-10
Human toxicity, cancer - organics	CTUh	1.3E-08	1.3E-08	1.3E-08	1.3E-08	1.3E-08	1.3E-08	1.3E-08
Human toxicity, non-cancer	CTUh	5.2E-08	5.3E-08	5.3E-08	5.3E-08	5.3E-08	5.2E-08	5.2E-08
Human toxicity, non-cancer - inorganics	CTUh	4.9E-08	5.2E-08	5.2E-08	5.1E-08	5.0E-08	5.0E-08	4.9E-08
Human toxicity, non-cancer - organics	CTUh	2.8E-09	1.6E-09	1.7E-09	1.9E-09	2.2E-09	2.4E-09	2.7E-09
Ionising radiation	kBq U-235 eq	1.8E-01	2.3E-01	2.2E-01	2.1E-01	2.0E-01	1.9E-01	1.8E-01
Land use	Pt	1.3E+01	1.4E+01	1.4E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01
Ozone depletion	kg CFC11 eq	2.3E-08	2.6E-08	2.5E-08	2.5E-08	2.4E-08	2.4E-08	2.3E-08
Photochemical ozone formation	kg NMVOC eq	2.0E-02	1.1E-02	1.2E-02	1.4E-02	1.6E-02	1.7E-02	1.9E-02
Resource use, fossils	MJ	2.7E+01	1.6E+01	1.7E+01	1.9E+01	2.1E+01	2.3E+01	2.6E+01
Resource use, minerals and metals	kg Sb eq	1.1E-04	1.1E-04	1.1E-04	1.1E-04	1.1E-04	1.1E-04	1.1E-04
Water use	m ³ depriv.	5.8E+00	1.4E+00	1.9E+00	2.7E+00	3.6E+00	4.5E+00	5.3E+00

Global warming tree: the diagrams depicted in Figure 16 and Figure 17 allow to understand the contribution of processes in climate change. In particular, the emissions are mainly caused by the production of PA66 (56.1 %, 3.71 kg CO₂ eq), DEPAL (11.5 %, 0.761 kg CO₂ eq) and GF (10.4 %, 0.689 kg CO₂ eq).

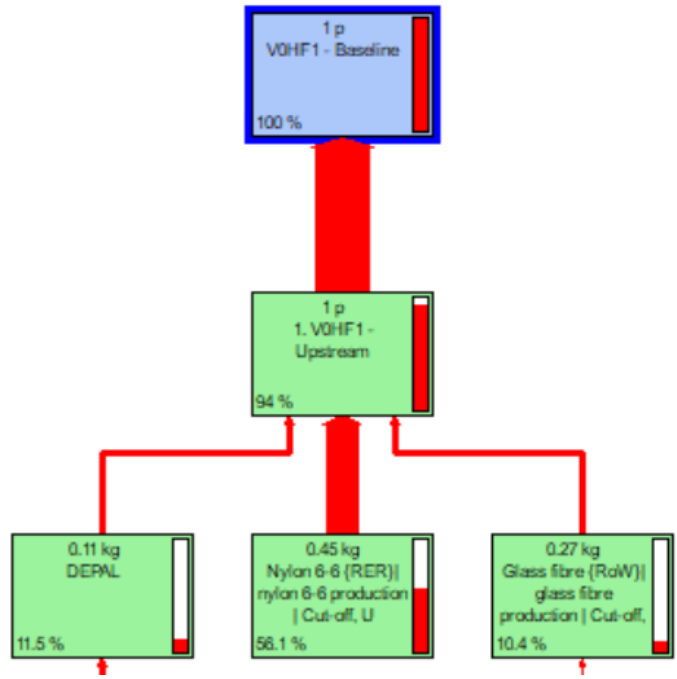


Figure 17. Results - V0HF1 - Baseline - GWP per percentage.

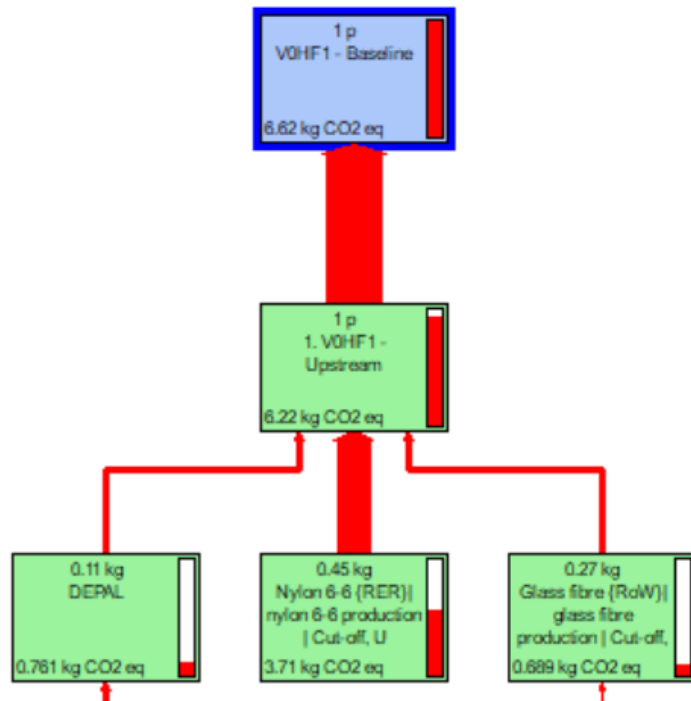


Figure 18. Results - V0HF1 - Baseline - GWP per contribution.

6.3 V0KB3

Baseline scenario: the environmental performance of the V0KB3 product baseline scenario is shown in Figure 18 and Figure 19. In total, the entire production process impacts 245.73 mPt. The most impacting process is the upstream phase (232.68 mPt; 94.72 % of the total), followed by the core phase (12.48 mPt; 5.07 %) and downstream (0.58 mPt; 0.24 %). The upstream phase mainly affects human health, with 219.33 mPt. Table 63 presents the indicator results per impact category. The product has a total impact of 6.99 kg CO₂ eq per FU. The upstream contributes 6.59 kg CO₂ eq (94.28 % of the total), followed by the core with 0.38 kg CO₂ eq (5.44 %) and downstream with 0.02 kg CO₂ eq (0.29 %).

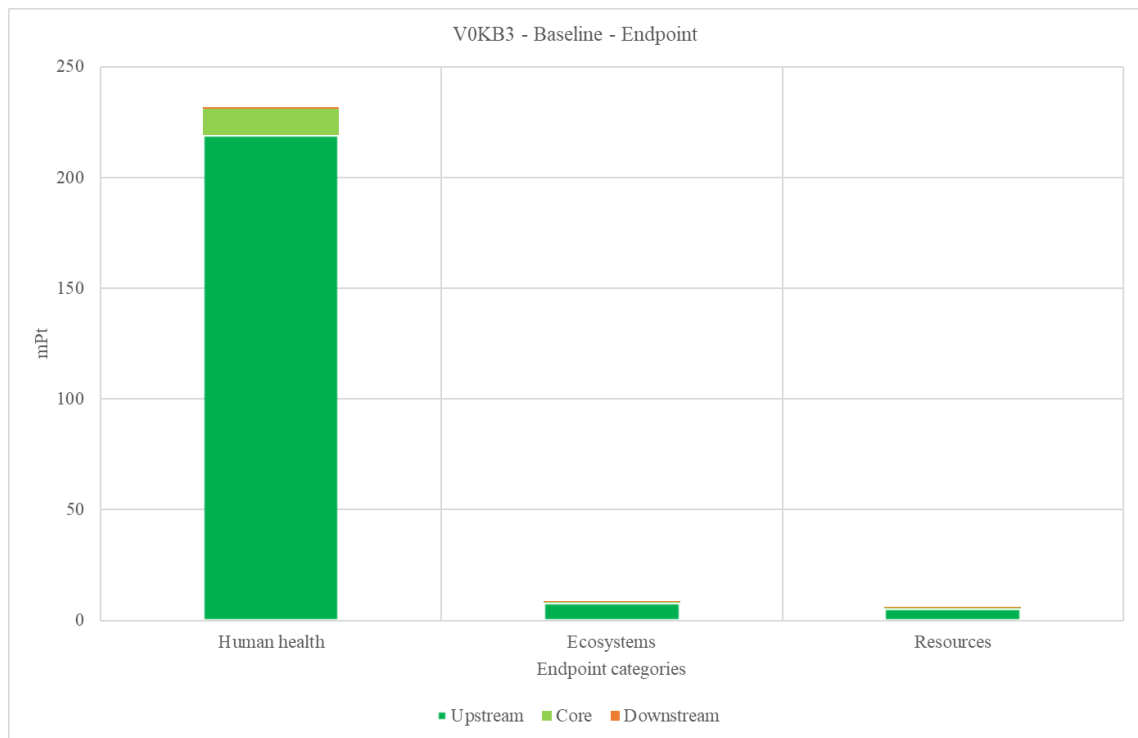


Figure 19. Results - V0KB3 - Baseline - Endpoint categories.

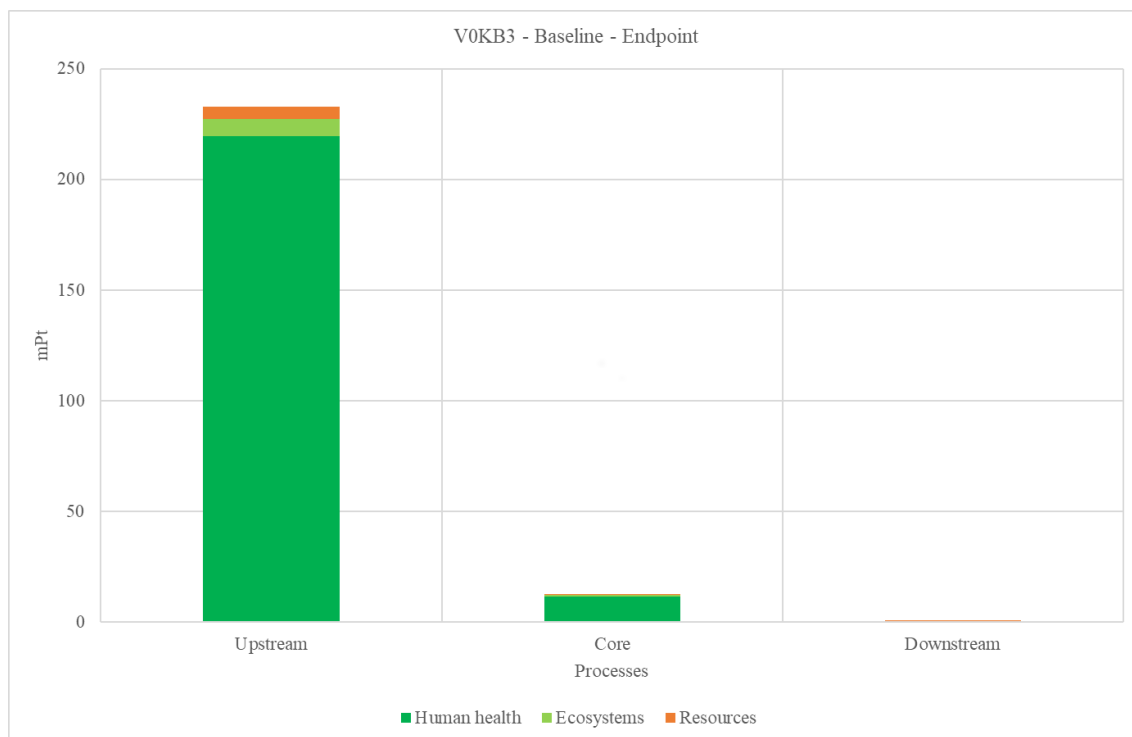


Figure 20. Results - V0KB3 - Baseline - Processes per Endpoint categories.

Table 63. Results - V0KB3 - Baseline - Impact categories.

Impact category	Unit	Total	Upstream	Core	Downstream
Acidification	mol H ⁺ eq	3.2E-02	3.1E-02	1.1E-03	3.1E-05
Climate change	kg CO ₂ eq	7.0E+00	6.6E+00	3.8E-01	1.6E-02
Climate change - Biogenic	kg CO ₂ eq	3.8E-02	1.6E-02	2.3E-02	9.2E-06
Climate change - Fossil	kg CO ₂ eq	6.9E+00	6.6E+00	3.6E-01	1.6E-02
Climate change - Land use and LU change	kg CO ₂ eq	8.5E-03	8.4E-03	6.1E-05	5.0E-06
Ecotoxicity, freshwater - part 1	CTUe	9.1E+00	8.5E+00	5.4E-01	4.6E-02
Ecotoxicity, freshwater - part 2	CTUe	5.1E+00	4.7E+00	3.1E-01	1.2E-02
Ecotoxicity, freshwater - inorganics	CTUe	1.1E+01	1.0E+01	5.3E-01	3.4E-02
Ecotoxicity, freshwater - organics - p.1	CTUe	1.9E+00	1.6E+00	2.5E-01	2.2E-02
Ecotoxicity, freshwater - organics - p.2	CTUe	1.4E+00	1.3E+00	7.9E-02	9.9E-04
Particulate matter	disease inc.	3.0E-07	2.9E-07	9.3E-09	9.8E-10

Eutrophication, marine	kg N eq	9.9E-03	9.6E-03	2.2E-04	7.3E-06
Eutrophication, freshwater	kg P eq	9.9E-04	9.5E-04	4.6E-05	1.0E-06
Eutrophication, terrestrial	mol N eq	6.2E-02	6.0E-02	2.3E-03	7.9E-05
Human toxicity, cancer	CTUh	7.5E-09	6.4E-09	1.0E-09	9.4E-11
Human toxicity, cancer - inorganics	CTUh	7.3E-10	7.1E-10	2.0E-11	1.1E-12
Human toxicity, cancer - organics	CTUh	6.8E-09	5.7E-09	1.0E-09	9.3E-11
Human toxicity, non-cancer	CTUh	5.1E-08	4.9E-08	1.8E-09	1.3E-10
Human toxicity, non-cancer - inorganics	CTUh	4.8E-08	4.6E-08	1.6E-09	1.2E-10
Human toxicity, non-cancer - organics	CTUh	2.9E-09	2.8E-09	1.2E-10	8.4E-12
Ionising radiation	kBq U-235 eq	3.1E-01	2.8E-01	3.1E-02	3.4E-04
Land use	Pt	1.5E+01	1.3E+01	1.3E+00	1.1E-01
Ozone depletion	kg CFC11 eq	3.6E-08	2.8E-08	7.7E-09	3.1E-10
Photochemical ozone formation	kg NMVOC eq	2.1E-02	2.0E-02	1.1E-03	5.2E-05
Resource use, fossils	MJ	2.8E+01	2.7E+01	1.1E+00	1.8E-02
Resource use, minerals and metals	kg Sb eq	9.6E-05	9.6E-05	7.2E-07	5.0E-08
Water use	m ³ depriv.	6.0E+00	5.8E+00	1.8E-01	8.3E-04

Core green scenarios: as regarding the core scenarios comparison analysis, the percentage reduction compared to the core phase of baseline scenario (12.48 mPt) is -56 % for MIX1 (6.98 mPt), -54 % for MIX2 (5.71 mPt), -8 % for 25 % FV (11.47 mPt), -16 % for 50 % FV (10.47 mPt), -34 % for 75 % FV (9.47 mPt) and -32 % for 100 % FV (8.47 mPt). In detail, Figure 20 shows that human health is the endpoint category that benefits most from using renewable energy. Table 64 reports the quantitative values. Regarding climate change, the estimated kg of CO₂ eq emissions are 0.21 kg CO₂ eq, 0.12 kg CO₂ eq, 0.33 kg CO₂ eq, 0.27 kg CO₂ eq, 0.21 kg CO₂ eq and 0.16 kg CO₂ eq for MIX1, MIX2, 25 % FV, 50 % FV, 75 % FV and 100 % FV, respectively.

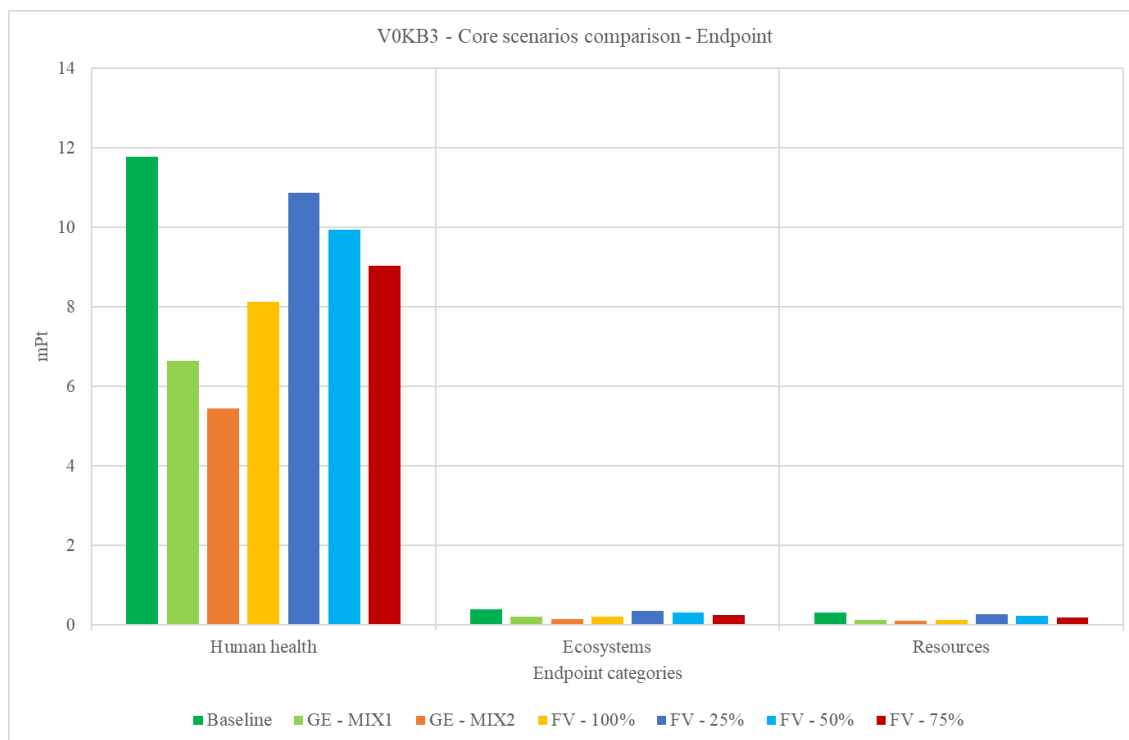


Figure 21. Results - V0KB3 - Green scenarios - Endpoint categories.

Table 64. Results - V0KB3 - Green scenarios - Impact categories.

Impact category	Unit	Baseline	GE - MIX1	GE - MIX2	FV - 100%	FV - 25%	FV - 50%	FV - 75%
Acidification	mol H ⁺ eq	1.1E-03	5.2E-04	3.2E-04	6.5E-04	1.0E-03	8.9E-04	7.7E-04
Climate change	kg CO ₂ eq	3.8E-01	2.1E-01	1.2E-01	1.6E-01	3.3E-01	2.7E-01	2.2E-01
Climate change - Biogenic	kg CO ₂ eq	2.3E-02	6.2E-02	6.0E-04	3.1E-04	1.7E-02	1.1E-02	5.9E-03
Climate change - Fossil	kg CO ₂ eq	3.6E-01	1.4E-01	1.2E-01	1.6E-01	3.1E-01	2.6E-01	2.1E-01
Climate change - Land use and LU change	kg CO ₂ eq	6.1E-05	5.8E-05	3.5E-05	9.9E-05	7.1E-05	8.0E-05	9.0E-05
Ecotoxicity, freshwater - part 1	CTUe	5.4E-01	4.4E-01	3.3E-01	6.0E-01	5.6E-01	5.7E-01	5.9E-01
Ecotoxicity, freshwater - part 2	CTUe	3.1E-01	2.4E-01	2.0E-01	3.6E-01	3.2E-01	3.4E-01	3.5E-01
Ecotoxicity, freshwater - inorganics	CTUe	5.3E-01	4.0E-01	2.9E-01	7.3E-01	5.8E-01	6.3E-01	6.8E-01
Ecotoxicity, freshwater - organics - p.1	CTUe	2.5E-01	2.2E-01	1.6E-01	2.1E-01	2.4E-01	2.3E-01	2.2E-01
Ecotoxicity, freshwater - organics - p.2	CTUe	7.9E-02	7.1E-02	6.8E-02	1.7E-02	6.4E-02	4.8E-02	3.2E-02
Particulate matter	disease inc.	9.3E-09	7.6E-09	5.6E-09	8.5E-09	9.1E-09	8.9E-09	8.7E-09

Eutrophication, marine	kg N eq	2.2E-04	1.2E-04	8.5E-05	1.3E-04	2.0E-04	1.8E-04	1.6E-04
Eutrophication, freshwater	kg P eq	4.6E-05	1.7E-05	9.9E-06	3.7E-05	4.4E-05	4.2E-05	3.9E-05
Eutrophication, terrestrial	mol N eq	2.3E-03	1.4E-03	8.4E-04	1.4E-03	2.1E-03	1.8E-03	1.6E-03
Human toxicity, cancer	CTUh	1.0E-09	8.7E-10	6.3E-10	9.3E-10	1.0E-09	9.8E-10	9.6E-10
Human toxicity, cancer - inorganics	CTUh	2.0E-11	1.4E-11	1.1E-11	2.7E-11	2.2E-11	2.3E-11	2.5E-11
Human toxicity, cancer - organics	CTUh	1.0E-09	8.6E-10	6.2E-10	9.1E-10	9.8E-10	9.6E-10	9.3E-10
Human toxicity, non-cancer	CTUh	1.8E-09	1.4E-09	1.0E-09	3.1E-09	2.1E-09	2.4E-09	2.8E-09
Human toxicity, non-cancer - inorganics	CTUh	1.6E-09	1.3E-09	9.4E-10	2.9E-09	2.0E-09	2.3E-09	2.6E-09
Human toxicity, non-cancer - organics	CTUh	1.2E-10	8.4E-11	6.7E-11	1.6E-10	1.3E-10	1.4E-10	1.5E-10
Ionising radiation	kBq U-235 eq	3.1E-02	3.6E-03	2.0E-03	5.7E-03	2.5E-02	1.9E-02	1.2E-02
Land use	Pt	1.3E+00	2.0E+00	5.5E-01	7.8E-01	1.1E+00	1.0E+00	9.0E-01
Ozone depletion	kg CFC11 eq	7.7E-09	3.1E-09	2.7E-09	5.7E-09	7.2E-09	6.7E-09	6.2E-09
Photochemical ozone formation	kg NMVOC eq	1.1E-03	5.6E-04	4.2E-04	6.1E-04	9.6E-04	8.4E-04	7.3E-04
Resource use, fossils	MJ	1.1E+00	2.6E-01	1.3E-01	4.3E-01	9.6E-01	7.8E-01	6.1E-01
Resource use, minerals and metals	kg Sb eq	7.2E-07	7.3E-07	5.9E-07	3.7E-06	1.5E-06	2.2E-06	2.9E-06
Water use	m ³ depriv.	1.8E-01	3.2E-01	8.8E-01	5.4E-02	1.5E-01	1.2E-01	8.7E-02

Upstream recycling scenarios: introducing recycled PA in the upstream phases decreases impacts in all categories. On the total environmental profile, the reduction impacts versus the baseline scenario (232.68 mPt) is -49 % for Grade A (118.54 mPt), -44 % for Grade B (129.96 mPt), -34 % for Grade C (152.78 mPt), -25 % for Grade D (175.61 mPt), -15 % for Grade E (198.44 mPt) and -5 % for Grade G (221.26 mPt) (Figure 21). As far as CO₂ eq emissions are concerned (Table 65), the V0KB3 with recycled polymer as a value of 2.60 kg CO₂ eq for Grade A, 3.00 kg CO₂ eq for Grade B, 3.80 kg CO₂ eq for Grade C, 4.60 kg CO₂ eq for Grade D, 5.40 kg CO₂ eq for Grade E and 6.20 kg CO₂ eq for Grade G.

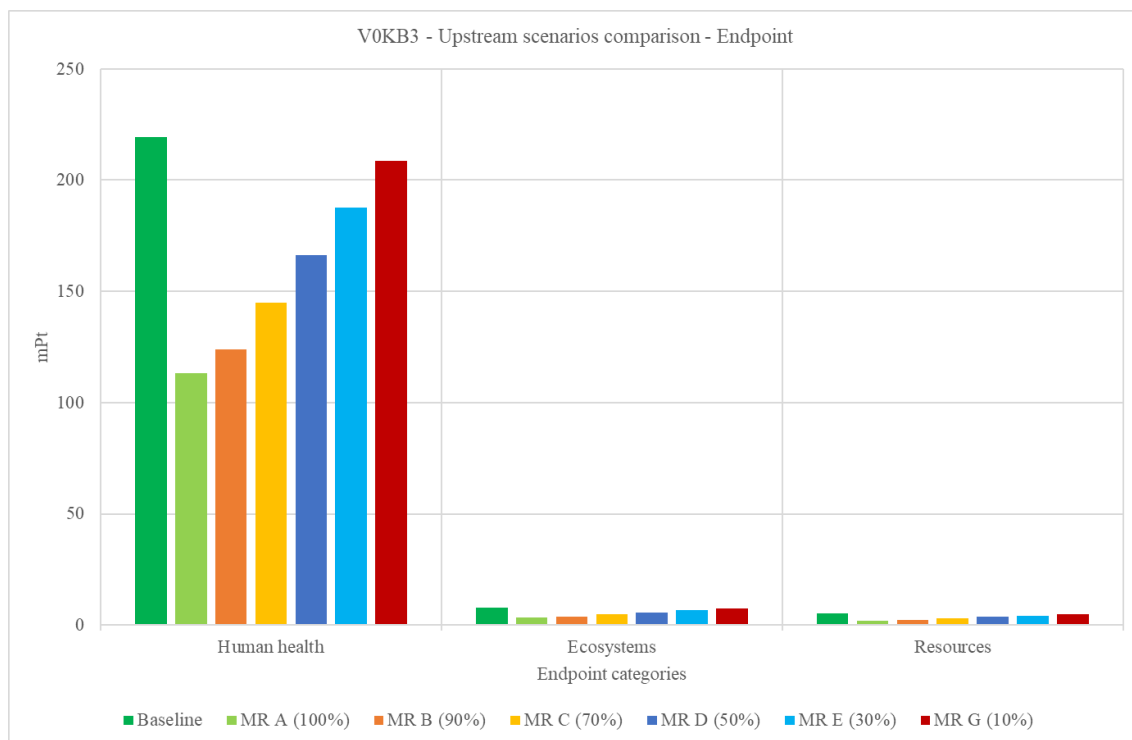


Figure 22. Results - V0KB3 - Recycling scenario - Endpoint categories.

Table 65. Results - V0KB3 - Recycling scenario - Impact categories.

