EcoProfile Methodology for Plastic Recyclates

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March 2025

Version 1.2

LCA method overview	
Background database	Ecoinvent v3.10
Dataset type	Cut-off, unit processes
Declared unit	'Production of 1 kg of mechanically recycled polymer pellets (or flakes) [...]'
ISO conformity	ISO 14040 and 14044 structure, internal review
LCIA method	Environmental Footprint 3.1
Software	openLCA 2.4
System boundary	Cradle-to-gate and gate-to-gate

Funded by the European Union's Horizon Europe Programme under Grant Agreement No. 101057067

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List of Abbreviations

Abbreviation	Definition
(r)ABS	(recycled) Acrylonitrile-butadiene-styrene
BFR	Brominated flame retardant
CED	Cumulative energy demand
DRS	Deposit Return Scheme
EoL	End-of-life
ECS	Eddy-current separation
ELV	End-of-life vehicles
EPS	Expanded polystyrene
EU27+3	European Union member states and Norway, Switzerland, and the United Kingdom
EF 3.1	Environmental Footprint version 3.1 (LCIA)
GPPS	General purpose polystyrene
(r)HDPE	(recycled) High density polyethylene
JRC	Joint Research Centre
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
(r)LDPE	(recycled) Low density polyethylene
(r)MPO	(recycled) Mixes polyolefins
NIR	Near-infrared
PBDD/F	Polybrominated dibenzo-p-dioxins and dibenzofurans
(r)PC	(recycled) Polycarbonate
(r)PE	(recycled) Polyethylene
(r)PET	(recycled) Polyethylene terephthalate
PlastEu	Plastics Europe
PLEX	Plastic litter extension for ecoinvent
PO	Polyolefins
(r)PP	(recycled) Polypropylene
PRE	Plastics Recyclers Europe
(r)(HI)PS	(recycled) (high impact) Polystyrene
(r)PVC	(recycled) Polyvinylchloride
SRP	Syndicat national des Régénérateurs de matières Plastiques
UNEP	United Nations Environment Programme
XRF	X-ray Fluorescence
ρ_x	Density of X at standard conditions

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This document describes the methodology used for producing EcoProfiles for mechanical recycled plastics as part of the Horizon Europe project PRIMUS[1].

1 INTRODUCTION AND OVERALL PICTURE

EcoProfiles represent life cycle inventories (LCIs) of chemicals from raw material extraction through production (cradle-to-gate) and are prominently used for chemical products, firstly by PlasticsEurope[2] (PlastEu) in 1993. The idea behind EcoProfiles is to communicate LCI data for European production averages of chemicals. This includes activities such as the mining and preparation of raw materials, the provision of energy, and the production steps leading to the final product, with consideration given to raw material extraction and emissions to air and water throughout this process chain. By default, EcoProfiles do not include further processing steps, such as the production of downstream products, the product's use phase, or its disposal. However, EcoProfiles serve as a valuable tool for understanding chemicals' impacts on resource requirements and environmental consequences in the manufacturing of a product[3]. Yet, presently available EcoProfiles comprise only aggregated datasets, limiting approaches to update the underlying models with new data or analyse environmental impacts across the supply chain in depth.[4]

Currently, more than 70 EcoProfile reports and LCI datasets have been published for high-volume commodity chemicals and primary polymers by PlasticsEurope[5]. They provide essential data to LCI databases like ecoinvent or GaBi. In contrast to primary plastics, high-quality LCI data for secondary plastics remains an understudied topic, lacking environmental comparability of plastic recyclates and primary materials (Figure 1, left). Recently, data for the production of rPS, rPVC, rLDPE, rHPDE, rPET, rPP have been presented by Syndicat national des Régénérateurs de matières Plastiques[6] (SRP). These reports, available exclusively in French, focus on the Life Cycle Impact Assessment (LCIA) and are accompanied by Excel LCI datasets upon request. Details on the production steps and unit process data were not available.

Along with a lack of EcoProfiles for recyclates, there is also a lack of data for recycled plastics in life cycle assessment (LCA) databases. Only two outdated and US-based LCI datasets for mechanically recycled plastics (rPET and rHDPE) and one Swiss-based LCI dataset (rPS, 45% recycling content) are available in the most comprehensive LCA database ecoinvent v3.10 (Figure 1, right), highlighting the need to advance LCI data on recycled material.

[1] PRIMUS Project. (2022). PRIMUS Project – Reforming Secondary Plastics to Become the Primary Raw Material Choice for Added Value Products. https://www.primus-project.eu/
[2] PlasticsEurope. (2022). *Eco-profiles program and methodology* (p. 39). https://plasticseurope.org/wp-content/uploads/2024/03/PlasticsEurope-Ecoprofiles-program-and-methodology_V3.1.pdf
[3] Fröhlich, T., & Wellenreuther, F. (2016). *Ifeu gGmbH: Ecoprofiles*. https://www.ifeu.de/en/topics/industry-and-products/ecoprofiles
[4] Hoffmann, J. (2024). *Increasing transparency for inventory data of plastic production by modeling the olefin supply chain*. openLCA.conf, Berlin. https://www.greendelta.com/wp-content/uploads/2024/04/openLCA.conf_2024_Jonas_Hoffmann.pdf
[5] PlasticsEurope. (2025). *Eco-profiles set*. Plastics Europe. https://plasticseurope.org/sustainability/circularity/life-cycle-thinking/eco-profiles-set/
[6] SRP. (2023). Éco-profils des MPR. SRP Recyclage. https://www.srprecycle.com/eco-profils-des-mpr-2024

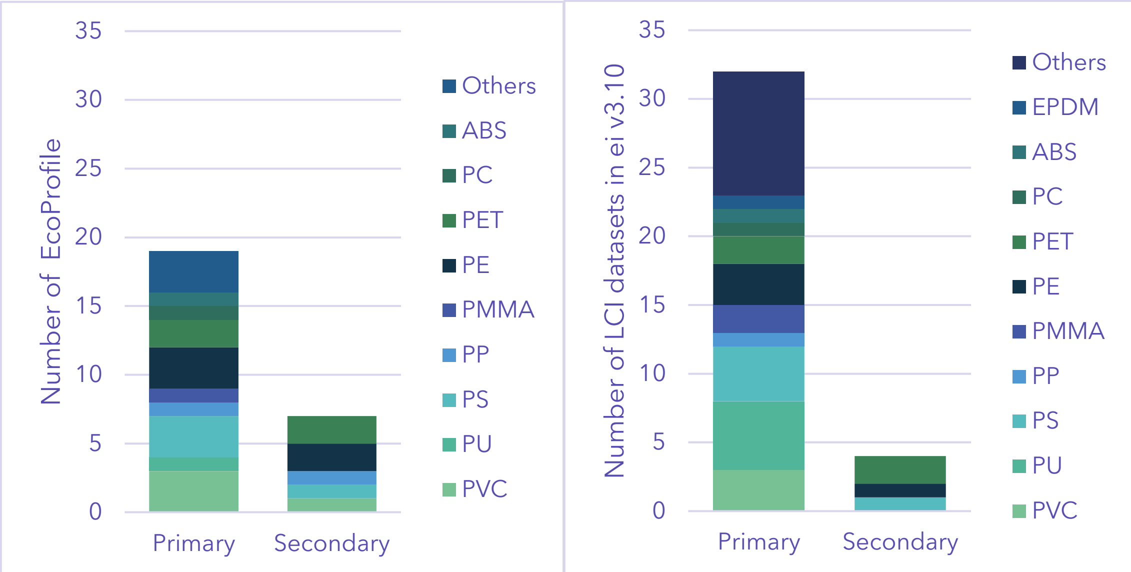

Figure 1. Comparison of available EcoProfiles (PlastEu vs. SRP) and LCI datasets in ecoinvent v3.10 for primary and secondary produced plastics

The lack of available environmental information related to recycled high-value plastics, such as rABS, rHIPS and rPP, prohibits environmental assessments concerning the potentially significant benefit of using these in a variety of applications. To close this knowledge gap, the **PRIMUS project** focuses on high-value plastics, aiming to provide detailed LCI data on these materials. A key objective was to demonstrate the potential of recyclates, particularly in high-value plastic products, by generating comprehensive LCI data for these recycled polymers in the form of EcoProfiles. These EcoProfiles of mechanically recycled plastic were created from European industry data and published alongside data sets for the respective polymers. The declared unit for all EcoProfiles that were provided is '**1 kg of plastic recyclate, unpacked**'. This is subject to further specification in each specific EcoProfile.