Impact category	Unit	Baseline	A (100%)	B (90%)	C (70%)	D (50%)	E (30%)	G (10%)
Acidification	mol H ⁺ eq	3.1E-02	1.4E-02	1.6E-02	1.9E-02	2.2E-02	2.6E-02	2.9E-02
Climate change	kg CO ₂ eq	6.6E+00	2.6E+00	3.0E+00	3.8E+00	4.6E+00	5.4E+00	6.2E+00
Climate change - Biogenic	kg CO ₂ eq	1.6E-02	3.1E-02	2.9E-02	2.6E-02	2.3E-02	2.0E-02	1.7E-02
Climate change - Fossil	kg CO ₂ eq	6.6E+00	2.6E+00	3.0E+00	3.8E+00	4.6E+00	5.4E+00	6.2E+00
Climate change - Land use and LU change	kg CO ₂ eq	8.4E-03	8.8E-03	8.8E-03	8.7E-03	8.6E-03	8.5E-03	8.5E-03
Ecotoxicity, freshwater - part 1	CTUe	8.5E+00	6.6E+00	6.8E+00	7.1E+00	7.5E+00	7.9E+00	8.3E+00
Ecotoxicity, freshwater - part 2	CTUe	4.7E+00	4.0E+00	4.1E+00	4.2E+00	4.4E+00	4.5E+00	4.7E+00
Ecotoxicity, freshwater - inorganics	CTUe	1.0E+01	8.4E+00	8.6E+00	9.0E+00	9.3E+00	9.7E+00	1.0E+01
Ecotoxicity, freshwater - organics - p.1	CTUe	1.6E+00	1.8E+00	1.8E+00	1.7E+00	1.7E+00	1.6E+00	1.6E+00
Ecotoxicity, freshwater - organics - p.2	CTUe	1.3E+00	3.8E-01	4.8E-01	6.7E-01	8.6E-01	1.0E+00	1.2E+00
Particulate matter	disease inc.	2.9E-07	1.2E-07	1.4E-07	1.7E-07	2.0E-07	2.4E-07	2.7E-07

Eutrophication, marine	kg N eq	9.6E-03	2.9E-03	3.6E-03	4.9E-03	6.3E-03	7.6E-03	9.0E-03
Eutrophication, freshwater	kg P eq	9.5E-04	8.4E-04	8.5E-04	8.7E-04	8.9E-04	9.1E-04	9.4E-04
Eutrophication, terrestrial	mol N eq	6.0E-02	2.8E-02	3.1E-02	3.8E-02	4.4E-02	5.0E-02	5.7E-02
Human toxicity, cancer	CTUh	6.4E-09	7.0E-09	6.9E-09	6.8E-09	6.7E-09	6.6E-09	6.5E-09
Human toxicity, cancer - inorganics	CTUh	7.1E-10	6.4E-10	6.4E-10	6.6E-10	6.7E-10	6.9E-10	7.0E-10
Human toxicity, cancer - organics	CTUh	5.7E-09	6.3E-09	6.3E-09	6.1E-09	6.0E-09	5.9E-09	5.8E-09
Human toxicity, non-cancer	CTUh	4.9E-08	5.0E-08	5.0E-08	5.0E-08	5.0E-08	4.9E-08	4.9E-08
Human toxicity, non-cancer - inorganics	CTUh	4.6E-08	4.9E-08	4.9E-08	4.8E-08	4.8E-08	4.7E-08	4.6E-08
Human toxicity, non-cancer - organics	CTUh	2.8E-09	1.4E-09	1.5E-09	1.8E-09	2.1E-09	2.4E-09	2.6E-09
Ionising radiation	kBq U-235 eq	2.8E-01	3.4E-01	3.3E-01	3.2E-01	3.1E-01	3.0E-01	2.9E-01
Land use	Pt	1.3E+01	1.5E+01	1.5E+01	1.4E+01	1.4E+01	1.4E+01	1.4E+01
Ozone depletion	kg CFC11 eq	2.8E-08	3.1E-08	3.0E-08	3.0E-08	2.9E-08	2.9E-08	2.8E-08
Photochemical ozone formation	kg NMVOC eq	2.0E-02	1.0E-02	1.1E-02	1.3E-02	1.5E-02	1.7E-02	1.9E-02
Resource use, fossils	MJ	2.7E+01	1.5E+01	1.6E+01	1.9E+01	2.1E+01	2.3E+01	2.6E+01
Resource use, minerals and metals	kg Sb eq	9.6E-05	9.6E-05	9.6E-05	9.6E-05	9.6E-05	9.6E-05	9.6E-05
Water use	m ³ depriv.	5.8E+00	8.0E-01	1.3E+00	2.3E+00	3.3E+00	4.3E+00	5.3E+00

Global warming tree: the diagrams depicted in Figure 22 and Figure 23 allow to understand the contribution of processes in climate change. In particular, the emissions are mainly caused by the production of PA66 (62.2 %, 4.26 kg CO₂ eq), red phosphorus masterbatches (15.0 %, 1.03 kg CO₂ eq) and GF (10.6 %, 0.725 kg CO₂ eq).

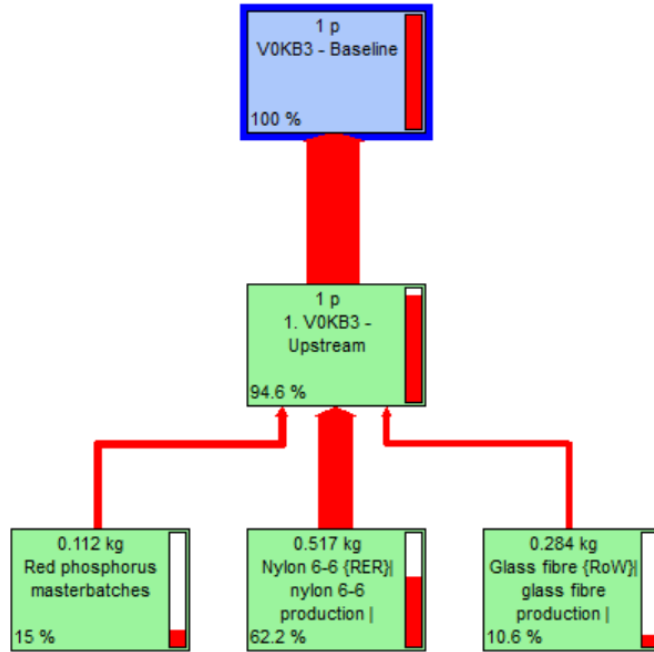


Figure 23. Results - V0KB3 - Baseline - GWP per percentage.

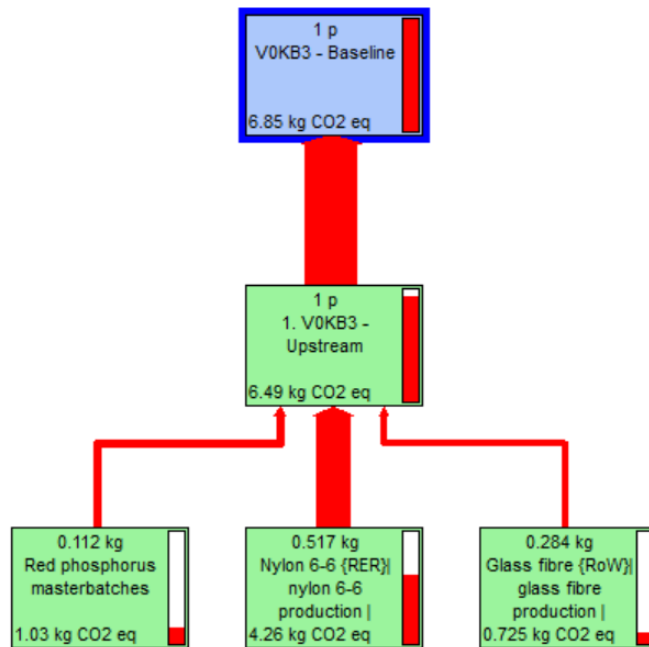


Figure 24. Results - V0KB3 - Baseline - GWP per contribution.

6.4 V2HF

Baseline scenario: the environmental performance of the V2HF product baseline scenario is shown in Figure 24 and Figure 25. In total, the entire production process impacts 268.32 mPt. The most impacting process is the upstream phase (244.13 mPt; 90.98 % of the total), followed by the core phase (23.62 mPt; 8.80 %) and downstream (0.58 mPt; 0.20 %). The upstream phase mainly affects human health, with 229.65 mPt. Table 66 presents the indicator results per impact category. The product has a total impact of 8.48 kg CO₂ eq per FU. The upstream contributes 7.95 kg CO₂ eq (93.75 % of the total), followed by the core with 0.51 kg CO₂ eq (6.01 %) and downstream with 0.02 kg CO₂ eq (0.24 %).

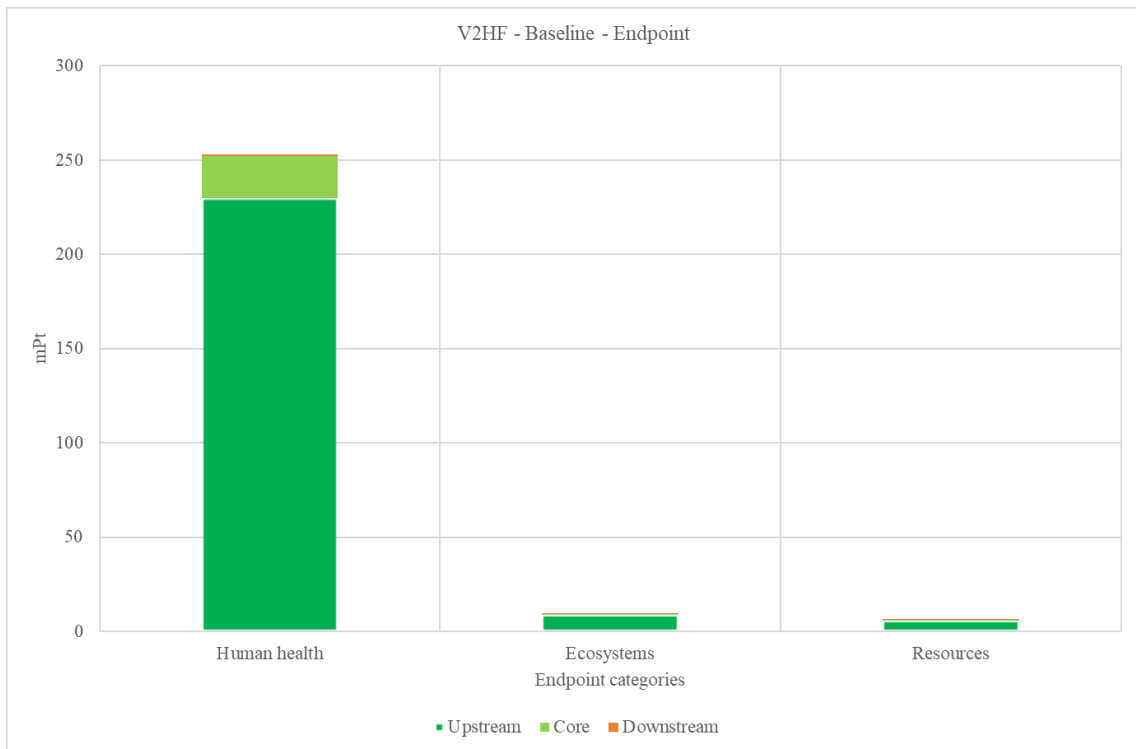


Figure 25. Results - V2HF - Baseline - Endpoint categories.

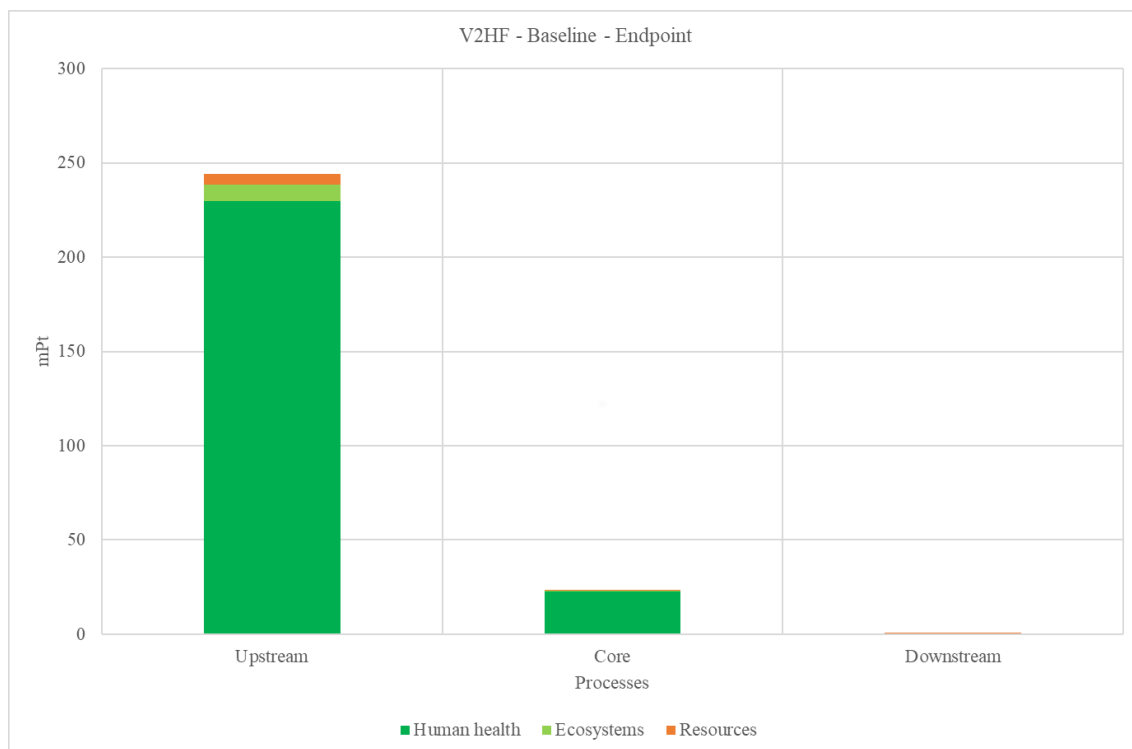


Figure 26. Results - V2HF - Baseline - Processes per Endpoint categories.

Table 66. Results - V2HF - Baseline - Impact categories.

Impact category	Unit	Total	Upstream	Core	Downstream
Acidification	mol H ⁺ eq	3.4E-02	3.3E-02	1.6E-03	3.1E-05
Climate change	kg CO ₂ eq	8.5E+00	8.0E+00	5.1E-01	1.6E-02
Climate change - Biogenic	kg CO ₂ eq	4.6E-02	7.8E-03	3.8E-02	9.2E-06
Climate change - Fossil	kg CO ₂ eq	8.4E+00	7.9E+00	4.7E-01	1.6E-02
Climate change - Land use and LU change	kg CO ₂ eq	8.9E-04	7.8E-04	1.0E-04	5.0E-06
Ecotoxicity, freshwater - part 1	CTUe	8.8E+00	7.0E+00	1.8E+00	4.6E-02
Ecotoxicity, freshwater - part 2	CTUe	2.0E+00	1.6E+00	3.9E-01	1.2E-02
Ecotoxicity, freshwater - inorganics	CTUe	7.3E+00	6.1E+00	1.2E+00	3.4E-02
Ecotoxicity, freshwater - organics - p.1	CTUe	3.1E+00	2.1E+00	9.1E-01	2.2E-02
Ecotoxicity, freshwater - organics - p.2	CTUe	4.3E-01	3.4E-01	8.9E-02	9.9E-04
Particulate matter	disease inc.	3.8E-07	3.6E-07	1.6E-08	9.8E-10

Eutrophication, marine	kg N eq	7.6E-03	7.2E-03	3.5E-04	7.3E-06
Eutrophication, freshwater	kg P eq	4.7E-04	4.0E-04	6.1E-05	1.0E-06
Eutrophication, terrestrial	mol N eq	7.7E-02	7.4E-02	3.6E-03	7.9E-05
Human toxicity, cancer	CTUh	1.4E-08	9.8E-09	3.9E-09	9.4E-11
Human toxicity, cancer - inorganics	CTUh	5.5E-10	5.1E-10	4.1E-11	1.1E-12
Human toxicity, cancer - organics	CTUh	1.3E-08	9.3E-09	3.9E-09	9.3E-11
Human toxicity, non-cancer	CTUh	3.7E-08	3.4E-08	3.1E-09	1.3E-10
Human toxicity, non-cancer - inorganics	CTUh	3.4E-08	3.1E-08	2.9E-09	1.2E-10
Human toxicity, non-cancer - organics	CTUh	3.4E-09	3.2E-09	1.9E-10	8.4E-12
Ionising radiation	kBq U-235 eq	1.2E-01	8.9E-02	3.4E-02	3.4E-04
Land use	Pt	5.3E+00	3.2E+00	1.9E+00	1.1E-01
Ozone depletion	kg CFC11 eq	2.7E-08	1.7E-08	9.6E-09	3.1E-10
Photochemical ozone formation	kg NMVOC eq	2.6E-02	2.5E-02	1.6E-03	5.2E-05
Resource use, fossils	MJ	1.9E+01	1.7E+01	1.4E+00	1.8E-02
Resource use, minerals and metals	kg Sb eq	1.1E-04	1.1E-04	1.1E-06	5.0E-08
Water use	m ³ depriv.	3.1E+00	2.9E+00	1.9E-01	8.3E-04

Core green scenarios: as regarding the core scenarios comparison analysis (Figure 26), the percentage reduction compared to the core phase of baseline scenario (23.62 mPt) is -23 % for MIX1 (18.12 mPt), -39 % for MIX2 (16.85 mPt), -4 % for 25 % FV (22.61 mPt), -9 % for 50 % FV (21.61 mPt), -13 % for 75 % FV (20.61 mPt) and -17 % for 100 % FV (19,61 mPt). In detail, Figure 26 shows that human health is the endpoint category that benefits most from using renewable energy. Table 67 reports the quantitative values. Regarding climate change, the estimated kg of CO₂ eq emissions are 0.33 kg CO₂ eq, 0.25 kg CO₂ eq, 0.45 kg CO₂ eq, 0.40 kg CO₂ eq, 0.34 kg CO₂ eq and 0.29 kg CO₂ eq for MIX1, MIX2, 25 % FV, 50 % FV, 75 % FV and 100 % FV, respectively.

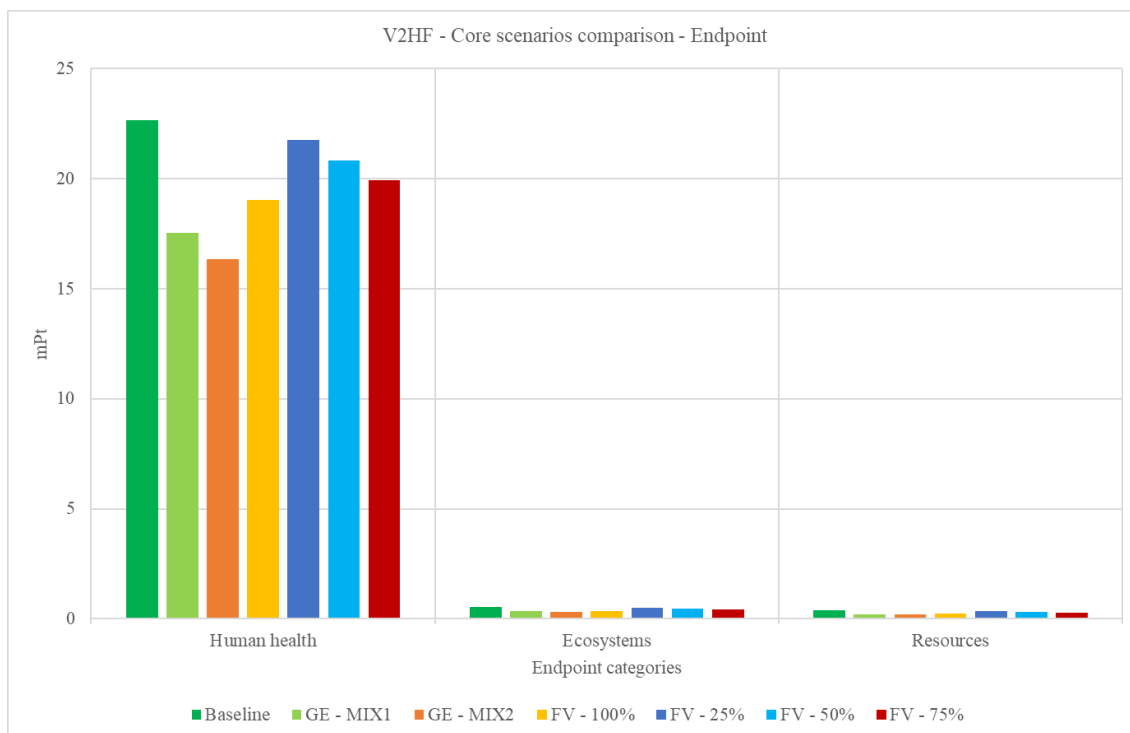


Figure 27. Results - V2HF - Green scenarios - Endpoint categories.

Table 67. Results - V2HF - Green scenarios - Impact categories.

Impact category	Unit	Baseline	GE - MIX1	GE - MIX2	FV - 100%	FV - 25%	FV - 50%	FV - 75%
Acidification	mol H ⁺ eq	1.6E-03	1.0E-03	8.3E-04	1.2E-03	1.5E-03	1.4E-03	1.3E-03
Climate change	kg CO ₂ eq	5.1E-01	3.3E-01	2.5E-01	2.9E-01	4.5E-01	4.0E-01	3.4E-01
Climate change - Biogenic	kg CO ₂ eq	3.8E-02	7.7E-02	1.6E-02	1.6E-02	3.3E-02	2.7E-02	2.2E-02
Climate change - Fossil	kg CO ₂ eq	4.7E-01	2.6E-01	2.3E-01	2.7E-01	4.2E-01	3.7E-01	3.2E-01
Climate change - Land use and LU change	kg CO ₂ eq	1.0E-04	9.8E-05	7.5E-05	1.4E-04	1.1E-04	1.2E-04	1.3E-04
Ecotoxicity, freshwater - part 1	CTUe	1.8E+00	1.7E+00	1.6E+00	1.8E+00	1.8E+00	1.8E+00	1.8E+00
Ecotoxicity, freshwater - part 2	CTUe	3.9E-01	3.2E-01	2.8E-01	4.5E-01	4.1E-01	4.2E-01	4.4E-01
Ecotoxicity, freshwater - inorganics	CTUe	1.2E+00	1.0E+00	9.3E-01	1.4E+00	1.2E+00	1.3E+00	1.3E+00
Ecotoxicity, freshwater - organics - p.1	CTUe	9.1E-01	8.8E-01	8.2E-01	8.8E-01	9.0E-01	8.9E-01	8.9E-01
Ecotoxicity, freshwater - organics - p.2	CTUe	8.9E-02	8.0E-02	7.7E-02	2.6E-02	7.3E-02	5.7E-02	4.2E-02
Particulate matter	disease inc.	1.6E-08	1.5E-08	1.3E-08	1.6E-08	1.6E-08	1.6E-08	1.6E-08

Eutrophication, marine	kg N eq	3.5E-04	2.5E-04	2.2E-04	2.6E-04	3.3E-04	3.1E-04	2.9E-04
Eutrophication, freshwater	kg P eq	6.1E-05	3.2E-05	2.5E-05	5.2E-05	5.9E-05	5.7E-05	5.4E-05
Eutrophication, terrestrial	mol N eq	3.6E-03	2.7E-03	2.2E-03	2.7E-03	3.4E-03	3.2E-03	2.9E-03
Human toxicity, cancer	CTUh	3.9E-09	3.8E-09	3.6E-09	3.9E-09	3.9E-09	3.9E-09	3.9E-09
Human toxicity, cancer - inorganics	CTUh	4.1E-11	3.6E-11	3.2E-11	4.8E-11	4.3E-11	4.5E-11	4.7E-11
Human toxicity, cancer - organics	CTUh	3.9E-09	3.8E-09	3.5E-09	3.8E-09	3.9E-09	3.9E-09	3.8E-09
Human toxicity, non-cancer	CTUh	3.1E-09	2.7E-09	2.3E-09	4.4E-09	3.4E-09	3.8E-09	4.1E-09
Human toxicity, non-cancer - inorganics	CTUh	2.9E-09	2.6E-09	2.2E-09	4.2E-09	3.2E-09	3.6E-09	3.9E-09
Human toxicity, non-cancer - organics	CTUh	1.9E-10	1.5E-10	1.4E-10	2.3E-10	2.0E-10	2.1E-10	2.2E-10
Ionising radiation	kBq U-235 eq	3.4E-02	6.1E-03	4.5E-03	8.2E-03	2.8E-02	2.1E-02	1.5E-02
Land use	Pt	1.9E+00	2.6E+00	1.2E+00	1.4E+00	1.8E+00	1.7E+00	1.6E+00
Ozone depletion	kg CFC11 eq	9.6E-09	5.0E-09	4.5E-09	7.6E-09	9.1E-09	8.6E-09	8.1E-09
Photochemical ozone formation	kg NMVOC eq	1.6E-03	1.1E-03	9.6E-04	1.2E-03	1.5E-03	1.4E-03	1.3E-03
Resource use, fossils	MJ	1.4E+00	5.2E-01	3.9E-01	6.9E-01	1.2E+00	1.0E+00	8.6E-01
Resource use, minerals and metals	kg Sb eq	1.1E-06	1.1E-06	1.0E-06	4.1E-06	1.9E-06	2.6E-06	3.4E-06
Water use	m ³ depriv.	1.9E-01	3.2E-01	8.8E-01	6.3E-02	1.6E-01	1.3E-01	9.5E-02

Upstream recycling scenarios: introducing recycled PA and GR recycled in the upstream phases decreases impacts in all categories. On the total environmental profile, the impacts are 72.72 mPt for Grade A, 89.86 mPt for Grade B, 124.14 mPt for Grade C, 158.42 mPt for Grade D, 192.70 mPt for Grade E, 226.99 mPt for Grade G and 221.22 mPt GF recycled (Figure 27). As far as CO₂ eq emissions are concerned (Table 68), the V2HF with recycled polymer and GR recycled as a value of 1.65 kg CO₂ eq for Grade A, 2.28 kg CO₂ eq for Grade B, 3.54 kg CO₂ eq for Grade C, 4.80 kg CO₂ eq for Grade D, 6.06 kg CO₂ eq for Grade E, 7.32 kg CO₂ eq for Grade G and 7.54 kg CO₂ eq for GF recycled.

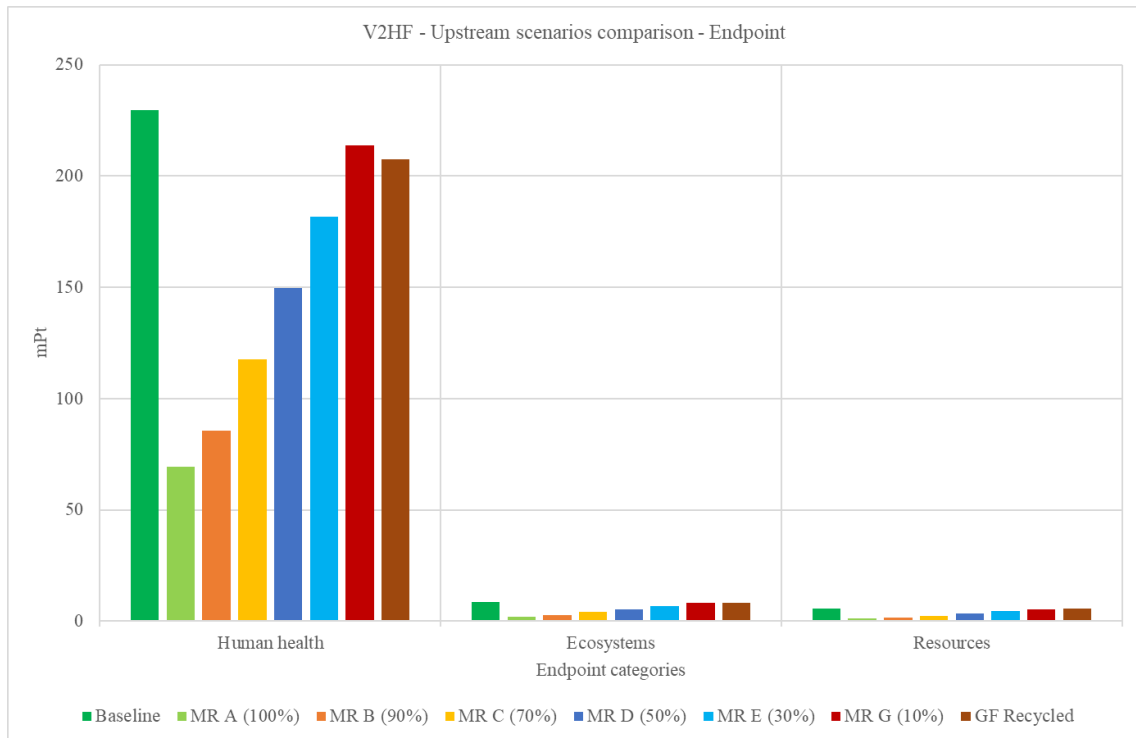


Figure 28. Results - V2HF - Recycling scenario - Endpoint categories.

Table 68. Results - V2HF - Recycling scenario - Impact categories.

Impact category	Unit	Baseline	A (100%)	B (90%)	C (70%)	D (50%)	E (30%)	G (10%)	GF Recycled
Acidification	mol H ⁺ eq	3.3E-02	8.2E-03	1.1E-02	1.6E-02	2.0E-02	2.5E-02	3.0E-02	2.9E-02
Climate change	kg CO ₂ eq	8.0E+00	1.6E+00	2.3E+00	3.5E+00	4.8E+00	6.1E+00	7.3E+00	7.5E+00
Climate change - Biogenic	kg CO ₂ eq	7.8E-03	4.1E-02	3.8E-02	3.1E-02	2.4E-02	1.8E-02	1.1E-02	7.3E-03
Climate change - Fossil	kg CO ₂ eq	7.9E+00	1.6E+00	2.2E+00	3.5E+00	4.8E+00	6.0E+00	7.3E+00	7.5E+00
Climate change - Land use and LU change	kg CO ₂ eq	7.8E-04	1.3E-03	1.2E-03	1.1E-03	1.0E-03	9.4E-04	8.3E-04	3.6E-04
Ecotoxicity, freshwater - part 1	CTUe	7.0E+00	6.4E+00	6.5E+00	6.6E+00	6.7E+00	6.8E+00	6.9E+00	6.2E+00
Ecotoxicity, freshwater - part 2	CTUe	1.6E+00	1.8E+00	1.8E+00	1.7E+00	1.7E+00	1.6E+00	1.6E+00	9.5E-01
Ecotoxicity, freshwater - inorganics	CTUe	6.1E+00	5.6E+00	5.7E+00	5.8E+00	5.9E+00	6.0E+00	6.0E+00	4.9E+00
Ecotoxicity, freshwater - organics - p.1	CTUe	2.1E+00	2.4E+00	2.4E+00	2.3E+00	2.3E+00	2.2E+00	2.2E+00	1.9E+00
Ecotoxicity, freshwater - organics - p.2	CTUe	3.4E-01	1.5E-01	1.7E-01	2.1E-01	2.5E-01	2.8E-01	3.2E-01	2.9E-01
Particulate matter	disease inc.	3.6E-07	8.1E-08	1.1E-07	1.6E-07	2.2E-07	2.8E-07	3.3E-07	3.4E-07

Eutrophication, marine	kg N eq	7.2E-03	1.7E-03	2.2E-03	3.3E-03	4.4E-03	5.6E-03	6.7E-03	6.6E-03
Eutrophication, freshwater	kg P eq	4.0E-04	4.2E-04	4.2E-04	4.2E-04	4.1E-04	4.1E-04	4.1E-04	2.7E-04
Eutrophication, terrestrial	mol N eq	7.4E-02	1.8E-02	2.4E-02	3.5E-02	4.6E-02	5.7E-02	6.8E-02	6.7E-02
Human toxicity, cancer	CTUh	9.8E-09	1.1E-08	1.0E-08	1.0E-08	1.0E-08	1.0E-08	9.9E-09	8.6E-09
Human toxicity, cancer - inorganics	CTUh	5.1E-10	4.4E-10	4.4E-10	4.6E-10	4.7E-10	4.8E-10	5.0E-10	1.7E-10
Human toxicity, cancer - organics	CTUh	9.3E-09	1.0E-08	1.0E-08	9.9E-09	9.7E-09	9.5E-09	9.4E-09	8.4E-09
Human toxicity, non-cancer	CTUh	3.4E-08	3.6E-08	3.5E-08	3.5E-08	3.5E-08	3.4E-08	3.4E-08	7.7E-09
Human toxicity, non-cancer - inorganics	CTUh	3.1E-08	3.5E-08	3.4E-08	3.3E-08	3.3E-08	3.2E-08	3.1E-08	4.7E-09
Human toxicity, non-cancer - organics	CTUh	3.2E-09	1.0E-09	1.2E-09	1.7E-09	2.1E-09	2.5E-09	3.0E-09	2.9E-09
Ionising radiation	kBq U-235 eq	8.9E-02	1.7E-01	1.6E-01	1.4E-01	1.3E-01	1.1E-01	9.7E-02	1.6E-02
Land use	Pt	3.2E+00	5.0E+00	4.8E+00	4.5E+00	4.1E+00	3.8E+00	3.4E+00	2.1E+00
Ozone depletion	kg CFC11 eq	1.7E-08	2.1E-08	2.1E-08	2.0E-08	1.9E-08	1.8E-08	1.7E-08	7.1E-09
Photochemical ozone formation	kg NMVOC eq	2.5E-02	5.5E-03	7.4E-03	1.1E-02	1.5E-02	1.9E-02	2.3E-02	2.3E-02
Resource use, fossils	MJ	1.7E+01	7.5E+00	8.5E+00	1.0E+01	1.2E+01	1.4E+01	1.6E+01	1.5E+01
Resource use, minerals and metals	kg Sb eq	1.1E-04	6.6E-05	7.1E-05	8.0E-05	8.8E-05	9.7E-05	1.1E-04	5.0E-05
Water use	m ³ depriv.	2.9E+00	8.2E-01	1.0E+00	1.4E+00	1.9E+00	2.3E+00	2.7E+00	2.8E+00

MR vs CR scenario: comparing MR PA and CR PA in the upstream phases decreases impacts in terms of kg CO₂ eq (Figure 28). V2HF with recycled PA has a value of 7.78 kg CO₂ eq for CR G, 7.74 kg CO₂ eq for MR G, 6.58 kg CO₂ eq for CR E, 6.48 kg CO₂ eq for MR E, 5.37 kg CO₂ eq for CR D, 5.21 kg CO₂ eq for MR D, 4.17 kg CO₂ eq for CR C, 3.94 kg CO₂ eq for MR C, 2.97 kg CO₂ eq for CR B, 2.67 kg CO₂ eq for MR B, 2.67 kg CO₂ eq for CR A and 2.04 kg CO₂ eq for MR A.

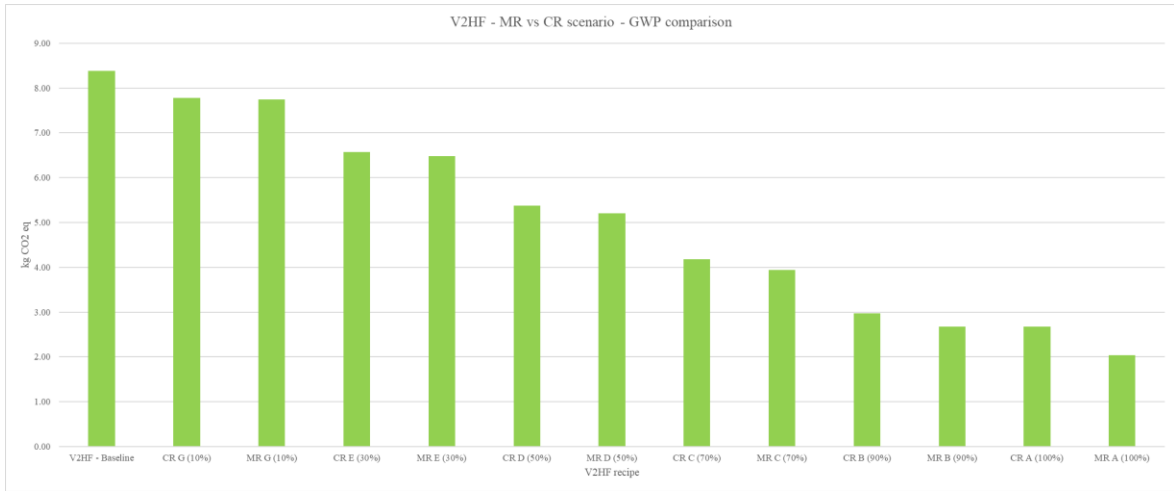


Figure 29. Results - V2HF - MR vs CR scenario - Endpoint categories.

Global warming tree: the diagrams depicted in Figure 29 and Figure 30 allow to understand the contribution of processes in climate change. In particular, the emissions are mainly caused by the production of PA6 (84.8 %, 6.74 kg CO₂ eq), melamine cyanurate (9.27 %, 0.737 kg CO₂ eq) and GF (5.61 %, 0.446 kg CO₂ eq).

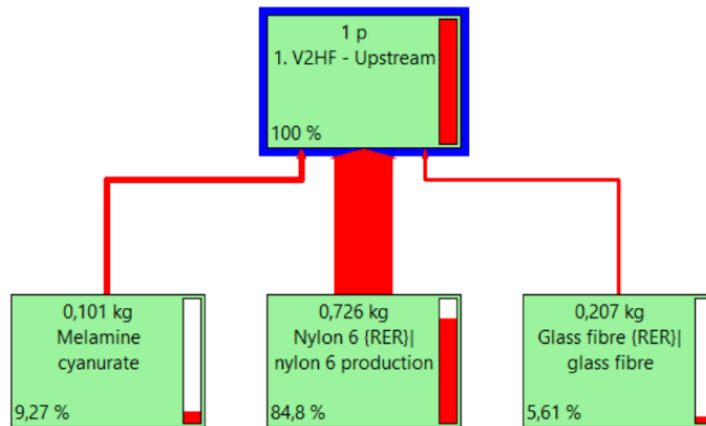


Figure 30. Results - V2HF - Baseline - GWP per percentage.

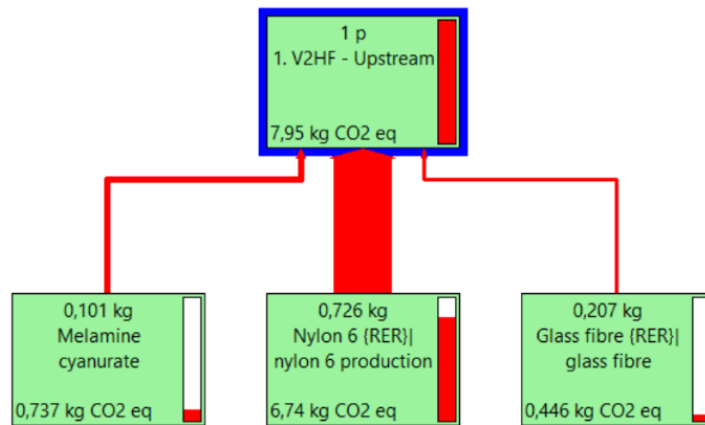


Figure 31. Results - V2HF - Baseline - GWP per contribution.

6.5 LATENE

Baseline scenario: the environmental performance of the LATENE product baseline scenario is shown in Figure 31 and Figure 32. In total, the entire production process impacts 99.76 mPt. The most impacting process is the upstream phase (92.80 mPt; 93.02 % of the total), followed by the core phase (6.68 mPt; 6.70 %) and downstream (0.29 mPt; 0.29 %). The upstream phase mainly affects human health, with 84.82 mPt. Table 69 presents the indicator results per impact category. The product has a total impact of 3.03 kg CO₂ eq per FU. The upstream contributes 2.76 kg CO₂ eq (91.09 % of the total), followed by the core with 0.26 kg CO₂ eq (8.58 %) and downstream with 0.02 kg CO₂ eq (0.66 %).

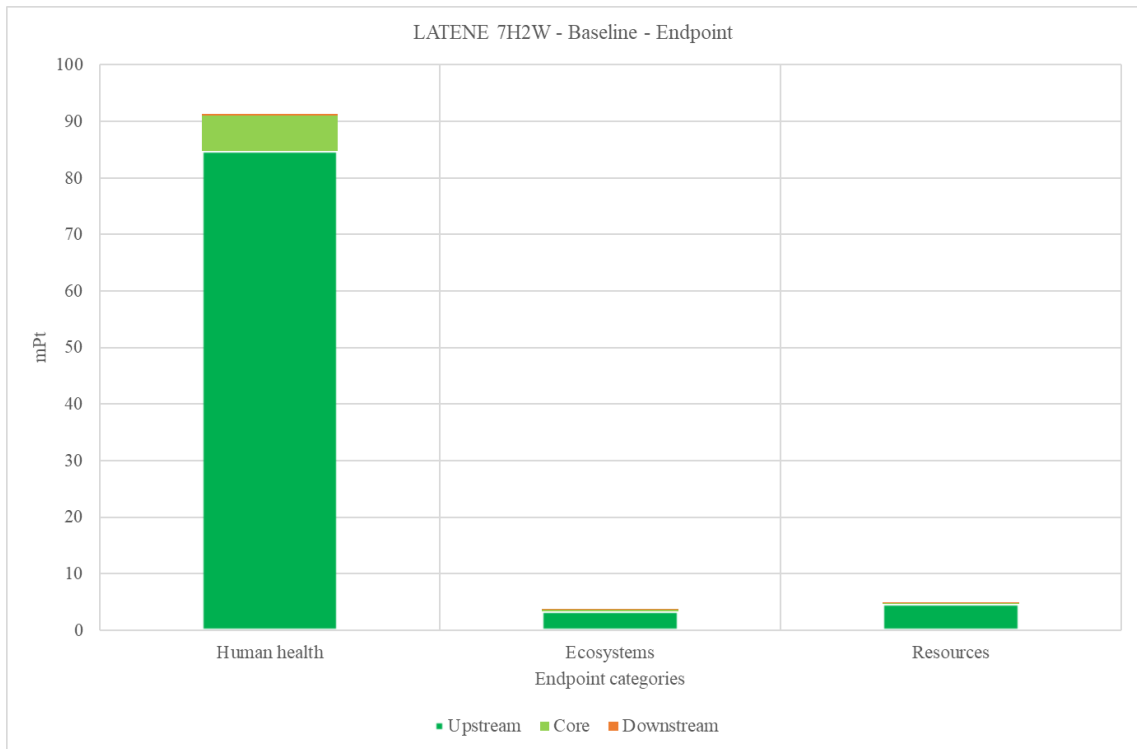


Figure 32. Results - LATENE - Baseline - Endpoint categories.

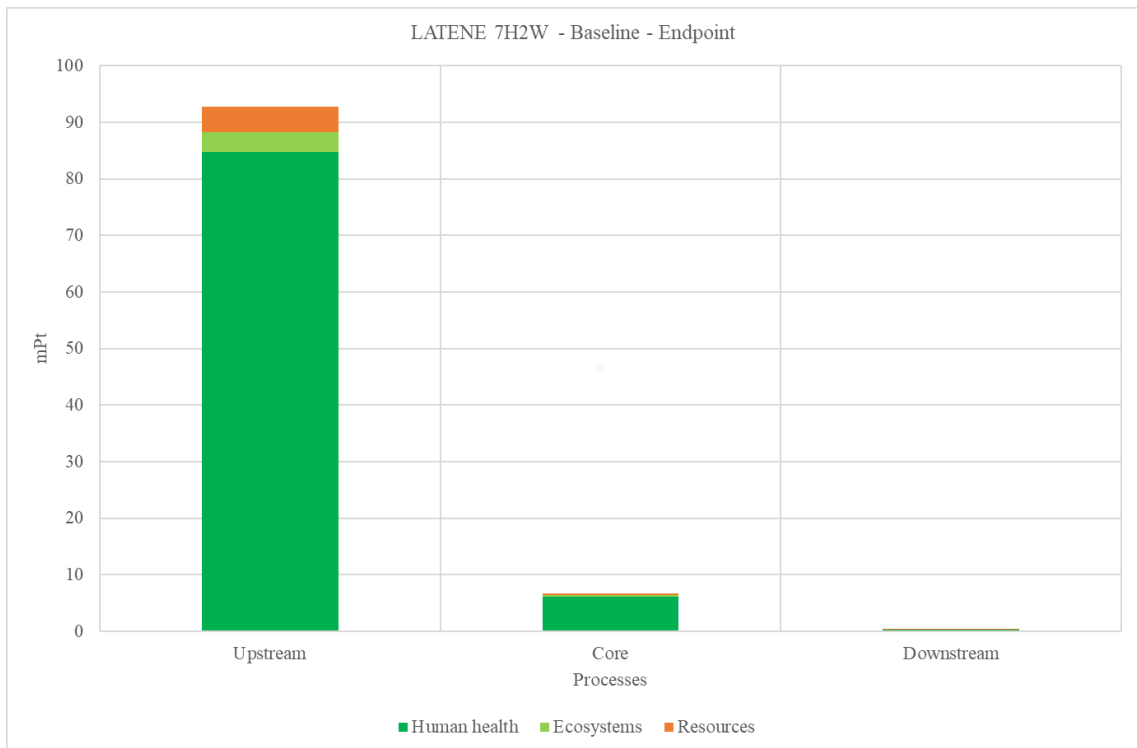


Figure 33. Results - LATENE - Baseline - Processes per Endpoint categories.

Table 69. Results - LATENE - Baseline - Impact categories.

Impact category	Unit	Total	Upstream	Core	Downstream
Acidification	mol H ⁺ eq	1.4E-02	1.3E-02	6.7E-04	1.5E-05
Climate change	kg CO ₂ eq	3.0E+00	2.8E+00	2.6E-01	1.3E-02
Climate change - Biogenic	kg CO ₂ eq	5.7E-03	5.4E-03	3.1E-04	4.2E-06
Climate change - Fossil	kg CO ₂ eq	3.0E+00	2.8E+00	2.6E-01	1.3E-02
Climate change - Land use and LU change	kg CO ₂ eq	2.4E-03	2.4E-03	7.7E-06	3.2E-07
Ecotoxicity, freshwater - part 1	CTUe	3.9E+00	3.9E+00	7.1E-02	1.9E-03
Ecotoxicity, freshwater - part 2	CTUe	8.8E+00	8.7E+00	9.5E-02	3.4E-03
Ecotoxicity, freshwater - inorganics	CTUe	1.1E+01	1.1E+01	1.5E-01	4.8E-03
Ecotoxicity, freshwater - organics - p.1	CTUe	1.0E+00	1.0E+00	2.1E-03	3.7E-05
Ecotoxicity, freshwater - organics - p.2	CTUe	3.1E-01	3.0E-01	1.1E-02	4.8E-04
Particulate matter	disease inc.	1.1E-07	9.9E-08	1.1E-08	6.3E-10
Eutrophication, marine	kg N eq	1.8E-03	1.7E-03	1.7E-04	3.2E-06
Eutrophication, freshwater	kg P eq	6.7E-05	6.6E-05	1.2E-06	1.1E-08
Eutrophication, terrestrial	mol N eq	2.0E-02	1.8E-02	1.8E-03	3.6E-05
Human toxicity, cancer	CTUh	4.1E-09	4.1E-09	2.7E-11	8.3E-13
Human toxicity, cancer - inorganics	CTUh	2.9E-10	2.8E-10	1.2E-11	3.6E-13
Human toxicity, cancer - organics	CTUh	3.8E-09	3.8E-09	1.5E-11	4.7E-13
Human toxicity, non-cancer	CTUh	2.1E-08	1.9E-08	1.3E-09	7.2E-11
Human toxicity, non-cancer - inorganics	CTUh	1.9E-08	1.7E-08	1.2E-09	6.6E-11
Human toxicity, non-cancer - organics	CTUh	1.9E-09	1.8E-09	1.1E-10	5.8E-12
Ionising radiation	kBq U-235 eq	5.3E-02	5.3E-02	5.1E-04	2.3E-05
Land use	Pt	1.2E+01	1.2E+01	1.0E-02	3.8E-04
Ozone depletion	kg CFC11 eq	9.9E-08	9.4E-08	5.3E-09	2.6E-10

Photochemical ozone formation	kg NMVOC eq	1.4E-02	1.3E-02	9.0E-04	3.2E-05
Resource use, fossils	MJ	7.7E+01	7.3E+01	3.5E+00	1.7E-01
Resource use, minerals and metals	kg Sb eq	1.6E-05	1.6E-05	8.9E-09	4.2E-10
Water use	m ³ depriv.	2.1E+00	2.1E+00	3.4E-03	7.2E-05

Global warming tree: the diagrams depicted in Figure 33 and Figure 34 allow to understand the contribution of processes in climate change. In particular, the emissions are mainly caused by the production of PP (68.6 %, 2.083 kg CO₂ eq), and ammonium polyphosphate (17.7 %, 0.536 kg CO₂ eq).

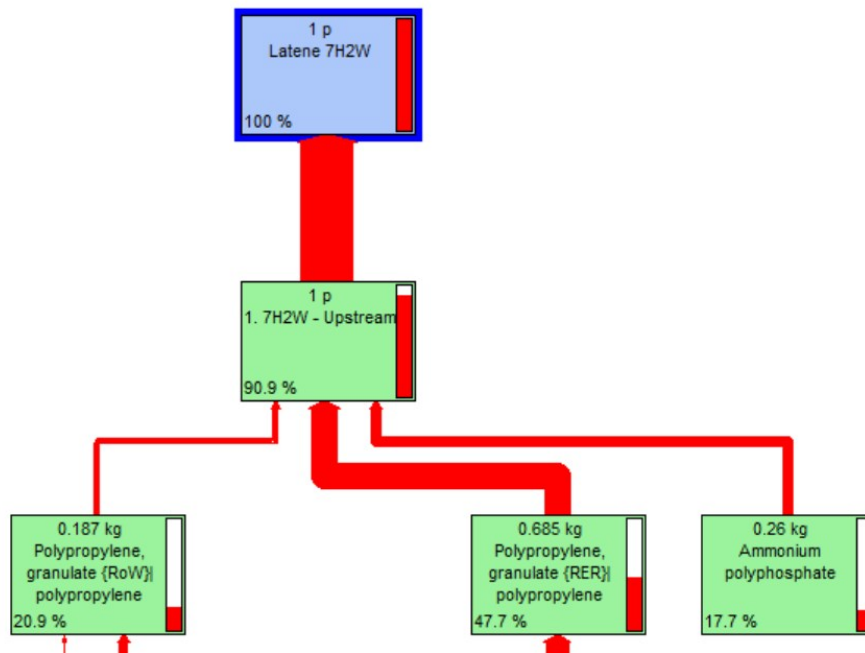


Figure 34. Results - LATENE - Baseline - GWP per percentage.

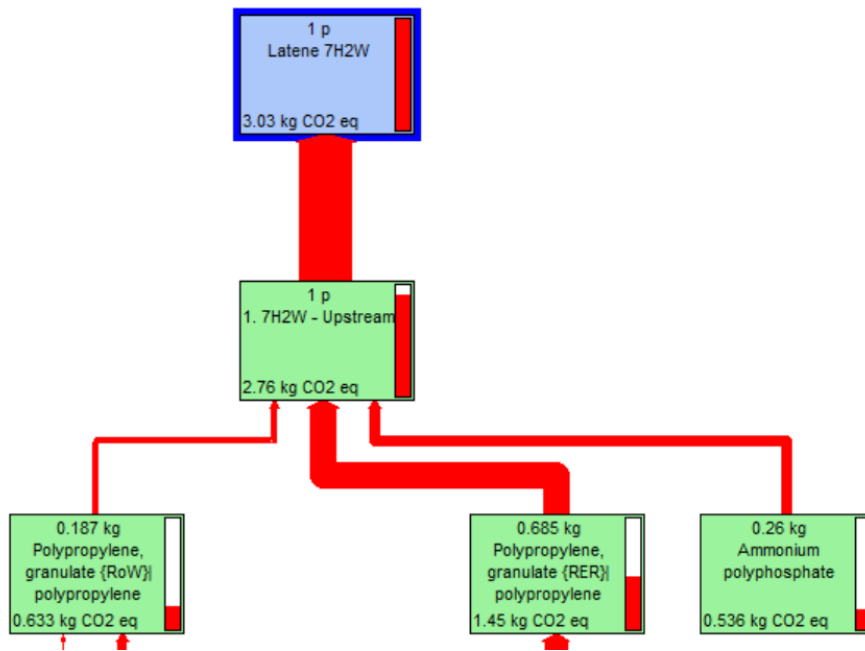


Figure 35. Results - LATENE - Baseline - GWP per contribution.

6.6 LARTON

Baseline scenario: the environmental performance of the LARTON product baseline scenario is shown in Figure 35 and Figure 36. In total, the entire production process impacts 213.73 mPt. The most impacting process is the upstream phase (194.67 mPt; 91.07 % of the total), followed by the core phase (18.77 mPt; 8.78 %) and downstream (0.29 mPt; 0.14 %). The upstream phase mainly affects human health, with 182.62 mPt. Table 70 presents the indicator results per impact category. The product has a total impact of 5.45 kg CO₂ eq per FU. The upstream contributes 5.07 kg CO₂ eq (93.03 % of the total), followed by the core with 0.36 kg CO₂ eq (6.61 %) and downstream with 0.01 kg CO₂ eq (0.18 %).

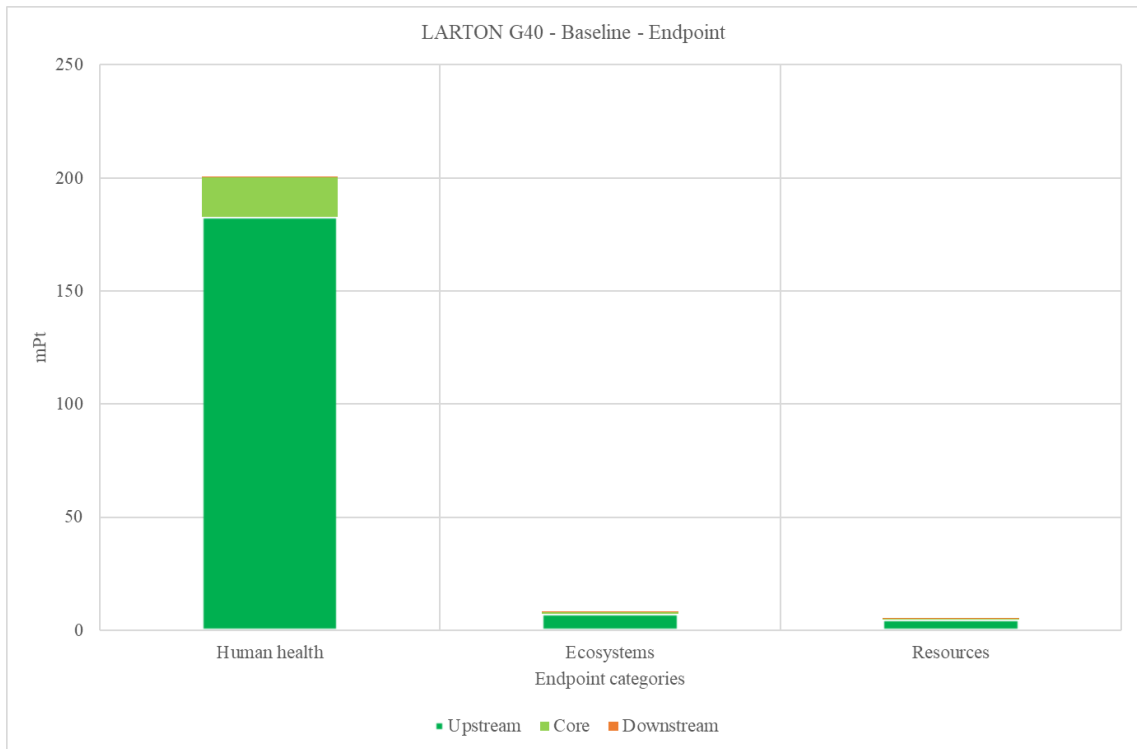


Figure 36. Results - LARTON - Baseline - Endpoint categories.

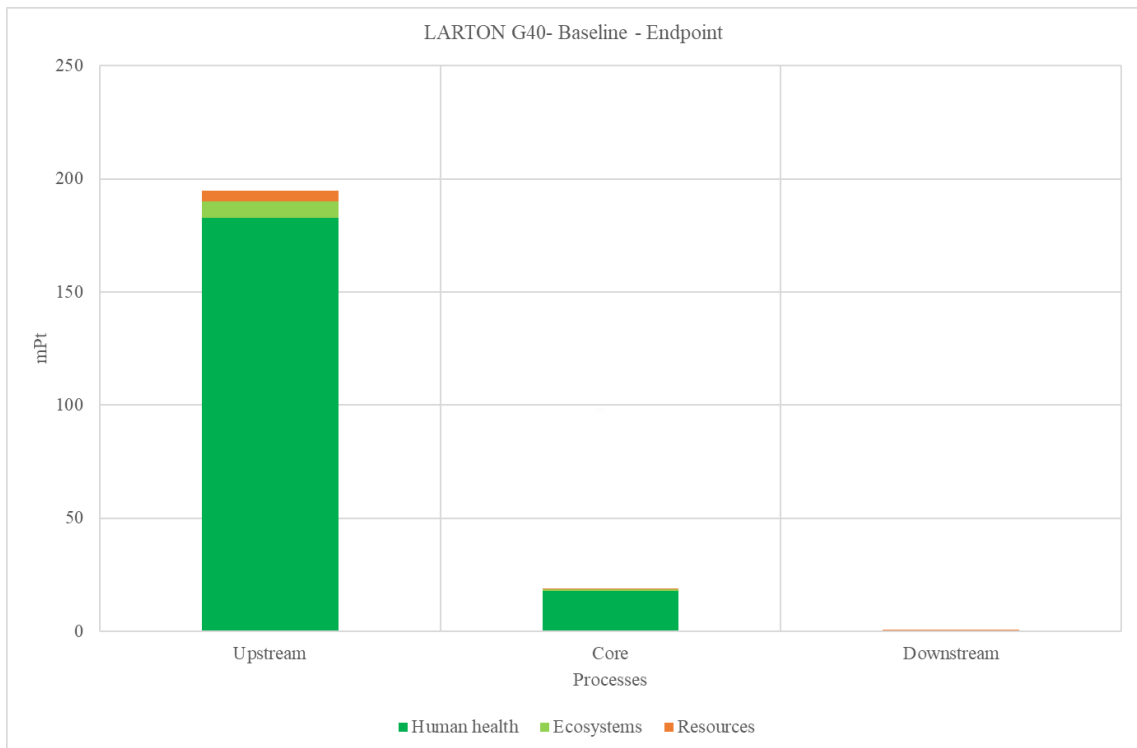


Figure 37. Results - LARTON - Baseline - Processes per Endpoint categories.

Table 70. Results - LARTON - Baseline - Impact categories.