The datasets developed according to the method presented in this report contribute to generating new knowledge on the environmental impacts of waste stream usage, thus facilitating the sustainability assessment of circular solutions[7] in the plastics value chain, in line with the focus of the PRIMUS project. See Table 1 on the next page for an overview of datasets that were published along with this report and their respective EcoProfile reports. Regionalised EcoProfile reports and datasets were be published in six versions, one for each region.

[7] Taveau, M., Ngo, T., Palola, S., Joshi, A., zu-Castell Rudenhausen, M., & Tenhunen-Lunkka, A. (2023). *Report on enhancing systemic actions to boost the circularity of target waste streams* (Deliverable No. 1.1). https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e503ab556a&appId=PPGMS

Table 1. Summary of EcoProfile reports published as part of the PRIMUS project. For average European EcoProfile reports, the geographical area was defined as the area of the European Union member states including Norway, Switzerland and the United Kingdom (EU27+3)

Type	**Scope**	**EcoProfile description**	**Polymer data-sets**
Flakes	**Gate-to-gate EU27+3**	**EU27+3 EcoProfile**	**rABS, rHDPE, rHIPS, rMPO, rPET, rPP**
	Cradle-to-gate EU27+3	EU27+3 EcoProfile including collection and sorting	rABS, rHDPE, rHIPS, rMPO, rPET, rPP
	Gate-to-gate Regionalised	EcoProfile regionalised to FR, NL, GB	rABS, rHIPS
	Gate-to-gate Regionalised	EcoProfile regionalised to AT, DE, FR, NL, GB	rPP
Pellets	**Gate-to-gate EU27+3**	**EU27+3 EcoProfile**	**rABS, rHDPE, rHIPS, rLDPE, rMPO, rPET, rPP, rPVC**
	Cradle-to-gate EU27+3	EU27+3 EcoProfile including collection and sorting	rABS, rHDPE, rHIPS, rLDPE, rMPO, rPET, rPP, rPVC
	Gate-to-gate Regionalised	EcoProfile regionalised to FR, NL, GB	rABS, rHIPS
	Gate-to-gate Regionalised	EcoProfile regionalised to AT, DE, FR, NL, GB	rPP

Data sets will be made available via openLCA Nexus (https://nexus.openlca.org).

2 ROLES AND RESPONSIBILITIES

About the Data owner

As the data has been collected by Plastics Recyclers Europe (PRE), the data is owned by PRE, who retain responsibility for the accuracy and integrity of the data.

LCA practitioner and dataset developer

The GreenDelta GmbH developed the LCA methodology and produced the EcoProfiles' data and reports. The datasets are also provided in a disaggregated format, allowing the users to successively update data or to use them with a background database of their choice.

Reviewer

VTT Research Centre of Finland reviewed the methodology, an exemplary EcoProfile report and the respective datasets. Persons involved have not been part of the PRIMUS project prior to the review. A final review statement is published herein.

The roles of each party are also described in the published datasets.

3 PURPOSE OF THIS DOCUMENT

- The document has been prepared by the fundamental principles and structure of ISO 14040/44 with guidance from the ILCD Handbook[8] to create EcoProfiles and LCI datasets of plastic recyclates
- The document aims to provide a methodological framework for LCA practitioners for the development and use of EcoProfiles in the field of plastic recycling harmonizing efforts with details about the generation of EcoProfiles with emphasis on recycled polymers in the scope of the PRIMUS project
- To deliver information to other stakeholders for their educated use of the EcoProfile datasets in the field of plastic recyclates

[8] European Commission. Joint Research Centre. Institute for Environment and Sustainability. (2010). *International Reference Life Cycle Data System (ILCD) Handbook :general guide for life cycle assessment: Detailed guidance*. Publications Office. https://data.europa.eu/doi/10.2788/38479

4 BACKGROUND AND DATA

A total of 23 PRE member sites participated in primary data collection. The geographical distribution of these sites is illustrated below (Figure 2) and shows that the majority of these sites were concentrated in western Europe, thereby excluding northern and eastern Europe from the primary data collection.

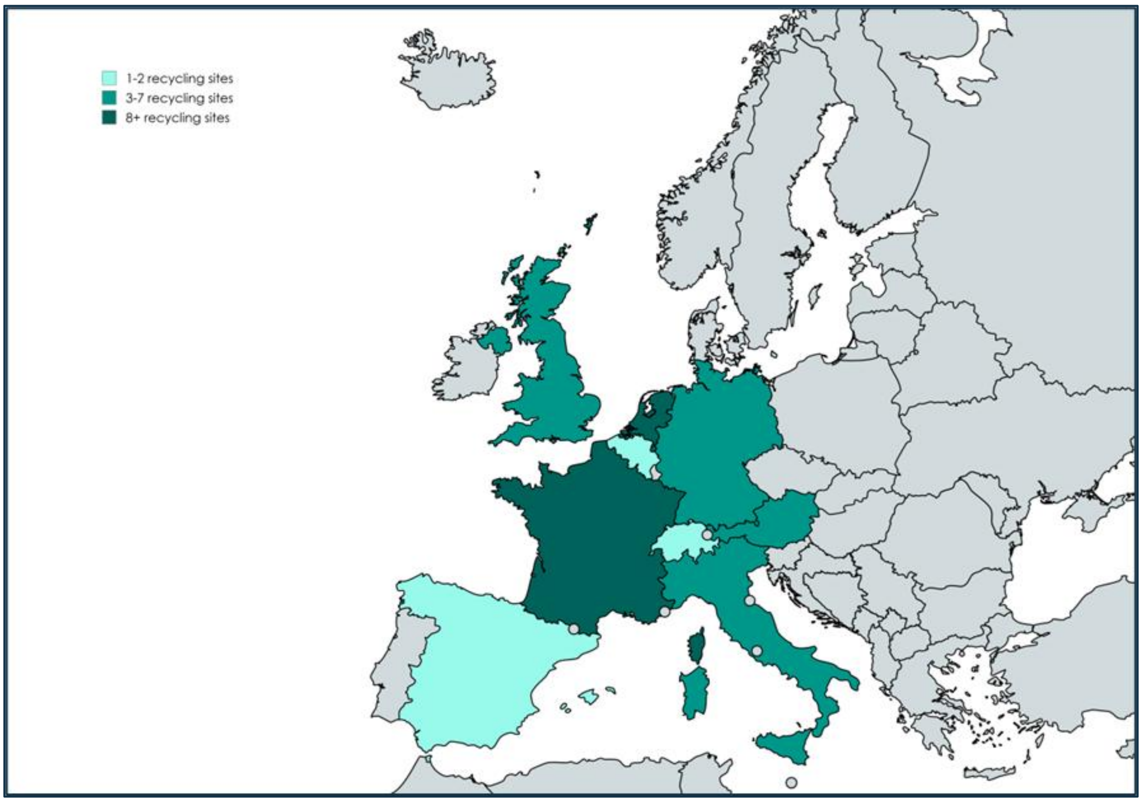

Figure 2. Recycling site coverage per country contributing data to the EcoProfile primary data collection

All of the data collection sites use a mechanical recycling approach to transform plastic waste into polymer flakes or pellets. This usually involves the processing steps depicted in Figure 3.

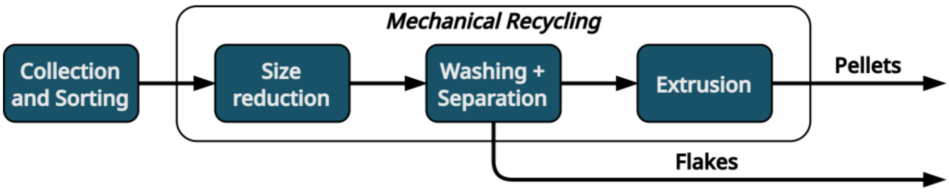

Figure 3. Waste management steps associated with mechanical recycling of general plastics waste;

The primary data collected was combined with existing literature data concerning plastic collection and transportation to create 'representative models' incorporating publicly accessible average European data, encompassing factors such as average feedstock, product mix, energy consumption, and environmental emissions.