Impact category	Unit	Total	Upstream	Core	Downstream
Acidification	mol H ⁺ eq	3.47E-02	2.93E-02	5.46E-03	1.48E-05
Climate change	kg CO ₂ eq	5.45E+00	5.07E+00	3.63E-01	1.29E-02
Climate change - Biogenic	kg CO ₂ eq	2.77E-02	2.74E-02	3.14E-04	4.20E-06
Climate change - Fossil	kg CO ₂ eq	5.42E+00	5.04E+00	3.62E-01	1.29E-02
Climate change - Land use and LU change	kg CO ₂ eq	3.88E-03	3.87E-03	1.07E-05	3.15E-07
Ecotoxicity, freshwater - part 1	CTUe	7.57E+02	7.57E+02	7.82E-02	1.90E-03
Ecotoxicity, freshwater - part 2	CTUe	5.16E+00	5.03E+00	1.31E-01	3.44E-03
Ecotoxicity, freshwater - inorganics	CTUe	3.35E+01	3.33E+01	1.90E-01	4.83E-03
Ecotoxicity, freshwater - organics - p.1	CTUe	7.28E+02	7.28E+02	2.67E-03	3.68E-05
Ecotoxicity, freshwater - organics - p.2	CTUe	8.57E-01	8.40E-01	1.60E-02	4.79E-04
Particulate matter	disease inc.	2.71E-07	2.58E-07	1.24E-08	6.32E-10
Eutrophication, marine	kg N eq	5.91E-03	4.54E-03	1.36E-03	3.23E-06
Eutrophication, freshwater	kg P eq	1.69E-04	1.68E-04	1.21E-06	1.08E-08
Eutrophication, terrestrial	mol N eq	6.46E-02	4.95E-02	1.51E-02	3.55E-05
Human toxicity, cancer	CTUh	1.18E-07	1.18E-07	4.77E-11	8.34E-13
Human toxicity, cancer - inorganics	CTUh	9.57E-10	9.25E-10	3.15E-11	3.60E-13
Human toxicity, cancer - organics	CTUh	1.17E-07	1.17E-07	1.62E-11	4.74E-13
Human toxicity, non-cancer	CTUh	1.27E-07	1.25E-07	1.35E-09	7.18E-11
Human toxicity, non-cancer - inorganics	CTUh	7.05E-08	6.92E-08	1.24E-09	6.60E-11
Human toxicity, non-cancer - organics	CTUh	5.60E-08	5.59E-08	1.09E-10	5.79E-12
Ionising radiation	kBq U-235 eq	1.46E-01	1.45E-01	5.80E-04	2.31E-05
Land use	Pt	7.29E+00	7.28E+00	1.13E-02	3.79E-04
Ozone depletion	kg CFC11 eq	2.62E-07	2.55E-07	6.57E-09	2.62E-10

Photochemical ozone formation	kg NMVOC eq	3.05E-02	2.61E-02	4.34E-03	3.21E-05
Resource use, fossils	MJ	9.79E+01	9.31E+01	4.68E+00	1.69E-01
Resource use, minerals and metals	kg Sb eq	1.18E-04	1.18E-04	8.55E-09	4.24E-10
Water use	m ³ depriv.	2.66E+00	2.66E+00	3.72E-03	7.20E-05

Global warming tree: the diagrams depicted in Figure 37 and Figure 38 allow to understand the contribution of processes in climate change. In particular, the emissions are mainly caused by the production of PPS (75.6 %, 4.120 kg CO₂ eq), GF (15.5 %, 0.846 kg CO₂ eq) and core phase (6.65 %, 0.363 kg CO₂ eq).

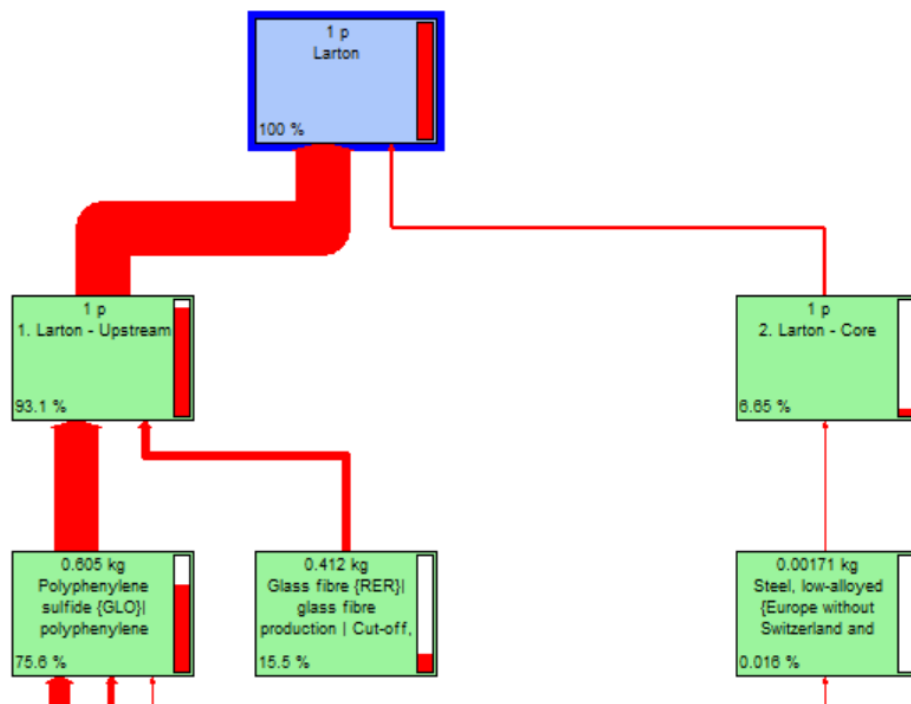


Figure 38. Results - LARTON - Baseline - GWP per percentage.

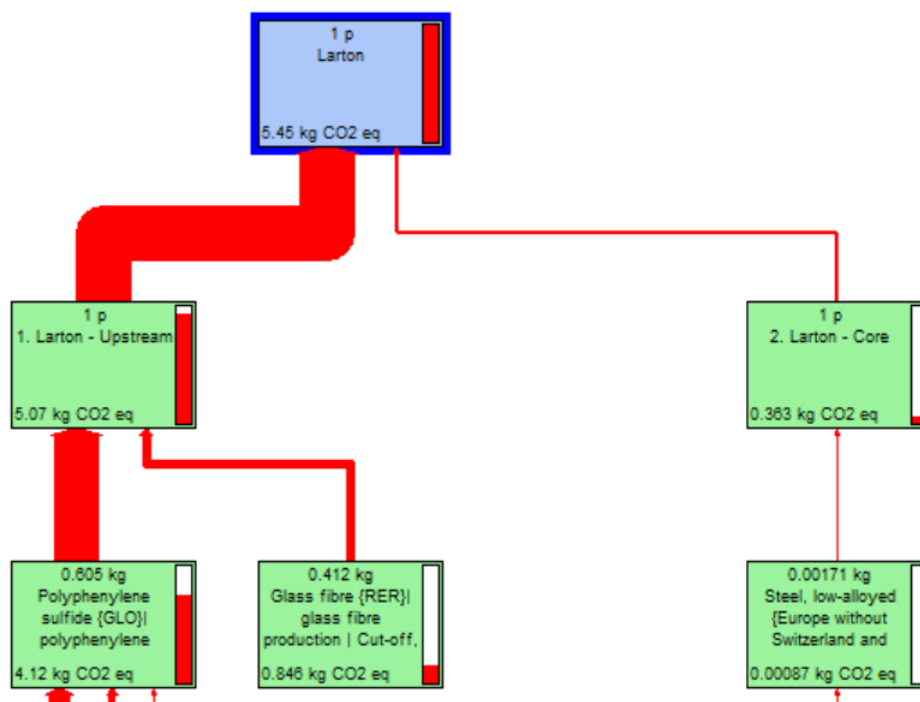


Figure 39. Results - LARTON - Baseline - GWP per contribution.

6.7 LATER

Baseline scenario: the environmental performance of the LATER product baseline scenario is shown in Figure 39 and Figure 40. In total, the entire production process impacts 187.74 mPt. The most impacting process is the upstream phase (171.57 mPt; 91.32 % of the total), followed by the core phase (15.87 mPt; 8.45 %) and downstream (0.29 mPt; 0.15 %). The upstream phase mainly affects human health, with 162.22 mPt. Table 71 presents the indicator results per impact category. The product has a total impact of 5.10 kg CO₂ eq per FU. The upstream contributes 4.55 kg CO₂ eq (89.22 % of the total), followed by the core with 0.53 kg CO₂ eq (10.39 %) and downstream with 0.01 kg CO₂ eq (0.20 %).

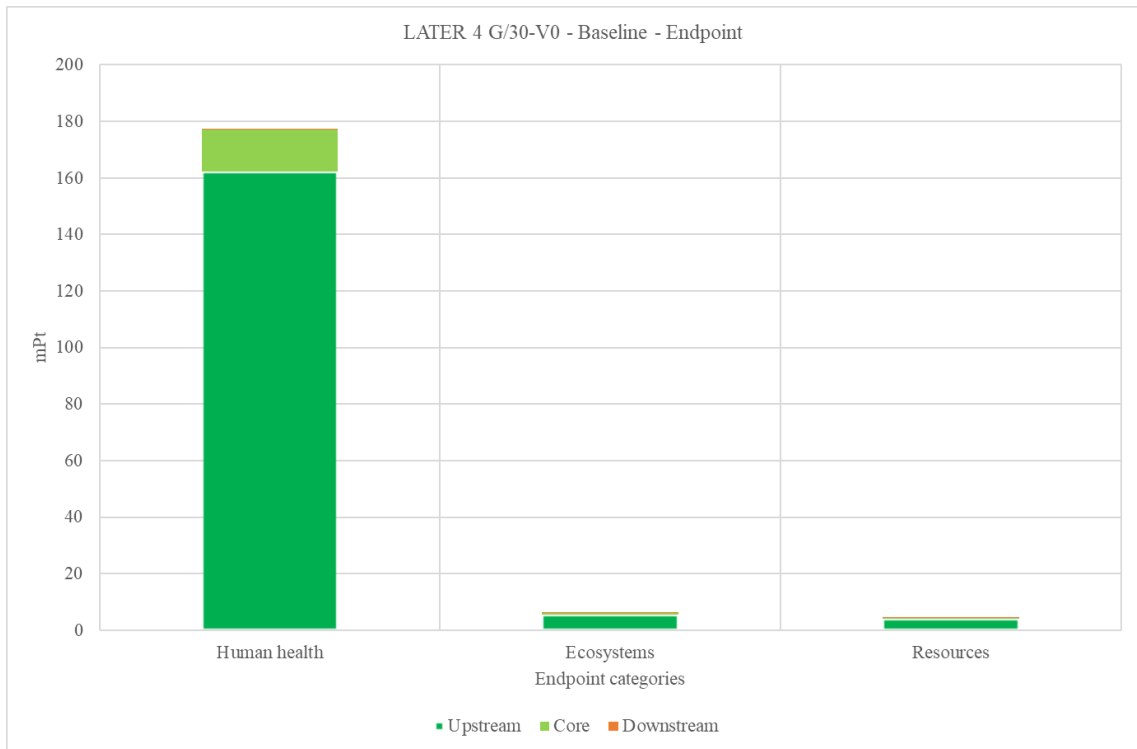


Figure 40. Results - LATER - Baseline - Endpoint categories.

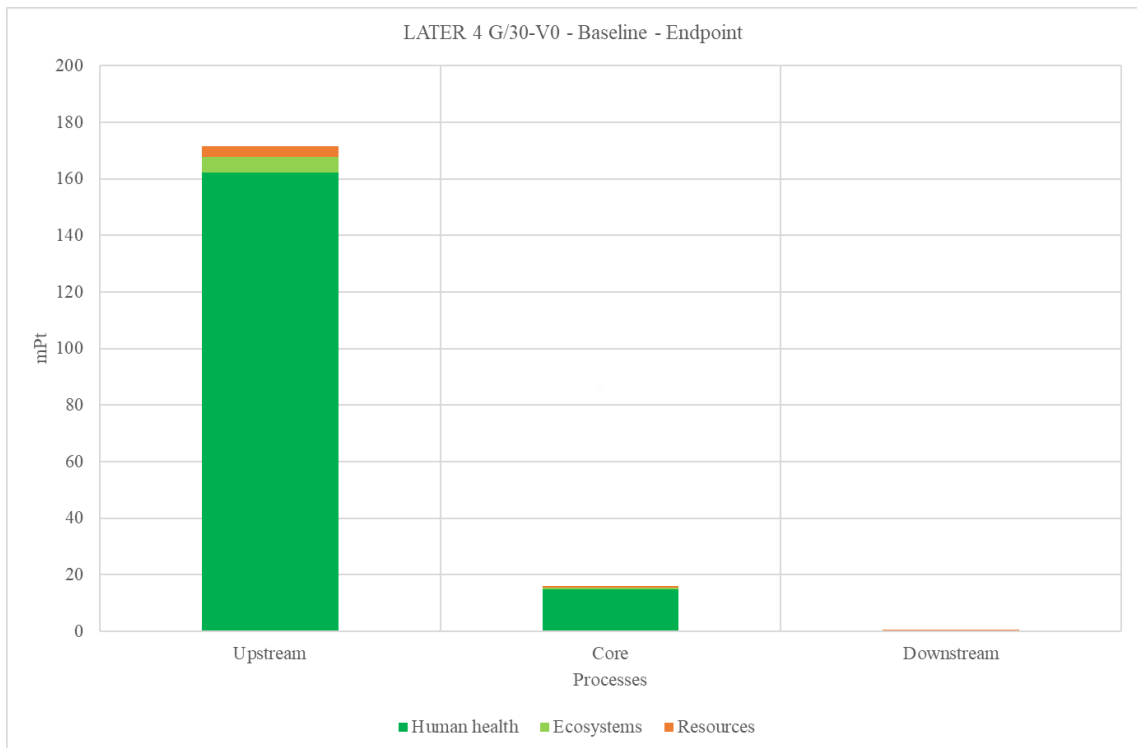


Figure 41. Results - LATER - Baseline - Processes per Endpoint categories.

Table 71. Results - LATER - Baseline - Impact categories.

Impact category	Unit	Total	Upstream	Core	Downstream
Acidification	mol H ⁺ eq	2.78E-02	2.54E-02	2.42E-03	1.48E-05
Climate change	kg CO ₂ eq	5.10E+00	4.55E+00	5.33E-01	1.29E-02
Climate change - Biogenic	kg CO ₂ eq	1.57E-02	1.54E-02	3.68E-04	4.20E-06
Climate change - Fossil	kg CO ₂ eq	5.08E+00	4.53E+00	5.33E-01	1.29E-02
Climate change - Land use and LU change	kg CO ₂ eq	2.33E-03	2.31E-03	1.71E-05	3.15E-07
Ecotoxicity, freshwater - part 1	CTUe	2.23E+01	2.22E+01	1.34E-01	1.90E-03
Ecotoxicity, freshwater - part 2	CTUe	9.77E+00	9.48E+00	2.85E-01	3.44E-03
Ecotoxicity, freshwater - inorganics	CTUe	2.47E+01	2.43E+01	3.90E-01	4.83E-03
Ecotoxicity, freshwater - organics - p.1	CTUe	6.57E+00	6.56E+00	4.26E-03	3.68E-05
Ecotoxicity, freshwater - organics - p.2	CTUe	7.91E-01	7.65E-01	2.54E-02	4.79E-04
Particulate matter	disease inc.	2.67E-07	2.43E-07	2.38E-08	6.32E-10
Eutrophication, marine	kg N eq	5.84E-03	5.25E-03	5.90E-04	3.23E-06
Eutrophication, freshwater	kg P eq	1.19E-04	1.17E-04	1.90E-06	1.08E-08
Eutrophication, terrestrial	mol N eq	6.54E-02	5.89E-02	6.45E-03	3.55E-05
Human toxicity, cancer	CTUh	5.47E-09	5.41E-09	5.17E-11	8.34E-13
Human toxicity, cancer - inorganics	CTUh	6.53E-10	6.27E-10	2.50E-11	3.60E-13
Human toxicity, cancer - organics	CTUh	4.81E-09	4.79E-09	2.68E-11	4.74E-13
Human toxicity, non-cancer	CTUh	7.04E-08	6.77E-08	2.69E-09	7.18E-11
Human toxicity, non-cancer - inorganics	CTUh	4.97E-08	4.71E-08	2.48E-09	6.60E-11
Human toxicity, non-cancer - organics	CTUh	2.07E-08	2.05E-08	2.04E-10	5.79E-12
Ionising radiation	kBq U-235 eq	7.94E-02	7.87E-02	6.66E-04	2.31E-05
Land use	Pt	5.32E+00	5.29E+00	2.56E-02	3.79E-04
Ozone depletion	kg CFC11 eq	8.06E-06	8.05E-06	8.58E-09	2.62E-10

Photochemical ozone formation	kg NMVOC eq	2.31E-02	2.07E-02	2.40E-03	3.21E-05
Resource use, fossils	MJ	8.11E+01	7.39E+01	7.07E+00	1.69E-01
Resource use, minerals and metals	kg Sb eq	8.28E-03	8.28E-03	2.55E-08	4.24E-10
Water use	m ³ depriv.	2.52E+00	2.52E+00	7.00E-03	7.20E-05

Global warming tree: the diagrams depicted in Figure 41 and Figure 42 allow to understand the contribution of processes in climate change. In particular, the emissions are mainly caused by the production of PPT (48.7 %, 2.480 kg CO₂ eq), FR 58 (23.0 %, 1.170 kg CO₂ eq), GF (13.0 %, 0.611 kg CO₂ eq) and core phase (10.5 %, 0.533 kg CO₂ eq).

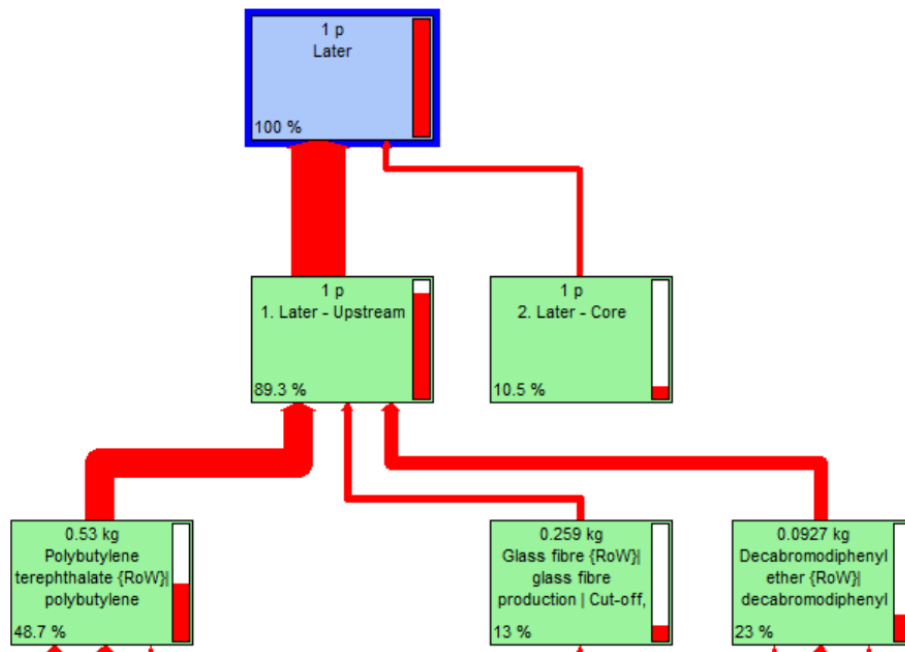


Figure 42. Results - LATER - Baseline - GWP per percentage.

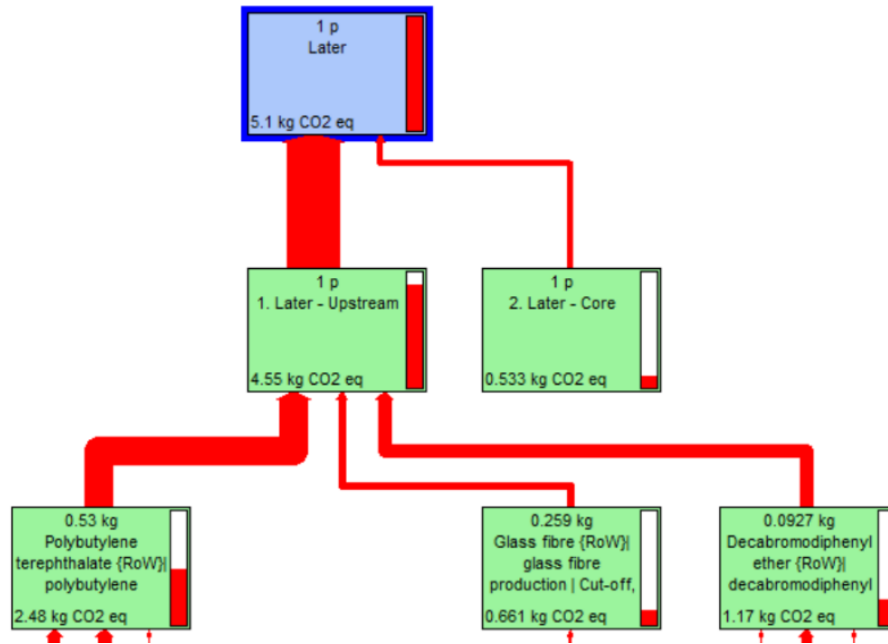


Figure 43. Results - LATER - Baseline - GWP per contribution.

6.8 Products comparison

Environmental profile: the outcomes of the environmental profile comparison are reported in Figure 43. The results indicate that V2HF has the highest impact with 268 mPt per FU, followed by V0HF1 with 267 mPt, V0KB3 with 246 mPt, V0CT1 with 244 mPt, LARTON with 214 mPt, LATER with 188 mPt and LATENE with 100 mPt, respectively -1 %, -8 %, -9 %, -10 %, -20 %, -63 % compared to V2HF. In particular, the most affected endpoint category is human health for all products. The other endpoint categories are significantly lower (Figure 44). In terms of GWP, considering the emissions per mass, V2HF has a contribution of 8.48 kg CO₂ eq, V0KB3 6.99 kg CO₂ eq, V0HF1 6.76 kg CO₂ eq, V0CT1 6.12 kg CO₂ eq, LARTON 5.45 kg CO₂ eq, LATER 5.10 kg CO₂ eq and LATENE 3.03 kg CO₂ eq (Figure 45). Table 72 details the results for each environmental indicator.

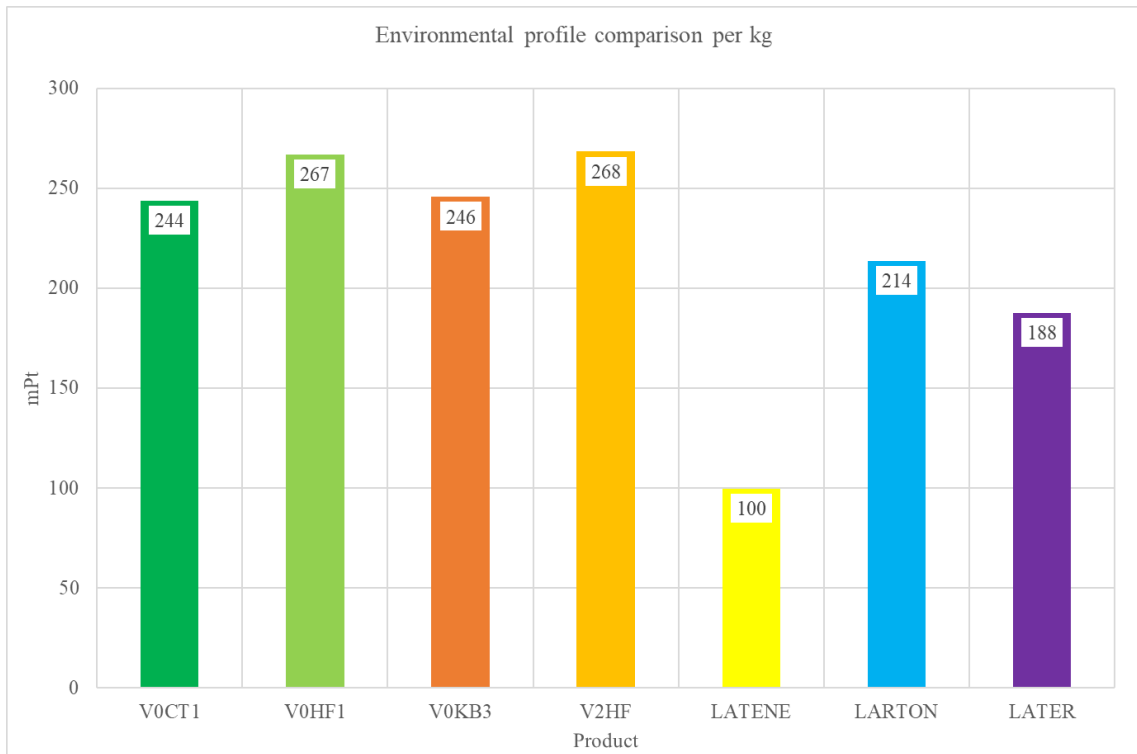


Figure 44. Results - Products comparison - Environmental profile per mass.

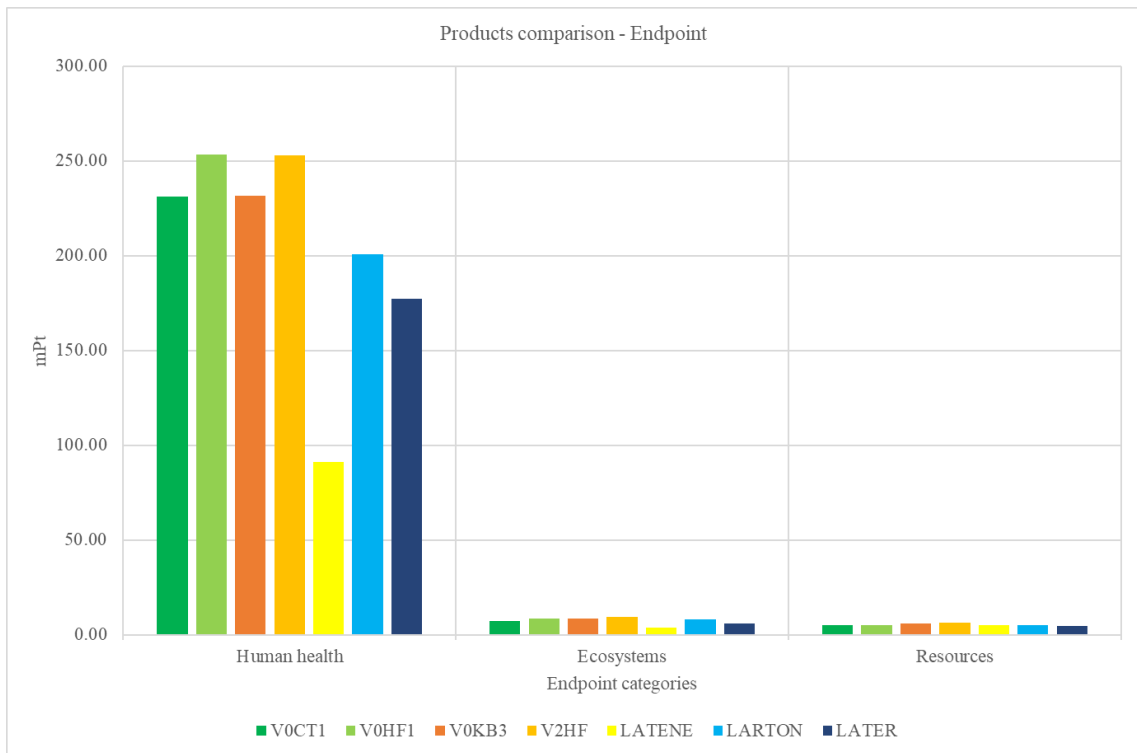


Figure 45. Results - Products comparison - Endpoint categories.

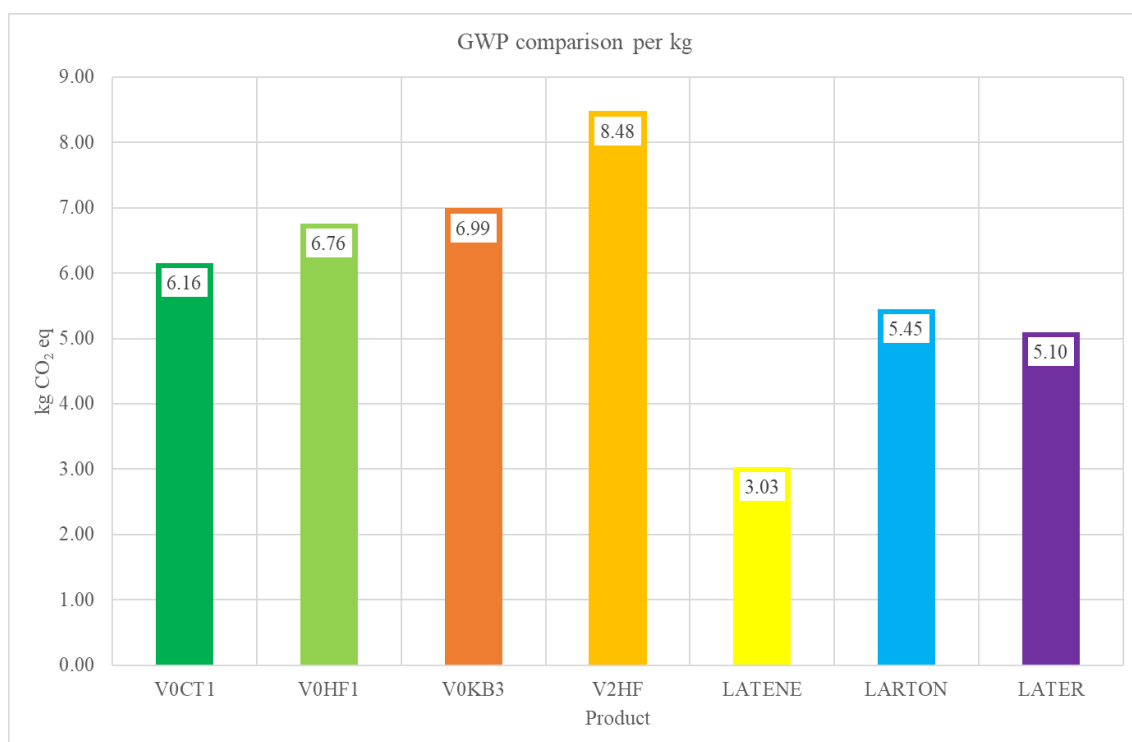


Figure 46. Results - Products comparison - GWP per mass.