What Figure 3 does not depict is the debate on the allocation of emissions originating in the various life cycles of a product composed of materials that are frequently recycled[36] within the LCA community. Should the impacts of secondary and primary production be shared between respective producers or are they to be seen as separate operations altogether? Two of the most prevalent solutions applied: the equal distribution of the emissions of primary, secondary and tertiary etc. material production between all life stages; or the allocation of the emissions related to the raw material production of each life cycle stage, respectively, and the allocation of the emissions of disposal to the last stage. For the EcoProfiles generated using the herein presented methodology, only the environmental impacts directly associated with the waste treatment and recycling of plastic waste are considered. The aim is to provide transparent data on the recycling of plastic waste to be used as raw materials for further manufacturing.

5 STATE-OF-THE-ART MECHANICAL RECYCLING

The thus created gate-to-gate datasets, encompassing only the processes directly related to mechanically recycled plastics production, may help in supporting the achievement of a circular economy for plastics. Achieving circularity within the plastics industry is essential to stay within the planetary boundaries.[9] In pursuit of this objective, the European Plastics Strategy[10], a cornerstone of the EU's Circular Economy Action Plan[11], plays a crucial role in the transition toward a carbon-neutral and circular economy in Europe. The strategy's key objectives include protecting the environment, reducing marine litter, lowering greenhouse gas emissions, and decreasing reliance on imported fossil fuels. To achieve these objectives, the strategy outlines several measures:

- Reducing plastic waste and littering
- Driving investment and innovation toward circular solutions
- Encouraging global action
- Improving the economics and quality of plastics recycling

The PRIMUS project and the herein developed EcoProfiles contribute to this policy[7] as we quantify the environmental advantages of mechanical recycling compared to primary plastic production and deliver best practice examples.

Throughout this document, we use the terms **flakes** for **ground** recovered plastic material and **pellets** for the output of the **extrusion** process. Different forms of

[9] Bachmann, M., Zibunas, C., Hartmann, J., Tulus, V., Suh, S., Guillén-Gosálbez, G., & Bardow, A. (2023). Towards circular plastics within planetary boundaries. Nature Sustainability, 6(5), 599–610. https://doi.org/10.1038/s41893-022-01054-9

[10] European Commission. A European Strategy for Plastics in a Circular Economy, No. COM/2018/028 final (2018). https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN

[11] European Commission. A New Circular Economy Action Plan For a Cleaner and More Competitive Europe, No. COM/2020/98 final (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0098

recyclates, e.g. flakes and regrinds, are also named flakes for consistency although their physical form and performance might differ. [12]

For a description of the state of the art of mechanical recycling, various academic and public sources as well as expertise from the PRIMUS project were consulted. The information is mainly based on Woidasky[13], UNEP[12], JRC[14] and publications of PRE[15].

5.1 Recovery of Plastic Waste

Sorting and mechanical recycling in Europe involves a series of operations that transform plastic waste into reclaimable raw materials. Henceforth, we differentiate between the recycling of packaging waste and WEEE plastic waste.

5.1.1 Mechanical Recycling for Packaging Plastic Waste

At first, the plastic waste is collected and sorted to be further processed (Figure 4). At the sorting plant, the waste undergoes classification and sieving, where plastics are separated from other wastes based on size and material type using large drums, wind shifters but also magnets. Next, the foremost plastic sorting occurs using optical or near-infrared (NIR) technology, which identifies polymers by type. The pre-sorted packaging plastics are then compacted and baled for easier transport to the respective recycling facility. It must be mentioned that collection and sorting are strongly dependent on regional and waste stream context.[16] For example, used PET is collected separately from other plastic packaging waste via deposit return schemes (DRS) in various countries. Hence, the collection and sorting are rather simple, co-collected waste is limited increasing recycling rate up to 11 times.[15]

Once the pre-sorted plastic waste arrives at the recycling plant as bales, the baled plastics are opened to prepare for processing. Separation based on particle size or physical properties such as density, colour, or magnetic properties can yield a processable polymer input with high purity, minimizing the content of foreign polymers.

[12] Secretariat of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. (2023, May 12). *Technical Guidelines for the Identification and Environmentally Sound Management of Plastic Wastes and for Their Disposal*. https://www.basel.int/Portals/4/Basel%20Convention/docs/plastic%20waste/UNEP-CHW.16-6-Add.3-Rev.1.English.pdf

[13] Woidasky, J. (2020). Plastics Recycling. In Wiley-VCH Verlag GmbH & Co. KGaA (Ed.), *Ullmann's Encyclopedia of Industrial Chemistry* (1st ed., pp. 1–29). Wiley. https://doi.org/10.1002/14356007.a21_057.pub2

[14] European Commission. Joint Research Centre. (2024). *EU-wide end-of-waste criteria for plastic waste: JRC technical proposals*. Publications Office. https://data.europa.eu/doi/10.2760/9234350

European Commission. Joint Research Centre. Institute for Prospective Technological Studies. (2014). *End-of-waste criteria for waste plastic for conversion: Technical proposals: final report*. Publications Office. https://data.europa.eu/doi/10.2791/13033

[15] Plastics Recyclers Europe. (2024). *Library: How does Recycling Work*. https://www.plasticsrecyclers.eu/library/

[16] Seyring, N., Dollhofer, M., Weißenbacher, J., Bakas, I., & McKinnon, D. (2016). Assessment of collection schemes for packaging and other recyclable waste in European Union-28 Member States and capital cities. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *34*(9), 947–956. https://doi.org/10.1177/0734242X16650516

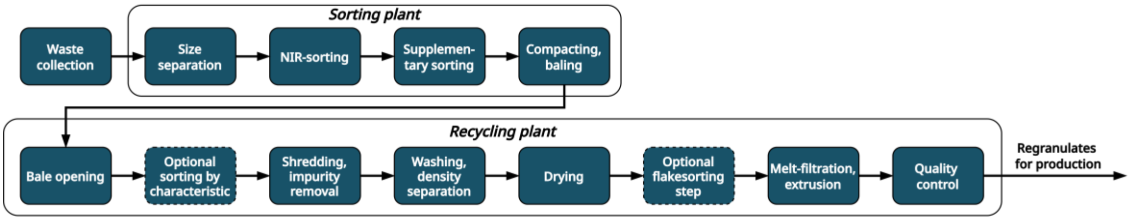

Figure 4. Sorting and mechanical recycling scheme for packaging plastics, from waste collection to final recycled pellets material for thermoforming of products. Based on EU BAT reference document[17] for waste treatment

The next step of recycling involves comminution and impurity removal, which involves shredding, followed by washing and density separation, where the plastics are cleaned and separated based on their density (float/sink process). The flotation principle allows to separate light materials, e.g. polyolefins like PE and PP, from denser materials, such as PET and PVC. Depending on the purity of the waste stream, only washing is performed to remove dust/dirt and other contaminants. Following the washing stage, the plastic material is dried in drums to remove moisture. Depending on the final quality requirements, another optional flake sorting step may be performed to remove any residual colorants or foreign materials. Finally, the plastic flakes undergo melting and extrusion, where they are melted, undergo filtration to remove impurities and then pelletised. These recycled pellets can be used as raw materials for producing new plastic products after quality control has been performed.[18]

5.1.2 Mechanical Recycling for WEEE Plastic Waste

In the case of WEEE, plastics wastes are sourced from discarded electronic and electrical appliances through designated recycling centres, take-back schemes and in-store deposit programs depending on regional context. All WEEE is sorted into various streams (e.g. white goods, monitors, lamps, and other WEEE) upon entering a (pre-)treatment facility, at the latest. Once collected, the materials undergo systematic sorting based on composition, polymer type, and potential contamination. In most cases, sorting and dismantling are automated processes to improve efficiency. However, for specific items such as television casings or other large household appliances (fridges, washing machines), manual dismantling is performed not only to maximize material recovery but also to comply with current regulations.

Following pre-sorting, the plastic waste is mechanically shredded to facilitate further processing. Magnetic separation and eddy-current separation (ECS) techniques are employed to remove ferrous and non-ferrous metals. Additional screening methods extract glass, wood, rubber and other residual impurities. To enhance separation efficiency, the shredded plastic material is further ground into finer particles and subjected to density-based separation using sink-float technology. Once the highest

[17] European Commission. Joint Research Centre. (2018). Best available techniques (BAT) reference document for waste treatment: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Publications Office. https://data.europa.eu/doi/10.2760/407967
[18] Plastics Recyclers Europe. (2023, September). *Factsheet: How does recycling work*. https://www.plasticsrecyclers.eu/wp-content/uploads/2023/09/Factsheet_How-does-recycling-work_general.pdf

level of purity is achieved, advanced washing techniques are applied to remove residual contaminants (oils, adhesives, paints). This stage typically involves washing with either cold or hot water, often supplemented with detergents or alkaline solutions, to eliminate any adsorbed substances. The purified WEEE plastic fractions are then dried and then subjected to extrusion, where they are melted and reshaped into pellets. Quality control using X-ray fluorescence (XRF) methods are often used to detect contaminants in the recycling stream, such as heavy atoms from chlorinated or brominated organic materials.[14,19] See Figure 5 for a visual representation of the process.

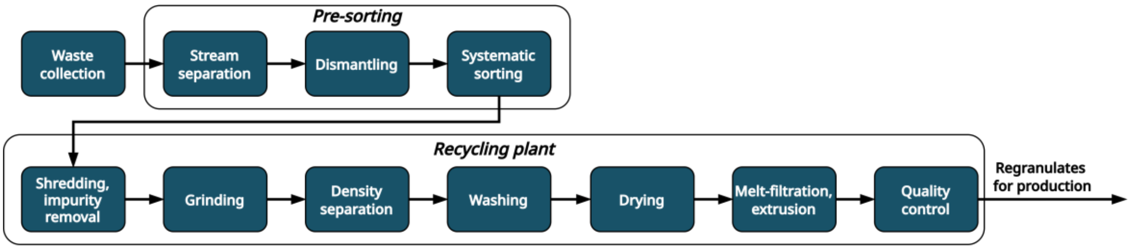

Figure 5. Sorting and mechanical recycling scheme for WEEE plastics, from waste collection to final recycled pellets material for thermoforming of products. Based on PRE WEEE recycling factsheet[19]

The most prevalent polymers recovered from WEEE plastics include polystyrene (17.3%), in casings for electronic devices and insulation materials, acrylonitrile butadiene styrene (25.4%), found in electronical housings, polypropylene (24.3%), in housings, and polycarbonate (PC) as well as polyamides (PA).[20]

5.1.3 Sustainability Considerations

From a life cycle perspective, mechanical recycling of plastics offers significant environmental benefits compared to primary production from additionally extracted raw materials, or disposing plastic waste via incineration.[21] By converting post-consumer or post-industrial waste into reusable raw materials, the process is likely to reduce the need for fossil resources, minimizing the emission of greenhouse gases.[6,22] As indicated above, the efficiency and environmental impact of the recycling process depend heavily on factors such as collection efficiency, sorting accuracy, and the quality of the recycled output. Impurities, such as food residues, additives, or mixed polymers, can lead to downcycling, meaning recycled plastic being used in lower-value applications, e.g. rPET fibres for textiles or rMPO for plastic lumber.

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[19] Plastics Recyclers Europe. (2023, September). Factsheet: WEEE Plastics Recycling. https://www.plasticsrecyclers.eu/wp-content/uploads/2023/09/Factsheet_How-does-recycling-work_WEEE.pdf

[20] Circular Plastic Alliance. (2020). State of play on collected and sorted plastic waste (WEEE). https://ec.europa.eu/docsroom/documents/43694

[21] European Commission. Joint Research Centre. (2023). Environmental and economic assessment of plastic waste recycling: A comparison of mechanical, physical, chemical recycling and energy recovery of plastic waste. Publications Office. https://data.europa.eu/doi/10.2760/0472

[22] Franklin Associates. (2018). Life Cycle Impacts for Postconsumer Recycled Resins: PET, HDPE, and PP. The Association of Plastic Recyclers. https://plasticsrecycling.org/wp-content/uploads/2024/08/2018-APR-LCI-report.pdf

Mechanical recycling is subject to limitations in the number of cycles a polymer can undergo before its properties degrade, affecting material performance and value. This does not result from the mechanical recycling itself, which leaves the material intact, but from the exposure to heat during processing and extrusion. After reaching the limitation of recycling cycles, optional chemical recycling or final disposal through incineration with and without energy recovery as well as landfilling of the polymer product becomes viable. Moreover, while some polymer mixtures are compatible and can be processed together, others are not. Products made of plastics degrade slowly in landfills and can take several decades to decompose completely, leading to run-off water and other direct emissions.[23] Thus, prioritizing recycling as the preferred end-of-life (EoL) option becomes essential.[21] Currently, the highest EoL recycling rates in the EU are found amongst PET (23%), LDPE (18%) and PVC (17%),[24] highlighting the need to improve collection and recycling efforts.

Facts provided in the following sections are based on findings of the data collection. The data only covered the recycling of PE, PVC, PET, PP, MPO, HIPS, hence, details on WEEE plastic, PP, PVC, PE, PET and MPO recycling are described in depth below. Other high-value polymers, namely PC, PU, PA, SAN, EPDM and EPS, were not covered in the data collection described in section 4, and were excluded from the assessment as well as the recycling description.

5.2 WEEE plastics (ABS, HIPS)

5.2.1 Introduction

In the last decades, the recycling of plastics from waste electrical and electronic equipment (WEEE) has gained significant traction due to regulatory advances but also improved recycling technologies. The waste stream consists mainly of high-value, durable items from WEEE streams, including fridges, consumer electronics and small household appliances and is often well defined (mono-fractional). Among these materials, polymers such as acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC) and high-impact polystyrene (HIPS) are predominately found.

This study focuses on rHIPS from post-consumer WEEE, which is commonly used in rigid electrical and thermal insulation applications, e.g. small home appliances, and medical devices, while other forms of polystyrene, such as expanded polystyrene (EPS) or general-purpose polystyrene (GPPS) were not found among the collected data. Another focus was the recycling of ABS, which is widely used in durable goods, such as electronics (laptop cases, vacuum cleaners), toy and automotive industries (dashboard components, seat backs). Within this project, the waste stream of ABS is

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[23] Wojnowska-Baryła, I., Bernat, K., & Zaborowska, M. (2022). Plastic Waste Degradation in Landfill Conditions: The Problem with Microplastics, and Their Direct and Indirect Environmental Effects. International Journal of Environmental Research and Public Health, 19(20), 13223. https://doi.org/10.3390/ijerph192013223 and Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. ACS Sustainable Chemistry & Engineering, 8(9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

[24] European Commission. Joint Research Centre. (2022). Modelling plastic flows in the European Union value chain: Material flow analysis of plastic flows at sector and polymer level towards a circular plastic value chain. Publications Office. https://data.europa.eu/doi/10.2760/66163

derived from WEEE and small home appliances. Our data showed that rHIPS was often solely sourced from WEEE streams but had small by-products such as rABS or rPU. Moreover, ABS was mixed with metal components or other plastics like HIPS and PP.

5.2.2 Recycling Process

ABS and HIPS are primarily collected and mechanically recycled from insulation applications (thermal and electrical). Their recycling generally follows mechanical processes involving collection, sorting, shredding, and extrusion. Initially, WEEE material is shredded and sorted to remove any non-plastic materials using magnetic sorting or eddy-current separation (ECS) since NIR sorting is challenging as black colorants (carbon black) are used. At this stage, mineral-filled PP can be removed here as well. Light parts of the plastic fraction, such was fouls, foams and wood, are removed by wind shifters. However, HIPS and ABS might still hold brominated flame retardants (BFRs) or other contaminants and is therefore subjected to sink-float technologies. Contaminated material can be separated by density separation (ϱ_{PS} = 1.04 – 1.09 kg/L, ϱ_{PO} = 0.9 – 1.0 kg/L, ϱ_{PS+BFR} = 1.17 – 1.20 kg/L). However, the presence of other additives and blends with other polymers (e.g. PC/ABS, ϱ_{ABS} = 1.33 – 1.37 kg/L, ϱ_{PC} = 1.2 kg/L) complicates the recycling process as it creates density overlaps. Further purification can be done by additional density separation steps to separate PS and PO, followed by electrostatic separation to sort ABS and PS. The further recycling process involves extrusion of the separated flakes to produce pellets.[25] During quality control, XRF methods are used to detect BFRs or other contaminants. The recycling efficiency of ABS across all sectors was calculated as 61% whereas (HI)PS was calculated as 55% in Europe (see Table 15).