Table 72. Results - Products comparison - Impact categories.

Impact category	Unit	V0CT1	V0HF1	V0KB3	V2HF	LATENE	LARTON	LATER
Acidification	mol H ⁺ eq	3.2E-02	3.4E-02	3.2E-02	3.4E-02	1.4E-02	3.47E-02	2.78E-02
Climate change	kg CO ₂ eq	6.2E+00	6.8E+00	7.0E+00	8.5E+00	3.0E+00	5.45E+00	5.10E+00
Climate change - Biogenic	kg CO ₂ eq	3.4E-02	2.9E-02	3.8E-02	4.6E-02	5.7E-03	2.77E-02	1.57E-02
Climate change - Fossil	kg CO ₂ eq	6.1E+00	6.7E+00	6.9E+00	8.4E+00	3.0E+00	5.42E+00	5.08E+00
Climate change - Land use and LU change	kg CO ₂ eq	1.3E-03	7.3E-03	8.5E-03	8.9E-04	2.4E-03	3.88E-03	2.33E-03
Ecotoxicity, freshwater - part 1	CTUe	9.2E+00	1.2E+01	9.1E+00	8.8E+00	3.9E+00	7.57E+02	2.23E+01
Ecotoxicity, freshwater - part 2	CTUe	4.6E+00	4.6E+00	5.1E+00	2.0E+00	8.8E+00	5.16E+00	9.77E+00
Ecotoxicity, freshwater - inorganics	CTUe	1.1E+01	1.2E+01	1.1E+01	7.3E+00	1.1E+01	3.35E+01	2.47E+01
Ecotoxicity, freshwater - organics - p.1	CTUe	1.4E+00	3.4E+00	1.9E+00	3.1E+00	1.0E+00	7.28E+02	6.57E+00
Ecotoxicity, freshwater - organics - p.2	CTUe	1.1E+00	1.2E+00	1.4E+00	4.3E-01	3.1E-01	8.57E-01	7.91E-01
Particulate matter	disease inc.	2.9E-07	3.2E-07	3.0E-07	3.8E-07	1.1E-07	2.71E-07	2.67E-07
Eutrophication, marine	kg N eq	9.1E-03	9.7E-03	9.9E-03	7.6E-03	1.8E-03	5.91E-03	5.84E-03
Eutrophication, freshwater	kg P eq	7.0E-04	1.0E-03	9.9E-04	4.7E-04	6.7E-05	1.69E-04	1.19E-04
Eutrophication, terrestrial	mol N eq	6.6E-02	6.9E-02	6.2E-02	7.7E-02	2.0E-02	6.46E-02	6.54E-02

Human toxicity, cancer	CTUh	6.9E-09	1.5E-08	7.5E-09	1.4E-08	4.1E-09	1.18E-07	5.47E-09
Human toxicity, cancer - inorganics	CTUh	7.3E-10	7.7E-10	7.3E-10	5.5E-10	2.9E-10	9.57E-10	6.53E-10
Human toxicity, cancer - organics	CTUh	6.1E-09	1.4E-08	6.8E-09	1.3E-08	3.8E-09	1.17E-07	4.81E-09
Human toxicity, non-cancer	CTUh	6.6E-08	5.4E-08	5.1E-08	3.7E-08	2.1E-08	1.27E-07	7.04E-08
Human toxicity, non-cancer - inorganics	CTUh	5.0E-08	5.1E-08	4.8E-08	3.4E-08	1.9E-08	7.05E-08	4.97E-08
Human toxicity, non-cancer - organics	CTUh	1.6E-08	2.9E-09	2.9E-09	3.4E-09	1.9E-09	5.60E-08	2.07E-08
Ionising radiation	kBq U-235 eq	1.1E-01	2.1E-01	3.1E-01	1.2E-01	5.3E-02	1.46E-01	7.94E-02
Land use	Pt	6.6E+00	1.4E+01	1.5E+01	5.3E+00	1.2E+01	7.29E+00	5.32E+00
Ozone depletion	kg CFC11 eq	3.9E-08	3.2E-08	3.6E-08	2.7E-08	9.9E-08	2.62E-07	8.06E-06
Photochemical ozone formation	kg NMVOC eq	2.0E-02	2.2E-02	2.1E-02	2.6E-02	1.4E-02	3.05E-02	2.31E-02
Resource use, fossils	MJ	2.1E+01	2.8E+01	2.8E+01	1.9E+01	7.7E+01	9.79E+01	8.11E+01
Resource use, minerals and metals	kg Sb eq	7.3E-03	1.1E-04	9.6E-05	1.1E-04	1.6E-05	1.18E-04	8.28E-03
Water use	m ³ depriv.	5.0E+00	5.9E+00	6.0E+00	3.1E+00	2.1E+00	2.66E+00	2.52E+00

Results comparison per density: the results for one litre of product are included in this section. Since the products subsequently undergo an injection moulding treatment, it is appropriate to report the results considering their densities (V0CT1 - 1.58 g cm⁻³, V0HF1 - 1.40 g cm⁻³, V0KB3 - 1.34 g cm⁻³, V2HF - 1.32 g cm⁻³, LATENE - 1.04 g cm⁻³, LARTON - 1.66 g cm⁻³ and LATER - 1.61 g cm⁻³). Regarding the environmental profile (Figure 46), V0CT1 has the most significant impact with 385 mPt per L, followed by V0HF1 with 374 mPt per L, LARTON with 355 mPt per L, V2HF with 354 mPt per L, V0KB3 with 329 mPt per L, LATER with 302 mPt per L and LATENE with 104 mPt per L. Finally, Figure 47 shows the results in terms of CO₂ eq. The outcomes report that V2HF emits 11.19 kg CO₂ eq per L, followed by V0CT1 with 9.73 kg CO₂ eq per L, V0HF1 9.46 kg CO₂ eq per L, V0KB3 9.37 kg CO₂ eq per L, LARTON 9.05 kg CO₂ eq per L, LATER 8.21 kg CO₂ eq per L while LATENE with 9.05 kg CO₂ eq per L.

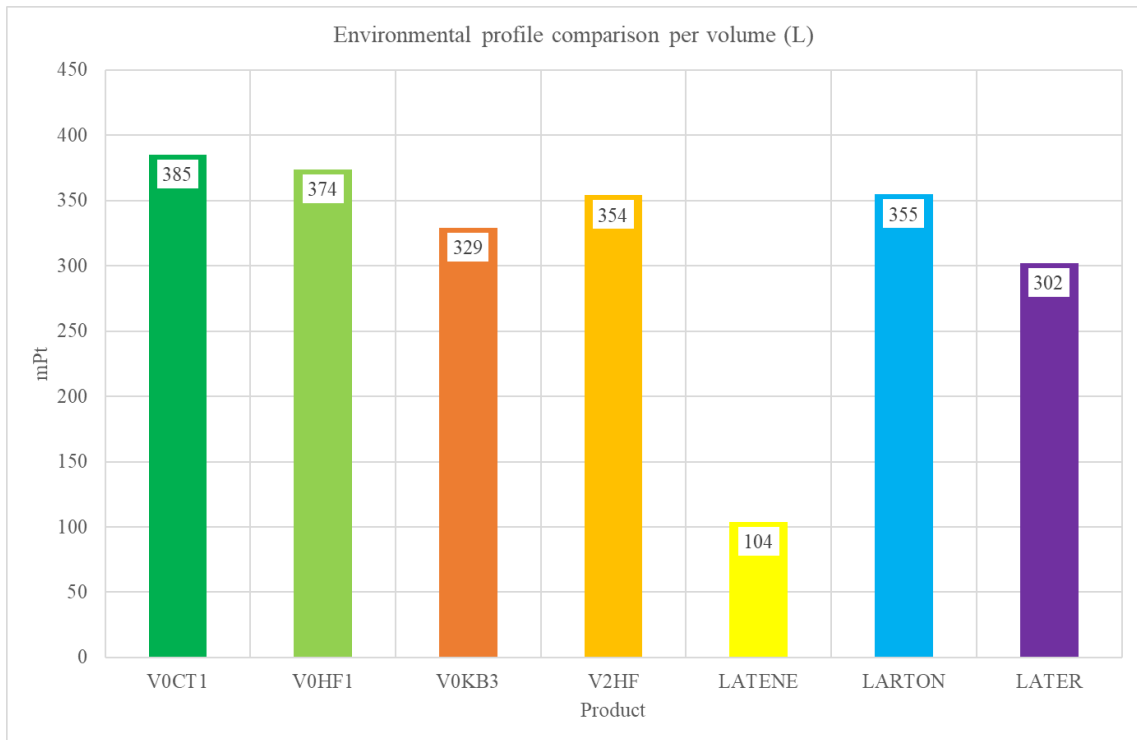


Figure 47. Results - Products comparison - Environmental profile per density.



Figure 48. Results - Products comparison - GWP per density.

7 CHAPTER 7: DISCUSSION

Nowadays, engineering thermoplastics are widely used in various industrial sectors due to their excellent mechanical properties. This work aims to demonstrate the environmental sustainability of seven different materials, which differ mainly in their main polymer and flame retardants [1].

7.1 Consideration about the results

The results show that the environmental profile is similar for all products, except for LATENE, which has significantly lower impacts. The similarity in impacts is primarily due to the lower influence of additives and flame retardants compared to polymers. In fact, regarding the flame retardants, the impacts range from 11% to 17% of the total. These findings are in agreement with what was proposed by Maga et al. (2023) [2]. In contrast, the upstream phase is responsible for the majority of the impacts, over 90% of the total in each material. This is mainly due to the production of raw materials, particularly the polymers such as PA66. The study of Delogu et al. (2015) [3] confirms the high environmental impact of PA66. The core phase contributes less than 10 % of the total, while the downstream phase is negligible for all the compounds considered in the analysis.

Regarding green industrial applications, these findings suggest that to minimise the environmental impact of thermoplastics further, efforts should focus not only on the production phase but also on introducing recycled polymers. The sensitivity analysis showed that up to 5-7 % environmental benefits can be achieved by replacing just 10 % of PA 66 with MRPA. In terms of industrial application, the central aspect that remains unclear is the optimal point for replacing PA66 with MRPA to increase the environmental sustainability of products while maintaining the same properties as the final thermoplastics, primarily considering that complete replacement is, currently, not possible. This aspect should be further explored in the future.

7.2 Policy implications

This research demonstrates that using alternative recycled materials to produce thermoplastics significantly increases the environmental sustainability of products while reducing their overall environmental impacts. For a green shift in the engineering plastics manufacturing sector, attention should therefore be focused on the study and development of products capable of maintaining or increasing performance while reducing the consumption of petroleum-based polymers [4]. The impact of various flame retardants and additives is more limited, at least in the context studied, but must still be considered further to reduce the impact of thermoplastics for engineering use production.

7.3 Limitations and future development

One of the main limitations of this study is the assumptions made during model development and the impact method used to conduct the LCA analysis. A further step in the study could be the use of a primary data model for MR and CR, which could better describe specific case studies rather than relying on proxy data. Another limitation concerns the complete replacement of the virgin polymer; in fact, it is often not feasible due to the reduction of the compound's mechanical properties. In future, the analysis could be expanded to evaluate the potential reuse of other recycled materials and to take into account the EoL of products. An economic assessment could also help estimate the optimal substitution point for PA66, ensuring that thermoplastics production remains economically viable for the market. According to the study by Baltrocchi et al. (2023) [5], the research is planned to be completed from a Life Cycle Thinking (LCT) perspective, incorporating both Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) analysis. This future analysis aims to evaluate the three pillars of sustainability: environmental, economic, and social [6].

7.4 Final considerations

The following points outline the main advantages and most significant gaps in development and research (Figure 48):

1. **Encouraging results.** The results of this research indicate the benefits of using recycled material in the production process.
2. **Evaluating technical feasibility.** Although the study explored the possibility of completely replacing the material, this is often not possible. Therefore, it is necessary to carefully evaluate the technical feasibility of maintaining the expected mechanical properties.
3. **Policy implications.** The results also underscore the need for robust and transparent regulatory support. Indeed, this study highlights the benefits of using recycled material. Regulatory support and financial incentives for research centres and corporate R&D departments could bring significant benefits and interest in the study and introduction of more sustainable materials.
4. **Economic impacts.** Future research should evaluate the cost-benefit, as understanding the economic feasibility of using recycled materials is crucial. While this has clear environmental benefits, the most significant resistance may come from the higher costs of these materials.
5. **Social impacts:** Plastic is often identified by popular opinion as the primary source of pollution and environmental impact. It would be helpful to understand the social implications of using recycled materials, which reduces environmental impacts.

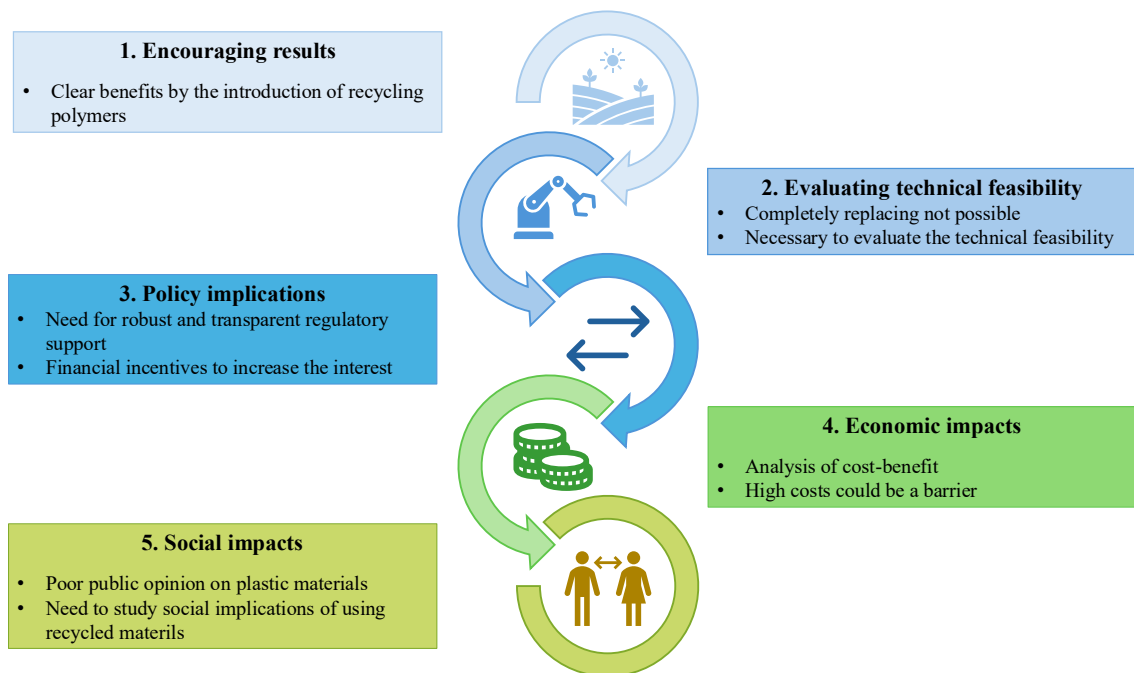


Figure 49. Closed loop of final considerations

7.5 References

- [1] Baltrocchi, A.P.D., Lotti, D., Carnevale Miino, M., Maggi, L., Rada, E.C., Torretta, V. (2025). Environmental impact of three different engineering thermoplastics: How much does it change when using recycled polyamide? *Journal of Cleaner Production* 514, 145769. doi:10.1016/j.jclepro.2025.145769.
- [2] Maga, D., Aryan, V., Beard, A. (2024). Toward Sustainable Fire Safety: Life Cycle Assessment of Phosphinate-Based and Brominated Flame Retardants in E-Mobility and Electronic Devices. *ACS Sustain Chem Eng* 12, 3652–3658. doi:10.1021/acssuschemeng.3c07096.
- [3] Delogu, M., Del Pero, F., Romoli, F., Pierini, M. (2015). Life cycle assessment of a plastic air intake manifold. *International Journal of Life Cycle Assessment*. 20, 1429–1443. doi:10.1007/s11367-015-0946-z.
- [4] Baltrocchi, A.P.D., Carnevale Miino, M., Maggi, L., Rada, E.C., Torretta, V. (2025). A comprehensive critical review of Life Cycle Assessment applied to thermoplastic polymers for mechanical and electronic engineering. *Environmental Technology Reviews* 14, 458–470. doi:10.1080/21622515.2025.2491632.
- [5] Baltrocchi, A.P.D., Ferronato, N., Calle Mendoza, I.J., Gorrity Portillo, M.A., Romagnoli, F., Torretta, V. (2023). Socio-economic analysis of waste-based briquettes production and consumption in Bolivia. *Sustain Prod Consum* 37, 191–201. doi:10.1016/j.spc.2023.03.004.
- [6] Purvis, B., Mao, Y., Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustain Sci* 14, 681–695. doi:10.1007/s11625-018-0627-5.

8 CHAPTER 8: CONCLUSIONS

This research evaluates the environmental performance of seven high-performance thermoplastic materials. The analysis was carried out using the LCA methodology and following the PCR 2010:16 Plastics in primary forms v4.0.0. The software used was SimaPro v10.1 with Ecoinvent 3.10 database. 1 kg and 1 L of product and was assumed as FU.

Main findings: the results show that the upstream phase significantly impacts all the products. In particular, the values are 226.87 mPt (93.3 % of the total) for V0CT1, 250.76 (94.01 %) for V0HF1, 232.68 mPt (94.72 %) for V0KB3, 244.13 mPt (90.98 %) for V2HF, 92.80 mPt (93.02 %) for LATENE, 194.67 mPt (91.07 %) for LARTON and 171.57 mPt (91.32 %) for LATER. The most affected endpoint category is human health. Regarding the core green energy scenarios, the use of energy from hydro (MIX2) brings a major decrease in impacts in core phases. Compared to the core baseline scenario, the reductions are -58 %, -53 %, -54 % and -39 % for V0CT1, V0HF1, V0KB3 and V2HF, respectively. Furthermore, the use of 100 % locally produced photovoltaic energy (FV - 100 %) would reduce environmental impacts of -25 % for V0CT1, -36 % for V0HF1, -32 % for V0KB3 and -17 % for V2HF, although little viable. The introduction of the recycled polymer allows for a decrease in the impact on all product processes. In detail, the range of benefits compared to the upstream baseline scenario is from -5 % (grade G) to -50 % (grade A), from -4 % (grade G) to -40 % (grade A), from -5 % (grade G) to -49 % (grade A), from -7 % (grade G) to -70 % (grade A) for V0CT1, V0HF1, V0KB3 and V2HF, respectively. The evaluation of the environmental profile per FU shows that the most impactful product is V2HF with 268 mPt, followed by V0HF1 with 267 mPt, V0KB3 with 246 mPt, V0CT1 with 244 mPt, LARTON with 214 mPt, LATER with 188 mPt and LATENE with 100 mPt, Regarding GWP, the emissions are 8.48 kg CO₂ eq for V2HF, 6.99 kg CO₂ eq for V0KB3, 6.76 kg CO₂ eq for V0HF1, 6.12 kg CO₂ eq for V0CT1, 5.45 kg CO₂ eq for LARTON, 5.10 kg CO₂ eq for LATER and 3.03 kg CO₂ eq for LATENE. Furthermore, the analysis per volume shows different results than the evaluation per mass. In fact, in this case, the most impactful product is V0CT1 with an environmental profile of 385 mPt per L (9.73 kg CO₂ eq per L), followed by V0HF1 with 374 mPt per L (9.46 kg CO₂ eq per L), LARTON

with 355 mPt per L (9.05 kg CO₂ eq) per L, V2HF with 354 mPt per L (11.19 kg CO₂ eq) per L, V0KB3 with 329 mPt per L (9.37 kg CO₂ eq) per L, LATER with 302 mPt per L (8.21 kg CO₂ eq) per L and LATENE with 104 mPt per L (3.16 kg CO₂ eq) per L.

The environmental analysis of the considered compounds shows significant impact variations depending on the flame retardant and its density. Initially, when evaluating GWP per FU according to the PCR (per kg), the compounds with flame retardants Rpm, DEPAL and BPS-at report a decreasing order of emissions. However, the hierarchy has changed when considering the overall impact based on the alternative FU where the impacts refer to the L. In fact, the environmental impacts were also calculated considering the density of the product. In this case, BPS-at, despite initially being in third place in terms of emissions per kg, turns out to be the compound with the highest GWP in terms of emissions per L, due to its highest density. In environmental decision-making processes related to compound selection, these results highlight the importance of considering impacts also by volume and not only by mass as proposed in the reference PCR.

Regarding the alternative scenarios, the analysis highlights the need to enhance environmental performance, focusing on the upstream phase. The findings show that the introduction of recycled polymers at different rates brings the most benefits compared to the other mitigation systems. Nevertheless, it is important to note that LATI does not directly manage the upstream phase. Therefore, albeit with smaller effects, using mitigation solutions to reduce core phase emissions, such as green energy, is strategic.

9 CHAPTER 9: ABROAD RESEARCH ACTIVITIES

During the doctoral program, three periods abroad were spent for a total of 12 months. Specifically, 3 months were spent at the Department of Chemistry at Aristotle University of Thessaloniki in Greece, 3 months at the Department of Mechanical and Materials Engineering at Universitat Politècnica de València in Spain, and 6 months at the Department of Civil and Environmental Engineering at Brunel University of London in the United Kingdom. The research activities carried out are detailed below.

9.1 Greece - Assessment of Environmental Sustainability of Drinking Water Treatments for Arsenic Removal

The environmental impacts of arsenic removal plants from water are numerous because the most commonly used methods for arsenic removal involve chemical agents, such as coagulants, oxidants, disinfectants, and energy-intensive processes, such as coagulation, adsorption, and oxidation [1-2]. These activities contribute to high energy consumption, atmospheric emissions, and chemical waste generation. Furthermore, the extraction, production, and disposal of materials used in these systems further contribute to resource depletion and environmental degradation [3].

This study evaluated the environmental sustainability of a drinking water treatment plant (DWTP) in northern Greece, specifically designed for the removal of arsenic from groundwater [4]. The analysis was conducted using LCA methods in order to identify the most impactful arsenic removal process and what possible solutions can be proposed to mitigate the impact of the entire DWTP.

The analysis was performed using SimaPro software and the Ecoinvent database. The FUs were (i) removal of 1 mg of arsenic and (ii) treatment of 1 m³ of contaminated groundwater. The SB include aeration, biological filtration, coagulation, filtration, and disinfection.

The coagulation and filtration phases dominate the environmental impact of arsenic removal, mainly due to the high electricity demand, accounting for approximately 54 % and 38 % of the total impacts, respectively. Disinfection stands out in overall plant operations due to its significant contribution to

GWP and PM. The removal of 1 mg of arsenic results in emissions of 2.79E-02 kg CO₂ eq, 5.00E-05 kg of PM_{2.5}, and 2.86E-03 kg and 6.20E-02 kg of 1,4-DCB, for carcinogenic and non-carcinogenic toxicity to humans, respectively. Treatment of 1 m³ of groundwater emits 3.02E-01 kg CO₂ eq and 5.91E-04 kg of PM_{2.5}. Most of the environmental impacts arise from electricity consumption in all critical phases. The use of reagents in disinfection also contributes significantly to the environmental profile. Scenarios involving renewable energy sources were evaluated. A mixed hydroelectric and wind supply reduced the environmental impact by approximately 36 %, while photovoltaic achieved a reduction of up to 53 %. However, the latter also increased environmental pricing parameters due to terrestrial ecotoxicity, highlighting a complex trade-off.

The results demonstrate that energy supply is critical to minimising the environmental impact of arsenic-removing wastewater treatment plants. Future research should extend to social and economic assessments for a more comprehensive sustainability profile. This is the first comprehensive study to quantify the environmental impacts of an arsenic-removing drinking water treatment plant. Its findings provide practical guidance for utilities and policymakers seeking to balance regulatory compliance with environmental sustainability, highlighting the crucial role of energy efficiency and renewable resources in future arsenic mitigation strategies. The findings of this research were reported in Baltrocchi et al. (2024) [4].

9.2 Spain - Environmental Sustainability and Economic Assessment of five filaments for 3D printing

3D printing is a promising alternative to traditional manufacturing as it allows for localised production and less waste; the main problem with this technology is electricity consumption [5-6]. However, environmental impacts vary greatly depending on the type of materials used [7]. In this context, the selection of printing materials plays a fundamental role in the environmental impact of 3D printed objects [8].

This study conducts an in-depth assessment of the environmental and economic sustainability of five common thermoplastic filaments Acrylonitrile butadiene styrene (ABS), High quality polyvinyl chloride

(FLEX), High impact polystyrene (HIPS), Polyethylene terephthalate glycol (PETG) and Polylactic acid (PLA) used in 3D printing, considering three print resolutions (0.30 mm, 0.15 mm, and 0.05 mm). The objective of this research is to identify the most environmentally sustainable and cost-benefits filament-print setting combination.

The environmental impact analysis was conducted using the LCA methodology, covering raw material production, polymer production, and manufacturing processes. The study was performed using SimaPro software, Ecoinvent database, and the ReCiPe 2016 impact assessment method. The FU of a printed part was used for both the LCA and the cost analysis. Economic costs included raw materials, energy, maintenance, and depreciation, allowing for a direct cost analysis per unit and per print layer. The primary data have been collected in the 3D printing lab of the Universitat Politècnica de València and refer to 2024.

The main results show that PETG consistently has the lowest environmental impacts (0.7-2.5 mPt) at all print resolutions. In contrast, FLEX and ABS showed the highest impacts, with values ranging from 2.5 to 3.9 mPt. The upstream phase (raw material extraction and filament production) contributed most to the total impacts for low and medium resolutions, while the core stage (printing phase) became dominant at high resolution due to increased print time and energy consumption. High-resolution prints (0.05 mm) significantly increased both environmental impact and costs (up to 212% more than low-resolution prints). Human health was the most impacted endpoint due to emissions from electricity consumption, with FLEX and ABS exhibiting the highest GWP in most environments.

Regarding the economic analysis, FLEX was the most expensive material (€ 2.02 - € 2.99 per part), primarily due to higher purchase costs and larger print quantities required. PLA was the most cost-effective option (€ 0.70 - € 2.57 per part), offering an optimal balance between cost and environmental performance. Costs per millimetre of print decreased with increasing print resolution, despite higher total costs per part; however, FLEX remained the most expensive material per layer. PETG emerged as the optimal filament for environmental sustainability across all print settings, while PLA offered the best balance between cost and sustainability. The analysis also demonstrated that improvements in environmental performance do not always align with economic gains, necessitating a balanced approach to material selection.

This research introduces a broader comparative framework for assessing the environmental and economic sustainability of 3D printing materials and print settings. The findings highlight the importance of integrating LCA and cost analysis to guide decisions on selecting materials and processes for additive manufacturing. In particular, material choice and print resolution can have a profound impact on both sustainability and budget. Decision makers should consider not only direct impacts, but also the intended application and performance requirements of the printed objects. The study promotes policies that encourage the adoption of recycled, bio-based, or environmentally friendly polymers, as well as the optimisation of print settings to minimise emissions and costs. The main limitations include the use of a single shape and the use of specific laboratory data; future work should extend to other geometries, regions, and technologies.

In conclusion, integrating environmental and economic analysis is crucial for sustainable additive manufacturing. The study concludes that PETG offers the most environmentally friendly profile, while PLA effectively balances cost and sustainability. The findings provide valuable guidance for researchers, industry stakeholders, and policymakers aiming to improve the sustainability of 3D printing practices. This study is currently under review on Baltrocchi et al. (2025a) [9].

9.3 United Kingdom - A Systematic Review on Life Cycle Assessment of Modular and Prefabricated Buildings

Nowadays, a significant share of global energy consumption, GHG emissions, and resource depletion is due to the construction sector [10]. To reduce environmental impacts, the entire industry must shift toward sustainable strategies such as improving energy efficiency, selecting construction methods, and using sustainable materials [11-12].

This systematic review evaluates how LCA assessment methodologies have been applied to modular and prefabricated buildings, providing a broad summary of key aspects of LCA (e.g., software, database, LCIA, FU, Reference Service Life, SB, and impact categories), the research gaps, and recommendations for future improvements in the construction industry. In total, 34 articles were selected for the final screening. Most articles were published in China, Hong Kong, Canada and Malaysia.

Modular and prefabricated construction methods generally demonstrate a lower environmental impact than conventional construction techniques, mainly due to reduced raw material use, increased energy efficiency during construction, and improved waste management. Among building materials, wood consistently exhibits the lowest GHG emissions during the production phase, followed by concrete and steel. However, steel structures offer significant advantages in EoL scenarios due to their high recyclability. The environmental performance of prefabricated buildings depends heavily on factors such as material selection, production, transportation, and final disposal strategies.