5.2.3 Sustainability Considerations

In general, WEEE plastic recycling is less prevalent than other polymers due to the challenges associated with its collection and processing. Mechanical recycling can result in reduced mechanical properties, such as decreased impact resistance, and potential for discoloration. The recycling of WEEE plastics is limited by their complex composition and the presence of additives, which can lead to lower quality recyclates. As mentioned above, WEEE plastics frequently contain brominated flame retardants, especially when used in electronics, automotive parts, and appliances that must meet flame-resistance standards. During incineration of WEEE plastic waste, formation of highly toxic polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/F), typically at temperatures between 250-500 °C, can occur and hence requires flue gas treatment. Moreover, brominated flame retardants are often used alongside the antagonist antimony trioxide (Sb_2O_3), a critical raw material, which further limits recycling efforts. However, ABS has higher intrinsic resistances to heat and impact than HIPS, which sometimes reduces the need for flame retardants in ABS, though stringent fire safety requirements may still warrant their use.

Recycled ABS and HIPS (or blends of both) can readily be re-introduced into their original applications (fridges, TVs), as demonstrated in the PRIMUS DEMO cases 1 and

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[25] Plastics Recyclers Europe. (2023, September). *Factsheet: How does recycling work for WEEE*. https://www.plasticsrecyclers.eu/wp-content/uploads/2023/09/Factsheet_How-does-recycling-work_WEEE.pdf

3. However, a challenge in WEEE plastics recycling is maintaining impact strength and colour consistency, often addressed by blending recycled material with primary material or functional additives. For HIPS and ABS, around 60-80% of plastics found in WEEE is black due to aesthetic and cost considerations, making recolouring of discoloured WEEE plastics a practical approach. Compared to other materials, the recycling rates for WEEE plastics are generally low due to process losses and contamination.

5.3 PP

5.3.1 Introduction

Polypropylene (PP) is a versatile polymer used across the packaging, automotive, and consumer goods sectors, as it is valued for its thermal resistance and mechanical properties. Its waste stream can include both rigid and flexible items predominantly from post-consumer waste. Specifically, PP is derived from various waste streams including WEEE, End-of-Life Vehicles (ELV), construction waste, commercial packaging and household waste.

In our study, industrial packaging, automotive industries and post-industrial construction are significant contributors to the PP waste stream. In the mixed plastics waste stream, PP is commonly found alongside PE, PVC, and other plastic types. The primary output is recycled PP pellets, often accompanied by recycled PE and sometimes mixed recycled polyolefines (rMPO).

5.3.2 Recycling Process

Polypropylene (PP) recycling is closely linked with PE recycling due to their similar applications and recycling processes and involves shredding, sorting (by density and optical methods), cleaning, drying and extrusion. PP (ϱ_{PP} = 0.84 – 0.90 kg/L) recycling requires sorting to separate it from other plastics, especially since it has a similar appearance to PE (ϱ_{HDPE} = 0.92 – 0.93 kg/L). Hence, after size reduction, mechanical recycling involves extensive sorting and cleaning to remove contaminants followed by washing, extrusion and pelletising. During the final reprocessing, recycled PP flake is fed to an extruder, melted, degassed and filtered before pelletising. Contaminants, such as labels and organic residues, can significantly affect the quality of recycled PP, leading to lower-grade applications. The recycling efficiency of PP across all sectors was calculated as 66% in the EU (see Table 15).

5.3.3 Sustainability Considerations

PP is used in various applications. Technical PP often contains fillers that raise density, such as talcum, increasing the complexity of the density separation. Mechanical recycling of PP may lead to reduced tensile strength and impact resistance, as well as possible discoloration and surface issues. The material has good oxidation stability, but recycled material may experience some degradation. However, due to degradation reactions, PP becomes more flexible with each processing cycle, as indicated by a decrease in tensile properties and an increase in melt flow index (MFI). In some cases, an impact modifier or primary material is added for better performance, see DEMO case 2 in the PRIMUS project.

5.4 **Rigid PVC**

5.4.1 Introduction

Polyvinyl chloride (PVC) is a polymer used mostly in the construction and demolition sector (doors, pipes, profiles, windows, flooring, roofing sheets), as well as electrical applications (cable insulation) due to its technical performance and water/solvent resistance. Pipes and windows made of PVC are the most important applications. Stabilizers, such as calcium-zinc or lead, have been commonly added to the material to prevent discoloration or dehydrochlorination.

Previously reported waste streams include both rigid and flexible PVC products. However, in this study, the data was collected solely for rigid PVC from window profiles. The main waste stream was pre-sorted PVC waste without large amounts of by-products.

5.4.2 Recycling Process

PVC is typically collected from the construction and building sectors through dedicated EPR and is rarely found in household waste. Hence, the provided waste stream is rather polymer-specific but can hold other contaminants like glass, wood, or metal. Depending on the origin of the PVC waste, mechanical recycling involves shredding, sorting (XRF and NIR selective), density separation (ϱ_{PVC} = 1.32–1.37 kg/L), grinding and extrusion. As a result, PVC is obtained as a micronized PVC, soft or rigid granules, or rigid pellets after extrusion.[26] The Recycling efficiency of PVC in Europe across all sectors was calculated as 59% (see Table 15).

5.4.3 Sustainability Considerations

PVC is highly recyclable, but recycling can be hampered primarily due to the complexity of the recycling process and the presence of problematic additives.[27] Hazardous additives, like phthalates (flexible PVC) and heavy metals like cadmium and lead (rigid PVC), are often found in PVC due to their long lifetime and primary formulation. As PVC products are used in applications with lengthy lifetime, the disposal is delayed, leading to phased-out additives still being found in present waste streams[28]. Increasing the recycled content in primary PVC generally results in higher melt viscosity, hardness, and density. High-quality PVC recyclate can be reused in similar applications as primary material.

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[26] Plastics Recyclers Europe. (2024, December). *Factsheet: How does recycling work for PVC*. https://www.plasticsrecyclers.eu/wp-content/uploads/2024/12/Factsheet_How-does-recycling-work_PVC-Window.pdf

[27] United Nations Environment Programme and Secretariat of the Basel, Rotterdam and Stockholm Conventions. (2023, May 3). Chemicals in Plastics: A technical Report. https://www.unep.org/resources/report/chemicals-plastics-technical-report

[28] Geyer, R., Jambeck, J. R., & Law, K. L. (2017). *Production, use, and fate of all plastics ever made*. Science Advances, 3(7), e1700782. https://doi.org/10.1126/sciadv.1700782

5.5 **PE, HDPE, LDPE**

5.5.1 Introduction

Polyethylene (PE), including high-density polyethylene (HDPE) and low-density polyethylene (LDPE), is commonly found in packaging, but also in durable products. LDPE is predominantly used in packaging films due to its flexibility and low melting point, whereas HDPE is known for its rigidity and is commonly found in containers, pipes, and household products.

In this study, HDPE was found to originate from post-industrial and post-consumer packaging (household, commercial), agricultural and construction wastes. The main waste stream was pre-sorted HDPE waste. HDPE is often obtained as by-product from PET recycling where caps are co-collected. In comparison to HDPE, the data collection produced fewer entries for LDPE. However, LDPE waste is derived post-consumer from household packaging, commonly alongside HDPE and PP waste streams.

5.5.2 Recycling Process

Recycling PE primarily involves cleaning to remove residues, shredding, separation and reprocessing into granules or pellets. Proper sorting is essential to distinguish between different types of polyethylene. In general, HDPE is used in more rigid and thicker products (e.g. bottles), that are easier to clean and handle. HDPE, with its higher density, is also more facile to sort via density separation (ϱ_{HDPE} = 0.93 – 0.97 kg/L, ϱ_{LDPE} = 0.91 – 0.94 kg/L)[29] or NIR technologies. Moreover, HDPE flakes can undergo a process called air elutriation to remove labels and sleeves that could impede recycling. Contrarily, LDPE recycling is generally more challenging due to contaminations, e.g. from food packaging, and the flexibility of the material, which can induce issues like clogging of the processing equipment. The primary challenge with LDPE films is removing contaminants, a process typically managed through washing and air classification techniques. Post-processing, LDPE may be suitable for less demanding applications due to quality degradation, e.g. garbage bags or construction panelling.[30] Recycling efficiencies have been calculated as 59% for LDPE and 82% for HDPE across all sectors within the EU (see Table 15).