The review highlights five key areas where LCA assessment of modular buildings can be improved:

1. **Methodological development:** There is significant methodological inconsistency across studies in terms of FU, SB, Reference Service Life, software/database selection, and LCIA methods, hindering direct comparisons. Most studies focus exclusively on GHG emissions, often omitting other important environmental impact categories such as water consumption, fossil fuel depletion, and ecotoxicity. Many studies limit their assessment to a selection of life cycle phases, often neglecting operational phases and EoL scenarios.
2. **Policy implications:** Current building standards and policies do not sufficiently integrate LCA-based criteria and do not address the entire life cycle or promote unified measurement standards. Policies should encourage the adoption of standard LCA frameworks and the integration of innovative, low-impact building materials and technologies, especially in developing regions.
3. **Stakeholder engagement and awareness:** Interdisciplinary cooperation between engineers, policymakers, manufacturers, and researchers is lacking. Greater attention is needed to collect primary data and ensure transparent reporting, as well as to extend studies to encompass social and economic impacts, for instance, by integrating SLCA and LCC for a comprehensive sustainability assessment.
4. **Digital tools and innovation:** Digital technologies such as Building Information Modelling (BIM) can improve data collection and LCA accuracy, but their adoption in current works is limited. Data automation and the use of digital tools are needed to improve transparency and comparability in LCA research.

5. Integration of the circular economy: Current studies lack comprehensive modelling for the reuse, recovery, and recycling of modular building components. Further research should clarify the long-term benefits of circular practices, such as reuse and the multiple life cycles of modular units, in reducing environmental impacts.

On balance, the reviewed literature reveals a lack of studies applying standardised LCA across all life cycle phases and regions. Few studies address the complete environmental profile, economic, and social sustainability dimensions. Research on quantifying the benefits of the circular economy is limited, and there is a general lack of data on the comparability of results due to divergent methodological choices. The whole review research is currently under review in Baltrocchi et al. (2025b) [13].

9.4 United Kingdom - Environmental Life Cycle Assessment of Fiber-reinforced Cement Composites

The construction sector is responsible for nearly 37 % of global CO₂ emissions and significant resource depletion [14]. Fiber-reinforced cement composites (FRCCs) represent a promising approach for enhancing durability and reducing material consumption. However, the sustainability of FRCCs depends on the type and origin of the reinforcing fibers. Some fibers, such as carbon fiber and glass fiber, have significant environmental impacts [15]. Recycled fibers from industrial and post-consumer waste can offer environmental benefits, but their impact varies depending on the recycling method [16-17].

This study applied LCA to evaluate the environmental impacts of sixteen virgin and recycled fibers (carbon fiber, glass fiber, basalt fiber, polypropylene fiber, hemp fiber and bamboo fiber) used in cement composites. Mechanical, thermal, and chemical recycling processes were evaluated, along with the effects of transportation and the performance of 1 m³ of cement composite. FUs were defined as 1 kg of fiber, 1 dm³ of fiber, and 1 m³ of cement composite.

The results show that virgin fibers and thermally or chemically recycled fibers generally have higher impacts in several categories, particularly in terms of climate change and resource use. In contrast, mechanically recycled fibers consistently have lower environmental impacts, with bio-based fibers offering additional benefits. For example, virgin carbon fiber emits 9.17 kg of CO₂ eq per kg, compared

to 0.9 kg of CO₂ eq per kg for mechanically recycled carbon fiber. Optimising transportation reduced impacts by up to 22 %, while long-distance transportation increased them by almost 20 %. For cement composites, FRCCs with mechanically recycled fibers achieved approximately 30 % lower emissions than conventional cement composite mix, while those with thermally or chemically recycled fibers often performed worse than virgin composites.

Mechanical recycling represents the most sustainable route to integrating fibers into cement composites. This study highlights the potential of recycled fibers, particularly bio-based and mechanically recycled fibers, to mitigate the environmental impact of building materials, thereby supporting the principles of the circular economy and promoting more sustainable construction practices. This research is currently under review on Baltrocchi et al. (2025c) [18].

9.5 References

- [1] Alka, S., Shahir, S., Ibrahim, N., Ndejiko, M.J., Vo, D.-V.N., Manan, F.A. (2021). Arsenic removal technologies and future trends: A mini review. *Journal of Cleaner Production* 278, 123805. doi:10.1016/j.jclepro.2020.123805.
- [2] Altowayti, W.A.H., Othman, N., Shahir, S., Alshalif, A.F., Al-Gheethi, A.A., AL-Towayti, F.A.H., Saleh, Z.M., Haris, S.A. (2022). Removal of arsenic from wastewater by using different technologies and adsorbents: a review. *International journal of environmental science and technology* 19, 9243-9266. doi:10.1007/s13762-021-03660-0.
- [3] Mahamallik, P., Swain, R. (2023). A mini-review on arsenic remediation techniques from water and future trends. *Water science and technology* 87, 3108-3123. doi:10.2166/wst.2023.190.
- [4] Baltrocchi, A.P.D., Carnevale Miino, M., Katsoyiannis, I.A., Tolkou, A.K., Maggi, L., Rada, E.C., Torretta, V. (2024). Assessment of environmental sustainability of drinking water treatments for arsenic removal. *Resources, Conservation and Recycling*. 211, 107878. doi:10.1016/j.resconrec.2024.107878.
- [5] Al Rashid, A., Koç, M. (2023). Additive manufacturing for sustainability and circular economy: needs, challenges, and opportunities for 3D printing of recycled polymeric waste. *Materials Today Sustainability* 24, 100529. doi:10.1016/j.jcomc.2024.100463.
- [6] Ford, S., Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production* 137, 1573-1587. doi:10.1016/j.jclepro.2016.04.150.
- [7] Cobos, C.M., Ferrandiz, S., Garzón, L., López, J., Rayon, E., 2025. Exploring the mechanical response of PLA/MWCNT and PLA/HNT composites obtained by additive manufacturing. *Rapid Prototyp J* 31, 179–188. doi:10.1108/RPJ-07-2024-0308.
- [8] Kartal, F., Kaptan, A., 2024. Sustainable Reinforcement of PLA Composites with Waste Beech Sawdust for Enhanced 3D-Printing Performance. *J Mater Eng Perform*. doi:10.1007/s11665-024-10277-0.

- [9] Baltrocchi A.P.D., Ferrandiz-Buo S., Carnevale Miino M., Torretta V. (2025a). Environmental Sustainability and Economic Assessment of 3D Printing: A Comparative Analysis of Different Polymers and Layer Definitions. *Under review* in Clean Technologies and Environmental Policy.
- [10] Myint, N.N., Shafique, M., Zhou, X., Zheng, Z. (2025). Net zero carbon buildings: A review on recent advances, knowledge gaps and research directions. *Case Studies in Construction Materials* 22, e04200. doi:10.1016/j.cscm.2024.e04200.
- [11] Araújo, A.G., Pereira Carneiro, A.M., Palha, R.P. (2020). Sustainable construction management: A systematic review of the literature with meta-analysis. *Journal of Cleaner Production* 256, 120350. doi:10.1016/j.jclepro.2020.120350.
- [12] Roopesh, M., Nishat, N., Rasetti, S., Hossain, M.A. (2024). Advanced machine learning techniques for cybersecurity: opportunities and emerging challenges. *International journal of science and engineering* 1, 93–105. doi:10.62304/ijse.v1i04.198.
- [13] Baltrocchi A.P.D., Shafique M., Torretta V. (2025b). A Systematic Review on Life Cycle Assessment of Modular Buildings. *Under review* in Sustainable Horizons.
- [14] United Nations Environment Programme, 2024. Global Status Report for Buildings and Construction Beyond foundations Global Status Report for Buildings and Construction Beyond foundations Mainstreaming sustainable solutions to cut emissions from the buildings sector. Nairobi. <https://doi.org/10.59117/20.500.11822/45095>
- [15] Moutik, B., Summerscales, J., Graham-Jones, J., Pemberton, R., 2024. Quality assessment of life cycle inventory data for fibre-reinforced polymer composite materials. *Sustain Prod Consum* 49, 474–491. <https://doi.org/10.1016/j.spc.2024.07.005>
- [16] Akbar, A., Liew, K.M., 2021. Multicriteria performance evaluation of fiber-reinforced cement composites: An environmental perspective. *Compos B Eng* 218. <https://doi.org/10.1016/j.compositesb.2021.108937>

[17] Sbahieh, S., Mckay, G., Al-Ghamdi, S.G., 2023. A comparative life cycle assessment of fiber-reinforced polymers as a sustainable reinforcement option in concrete beams. *Front Built Environ* 9. <https://doi.org/10.3389/fbuil.2023.1194121>

[18] Baltrocchi A.P.D., Shafique M., Torretta V. (2025c). Life Cycle Assessment of recycling process of waste reinforced fibers for concrete composites. *Submitted* in *Sustainable Production and Consumption*

10 CHAPTER 10: LIST OF PUBLICATIONS AND CONFERENCES

Parts of this doctoral thesis have been previously published in peer-reviewed journals and presented at national and international conferences as listed above.

10.1 Publications

1. Ferronato N., Baltrocchi A.P.D., Romagnoli F., Calle Mendoza I.J., Gorrity Portillo M.A., Torretta V. (2023). Environmental Life Cycle Assessment of biomass and cardboard waste-based briquettes production and consumption in Andean areas. *Energy for Sustainability Development*, 72, 139-150. doi: 10.1016/j.esd.2022.12.005.
2. Baltrocchi A.P.D., Ferronato N., Calle Mendoza I.J., Gorrity Portillo M.A., Romagnoli F., Torretta V. (2023). Socio-economic analysis of waste-based briquettes production and consumption in Bolivia. *Sustainable Production and Consumption*, 37, 191-201. doi: 10.1016/j.spc.2023.03.004.
3. Baltrocchi A.P.D., Carnevale Miino M., Katsoyiannis I.A., Tolkou A.K., Maggi L., Rada E.C., Torretta V. Assessment of Environmental Sustainability of Drinking Water Treatments for Arsenic Removal. *Resources, Conservation & Recycling*. 211, 107878. doi: 10.1016/j.resconrec.2024.107878.
4. Baltrocchi A.P.D., Carnevale Miino M., Maggi L., Rada E.C., Torretta V. (2025). A comprehensive critical review of Life Cycle Assessment applied to thermoplastic polymers for mechanical and electronic engineering. *Environmental Technology Reviews*. 14(1), 458-471. doi: 10.1080/21622515.2025.2491632.
5. Baltrocchi A.P.D., Lotti D., Carnevale Miino M., Maggi L., Rada E.C., Torretta V. (2025). Environmental sustainability of three different engineering thermoplastics: What is the impact of using recycled polyamide? *Journal of Cleaner Production*. 514, 145769. doi: 10.1016/j.jclepro.2025.145769.
6. Baltrocchi A.P.D., Ferrandiz-Buo S., Carnevale Miino M., Torretta V. (2025). Environmental Sustainability and Economic Assessment of 3D Printing: A Comparative Analysis of Different Polymers and Layer Definitions. *Under review* in *Clean Technologies and Environmental Policy*.

7. Baltrocchi A.P.D., Shafique M., Torretta V. (2025). A Systematic Review on Life Cycle Assessment of Modular Buildings. *Under review* in Sustainable Horizons.

8. Baltrocchi A.P.D., Shafique M., Torretta V. (2025). Life Cycle Assessment of recycling process of waste reinforced fibers for concrete composites. *Submitted* in Sustainable Production and Consumption

10.2 Conferences

1. Speaker at VI Giornata di studio “Rifiuti e Life Cycle Thinking” – 7 March 2023 (Milan, Italy) – Baltrocchi A.P.D., Ferronato N., Torretta V. Valutazione delle bricchette di materiale cellulosico come combustibile alternativo: applicazione dell’approccio Life Cycle Thinking ad un caso studio boliviano.

2. Speaker at CSRW24 – 1st International Conference on Circularity, Sustainability and Resilience in Water, Wastewater and Sludge Management – 11-13 February 2024 (Varese, Italy) – Baltrocchi A.P.D., Maggi L., Tolkou A.K., Karaeva A., Kyzas G.Z. Arsenic(III) removal from water by the synergistic action of Graphene Oxide (GO) and Granular Ferric Hydroxide (GFH).

3. Speaker at CONECT24 – XVII International Scientific Conference of Environmental and Climate Technologies – 15-17 May 2024 (Riga, Latvia) – Baltrocchi A.P.D., Lotti D., Carnevale Miino M., Romagnoli F., Torretta V. Environmental performance of a polymer-based thermoplastic compound with brominated flame retardants.

4. Speaker at SIDISA24 – XII International Symposium on Environmental Engineering – 1-4 October 2024 (Palermo, Italy) – Baltrocchi A.P.D., Lotti D., Carnevale Miino M., Maggi L., Morosini C., Conti F., Rada E.C., Torretta V. CO₂ emissions and primary energy used in thermoplastic with flame retardant process production: a Life Cycle Assessment comparison between three compounds.

5. Speaker at GITISA Young 2025 – 1st National Congress of Young Researchers in Sanitary Environmental Engineering – 3-5 June 2025 (Paestum, Italy) – Baltrocchi A.P.D., Lotti D., Carnevale Miino M., Torretta V. Environmental Sustainability of Engineering Thermoplastics: A Life Cycle Assessment Approach.

6. Speaker at ICESA 2025 – 6th International Conference on Environmental Sciences and Applications
– 27-29 October 2025 (Barcelona, Spain) – Baltrocchi A.P.D., Lotti D., Carnevale Miino M., Torretta
V. Life Cycle Assessment of thermoplastic compound based on Polyamide 6: A Comparison Between
Chemical and Mechanical Recycling (*abstract accepted, to be presented*).

ANNEX I

The input and output data sources and the Ecoinvent database used for the evaluated LATI products Life Cycle Inventory (LCI) are reported below. In accordance with LATI, some primary data have been omitted as they are confidential data. The inventory of (i) V0CT1 are reported from Table 73 to Table 76, (ii) V0HF1 from Table 77 to Table 80, (iii) V0KB3 from Table 81 to Table 84, (iv) V2HF from Table 85 to Table 88, (v) LATENE from Table 89 to Table 92, (vi) LARTON from Table 93 to Table 96 and (vii) LATER from Table 97 to Table 100.

Table 73. LCI per FU - V0CT1 Upstream - Raw materials production (I = input, O = output).

Process	Quantity	Unit	I/O	Ecoinvent Database
Ethylene copolymer process production - Italy	<i>omissis</i>	kg	I	Ethylene {RoW} market for ethylene Cut-off, U Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U
Packaging copolymer	2.54E-05	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet ethylene copolymer	6.78E-07	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Brominated polystyrene process production - USA	<i>omissis</i>	kg	I	Polystyrene, general purpose {GLO} market for polystyrene, general purpose Cut-off, U Bromine {GLO} market for bromine Cut-off, U
Packaging brominated polystyrene	5.21E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet brominated polystyrene	1.39E-05	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Antimony trioxide process production - China	<i>omissis</i>	kg	I	Stibnite concentrate {GLO} market for stibnite concentrate Cut-off, U
Packaging antimony trioxide	5.59E-05	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U

Pallet antimony trioxide	1.49E-06	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Zinc borate process production - Italy	<i>omissis</i>	kg	I	Zinc oxide {GLO} market for zinc oxide Cut-off, U Boric oxide {GLO} market for boric oxide Cut-off, U
Packaging zinc borate	2.03E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet zinc borate	5.42E-06	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Polyamide 6,6 process production - Italy	<i>omissis</i>	kg	I	Nylon 6-6 {RER} nylon 6-6 production Cut-off, U
Glass fibre process production - Brazil	<i>omissis</i>	kg	I	Glass fibre {RoW} glass fibre production Cut-off, U
Packaging glass fibre	5.89E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet glass fibre	1.73E-05	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Final product packaging pallet	6.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product packaging PE bag	3.60E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
Final product packaging ALU bag	3.60E-03	kg	I	Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U
Final product packaging cap	1.64E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U

Table 74. LCI per FU - V0CT1 Core - Raw and other materials transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Transport ethylene copolymer	5.22E+00	kgkm	512 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo brominated polystyrene	1.25E+03	kgkm	6,000 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport cargo antimony trioxide	3.52E+02	kgkm	15,750 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo antimony trioxide	4.13E+00	kgkm	184 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport zinc borate	3.02E+01	kgkm	370 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport zinc borate	7.34E+00	kgkm	90 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport polyamide 6,6	3.48E+01	kgkm	80 km	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U

Transport glass fibre	tir	5.72E+03	kgkm	22 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo glass fibre	ship	2.60E+01	kgkm	10,000 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport glass fibre	tir	5.02E+01	kgkm	193 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport pallet	tir	1.53E-02	kgkm	228 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport packaging bag	tir	6.70E+00	kgkm	931 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cap	tir	1.97E-02	kgkm	12 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 75. LCI per FU - V0CT1 Core - Manufacturing.

Process	Quantity	Unit	I/O	Ecoinvent Database
Facility electricity	3.58E-01	kWh	I	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U
Facility methane	9.06E-01	MJ	I	Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U
Extruder electricity	3.10E-01	kWh	I	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U

Extruder maintenance materials	1.11E-02	kg	I	Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U
Aqueduct water	3.86E-01	kg	I	Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U
Well water	1.66E-04	m ³	I	Water, well, IT
Metal scrap	1.11E-02	kg	O	Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U
WW treatment	5.53E-04	m ³	O	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U
Wood	3.88E-05	kg	O	Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U
Plastic mixture	1.84E-02	kg	O	Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U

Table 76. LCI per FU - V0CT1 Downstream - Final product transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Final transport	6.56E+01	kgkm	65 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 77. LCI per FU - V0HF1 Upstream - Raw materials production.

Process	Quantity	Unit	I/O	Ecoinvent Database
DEPAL process production - Germany	<i>omissis</i>	kg	I	Ethylene {RoW} market for ethylene Cut-off, U Phosphorus, white, liquid {GLO} market for phosphorus, white, liquid Cut-off, U Aluminium sulfate, powder {RoW} market for aluminium sulfate, powder Cut-off, U

Packaging DEPAL	2.75E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet DEPAL	7.33E-06	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Melamine				Melamine {GLO} market for melamine Cut-off, U
polyphosphate process production - China	<i>omissis</i>	kg	I	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO} market for phosphoric acid, industrial grade, without water, in 85% solution state Cut-off, U
Packaging Melamine polyphosphate	2.50E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet Melamine polyphosphate	6.67E-06	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Polyamide 6 process production - Italy	<i>omissis</i>	kg	I	Nylon 6 {RER} nylon 6 production Cut-off, U
Zinc borate process production - Italy	<i>omissis</i>	kg	I	Zinc oxide {GLO} market for zinc oxide Cut-off, U Boric oxide {GLO} market for boric oxide Cut-off, U
Packaging zinc borate	2.50E-05	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet zinc borate	6.67E-07	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Polyamide 6,6 process production - Italy	<i>omissis</i>	kg	I	Nylon 6-6 {RER} nylon 6-6 production Cut-off, U
Glass fibre process production - Brazil	<i>omissis</i>	kg	I	Glass fibre {RoW} glass fibre production Cut-off, U
Packaging glass fibre	6.14E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet glass fibre	1.80E-05	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U

Final product packaging pallet	6.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product packaging PE bag	3.60E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
Final product packaging ALU bag	3.60E-03	kg	I	Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U
Final product packaging cap	1.64E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U

Table 78. LCI per FU - V0HF1 Core - Raw other materials transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Transport tir DEPAL	8.82E+01	kgkm	800 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir Melamine polyphosphate	1.55E+01	kgkm	155 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo ship Melamine polyphosphate	1.10E+03	kgkm	11,000 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport tir Melamine polyphosphate	2.81E+01	kgkm	280 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir polyamide 6	6.72E+00	kgkm	112 km	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U

Transport zinc borate	tir	4.61E+00	kgkm	460 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport polyamide 6,6	tir	3.60E+01	kgkm	80 km	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U
Transport glass fibre	tir	6.20E+01	kgkm	229 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo glass fibre	ship	2.57E+03	kgkm	9,500 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport glass fibre	tir	5.22E+01	kgkm	193 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport pallet	tir	1.53E-02	kgkm	228 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport packaging bag	tir	6.70E+00	kgkm	931 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cap	tir	1.97E-02	kgkm	12 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 79. LCI per FU - V0HF1 Core - Manufacturing.

Process	Quantity	Unit	I/O	Ecoinvent Database
Facility electricity	3.58E-01	kWh	I	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U
Facility methane	9.06E-01	MJ	I	Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U
Extruder electricity	4.69E-01	kWh	I	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U
Extruder maintenance materials	1.11E-02	kg	I	Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U
Aqueduct water	3.86E-01	kg	I	Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U
Well water	1.66E-04	m ³	I	Water, well, IT
Metal scrap	1.11E-02	kg	O	Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U
WW treatment	5.53E-04	m ³	O	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U
Wood	3.27E-05	kg	O	Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U
Plastic mixture	1.16E-03	kg	O	Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U

Table 80. LCI per FU - V0HF1 Downstream - Final product transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
				Transport, freight, lorry 7.5-16 metric ton, EURO6
Final transport	6.56E+01	kgkm	65 km	{RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 81. LCI per FU - V0KB3 Upstream - Raw materials production.

Process	Quantity	Unit	I/O	Ecoinvent Database
				Ethylene {RoW} market for ethylene Cut-off, U
Red phosphorus masterbatches production - Italy	<i>omissis</i>	kg	I	Phosphorus, white, liquid {GLO} market for phosphorus, white, liquid Cut-off, U
Packaging red phosphorus masterbatches	2.79E-04	kg	I	Aluminium sulfate, powder {RoW} market for aluminium sulfate, powder Cut-off, U
Pallet red phosphorus masterbatches	7.44E-06	p	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
				EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
				Methacrylic acid {RER} methacrylic acid production Cut-off, U
Ionomer (impact modifier) process production - Belgium	<i>omissis</i>	kg	I	Ethylene {RoW} market for ethylene Cut-off, U
Packaging Ionomer (impact modifier)	2.03E-04	kg	I	Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U
Pallet Ionomer (impact modifier)	6.67E-06	p	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
				EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Polyamide 6,6 process production - Italy	<i>omissis</i>	kg	I	Nylon 6-6 {RER} nylon 6-6 production Cut-off, U

Glass fibre process production - Brazil	<i>omissis</i>	kg	I	Glass fibre {RoW} glass fibre production Cut-off, U
Packaging glass fibre	6.45E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet glass fibre	1.89E-05	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Final product packaging pallet	6.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product packaging PE bag	3.60E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
Final product packaging ALU bag	3.60E-03	kg	I	Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U
Final product packaging cap	1.64E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U

Table 82. LCI per FU - V0KB3 Core - Raw and other materials transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Transport tir red phosphorus masterbatches	6.15E+01	kgkm	550 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir Ionomer (impact modifier)	8.64E+01	kgkm	850 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir polyamide 6,6	3.60E+01	kgkm	80 km	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U

Transport glass fibre	tir	6.20E+01	kgkm	229 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo glass fibre	ship	2.57E+03	kgkm	9,500 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport glass fibre	tir	5.22E+01	kgkm	193 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport pallet	tir	1.53E-02	kgkm	228 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport packaging bag	tir	6.70E+00	kgkm	931 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cap	tir	1.97E-02	kgkm	12 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 83. LCI per FU - V0KB3 Core - Manufacturing.

Process	Quantity	Unit	I/O	Ecoinvent Database
Facility electricity	3.58E-01	kWh	I	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U
Facility methane	9.06E-01	MJ	I	Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U
Extruder electricity	3.17E-01	kWh	I	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U

Extruder maintenance materials	1.11E-02	kg	I	Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U
Aqueduct water	3.86E-01	kg	I	Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U
Well water	1.66E-04	m ³	I	Water, well, IT
Metal scrap	1.11E-02	kg	O	Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U
WW treatment	5.53E-04	m ³	O	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U
Wood	3.31E-05	kg	O	Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U
Plastic mixture	1.51E-03	kg	O	Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U

Table 84. LCI per FU - V0KB3 Downstream - Final product transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
				Transport, freight, lorry 7.5-16 metric ton, EURO6
Final transport	6.56E+01	kgkm	65 km	{RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 85. LCI per FU - V2HF Upstream - Raw materials production (I = input, O = output).

Process	Quantity	Unit	I/O	Ecoinvent Database
Melamine cyanurate process production - China	<i>omissis</i>	kg	I	Melamine {GLO} market for melamine Cut-off, U Hydrogen cyanide {RoW} hydrogen cyanide production Cut-off, U
Packaging cyanurate	2.90E-03	kg	I	Corrugated board box {RoW} market for corrugated board box Cut-off, U

Pallet Melamine cyanurate	6.76E-06	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Polyamide 6 process production - Italy	<i>omissis</i>	kg	I	Nylon 6 {RER} nylon 6 production Cut-off, U
Packaging Polyamide 6	1.80E-03	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet Polyamide 6	4.80E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Glass fibre process production - Italy	<i>omissis</i>	kg	I	Glass fibre {RoW} glass fibre production Cut-off, U
Packaging glass fibre	6.21E-03	kg	I	Corrugated board box {RER} market for corrugated board box Cut-off, U
Pallet glass fibre	1.38E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product packaging pallet	6.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product packaging PE bag	3.60E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
Final product packaging ALU bag	3.60E-03	kg	I	Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U
Final product packaging cap	1.64E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U

Table 86. LCI per FU - V2HF Core - Raw and other materials transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW}
Melamine cyanurate	1.56E+01	kgkm	155 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo ship				
Melamine cyanurate	1.15E+03	kgkm	11,000 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport tir				
Melamine cyanurate	2.92E+01	kgkm	280 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 16-32 metric ton, EURO6 {RER}
polyamide 6	5.77E+02	kgkm	800 km	market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
glass fibre	1.17E+01	kgkm	55 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
pallet	1.53E-02	kgkm	228 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
packaging bag	6.70E+00	kgkm	931 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
cap	1.97E-02	kgkm	12 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 87. LCI per FU - V2HF Core - Manufacturing.

Process	Quantity	Unit	I/O	Ecoinvent Database
Facility electricity	6.58E-01	kWh	I	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U
Facility methane	9.06E-01	MJ	I	Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U
Extruder maintenance materials	1.73E-04	kg	I	Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U
Aqueduct water	3.86E-01	kg	I	Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U
Well water	1.66E-04	m ³	I	Water, well, IT
Metal scrap	1.73E-04	kg	O	Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U
WW treatment	5.53E-04	m ³	O	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U
Cardboard	9.10E-03	kg	O	Waste paperboard {IT} market for waste paperboard Cut-off, U
Wood	6.85E-05	kg	O	Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U
Plastic mixture	3.62E-02	kg	O	Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U

Table 88. LCI per FU - V2HF Downstream - Final product transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
				Transport, freight, lorry 7.5-16 metric ton, EURO6
Final transport	6.56E+01	kgkm	65 km	{RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 89. LCI per FU - LATENE Upstream - Raw materials production (I = input, O = output).

Process	Quantity	Unit	I/O	Ecoinvent Database
Polypropylene process production – South Africa	<i>omissis</i>	kg	I	Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U
Packaging Polypropylene	1.04E-02	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet Polypropylene	6.93E-06	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Polypropylene process production – Belgium	<i>omissis</i>	kg	I	Polypropylene, granulate {RER} market for polypropylene, granulate Cut-off, U
Packaging Polypropylene	6.65E-02	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet Polypropylene	4.43E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
				Melamine {RoW} melamine production Cut-off, U
				Hydrogen cyanide {RoW} hydrogen cyanide production Cut-off, U
Ammonium polyphosphate process production - Spain	<i>omissis</i>	kg	I	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO} market for phosphoric acid, industrial grade, without water, in 85% solution state Cut-off, U

Packaging polyphosphate	Ammonium	2.60E-02	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet polyphosphate	Ammonium	1.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product pallet	packaging	6.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product PE bag	packaging	3.60E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
Final product ALU bag	packaging	3.60E-03	kg	I	Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U
Final product cap	packaging	1.64E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U

Table 90. LCI per FU - LATENE Core - Raw and other materials transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Transport Polypropylene	6.08E+01	kgkm	532 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo Polypropylene	1.31E+03	kgkm	11,500 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport Polypropylene	6.78E+01	kgkm	593 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport Polypropylene	6.29E+02	kgkm	860 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Transport	tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
Ammonium polyphosphate		3.73E+02	kgkm	1304 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Trasport pallet	tir	1.53E-02	kgkm	228 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport packaging bag	tir	6.70E+00	kgkm	931 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cap	tir	1.97E-02	kgkm	12 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 91. LCI per FU - LATENE Core - Manufacturing.

Process	Quantity	Unit	I/O	Ecoinvent Database
Facility electricity - Wind power	5.59E-01	kWh	I	Green energy - 100% Wind power - Electricity, high voltage {IT} market for electricity, high voltage Cut-off, U
Facility electricity PV	1.73E-02	kWh	I	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U
Facility electricity PV sold	-9.01E-05	kWh	I	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U
Facility methane	6.38E-01	MJ	I	Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U

Extruder maintenance materials	1.68E-03	kg	I	Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U
Aqueduct water	3.88E-01	kg	I	Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U
Well water	1.83E-04	m ³	I	Water, well, IT
Metal scrap	1.68E-03	kg	O	Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U
WW treatment	5.72E-04	m ³	O	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U
Plastic mixture	1.41E-01	kg	O	Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U
Wood	6.86E-05	kg	O	Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U

Table 92. LCI per FU - LATENE Downstream - Final product transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
				Transport, freight, lorry 7.5-16 metric ton, EURO6
Final transport	6.56E+01	kgkm	65 km	{RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 93. LCI per FU - LARTON Upstream - Raw materials production (I = input, O = output).

Process	Quantity	Unit	I/O	Ecoinvent Database
Polyphenylene sulfide process production - China	<i>omissis</i>	kg	I	Polyphenylene sulfide {GLO} polyphenylene sulfide production Cut-off, U
Packaging sulfide	2.52E-03	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U

Pallet sulfide	Polyphenylene	4.03E-05	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
PE masterbatch production	process – United Kingdom	<i>omissis</i>	kg	I	Carbon black {GLO} market for carbon black Cut-off, U Polyethylene, high density, granulate {GLO} market for polyethylene, high density, granulate Cut-off, U
Packaging PE masterbatch		7.41E-05	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet PE masterbatch		8.23E-07	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Glass fibre production – France	process	<i>omissis</i>	kg	I	Glass fibre {RER} glass fibre production Cut-off, U
Packaging glass fibre		1.50E-03	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet glass fibre		6.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product pallet	packaging	6.73E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product PE bag	packaging	3.60E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
Final product ALU bag	packaging	3.60E-03	kg	I	Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U
Final product cap	packaging	1.64E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U

Table 94. LCI per FU - LARTON Core - Raw and other materials transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW}
Polyphenylene sulfide	3.65E+01	kgkm	60 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo ship				Transport, freight, sea, container ship {GLO} market for
Polyphenylene sulfide	1.74E+04	kgkm	29,000 km	transport, freight, sea, container ship Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
Polyphenylene sulfide	6.44E+02	kgkm	1,060 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 16-32 metric ton, EURO6 {RER}
PE masterbatch	1.99E+01	kgkm	1,600 km	market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
glass fibre	1.53E+02	kgkm	370 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
pallet	1.53E-02	kgkm	228 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
packaging bag	6.70E+00	kgkm	931 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir				Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}
cap	1.97E-02	kgkm	12 km	market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 95. LCI per FU - LARTON Core - Manufacturing.

Process	Quantity	Unit	I/O	Ecoinvent Database
Facility electricity - Wind power	5.59E-01	kWh	I	Green energy - 100% Wind power - Electricity, high voltage {IT} market for electricity, high voltage Cut-off, U
Facility electricity PV	1.73E-02	kWh	I	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U
Facility electricity PV sold	-9.01E-05	kWh	I	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U
Facility methane	6.38E-01	MJ	I	Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U
Extruder maintenance materials	1.68E-03	kg	I	Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U
Aqueduct water	3.88E-01	kg	I	Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U
Well water	1.83E-04	m ³	I	Water, well, IT
Metal scrap	1.68E-03	kg	O	Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U
WW treatment	5.72E-04	m ³	O	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U
Plastic mixture	3.34E-02	kg	O	Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U
Wood	6.86E-05	kg	O	Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U

Table 96. LCI per FU - LARTON Downstream - Final product transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
				Transport, freight, lorry 7.5-16 metric ton, EURO6
Final transport	6.56E+01	kgkm	65 km	{RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 97. LCI per FU - LATER Upstream - Raw materials production (I = input, O = output).

Process	Quantity	Unit	I/O	Ecoinvent Database
Polybutadiene production - China	<i>omissis</i>	kg	I	Polybutylene terephthalate {RoW} polybutylene terephthalate production Cut-off, U
Packaging Polybutadiene	1.77E-03	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet Polybutadiene	3.53E-05	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Ethylene copolymer process production - Belgium	<i>omissis</i>	kg	I	Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U
Packaging Ethylene copolymer	2.47E-04	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet Ethylene copolymer	2.75E-06	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Antimony trioxide production - China	<i>omissis</i>	kg	I	Stibnite concentrate {GLO} market for stibnite concentrate Cut-off, U
Packaging antimony trioxide	1.15E-04	kg	I	Ethylene {RoW} market for ethylene Cut-off, U Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet antimony trioxide	1.92E-06	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U

Glass fibre process production - Belgium	<i>omissis</i>	kg	I	Glass fibre {RER} glass fibre production Cut-off, U
Packaging Glass fibre	1.24E-03	kg	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Pallet Glass fibre	2.06E-05	p	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
PE masterbatch process production - Germany	<i>omissis</i>	kg	I	Carbon black {GLO} market for carbon black Cut- off, U
Packaging PE masterbatch	4.94E-05	kg	I	Polyethylene, high density, granulate {GLO} market for polyethylene, high density, granulate Cut-off, U
Pallet PE masterbatch	5.49E-07	p	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
TBBPA process production - USA	<i>omissis</i>	kg	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Packaging TBBPA	5.56E-04	kg	I	Decabromodiphenyl ether {RoW} decabromodiphenyl ether production Cut-off, U
Pallet TBBPA	6.18E-06	p	I	Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U
Final product packaging pallet	6.73E-05	p	I	EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U
Final product packaging PE bag	3.60E-03	kg	I	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U
Final product packaging ALU bag	3.60E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
				Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U

Final product packaging cap	1.64E-03	kg	I	Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U
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Table 98. LCI per FU - LATER Core - Raw and other materials transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
Transport train Polybutadiene	1.65E+03	kgkm	3,100 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo ship Polybutadiene	4.94E+03	kgkm	9,300 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport tir Polybutadiene	9.78E+01	kgkm	184 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir Ethylene copolymer	3.52E+01	kgkm	850 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport tir antimony trioxide	2.35E+00	kgkm	370 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo ship antimony trioxide	4.56E+02	kgkm	9,300 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport tir antimony trioxide	5.33E+00	kgkm	148 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Transport Glass fibre	tir	2.79E+02	kgkm	900 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport PE masterbatch	tir	7.22E+00	kgkm	871km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport TBBPA	tir	1.28E+02	kgkm	370 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cargo TBBPA	ship	6.87E+02	kgkm	7,363 km	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U
Transport TBBPA	tir	8.94E+01	kgkm	958 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport pallet	tir	1.53E-02	kgkm	228 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport packaging bag	tir	6.70E+00	kgkm	931 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U
Transport cap	tir	1.97E-02	kgkm	12 km	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

Table 99. LCI per FU - LATER Core - Manufacturing.

Process	Quantity	Unit	I/O	Ecoinvent Database
Facility electricity - Wind power	5.59E-01	kWh	I	Green energy - 100% Wind power - Electricity, high voltage {IT} market for electricity, high voltage Cut-off, U
Facility electricity PV	1.73E-02	kWh	I	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U
Facility electricity PV sold	-9.01E-05	kWh	I	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U
Facility methane	6.38E-01	MJ	I	Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U
Extruder maintenance materials	1.68E-03	kg	I	Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U
Aqueduct water	3.88E-01	kg	I	Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U
Well water	1.83E-04	m ³	I	Water, well, IT
Metal scrap	1.68E-03	kg	O	Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U
WW treatment	5.72E-04	m ³	O	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U
Plastic mixture	3.42E-02	kg	O	Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U
Wood	6.73E-05	kg	O	Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U

Table 100. LCI per FU - LATER Downstream - Final product transport.

Process	Quantity	Unit	Distance	Ecoinvent Database
				Transport, freight, lorry 7.5-16 metric ton, EURO6
Final transport	6.56E+01	kgkm	65 km	{RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U

ANNEX II

Table 101 provides detailed descriptions of the processes used in the LCA model in accordance with Ecoinvent v3.10 database.

Table 101. Description of processes from Ecoinvent v3.10 database (GLO: Global, IT: Italy, RER: Europe, RoW; Rest of World).

Process	Description from Ecoinvent v3.10 database
Aluminium sulfate, powder {RoW} market for aluminium sulfate, powder Cut-off, U	This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'aluminium sulfate, powder', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included. 'aluminium sulfate, powder' is an inorganic substance with a CAS no. : 010043-01-3. It is called 'dialuminum trisulfate' under IUPAC naming and its molecular formula is: Al ₂ O ₁₂ S ₃ . It is solid under normal conditions of temperature and pressure and may have a crystalline/pellets/powder form. The substance is modelled as a pure substance. On a consumer level, is used in the following products: pH regulators and water treatment products, water treatment chemicals, fertilisers, cosmetics and personal care products and washing & cleaning products. On industrial sites, the substance is used for the manufacture of products in the following sectors: laboratory chemicals, pH regulators and water treatment products, paper chemicals and dyes, leather treatment products, textile treatment products and dyes and coating products.
Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U	This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'aluminium, wrought alloy', in the Global geography. In this market, expert judgement was used to develop product specific transport distance estimations.
Ammonia, anhydrous, liquid {RoW} market for ammonia, anhydrous, liquid Cut-off, U	This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer

	<p>and for the losses during that process, when relevant. This is the market for 'ammonia, anhydrous, liquid', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included. Ammonia, anhydrous, liquid' is an inorganic substance with a CAS no. : 007664-41-7. It is called 'azane' under IUPAC naming and its molecular formula is: NH₃. It is gas under normal conditions of temperature and pressure and has a distinct pungent odour. The substance is modelled as a pure substance. On a consumer level, is used in the following products: cosmetics and personal care products, heat transfer fluids, washing & cleaning products and coating products. On industrial sites, the substance is used for the manufacture of products in the following sectors: chemicals, textile, leather or fur, pulp, paper and paper products, plastic products and fabricated metal products. Based on EU regulations (REGULATION (EU) 2019/1009), if this substance would be used as fertiliser, it could be labelled as N-P-K of: (82-0-0).</p>
Boric oxide {GLO} market for boric oxide Cut-off, U	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'boric oxide', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included.</p>
Bromine {GLO} market for bromine Cut-off, U	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This dataset represents the supply of 1 kg of bromine from activities that produce it within the geography of this dataset. In this market, expert judgement was used to develop product-specific transport distance estimations based on the default transport distances for markets, provided in the 'Default Transport Assumptions' file available on theecoinvent website (https://www.ecoinvent.org/support/documents-and-files/documents-and-files.html). See exchange comments for additional details.</p>
Carbon black {GLO} market for carbon black Cut-off, U	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'carbon black', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included. 'carbon black' is an inorganic substance with</p>

	<p>a CAS no. : 101239-80-9. It is called 'carbon' under IUPAC naming and its molecular formula is: C. It is solid under normal conditions of temperature and pressure as a black powder. It is modelled as a pure substance. On a consumer level, is used in the following products: inks and toners, adhesives and sealants, coating products, fillers, putties, plasters, modelling clay, textile treatment products and dyes, finger paints, lubricants and greases and cosmetics and personal care products. There is no publicly available information about the consumption of this substance on industrial sites.</p>
<p>Decabromodiphenyl ether {RoW} decabromodiphenyl ether production Cut-off, U</p>	<p>Decabromodiphenyl ether is mainly used as a flame retardant for plastics and textile products (Pakalin et al., 2007). The global demand for the product decabromodiphenyl ether in 2001 was of 56100 tonnes and the European demand was of 7600 tonnes. This product is not produced in Europe anymore but only imported (Pakalin 2007).</p> <p>Reference(s):</p> <p>Gendorf (2016) Umwelterklärung 2015, Werk Gendorf Industriepark, www.gendorf.de</p> <p>Pakalin, S. et al. 2007. "REVIEW ON PRODUCTION PROCESSES OF DECABROMODIPHENYL ETHER (DECABDE) USED IN POLYMERIC APPLICATIONS IN ELECTRICAL AND ELECTRONIC EQUIPMENT, AND ASSESSMENT OF THE AVAILABILITY OF POTENTIAL ALTERNATIVES TO DECABDE'. EUROPEAN COMMISSION, European Communities, Italy.</p> <p>For more information on the model please refer to the dedicate ecoinvent report, access it in the Report section of ecoQuery (http://www.ecoinvent.org/login-databases.html)</p>
<p>Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted- roof installation, multi-Si, panel, mounted Cut-off, U</p>	<p>This dataset represents the production of grid-connected low voltage electricity with a 3 kWp building integrated photovoltaic (PV) module in Italy in 2012. The 3 kWp module has been chosen as basic module for building integrated PV electricity production. Larger modules can easily be built with these 3 kWp modules without producing a significant error in environmental impact calculations. The module is a multi-Si panel installed on a slanted roof. An inverter is used to convert the low voltage DC power into AC power.</p>
<p>Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This dataset describes the electricity available on the high voltage level in Italy. This is done by showing the transmission of 1kWh electricity at high voltage. Included activities start: This activity starts from 1kWh of electricity fed into the medium voltage transmission network. Included activities end: This activity ends with the transport of 1 kWh of medium voltage electricity in the transmission network over aerial lines and cables.</p> <p>This dataset includes:</p>

	<ul style="list-style-type: none"> - electricity inputs produced in this country and from imports and transformed to medium voltage - the transmission network - direct emissions to air (SF6 from the insulation gas in the high voltage level switchgear are allocated to the electricity demand on medium voltage). - electricity losses during transmission <p>This dataset doesn't include</p> <ul style="list-style-type: none"> - electricity losses during transformation from high to medium voltage or medium to low, as these are included in the dataset for transformation - leakage of insulation oil from cables and electro technical equipment (transformers, switchgear, circuit breakers) because this only happens in case of accidental release - SF6 emissions during production and deconstruction of the switchgear, as these are accounted for in the transmission network dataset. <p>Energy values: Undefined</p> <p>Geography: The inventory is modelled for Italy</p> <p>Technology level: Current</p> <p>Technology: Average technology used to transmit and distribute electricity. Includes underground and overhead lines, as well as air-, vacuum- and SF6-insulated high-to-medium voltage switching stations. Electricity production according to related technology datasets.</p> <p>Definition of the voltage levels:</p> <ul style="list-style-type: none"> - High voltage level above 24 kV (large scale industry) - Medium voltage level between 1 kV and 24 kV (medium to small scale industry, service sector and public buildings)
<p>Ethylene {RoW} market for ethylene Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. Data are derived from the Eco-profiles of the European plastics industry (PlasticsEurope). Not included are the values reported for: recyclable wastes, amount of air / N2 / O2 consumed, unspecified metal emission to air and to water, mercaptan emission to air, unspecified CFC/HCFC emission to air, dioxin to water. The amount of "sulphur (bonded)" is assumed to be included into the amount of raw oil.</p>
<p>EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer</p>

	and for the losses during that process, when relevant. This dataset represents the European market for EUR-flat pallets. Transport distance based on eurostat transport statistics.
EUR-flat pallet {RoW} market for EUR-flat pallet Cut-off, U	This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This dataset represents the global market for EUR-flat pallets. Transport according to the ecoinvent Default Transport Assumptions for global transport, accessible at https://www.ecoinvent.org/files/transport_default_20191112.xlsx , based on transport statistics, according to a methodology developed by Borcken & Weidema (2013).
Glass fibre {RoW} glass fibre production Cut-off, U	Inventory based on a state of the art report for the European glass manufacturing industry. Data had to be estimated from ranges given for different parameters. [This dataset was already contained in the ecoinvent database version 2. It was not individually updated during the transfer to ecoinvent version 3. Life Cycle Impact Assessment results may still have changed, as they are affected by changes in the supply chain, i.e. in other datasets. This dataset was generated following the ecoinvent quality guidelines for version 2. It may have been subject to central changes described in the ecoinvent version 3 change report (http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/), and the results of the central updates were reviewed extensively. The changes added e.g. consistent water flows and other information throughout the database. The documentation of this dataset can be found in the ecoinvent reports of version 2, which are still available via the ecoinvent website. The change report linked above covers all central changes that were made during the conversion process.]
Heat, district or industrial, natural gas {IT} heat and power co-generation, natural gas, conventional power plant, 100MW electrical Cut-off, U	This dataset represents the production of high voltage electricity and heat in a conventional steam boiler natural gas power plant with CHP (combined heat and power) in Italy in 2012. For electricity production with natural gas, four different datasets relying to different power plant types exist: <ul style="list-style-type: none"> - conventional power plant with / without CHP - combined cycle power plant with / without CHP At the moment, these datasets differ in nothing but the efficiency. High voltage electricity (at the busbar) is the reference product, whereupon heat is a by-product in CHP plants. Out of all fossile fuels, natural gas holds worldwide the highest share of CHP plants besides peat. Furthermore, natural gas power plants are today often designed with combined cycles. The approximate share of combined cycle natural gas power plants in Italy amounts to ca. {{cc_share}}. {{chp}} combined heat power plants (calculations made with IEA/OECD statistics and own assumptions).

	<p>The efficiency calculations are based on IEA/OECD statistics (fuel inputs, electricity produced) and some own calculation assumptions. Reducing factors such as contaminations of important plant parts, cooling conditions or part load have been taken into account. Even if efficiencies vary with different surrounding temperatures, a medium efficiency is assumed for all countries. Temperature adjustments would be related to high uncertainties.</p> <p>Water is used for wet cooling and as feed water in the steam circuit. In this dataset, 100% wet cooling and no once-through cooling is assumed.</p> <p>EMISSIONS:</p> <p>Different sources served as basis for assumption of average emissions. Where possible, the most recent sources were taken into account, whereas older sources were taken in order to determine the remaining data gaps. The emissions have been fixed for the former UCTE region* and have been overtaken as such for all countries without value adaptation (adaptation of the uncertainty). See ecoinvent report "Erdgas" given as main source for details (Tab. 11.15). In the following a short overview:</p> <ul style="list-style-type: none"> - Emissions of NO_x, CO, CO₂, SO₂, particles, N₂O and CH₄ are mainly taken from CORINAIR 2001, EPA, and a variety of other data sources - NO_x emissions are a major challenge in natural gas power plants. With rising temperature, emissions also rise; band widths of NO_x emissions in literature are correspondingly large. There are several methods to diminish these emissions. - CO is a result of incomplete burning. For economic and technical reasons, plant combustion is optimized and CO emissions are low. - CO₂ and SO₂ emissions are dependent on the composition of the used fuel. Due to the low sulfur content of the used natural gas, no desulfurization has to take place. - Organic compound emissions are estimated on the basis of EPA 1998. - Particles are assumed to be smaller than 2.5 micro-m <p>former UCTE: Union for the Coordination of the Transmission of Electricity, since 2009 replaced by ENTSO-E European Network of Transmission System Operators for Electricity.</p> <p>Sources:</p> <ul style="list-style-type: none"> - CORINAIR 2001. EMEP/CORINAIR 2001: Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook, Third Edition. Copenhagen: European Environment Agency, 2001. http://reports.eea.eu.int/technical_report_2001_3/en. - EPA 1998. US Environmental Protection Agency (1998). Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Chapter 1: External Combustion Sources, Natural Gas Combustion - Final Section - Supplement D, July 1998. CHIEF (Clearinghouse for Inventories and Emission Factors). Research Triangle Park, North Carolina. http://www.epa.gov/ttn/chief/ap42/.
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	<p>- Rentz O., Karl U., Peter H. (2002). Ermittlung und Evaluierung von Emissionsfaktoren für Feuerungsanlagen in Deutschland für die Jahre 1995, 2000 und 2010. Deutsch-Französisches Institut für Umweltforschung, Uni Karlsruhe. Endbericht. Im Auftrag des Umweltbundesamtes. Forschungsbericht 299 43 142. Umweltbundesamt. Berlin.</p>
<p>Hydrogen cyanide {RoW} hydrogen cyanide production Cut-off, U</p>	<p>Data are derived from the Eco-profiles of the European plastics industry (PlasticsEurope). Not included are the values reported for: recyclable wastes, amount of air / N₂ / O₂ consumed, unspecified metal emission to air and to water, mercaptan emission to air, unspecified CFC/HCFC emission to air, dioxin to water. The amount of "sulphur (bonded)" is assumed to be included into the amount of raw oil.</p>
<p>Melamine {GLO} market for melamine Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'melamine', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included. Melamine' is an organic substance with a CAS no. : 108-78-1. It is called '1,3,5-triazine-2,4,6-triamine' under IUPAC naming and its molecular formula is: C₃H₆N₆. Other names are Cyanurotriamide, Cyanuramide, Isomelamine, and Cyanurotriamine. Melamine is at room temperature a fine white powdered crystal. Its solubility in water is depending on temperature. Almost 100% of melamine is produced out of urea. Different production techniques can be distinguished. All of them are either high-pressure reactions without any catalysts or catalytic reactions at low pressure. This product represents a 50:50 mix of melamine produced by the BASF process (as representative for the low-pressure reactions) and the Montedison process (example of high pressure process). Most melamine is used for the reaction with formaldehyde for the production of resins used in laminating and adhesive applications. Among these applications, one of the most important ones is the use of melamine for the upper sheet e. g. of tabletops. A second important use of melamine is its function as amino cross-linker in heat-cured systems – e. g. in the automotive industry. Furthermore, this substance is also applied in other fields like wet-strength resins for paper industry, ion-exchange resins, plastic moulding compounds or fire retardants in PUR foam.</p>
<p>Methacrylic acid {RER} methacrylic acid production Cut-off, U</p>	<p>The process "methacrylic acid, at plant, RER" is modelled for the production of methacrylic acid from acetone in Europe. Raw materials are modelled with a stoichiometric calculation. Emissions are estimated. Energy consumptions, infrastructure and transports are calculated with standard values. Methacrylic acid (CH₂C(CH₃)COOH, CAS 79-41-4, a-methylacrylic acid, 2-methylpropenoic acid) is a colourless, moderately volatile, corrosive liquid with a strongly acrid odour. Methacrylic Acid and Methyl Methacrylate from Acetone</p>

	<p>Cyanohydrin. The most common approach to methacrylic acid synthesis is the hydrolysis of methacrylamide sulfate, obtained from acetone cyanohydrin. Methyl methacrylate may be prepared directly in a similar way by adding methanol in the final reaction step. Dry acetone and hydrogen cyanide react in the presence of a basic catalyst to give the cyanohydrin, which is then reacted with excess concentrated sulfuric acid (1.4 – 1.8 mol per mole of cyanohydrin) to form methacrylamide acid sulfate: The sulfuric acid serves both as a specific reactant and as a solvent for the reaction, which appears to involve an α-sulfatoamide intermediate. If insufficient sulfuric acid is used, the reaction mass becomes a slurry or solid that is difficult or impossible to cool and pump. Both the sulfuric acid and the acetone cyanohydrin must be anhydrous in order to minimize hydrolysis of the sulfato derivative to α-hydroxyisobutyramide. The initial reaction is carried out continuously in a series of stirred tank reactors. Good heat transfer is required to assure removal of the heat of reaction. Thorough mixing is also necessary to avoid decomposition of the cyanohydrin to acetone and hydrogen cyanide, which can react to form byproduct acetone sulfonates and formamide sulfate. After initial reaction is completed at 80 – 110 °C, the mixture is subjected to brief thermal cracking at ca. 125 – 160 °C to convert most of the α-hydroxyisobutyramide byproduct to methacrylamide sulfate, along with some acetone, carbon monoxide, and water. Total residence time at this stage of the process is about 1 h. In a second stage, the methacrylamide sulfate stream is either hydrolyzed with excess water to give methacrylic acid and ammonium acid sulfate, or it is treated with aqueous methanol in a combined hydrolysis – esterification step to produce a mixture of methyl methacrylate and methacrylic acid. Several modifications are possible in the hydrolysis – esterification step. For example, the methacrylamide sulfate, water, methanol, and recycle streams can be led through a series of continuous reactors at 80 – 110 °C with a 2 – 4 h residence time. The reactor effluent then passes to a stripping column where crude methyl methacrylate, water, and excess methanol are removed overhead. The waste acid ammonium sulfate residue can be either treated with ammonia for conversion to fertilizer or burned to regenerate sulfuric acid. Crude methyl methacrylate is extracted with water to recover methanol, which is concentrated and recycled to the esterification reactor. Washed ester is then purified by further distillation. The overall yield based on acetone cyanohydrin is in the range of 80 – 90 %. In the manufacture of methacrylic acid, methacrylamide sulfate is reacted with water under conditions similar to those used for formation of the ester. The reactor effluent separates into two phases. The upper organic layer is distilled to provide pure methacrylic acid. The lower layer is steam stripped to recover dilute aqueous methacrylic acid, which is recycled to the hydrolysis reactor. The waste acid stream is treated as in the manufacture of the ester. In an alternative process, the methanolysis reaction is carried out at a pressure of ca. 800 kPa in one or more reactors operated at 100 – 150 °C. The reactor effluent is separated into two layers while still</p>
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	<p>under pressure. The lower layer is steam stripped to recover methacrylic acid for recycle to the esterification reactor, and acid waste is treated as described previously. The upper layer is passed to a distillation column where light ends (primarily dimethyl ether) are removed. The bottoms from this column are washed with aqueous ammonia to recover methanol and methacrylic acid for recycle to the esterification reactor. The crude, washed methyl methacrylate is then dehydrated in a downstream distillation column and distilled in a product column to provide pure methyl methacrylate. A sulfuric acid regeneration plant is usually operated in conjunction with the methyl methacrylate plant, because approximately 1.6 kg of sulfuric acid is required to produce each kilogram of methyl methacrylate. The presence of a regeneration facility avoids the need to dispose of large quantities of ammonium sulfate contaminated with organic material. One of the driving forces for development of the alternative routes discussed in Sections Methacrylic Acid from Isobutene, Methacrylic Acid from Isobutyric Acid, Methacrylic Acid From Ethylene has been the desire to eliminate the need for sulfuric acid regeneration. An additional concern is the hazard associated with transporting hydrogen cyanide, which is not always generated at the methacrylate plant site. On the other hand, both acetone (from phenol manufacture) and hydrogen cyanide (from acrylonitrile manufacture) have the economic advantage of being themselves industrial byproducts. Asahi Chemical manufactures methyl methacrylate by the sulfuric acid hydrolysis of methacrylonitrile, using a plant originally designed for the acetone cyanohydrin process. The requisite methacrylonitrile is obtained by ammoxidation of isobutene, avoiding the need for hydrogen cyanide.</p> <p>Methacrylic Acid from Isobutene: In recent years many companies have investigated the manufacture of methacrylic acid by two-stage catalytic oxidation of isobutene or tert-butanol. Nihon Methacryl Monomer (a joint venture of Sumitomo and Nippon Shokubai) and Mitsubishi Rayon have both constructed commercial plants using this technology. In the first stage of the process, isobutene is oxidized to methacrolein (Acrolein and Methacrolein – Methacrolein), and in a second stage the methacrolein is oxidized to methacrylic acid. A published account of process and catalyst developments contrasts methacrylic acid production from isobutene with a similar process for preparing acrylic acid from propene. Selectivity of the second-stage catalysts is best at modest conversions (65 – 85 %). In the Sumitomo–Nippon Shokubai process, the first-stage reactor is operated at high conversion, and its effluent passes directly to the second oxidation reactor. Conversion in the second stage is kept low in order to ensure good catalyst selectivity and increase catalyst life. Unreacted methacrolein from the second-stage reactor effluent is separated and recycled. The overall yield of methacrylic acid from isobutene is about 65 – 70 %. Typical catalysts for the first stage are multicomponent metal oxides containing bismuth, molybdenum, and several other metals to promote activity and modify selectivity. Second-stage catalysts are</p>
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	<p>based on phosphomolybdic acid, but they usually contain an alkali metal to control the acidity. Other elements such as copper and vanadium may also be present. Reactor effluent from the second-stage oxidation passes to a quencher where crude aqueous methacrylic acid is obtained. The gaseous effluent from the quencher is passed to an absorber the unreacted methacrolein is absorbed, usually in aqueous carboxylic acid. Absorber off-gases are sent to a combustion unit before being discharged to the atmosphere. A portion of the incinerated gases may be recycled to the first-stage reactor to provide inert gas diluent for the feed. The methacrolein absorbate is transferred to a methacrolein recovery tower from which methacrolein is recycled to the second-stage oxidation reactor; recovered absorbent solution is returned to the absorber. The crude, aqueous methacrylic acid is sent to a solvent extraction unit for methacrylic acid recovery. Next, a solvent recovery/dehydration tower affords crude methacrylic acid as a bottoms product. The overhead organic solvent layer is recycled to the extraction step, whereas the overhead aqueous layer is combined with extractor raffinate and sent to a solvent stripping tower before being subjected to wastewater treatment. Dry, crude methacrylic acid from the extract stripper can be further purified if methacrylic acid is the desired end product, or it can be sent directly to an esterification reactor where catalyst and methanol are added for conversion to methyl methacrylate. Crude ester is extracted with water (j) to recover excess methanol, which is removed by distillation and recycled to the esterification reactor. The washed, crude ester is sent to a light ends stripper for removal of light byproducts (e.g., methyl acetate) and then distilled to provide pure methyl methacrylate. The bottoms from the final distillation column are recycled to the first extraction step with the exception of a small bleed for removal of inhibitor residues. Plants based on the C-4 route were introduced in Japan by Nippon Shokubai in 1982 and by Mitsubishi Rayon in 1983. A joint venture plant operated by Sumitomo and Nippon Shokubai came on stream in 1984. Mitsui Toatsu and Kyowa Gas have also announced plans to construct a plant of this type. Several firms, including Nippon Kayaku, Mitsui Toatsu, Rohm and Haas, and Oxirane have carried out extensive research on the isobutene process. In 1987 ARCO acquired exclusive worldwide rights to Halcon SD technology using C4-feedstocks. Halcon has proposed a variation of this process that commences with dehydrogenation of isobutane.</p> <p>Methacrylic Acid from Isobutyric Acid: Acid-catalyzed carbonylation of propene to isobutyric acid, followed by oxidative dehydrogenation, presents still another route to methacrylic acid. In this case the starting material is propene itself rather than the oxydized derivative acetone, as in the acetone cyanohydrin route. Although the propene – isobutyric acid – methacrylic acid route is not currently in commercial use, several major methyl methacrylate manufacturers have research efforts aimed at its commercialization. In the first stage of the process, propene, carbon monoxide, and water are reacted in the presence of a strong acid catalyst to produce isobutyric acid. Sulfuric acid, hydrogen fluoride, and boron</p>
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fluoride have all been reported to be effective catalysts. Patents to Röhm and Ashland Oil describe variations that involve preliminary preparation of isobutyryl fluoride, which is then hydrolyzed to isobutyric acid. Alternatively, isobutyric acid may be synthesized directly by including carefully controlled amounts of water in the carbonylation step. Hydrogen fluoride (which acts as both solvent and catalyst), carbon monoxide, and propene (14 – 40 : 1.5 : 1) are reacted in the presence of a slight stoichiometric deficiency of water relative to propene to generate isobutyric acid. Reaction conditions are included in the patent literature; these range from about 30 °C at 20 MPa to 120 °C at 14 MPa. Depending upon the temperature and pressure, residence time during the carbonylation step varies from about 5 to 30 min. Reactor effluent is passed to staged flash tanks, in the first of which excess carbon monoxide can be recovered for recycle to the carbonylation reactor. The second tank permits removal of inert gases, which can be passed to the atmosphere after scrubbing with caustic solution to remove any hydrogen fluoride or isopropyl fluoride. The bulk of the hydrogen fluoride is separated overhead in a distillation tower for recycle to the carbonylation reactor. The bottoms from this tower pass to a hydrolysis stripper where any remaining fluorine-containing materials are reacted with water; hydrogen fluoride is stripped off for recycle. A final distillation step provides isobutyric acid overhead for feed to the second part of the process. Bottoms from this distillation contain small amounts of C7 and C10 carboxylic acids resulting from multiple condensations of propene prior to reaction with carbon monoxide. The overall selectivity with respect to propene is reported to be 95 – 97 %. The preceding steps must be carried out in a facility carefully designed to prevent fugitive fluoride emissions. In the second stage of the process, isobutyric acid, steam, and air are passed over a fixed-bed catalyst in a multitubular reactor, causing oxidative dehydrogenation to methacrylic acid. The reactor effluent is sent to a quench tower from which an aqueous methacrylic acid stream is obtained. This part of the process is similar to the methacrolein oxidation step in the C-4 process described in Section Methacrylic Acid from Isobutene. In addition to carbon monoxide and carbon dioxide, which are incinerated with other noncondensable gases, the crude methacrylic acid stream contains acetone and acetic acid as byproducts. If desired, and with proper choice of quench tower conditions, the acetone can be directed to the incinerator along with the noncondensables. If methacrylic acid is to be isolated, the crude product may be extracted into a solvent and dehydrated in a distillation tower. Isobutyric and acetic acids are then separated by distillation as light ends prior to final distillation of the methacrylic acid. The distillative separation of isobutyric acid from methacrylic acid is very difficult; normal boiling points of the two materials are 155 and 162 °C, respectively. Catalysts for the oxidative dehydrogenation of isobutyric acid to methacrylic acid are of two general types. The first series, often referred to as Mo – P – V mixed oxide catalysts, were developed by Mitsubishi Chemical Industries, Röhm, and others,