5.5.3 Sustainability Considerations

Both LDPE and HDPE are recyclable, with HDPE being more commonly recycled due to its improved processability. Due to challenges with contamination and losses resulting from the removal of light LDPE foils at an early stage, LDPE has a lower recycling efficiency than HDPE. Furthermore, mechanical recycling can reduce the quality of both HDPE and LDPE, leading to decreased tensile strength and impact resistance, along with potential colour changes and surface defects. Polyethylene generally has good oxidation stability, but recycled materials may suffer from reduced

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[29] PlasticsEurope. (2025). *Polyolefins - Plastics Europe*. https://plasticseurope.org/plastics-explained/a-large-family/polyolefins/

[30] Plastics Recyclers Europe. (2023, September). *Factsheet: How does recycling work for LDPE*. https://www.plasticsrecyclers.eu/wp-content/uploads/2023/09/Factsheet_How-does-recycling-work_LDPE.pdf and Plastics Recyclers Europe. (2023, September). *Factsheet: How does recycling work for HDPE*. https://www.plasticsrecyclers.eu/wp-content/uploads/2023/09/Factsheet_How-does-recycling-work_HDPE.pdf

stability over time. Due to cross-linking reactions, HDPE and LDPE become stiffer with additional processing cycles, as shown by increases in tensile properties while the MFI decreases. Hence, plasticizer might be added to HDPE and LDPE after mechanical recycling.[13]

5.6 **PET**

5.6.1 Introduction

Polyethylene terephthalate (PET) is one of the most recycled polymers in Europe. It is largely used in beverage bottles and food packaging (trays and foil), due to its clear appearance as well as temperature and chemical resistance. The European PET recycling industry is highly developed and well understood: A market report[31] displays a breakdown of PET recycling capacity by country within the EU27+3, with Germany, Spain, and France having the highest capacities. Furthermore, the waste stream is dominated by clear and coloured bottles from consumer use, as PET bottles are often collected via DRS. This allows clean waste streams with only food, plastic caps, and labels as contaminants. We found that PET originated solely from household and DRS post-consumer waste streams. The main waste stream was clean PET waste with mostly HPDE and lower quality PET as by-product.

5.6.2 Recycling Process

Commonly, PET waste (ϱ_{PET} = 1.33 – 1.37 kg/L) is obtained from household waste or DRS. The waste stream is frequently separated between bottle PET and tray PET, which possess different melt flow index values. The bottle caps are made of HDPE or PP, whereas the flexible foil on PET trays and bottle labels is also PET. The recycling usually includes sorting, granulation, density separation, washing, drying, extrusion and pelletizing. To improve the selectivity of the recycling process, floating PP or PE labels can be removed from sinking PET through density separation. Prior to sink-float separation, PET waste is often washed with sodium hydroxide solution to selectively alter its hydrophobicity. In the overall process, contamination with substances like acetic acid or moisture can lead to chain degradation during melt processing. Challenges include removing caps (ϱ_{HDPE} = 0.93 – 0.97 kg/L), labels and dealing with coloured PET, which has limited recycling options. However, as a result, rPET is obtained as bottle and trays quality.[32] The PET recycling efficiency in Europe was calculated as 76% across all sectors (see Table 15 Annex).

5.6.3 Sustainability Considerations

PET is a highly recyclable material, with a recycling rate of approximately 40-50% in Europe, especially for beverage bottles. While mechanical recycling can impact the material's strength and clarity, potentially reducing its performance in various

[31] Plastics Recyclers Europe, PETCORE Europe, NMWE, & UNESDA Soft Drinks Europe. (2022). PET Market in Europe: State of Play. https://www.plasticsrecyclers.eu/wp-content/uploads/2024/05/PET-Market-in-Europe-State-of-Play-2022-Data-V3.pdf

[32] Plastics Recyclers Europe. (2023, September). *Factsheet: How does recycling work for PET trays*. https://www.plasticsrecyclers.eu/wp-content/uploads/2023/09/Factsheet_How-does-recycling-work_PET-Tray.pdf and Plastics Recyclers Europe. (2023, September). *Factsheet: How does recycling work for PET bottles*. https://www.plasticsrecyclers.eu/wp-content/uploads/2023/09/Factsheet_How-does-recycling-work_PET-Bottle.pdf

applications, PET's good oxidation stability means that recycled PET may only exhibit minor decreases in stability over time. Due to the fact that PET is mainly used in food contact application, hazardous additives are rarely used for PET. However, the quality of collected PET varies significantly across Europe due to differences in collection methods, bale quality, and handling of mixed PET waste. Although PET trays have a lower recycling rate due to less developed collection and sorting systems, PET retains good mechanical properties across several recycling cycles, though it becomes more brittle over time due to chain scission. Addressing issues such as colour contamination and yellowing from oxidation is vital for producing high-quality PET recyclates, which can be used in both food-grade applications when properly processed, and in non-food products like textiles. However, the PET mass balance highlights significant losses during collection and sorting stages in spite of existing DRS.[31]

5.7 **MPO**

5.7.1 Introduction

Mixed polyolefins (MPO) encompass a combination of polyethylene (PE) and polypropylene (PP) waste streams. These materials are frequently found in mixed household and packaging waste streams and pose challenges for separation due to their similar properties. MPO is a downcycled polymer, thus, the recycling rate is not reliable.

Within our study, mixed polyolefins are caps and labels but also low-quality, rejected materials from PP and PE recycling that are not subjected to waste treatment.

5.7.2 Recycling Process

MPO recycling focuses on separating and processing mixed PE and PP from other waste streams. While flotation in water is used to separate polyolefins (ϱ_{MPO} < 1.0 kg/L) from denser materials like PET (ϱ_{PET} = 1.33 – 1.37 kg/L), MPO recycling involves the blending of collected waste without fully separating the individual polyolefins. The resulting fractions are categorized as either 'hard' MPO (mostly PP and HDPE) or 'soft' MPO (PP and LDPE). Hard MPO fractions are often used for products like plastic lumber or profiles, although the immiscibility of PE and PP can reduce mechanical performance, often necessitating the addition of modifiers or primary material. Soft MPO fractions, mainly consisting of PP and LDPE, are typically used in flexible applications like packaging films.[13]

5.7.3 Sustainability Considerations

While MPO recycling reduces waste, it is often limited to downcycled products with lower market value. The development of compatibilizers and more efficient sorting technologies could improve the performance of MPO recyclate. However, mixes of PP and LDPE or HDPE can lead to phase separation due to immiscibility on the molecular level. This results in compromised mechanical properties, such as reduced tensile strength and lower impact resistance, which mandates additives, such as compatibilizers. Together with other materials, rMPO can be extruded or blown into plastic lumber for applications such as garden furniture, fences, decking, and construction materials.

6 GOAL AND SCOPE

The herein generated EcoProfiles represent a European average life cycle inventory (LCI) in a 'cradle-to-gate' or 'gate-to-gate' fashion for mechanical recycling to obtain recyclate flakes or pellets. Also, the LCIA for each EcoProfile and comparison for 'cradle-to-gate' EcoProfiles with primary production is provided. For PRIMUS-relevant recyclates, EcoProfiles with regionalised context were presented as well.

Comparative studies based on EcoProfile data should not be performed at level of materials, which have different properties, but rather at a level of full LCA studies of products with recyclates, as the EcoProfiles only represent a small section of the life cycle and are not directly related to the functionality of the respective polymer.

The generated EcoProfiles and datasets are intended to be used by

- recyclers to support product-orientated environmental management and continuous improvement of production processes but also to benchmark environmental performance
- downstream users of plastic recyclates as defined in the PRIMUS project
- the LCA community and sustainability researchers to use the methodology and the data for research purpose boosting the usage of recycled plastics due to improved environmental performance

6.1 Goal

This work has the aim to assess recyclates and their supply chain (cradle-to-gate) to understand their sustainability dimension and provide the grounds for incorporating recycled plastic use in LCAs. To achieve this goal, harmonized LCI data shall be provided for each produced EcoProfile on a European level as well as on regionalized levels. The produced datasets (gate-to-gate) shall further be available with added generic collection and sorting processes for ease of modelling leading to cradle-to-gate EcoProfiles. Lastly, the produced datasets shall be categorized by produced output: Recycled plastic flakes or recycled plastic pellets.