and they are similar in composition to catalysts used in the oxidation of methacrolein. Most are phosphomolybdic acid derivatives, usually with some replacement of molybdenum by vanadium or tungsten. The better catalysts frequently contain at least some copper, and they are partially neutralized by cesium, rubidium, or potassium. Some catalysts are reported to achieve conversions of 99.8 % with selectivities above 74 %. A second type of catalyst has been intensively studied by Ashland Oil. These include iron phosphate materials and give selectivities of about 84 – 85 % at conversions in the 85 – 95 % range. Such catalysts are used at about 400 °C, in contrast to ca. 300 °C for the phosphomolybdate catalysts. Iron phosphate catalysts require high levels of steam in the reactor feed for optimum selectivity and life. According to patents issued to Röhm, crude reactor product from the oxidative dehydrogenation step can be sent directly to the esterification reactor, which constitutes the starting point for the third section of the process. In this case, the product methyl methacrylate must be separated from methyl acetate and methyl isobutyrate. Separation of methyl isobutyrate from methyl methacrylate is difficult because its boiling point (92 °C) is close to that of methyl methacrylate (101 °C). The esterification step is similar to that described in Section Methacrylic Acid from Isobutene for the C-4 process. Norsolor has an exclusive European license to the Ashland Oil technology, which Norsolor has further developed in a pilot plant at St. Avold (France). Röhm has developed its own process for this route in a pilot plant at Darmstadt. An alternative process involves the hydroformylation of propene to give isobutyraldehyde, followed by oxidation of the aldehyde to isobutyric acid.

Methacrylic Acid From Ethylene: Other routes to methacrylic acid include the condensation of formaldehyde with propionic acid to generate methacrylic acid and the condensation of formaldehyde with propanal to give methacrolein. BASF has developed such a process based on ethylene, synthesis gas, and formaldehyde. A plant with a production capacity of 40 000 t/a came on stream at Ludwigshafen in 1990. Ethylene is first hydroformylated to give propanal, which is then condensed with formaldehyde to produce methacrolein. Catalytic air oxidation of methacrolein to methacrylic acid completes the synthesis, a step that is common to the C-2 and C-4 routes: An alternative process would entail oxidation of propanal to propionic acid, condensation of which with formaldehyde would give methacrylic acid directly. The fracture toughness of boron carbide can be improved by addition of yttria or of yttria in combination with other oxides. The fracture toughness of B4C can be increased to 3.9 MPa·m^{1/2} by vacuum sintering at 1900 – 1975°C of powder compacts of composition 97.5 wt % B4C and 2.5 wt % carbon packed in a yttria grit of 0.15 – 1.4 mm grain size. The vacuum allows yttria vapor to penetrate the powder compact and promote reaction sintering of carbon-doped B4C to full density (2.62 g/cm³). X-ray diffraction showed that yttrium boride and yttrium borocarbide were coexistent with B4C. The method disclosed in uses liquid-phase sintering under vacuum or streaming argon of powder compacts comprising

	<p>B4C powder (average particle size 0.6 – 3.5 µm) and 1 – 28 wt % additions of Y2O3 in combination with Al2O3 or aluminum nitride (AlN) and La2O3 or CeO2.</p> <p>Methacrylic acid and methacrylate esters are used to prepare a wide range of polymers. Poly(methyl methacrylate) is the primary polymer in this category, and it provides water-clear, tough plastics that are used in sheet form in glazing, signs, displays, and lighting panels. Automotive lighting lenses and similar products can be prepared from molding pellets. Methyl methacrylate incorporated into copolymers forms the basis for durable coatings and inks. Higher methacrylate polymers are useful in the manufacture of oil additives, solventless inks and coatings, and binders for xerography. Salts of poly(methacrylic acid) can serve as the basis for water-soluble thickeners and detergent additives.</p> <p>References:</p> <p>Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hirschier R., Nemecek T., Rebitzer G. and Spielmann M. (2007) Overview and Methodology. Final report ecoinvent v2.0 No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.</p> <p>Gendorf (2000) Umwelterklärung 2000, Werk Gendorf. Werk Gendorf, Burgkirchen as pdf-File under: http://www.gendorf.de/pdf/umwelterklaerung2000.pdf</p> <p>William Bauer Jr.: Methacrylic Acid and Derivatives. Published online: 2000. In: Ullmann's Encyclopedia of Industrial Chemistry, Seventh Edition, 2004 Electronic Release (ed. Fiedler E., Grossmann G., Kersebohm D., Weiss G. and Witte C.). 7 th Electronic Release Edition. Wiley InterScience, New York, Online-Version under: DOI: 10.1002/14356007.a16_441</p>
<p>Mixed plastics (waste treatment) {GLO} recycling of mixed plastics Cut-off, U</p>	<p>This dataset was created by PRé Consultants. This is an empty process because of the cut-off at recycling. The recycling benefit and costs are allocated to the production of the recycled plastic. To include this benefit and cost the following data should be included: Polyethylene, high density, granulate {RER} production (0,461kg), Polyvinylchloride, emulsion polymerised {RER} polyvinylchloride production, emulsion polymerisation (0,03kg), Polyvinylchloride, suspension polymerised {RER} polyvinylchloride production, suspension polymerisation (0,033), Polyvinylchloride, bulk polymerised {RER} polyvinylchloride production, bulk polymerisation (0,005 kg), Polyethylene terephthalate, granulate, bottle grade {RER} production (0,183 kg), Polystyrene, general purpose {RER} production (0,048 kg) and Polypropylene, granulate {RER} production (0,266 kg) should be used as avoided product and 0,6 kWh Electricity, medium voltage {RoW} market for should be used as input from technosphere. These are rough estimates and should not be used if recycling is important. The use of avoided products may lead to double counting in cases where the benefits and burdens of the avoided products are already processed in the ecoinvent processes.</p>

<p>Nylon 6 {RER} nylon 6 production Cut-off, U</p>	<p>Data are derived from the Eco-profiles of the European plastics industry (PlasticsEurope). Not included are the values reported for: recyclable wastes, amount of air / N2 / O2 consumed, unspecified metal emission to air and to water, mercaptan emission to air, unspecified CFC/HCFC emission to air, dioxin to water. The amount of "sulphur (bonded)" is assumed to be included into the amount of raw oil. [This dataset was already contained in the ecoinvent database version 2. It was not individually updated during the transfer to ecoinvent version 3. Life Cycle Impact Assessment results may still have changed, as they are affected by changes in the supply chain, i.e. in other datasets. This dataset was generated following the ecoinvent quality guidelines for version 2. It may have been subject to central changes described in the ecoinvent version 3 change report (http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/), and the results of the central updates were reviewed extensively. The changes added e.g. consistent water flows and other information throughout the database. The documentation of this dataset can be found in the ecoinvent reports of version 2, which are still available via the ecoinvent website. The change report linked above covers all central changes that were made during the conversion process.]</p>
<p>Nylon 6-6 {RER} nylon 6-6 production Cut-off, U</p>	<p>Data are derived from the Eco-profiles of the European plastics industry (PlasticsEurope). Not included are the values reported for: recyclable wastes, amount of air / N2 / O2 consumed, unspecified metal emission to air and to water, mercaptan emission to air, unspecified CFC/HCFC emission to air, dioxin to water. The amount of "sulphur (bonded)" is assumed to be included into the amount of raw oil. [This dataset was already contained in the ecoinvent database version 2. It was not individually updated during the transfer to ecoinvent version 3. Life Cycle Impact Assessment results may still have changed, as they are affected by changes in the supply chain, i.e. in other datasets. This dataset was generated following the ecoinvent quality guidelines for version 2. It may have been subject to central changes described in the ecoinvent version 3 change report (http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/), and the results of the central updates were reviewed extensively. The changes added e.g. consistent water flows and other information throughout the database. The documentation of this dataset can be found in the ecoinvent reports of version 2, which are still available via the ecoinvent website. The change report linked above covers all central changes that were made during the conversion process.]</p>
<p>Packaging film, low density polyethylene {RER} packaging film production, low density polyethylene Cut-off, U</p>	<p>Example process for the utilization of the different converting modules in the database. [This dataset was already contained in the ecoinvent database version 2. It was not individually updated during the transfer to ecoinvent version 3. Life Cycle Impact Assessment results may still have changed, as they are affected by changes in the supply chain, i.e. in other datasets. This dataset was generated following the ecoinvent quality guidelines for version</p>

	<p>2. It may have been subject to central changes described in the ecoinvent version 3 change report (http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/), and the results of the central updates were reviewed extensively. The changes added e.g. consistent water flows and other information throughout the database. The documentation of this dataset can be found in the ecoinvent reports of version 2, which are still available via the ecoinvent website. The change report linked above covers all central changes that were made during the conversion process.]</p>
<p>Phosphoric acid, industrial grade, without water, in 85% solution state {GLO} market for phosphoric acid, industrial grade, without water, in 85% solution state Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'phosphoric acid, industrial grade, without water, in 85% solution state', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included. Phosphoric acid, industrial grade, without water, in 85% solution state' is an inorganic substance with a CAS no. : 007664-38-2. It is called 'phosphoric acid' under IUPAC naming and its molecular formula is: H₃O₄P. It is liquid under normal conditions of temperature and pressure and it has no odour. This dataset represents a pure substance (100% active substance). Industrially, this product is mostly used in 85% solution state. Modelling this substance in a solution requires the user to add the water and/or solvent in their models. To achieve the industrial grade, the fertiliser grade phosphoric acid is purified using solvent to remove impurities. Due to the sulfuric acid added during the extraction, a high yield is achieved: it is about 98% (in % of P₂O₅ input). On a consumer level, is used in the following products: fertilisers, polishes and waxes, washing & cleaning products and welding & soldering products. There is no publicly available information about the consumption of this substance on industrial sites.</p>
<p>Phosphorus, white, liquid {GLO} market for phosphorus, white, liquid Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'phosphorus, white, liquid', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included. Phosphorus, white, liquid is an inorganic substance with a CAS no. : 012185-10-3. It is called 'phosphorus' under IUPAC naming and its molecular formula is: P. It is solid with a sharp, pungent odour similar to garlic. The substance is modelled as a pure substance. On a consumer level, is used in the following products: Building/construction materials, Electrical and electronic products,</p>

	<p>Metal products, Plastic and rubber products, matches and flares. On industrial sites, the substance is used for the manufacture of products in the following sectors: as a component of steel slab, Agricultural chemicals (non-pesticidal), alloy for steelmaking, Flame retardants, Intermediates, Material Recovery, Metal Alloy Constituent, Processing aids, Steel production, alloy in metal production, matches and flares</p>
<p>Plastic flake, consumer electronics, for recycling {GLO} market for plastic flake, consumer electronics, for recycling Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'plastic flake, consumer electronics, for recycling', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included.</p>
<p>Polyethylene, high density, granulate, recycled {Europe without Switzerland} polyethylene production, high density, granulate, recycled Cut-off, U</p>	<p>The functional unit represents the production of 1 kg of polyethylene, high density, granulate, recycled. Energy demand and auxiliary materials of recycling process was extrapolated from the production of recycled PE granulate in the USA. Data for material losses was derived from the production of recycled PE granulate in Switzerland. The delivered sorted waste polyethylene is further sorted and cleaned in a first step in order to remove any unwanted debris. The plastic then needs to be homogenised, so that only HDPE will be processed. If there are other plastic polymers in the batch, this can ruin the recycled end-product. HDPE has a lower specific density than PET, meaning that these plastic polymers can be separated by using sink-float separation. However, HDPE has a similar specific density to PP. In this case, Near Infrared Radiation (NIR) techniques can be used, unless the plastic is too dark and absorbs the infrared waves. HDPE is then shredded and melted down to further refine the polymer. The plastic is then cooled into pellets which can be used in manufacturing. For further information see Kägi et al. (2017). Life Cycle Inventories for Swiss Recycling Processes - Part Carbotech: Recycling of Cardboard, Glass, PE, PET, Tinplate</p>
<p>Polyphenylene sulfide {GLO} polyphenylene sulfide production Cut-off, U</p>	<p>The functional unit represent 1 kg of solid PPS. Large uncertainty of the process data due to weak data on the production process and missing data on process emissions. [This dataset was already contained in the ecoinvent database version 2. It was not individually updated during the transfer to ecoinvent version 3. Life Cycle Impact Assessment results may still have changed, as they are affected by changes in the supply chain, i.e. in other datasets. This dataset was generated following the ecoinvent quality guidelines for version 2. It may have been subject to central changes described in the ecoinvent version 3 change report (http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/), and the results of the central updates were reviewed extensively. The changes added e.g. consistent water flows and other information throughout the database. The documentation of this dataset can be found in the ecoinvent reports of version 2, which are still available via the</p>

	ecoinvent website. The change report linked above covers all central changes that were made during the conversion process.]
Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'polypropylene, granulate', in the Global geography. In this market, expert judgement was used to develop product specific transport distance estimations. 'polypropylene, granulate', is a plastic product of fossil origin, it is not biodegradable and it is a thermoplastic material. This product consists of 100% virgin material with no content of recycled material. The product is used in the following applications and sectors: one of the top three widely used polymers today with extremely wide range of applications as plastic or as fiber, either transparent or pigmented, such as food packaging, textiles, automotive components, furniture market, medical devices, and consumer goods.</p>
Polypropylene, granulate {RER} polypropylene production, granulate Cut-off, U	<p>The dataset represents the production mix of commercial PP production technologies: slurry suspension polymerisation, Bulk suspension polymerisation, gas phase polymerisation using Ziegler-Natta and Metallocene catalysts. PP is usually manufactured with the gas phase or the suspension (slurry) process. Modern suspension processes, however, use liquid monomers instead of a solvent and are termed “bulk” process. In the gas phase processes a fluidised bed of polymer particles and catalyst is maintained by a steady gaseous monomer feed from the bottom of the reactor. Polymer powder is continuously extracted at the bottom of the fluidised bed reactor. Unreacted monomer gas from the top is compressed and recycled to the reactor inlet. Catalyst, and co-catalyst if necessary, is also continuously fed to the reactor. Typically Ziegler-Natta catalysts are used for gas phase polymerisation where the catalyst is supported on inert silica particles so that the reaction takes place at the catalyst surface. The suspension polymerisation can be described as precipitation process. The formation of the polymer takes place in a hydrocarbon diluent and under conditions, where the monomer is soluble in the solution. The precipitated polymer, however, is insoluble and forms a fine suspension. The polymer is then separated by centrifugation. The suspension process can be combined with a stirred tank reactor or a loop reactor. Different diluents can be chosen, like C5 to C9 hydrocarbons, hexane, or isobutane. The bulk suspension process describes the slurry suspension process used for the production of PP where the monomer propylene is used as solvent instead of other hydrocarbons. Modern suspension processes for the production of PP use liquid monomers instead of gaseous. After the reaction phase, most of the residual (unreacted) monomers (which are mostly present as gases) are separated from the polymer and are either recycled back into the process or flared of. Depending on the</p>

	<p>purity of the separated monomers, the gas can either be fed directly back into the production line or the monomers are returned to a purification unit. To limit the accumulation of impurities in the process, usually a small side-stream (purge) of the unreacted gas is sent back to the cracker or to a dedicated purification unit. After polymerisation, the polymer is usually fed di-rectly into a hot melt extruder, where additives can be added to the melted polymer if required. The polymer is then pelletised in an underwater pelletiser. The pelletised product is dried, blended where required and degassed.</p>
<p>Polypropylene, granulate {RoW} polypropylene production, granulate Cut-off, U</p>	<p>The dataset represents the production mix of commercial PP production technologies: slurry suspension polymerisation, Bulk suspension polymerisation, gas phase polymerisation using Ziegler-Natta and Metallocene catalysts. PP is usually manufactured with the gas phase or the suspension (slurry) process. Modern suspension processes, however, use liquid monomers instead of a solvent and are termed “bulk” process. In the gas phase processes a fluidised bed of polymer particles and catalyst is maintained by a steady gaseous monomer feed from the bottom of the reactor. Polymer powder is continuously extracted at the bottom of the fluidised bed reactor. Unreacted monomer gas from the top is compressed and recycled to the reactor inlet. Catalyst, and co-catalyst if necessary, is also continuously fed to the reactor. Typically Ziegler-Natta catalysts are used for gas phase polymerisation where the catalyst is supported on inert silica particles so that the reaction takes place at the catalyst surface. The suspension polymerisation can be described as precipitation process. The formation of the polymer takes place in a hydrocarbon diluent and under conditions, where the monomer is soluble in the solution. The precipitated polymer, however, is insoluble and forms a fine suspension. The polymer is then separated by centrifugation. The suspension process can be combined with a stirred tank reactor or a loop reactor. Different diluents can be chosen, like C5 to C9 hydrocarbons, hexane, or isobutane. The bulk suspension process describes the slurry suspension process used for the production of PP where the monomer propylene is used as solvent instead of other hydrocarbons. Modern suspension processes for the production of PP use liquid monomers instead of gaseous. After the reaction phase, most of the residual (unreacted) monomers (which are mostly present as gases) are separated from the polymer and are either recycled back into the process or flared of. Depending on the purity of the separated monomers, the gas can either be fed directly back into the production line or the monomers are returned to a purification unit. To limit the accumulation of impurities in the process, usually a small side-stream (purge) of the unreacted gas is sent back to the cracker or to a dedicated purification unit. After polymerisation, the polymer is usually fed di-rectly into a hot melt extruder, where additives can be added to the melted polymer if required. The polymer is then pelletised in an underwater pelletiser. The pelletised product is dried, blended where required and degassed.</p>

<p>Polystyrene, general purpose {GLO} market for polystyrene, general purpose Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'polystyrene, general purpose', in the Global geography. In this market, expert judgement was used to develop product specific transport distance estimations. 'polystyrene, general purpose', is a plastic product of fossil origin, it is not biodegradable and it is a thermoplastic material. This product consists of 100% virgin material with no content of recycled material. The product is used in the following applications and sectors: many applications such as food and non-food packaging, disposable cups and cutlery, furniture, toys and consumer goods, as well as electronics and appliances.</p>
<p>Scrap steel {Europe without Switzerland} market for scrap steel Cut-off, U</p>	<p>This is a market activity, representing a treatment mix. In the case of products needing treatment, market mixes are supplied by the activities treating the product in the geography defined by the market, and they supply the activities needing to treat the product, as they have generated it as a by-product in the Undefined processes (present as a negative input in system models). Transport to the treating facility or losses are also accounted in this type of markets, when relevant. This is the market for 'scrap steel', in the geography of Europe without Switzerland. The scrap steel is treated in the same place as it is produced. That is why regional market activities are in this case adequate. The same transport distances as in the global market are used.</p>
<p>Steel, low-alloyed {Europe without Switzerland and Austria} steel production, electric, low-alloyed Cut-off, U</p>	<p>This activity represents the production of secondary low-alloyed steel in an electric arc furnace (EAF). The process comprises the following operations: 1) mixing and pretreatment (if required) of ferrous materials (including alloying additions), principally ferrous scrap; 2) furnace charging and scrap melting; 3) steel and scrap tapping; 4) secondary metallurgical treatment in a ladle furnace; and 5) casting (continuous and/or ingot).</p> <p>Modelling approach: Data on were mostly taken from the IPPC Best Available Technology report from the European Commission (Remus et al., 2013); note that where only data ranges were provided, the geometric mean of reported values was used here. The proportion of each by-product that is recycled internally (i.e. returned as an input to the process after it has been produced) is based on measured data from plants worldwide reported by worldsteel (2010): EAF slag, 3%; secondary metallurgy slag, 14%; and dust, 10%.</p> <p>References:</p> <p>Remus, R., Aguado-Monsonet, M. A., Roudier, S. & Samcho, L. D. (2013). JRC reference report - Best available techniques (BAT) reference document for iron and steel production. Joint Research Centre - European Commission, Luxembourg.</p> <p>Worldsteel (2010). Steel industry by-products. World Steel Association: Brussels, Belgium."</p>

<p>Stibnite concentrate {GLO} market for stibnite concentrate Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'stibnite ore, 70% stibnite', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included.</p>
<p>Tap water {Europe without Switzerland} tap water production, underground water without treatment Cut-off, U</p>	<p>This dataset is created as a child of global dataset with edited production volume. This dataset represents production of 1 kg of tap water under pressure at facility gate, ready for distribution in network. It represents average operation of tap water from underground water without further treatments. Water is pumped from aquifer and pressurized for distribution. Inventory was constructed from reported energy inputs and wastes from a single plant located in Québec assumed to represent 53% of total production of tap water from this technology.</p>
<p>Textile, nonwoven polypropylene {GLO} market for textile, nonwoven polypropylene Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This dataset represents the supply of textile, non-woven polypropylene from activities that produce it within the geography of this dataset. The transport amounts are based on the default transport distances for markets, provided in the 'Default Transport Assumptions' file available on the ecoinvent website (https://www.ecoinvent.org/support/documents-and-files/documents-and-files.html). See exchange comments for additional details.</p>
<p>Transport, freight, lorry 16-32 metric ton, EURO6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'transport, freight, lorry 16-32 metric ton, EURO6', in the geography of Europe. This market contains no transport or losses, as they are irrelevant for the delivered product. This is delivering the service of transportation of 1 metric ton across the distance of 1 km. This service only considers the transportation of goods. The vehicle operates with diesel, its emission standard is classified as EURO6 and it falls under the lorry size class of 16-32 metric tons. The average freight load factor of a 16-32 metric ton lorry is 5.79 tonnes, with a gross vehicle weight (GVW) of 15.79 tonnes. It has a lifetime capacity of 540,000 km. Data for transport is calculated for an average load factor, including empty return trips.</p>

<p>Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'transport, freight, lorry 7.5-16 metric ton, EURO6', in the geography of Europe. This market contains no transport or losses, as they are irrelevant for the delivered product. This is delivering the service of transportation of 1 metric ton across the distance of 1 km. This service only considers the transportation of goods. The vehicle operates with diesel, its emission standard is classified as EURO6 and it falls under the lorry size class of 7.5-16 metric tons. The average freight load factor of a 7.5-16 metric ton lorry is 3.29 tonnes, with a gross vehicle weight (GVW) of 9.29 tonnes. It has a lifetime capacity of 540,000 km. Data for transport is calculated for an average load factor, including empty return trips.</p>
<p>Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW} market for transport, freight, lorry 7.5-16 metric ton, EURO6 Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'transport, freight, lorry 7.5-16 metric ton, EURO6', in the Global geography. This market contains no transport or losses, as they are irrelevant for the delivered product. This is delivering the service of transportation of 1 metric ton across the distance of 1 km. This service only considers the transportation of goods. The vehicle operates with diesel, its emission standard is classified as EURO6 and it falls under the lorry size class of 7.5-16 metric tons. The average freight load factor of a 7.5-16 metric ton lorry is 3.29 tonnes, with a gross vehicle weight (GVW) of 9.29 tonnes. It has a lifetime capacity of 540,000 km. Data for transport is calculated for an average load factor, including empty return trips.</p>
<p>Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'transport, freight, sea, container ship', in the Global geography. This market contains no transport or losses, as they are irrelevant for the delivered product. This is delivering the service of transportation of 1 metric ton across the distance of 1 km. This service only considers the transportation of packaged goods stored in containers like chemicals, grains, metals, electronics, etc. The ship operates with heavy fuel oil and has a mass of 18,165,000 kg. The DWT (load capacity) of the container ship is 43,000 tonnes, and it is estimated to transport</p>

	<p>an average of 7,200 million tonne.kms per year for 25 years. The transport node indirectly considers empty trips (if any) by taking into account the total amount of freight transported throughout the lifetime of the mobile infrastructure.</p>
<p>Waste polyethylene, for recycling, sorted {Europe without Switzerland} market for waste polyethylene, for recycling, sorted Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'waste polyethylene, for recycling, sorted', in the geography of Europe without Switzerland. This is a constrained market for consequential system model, for attributional system models, this is a regular market. In the case of consequential system model, details about the marginal consumer can be found in the comment of the conditional exchange (by-product). No transport is included in this market since it has already been included in the collection activity (i.e., market for the corresponding unsorted waste material).</p>
<p>Waste wood, untreated {IT} market for waste wood, untreated Cut-off, U</p>	<p>This is a market activity, representing a treatment mix. In the case of products needing treatment, market mixes are supplied by the activities treating the product in the geography defined by the market, and they supply the activities needing to treat the product, as they have generated it as a by-product in the Undefined processes (present as a negative input in system models). Transport to the treating facility or losses are also accounted in this type of markets, when relevant. This market dataset models the disposal mix for 1 kg of waste wood, untreated in Italy using country-specific data. The mix is composed by the following technologies: 1% of open burning, 55% of sanitary landfill, 44% of municipal incineration. Values are rounded without decimals. If a technology is listed, it participates in the technology mix. The transport from the production site of the waste to the different treatment facilities where the waste is treated is accounted here. Collection of the waste is included in the transport estimate, reflecting transport distances from eurostat. There are no losses considered in the dataset. Reference: eurostat, 2018, Summary of annual road freight transport by type of operation and type of transport (1 000 t, Mio Tkm, Mio Veh-km), Retrieved online at: http://ec.europa.eu/eurostat/web/transport/data/database on 05 of June 2018.</p>
<p>Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U</p>	<p>This is a market activity, representing a treatment mix. In the case of products needing treatment, market mixes are supplied by the activities treating the product in the geography defined by the market, and they supply the activities needing to treat the product, as they have generated it as a by-product in the Undefined processes (present as a negative input in system models). Transport to the treating facility or losses are also accounted in this type of markets, when relevant. This is the market for 'wastewater, average', in the geography of</p>

	<p>Europe without Switzerland. Transport from producers to consumers of this product in the geography covered by the market is included.</p>
<p>Zinc oxide {GLO} market for zinc oxide Cut-off, U</p>	<p>This is a market activity. Each market represents the consumption mix of a product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and also the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. This is the market for 'zinc oxide', in the Global geography. Transport from producers to consumers of this product in the geography covered by the market is included.</p>