By publishing multiple configurations of EcoProfiles, which include specific inventories, as well as delivering disaggregated datasets, and a detailed documentation of every step in this methodology, our approach aims to enhance clarity and address the issue of unharmonized LCI datasets. In this respect, these EcoProfiles for recyclates are available in a more transparent way than the 'classic' EcoProfiles from PlasticsEurope[2] representing primary plastics. Hence, we published also disaggregated, transparent unit process data sets which enables a deeper analysis of key contributors to environmental impacts. Next to the LCI data, which is relevant for LCA practitioners, also LCIA data, relevant to recyclers and other stakeholders, was presented and referenced to the production of primary plastic.

6.2 Scope

The scope of the EcoProfiles is the production of plastic recyclate flakes and pellets through mechanical recycling processes in a European regional context (EU27+3). Furthermore, the technological scope is limited to mechanical recycling with separate collection, sorting and recycling steps. EcoProfiles were only created for polymer streams where a sufficient number data points to warrant non-disclosure (≥3 recycling sites) were provided. Moreover, a minimum requirement of at least two different European regions being represented per recyclate EcoProfie was used to functionally represent a mix of European recycled polymer production processes).

6.2.1 Declared Unit

For the EcoProfiles, the declared unit is generally defined as

'Production of 1 kg of mechanically recycled polymer pellets (/flakes), obtained from a specific waste stream, at gate, unpackaged, representing X% of a European average'

and has to be adapted per waste (post-industrial or post-consumer) and polymer type.

As we were not able to quantify the quality of the produced recyclates, we highly encourage to revise the concept of substitution factors[33] for using the datasets.

6.2.2 Reference Flow

For each of the EcoProfiles, the reference flow is defined as

'1 kg of mechanically recycled polymer pellets (/flakes), unpackaged '

6.2.3 System Boundaries

The system boundaries were defined following the plastics recycling scheme as published on the PRE website[34] and are in line with the goal:

- The system starts with the collection of burden-free polymeric waste, and includes the collection, sorting and recycling processes and ends with recyclate flakes or pellets depending on the EcoProfile.
- The recyclates are regarded as single-polymer outputs and not modelled as mixtures of polymers being produced, though this may differ from real circumstances of plastic recycling.
- The first life cycle stages of the polymers are disregarded (cut-off).

[33] Bayer, K., Scharz, T., Jansen, J.-O., Fleischer, G., Vetter, M., Wiedemann, & Graser. (2001, November 8). *Neuere Entwicklungen zur Erfassung und Verwertung von Kunststoffabfällen*. https://www.abfallratgeber.bayern.de/publikationen/abfallverwertung/doc/kunststoffabfaelle.pdf, European Commission. Joint Research Centre. (2023). Environmental and economic assessment of plastic waste recycling: A comparison of mechanical, physical, chemical recycling and energy recovery of plastic waste. Publications Office. https://data.europa.eu/doi/10.2760/0472 and Rigamonti, L., Taelman, S. E., Huysveld, S., Sfez, S., Ragaert, K., & Dewulf, J. (2020). A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies. Waste Management, 114, 331–340. https://doi.org/10.1016/j.wasman.2020.07.015

[34] Plastics Recyclers Europe. (2023). *How does recycling work?*. https://www.plasticsrecyclers.eu/plastic-recycling/how/

As we offer two different versions of EcoProfiles, two set of system boundaries occur:

- **Gate-to-gate** covers the mechanical recycling of sorted plastic waste by bale opening, optical sorting, impurity removal, washing and density separation, drying, final sorting and optionally extrusion with melt-filtration followed by cutting. The order and number of process steps might differ depending on the polymer type and final product (flake vs. pellets).
- **Cradle-to-gate** covers the collection plastic waste and size separation, optical sorting, additional sorting and baling followed by the same steps as above.

In both cases the system boundaries included:

- Production of additives, chemicals, electricity, transport and the waste treatment of residual wastes (municipal waste, residual polymer waste, waste water) was derived from background datasets from ecoinvent v3.10 cut-off.

Notable exclusions from the system boundaries are:

- Packaging materials of the produced polymer
- Further processing of separated secondary materials
- Energy consumption and waste generated from sales, administrative staff research and development as well as related activities

A visual representation of the modelled cradle-to-gate (extended) and gate-to-gate (core) systems including all the individual process steps is displayed below. Note that the system boundaries differ for the EcoProfiles depending on the production of flakes or pellets and the inclusion of collection and sorting processes (Figure 6).

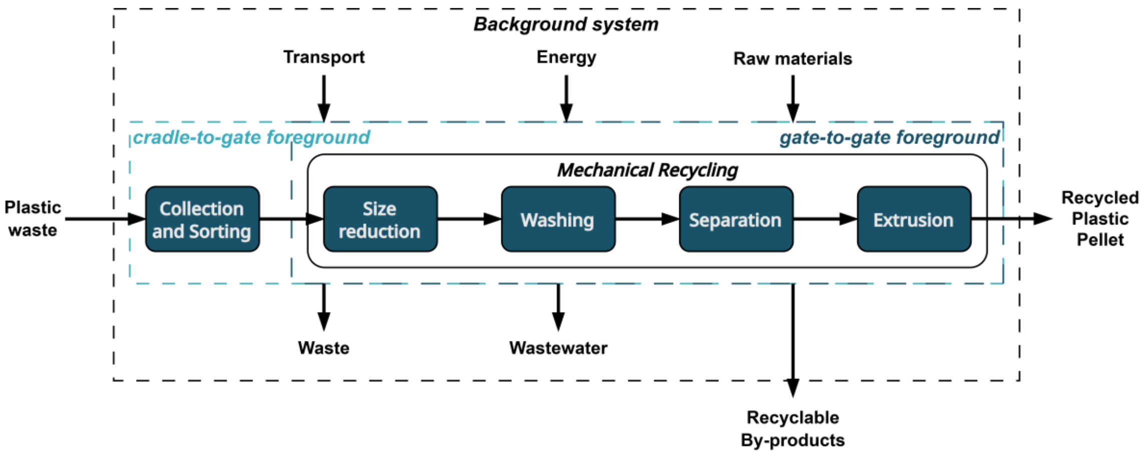

Figure 6. Exemplary system boundaries for polymer flakes including cradle-to-gate scope with collection and sorting as well as gate-to-gate scope encompassing only the mechanical recycling processes

Moreover, some further consideration for the system boundaries:

- The **cut-off approach** used for burden free waste inputs also applies to waste outputs of the process that are to be recycled. Thus, recycling processes of waste generated as part of the model are beyond its scope
- The disaggregation of provided data for multi-output processes producing both flake and pellets was performed to the best of our ability, however, it was

not always possible to separate the inventory sufficiently. Therefore, impacts associated with the extrusion of flakes to pellets may be contained in flake EcoProfiles as well

- There is a strong relation between quality of the processed waste and the functionality of produced recyclate which could not be depicted in this study
- The manufacturing of the final plastic product, its use phase and its EoL management are not included within the system boundaries of the herein presented EcoProfiles for polymer recycling

6.2.4 Data Quality Requirement

As high-quality data is needed for further use of the produced EcoProfiles in the life cycle community, primary data collected for these EcoProfiles have undergone a close examination of data quality. Uncertainties regarding the quality of data are expressed in numerical values, which articulate our confidence in the communicated impact assessment result stemming from the created inventory.

Due to the fact that the EcoProfiles have been prepared with primary data, data gaps and varying data quality for different production sites have been observed. Hence, a data quality assessment of the foreground processes based on the primary data collection has been conducted to compensate this factor. The data quality has been assigned per exchange of the disaggregated product LCI according to the ecoinvent Data Quality System[35] (Figure 7):

▾ Indicators & Scores

	1	2	3	4	5	Add score
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimates	Remove indicator
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods	Remove indicator
Temporal correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of data unknown or more than 15 years of difference to the time period of the data set	Remove indicator
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)	Remove indicator
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology	Remove indicator
Add indicator	Remove score	Remove score	Remove score	Remove score	Remove score	

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[35] Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O., & Wernet, G. (2013). *Overview and Methodology: Data quality guideline for the ecoinvent version 3* (Ecoinvent Report No. 1(v3)). https://forum.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf

Uncertainties

	1	2	3	4	5
Reliability	1.0	1.0502	1.0936	1.1959	1.4918
Completeness	1.0	1.0202	1.0502	1.0936	1.1959
Temporal correlation	1.0	1.0287	1.0936	1.1959	1.4918
Geographical correlation	1.0	1.0101	1.0202	1.0502	1.0936
Further technological correlation	1.0	1.0502	1.1959	1.4918	1.9993

Figure 7. Data quality and numerical uncertainties per flow as displayed in openLCA

According to the ecoinvent Data Quality System, a score ranging from 1 to 5 in the categories reliability, completeness, temporal correlation, geographical correlation and further technological correlation is assigned to each exchange of the EcoProfile life cycle inventory. From the scores, a multiplicative standard deviation value is calculated, which was used to calculate the uncertainty provided in the final inventory results see chapter 6.2.7.3.

6.2.5 Data Collection

PRIMARY DATA

Primary or foreground data for plastic recycling was collected by PRE. Information on materials, energy, fuel and water usage as well as transport services were collected. To handle varying resolution of data, a data quality system was established. The data presented in the EcoProfiles derives from activity in the years 2021 and 2022. The reference year was 2022 in all cases. In cases where data gaps appeared, they were closed by defining a set of standard inputs and outputs to replace ill-defined inputs and outputs. For instance, if the quality of a produced recycled output was unknown, the worst-case scenario, recycled plastic flakes, was assumed.

SECONDARY OR BACKGROUND DATA

Secondary or background data represent processes outside of the operational control of the recycler or for which primary data is not available. The selected generic datasets were recorded and reported. However, if possible, secondary datasets with geographical specificity were used, e.g. the energy supply was modelled on a location-specific basis. Secondary data was used to close gaps in primary data collection where needed. Important examples of this are transport of waste from the production sites and the use of background data proxies for compounding additives and colour masterbatches used for extrusion.

COVERAGE

As primary data was collected from a finite sample of recyclers, inputs and outputs of individual recycling processes may differ from the inventory reported through the EcoProfiles. To represent this, PRE's 2022 data on the plastics recycling industry in Europe was used to calculate the percentage of total installed recycling capacity represented by polymer, see Table 2 for this. The column 'Coverage' is calculated as the fraction of the two columns to the left, the 'Total reported Capacity', which is the total installed recycling capacity of primary data providers for the polymers and waste streams in question, and the 'Total reported European capacity', which is the total installed recycling capacity of plastics recyclers in Europe as extracted from PRE's 2022 publication[20].

Table 2. Overview of the covered capacity of waste polymer streams according to primary data and PRE publication[20]

Polymer/Stream	Total reported capacity (kt)	Total reported European capacity (kt)	Coverage
All		12500	
PE, PP	170	3250	5.2%
PET	255	3000	8.5%
HDPE rigid	50	1750	2.9%
PVC	70	1125	6.0%
Mixed Plastics	106	750	14.1%
WEEE	185	625	29.6%

6.2.6 Modelling Assumptions

Modelling sorting, collection and transport of waste

As neither the primary data did not include data for the sorting, collection and transport processes associated with the recycling of the polymers under study, tertiary data published by Haupt et al.[36] was used to model these processes allowing a 'cradle-to-gate' scenario. The publication offers polymer-specific outputs per process, which were used in accordance with the polymer under study where available. A simplification of the modelling approach using secondary data for the waste collection vehicle from the background database has been carried out:

- The original publication contained data for LDPE, HDPE, PP and PET sorting efficiencies, which were used without modification for those waste streams.
- For stream of MPO, an average of LDPE and PP has been used, while for the remaining waste streams of PS, ABS and PVC, an average of the efficiencies described in the original source was used. Collection has been adapted based on the waste stream used in the recycling facility.
- All WEEE and PET waste inputs are modelled to be collected through central collection points instead of curb-side pickup, which was used for MPO waste, PE waste, PVC waste and PP waste.

[36] Haupt, M., Kägi, T., & Hellweg, S. (2018). *Life cycle inventories of waste management processes*. Data in Brief, 19, 1441–1457. https://doi.org/10.1016/j.dib.2018.05.067

Table 3. Collection and sorting approach by waste stream used in the model. See Table 4 and Table 5 for LCI details

Polymer waste stream	**Curbside collection**	**Collection point**	**Polymer-specific sorting**
WEEE or ELV (e.g. ABS/PP/PS/TPO)		**X**	
HDPE	**X**		**X**
LDPE	**X**		**X**
Mixed Polyolefins	**X**		
PET		**X**	**X**
Household PP	**X**		**X**
PVC	**X**		

Table 4. LCI required for the collection of 1 kg of polymer via different waste collection schemes. See Table 5 for their respective use

Input	**Curbside collection value**	**Collection point value**
Steel pipe		4.30E-5 kg
Extruded polypropylene		4.40E-4 kg
Extruded LDPE	1.66E-2 kg	1.66E-2 kg
Injection moulded HDPE		3.90E-4 kg
Polyethylene fleece	5.00E-9 kg	5.00E-9 kg
Alloyed steel sheet		4.83E-5 kg
Containerboard		4.40E-4 kg
Polypropylene flakes	1.00E-4 kg	1.00E-4 kg
LDPE flakes	1.00E-4 kg	1.00E-4 kg
Lorry transport	0.130 tkm	0.130 tkm
Passenger car transport		9.60E-2 km
Waste collection vehicle	6.10E-8 item(s)	
Waste collection service	5.00E-3 tkm	

Table 5. LCI of waste sorting process according to polymer. HDPE, LDPE and PP differ only in the sorting efficiency of the process, and thus, produced waste. Average values of the 4 polymer waste stream types were used for the missing waste streams

Inputs	**Sorting value HDPE/LDPE/PP**	**Sorting value PET**
Diesel, combusted	8.02E-2 MJ	1.07E-1 MJ
Low-voltage electricity	3.76E-2 kWh	4.36E-2 kWh
Heat, non-natural gas	3.29E-2 MJ	2.42E-2 MJ
Steel wire	5.60E-3 kg	5.60E-3 kg
Waste sorting infrastructure	2.00E-9 item(s)	2.00E-9 item(s)
Outputs		
Sorted waste (i_{sort})	0.94 (HDPE) / 0.77 (PP) / 0.54 (LDPE) kg	0.85 kg
Municipal solid waste		6.00E-2 kg
MSW for clinker production	1 – i_{sort} kg	9.00E-2 kg
Wastewater		3.57E-8 m^3

Modelling solutions

Many of the material inputs given in primary data were used in a dissolved state. Therefore, the solution percentage was assumed to be given in mass fractions and modelled as such using pure reactants available in the background database adding tap water where necessary.

Modelling internal transport via forklifts

Some reported datasets included data on internal transport via forklifts, using propane fuel. It was assumed that other datasets reporting the consumption of propane fuel or diesel fuel also made use of forklifts. Since combustion of the fuel alone does not fully cover the environmental concerns associated with forklifts, a process including particulate matter emissions from tyre wear was created based on the background database process 'market for tyre wear emissions, lorry | tyre wear emissions, lorry | Cutoff, U'. The used emission factor per t*km of transport service was scaled with gross vehicle weight[37] as information in the background database states a linear relationship. Average fuel consumption from a tertiary source was used to relate the combusted fuel to the distance of the transport service[38].

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[37] Ziółkowski, A., Fuć, P., Jagielski, A., & Bednarek, M. (2022). *Analysis of Emissions and Fuel Consumption in Freight Transport*. Energies, 15(13), 4706. https://doi.org/10.3390/en15134706

[38] Fuc, P., Kurczewski, P., Lewandowska, A., Nowak, E., Selech, J., & Ziolkowski, A. (2016). *An environmental life cycle assessment of forklift operation: A well-to-wheel analysis*. The International Journal of Life Cycle Assessment, 21(10), 1438–1451. https://doi.org/10.1007/s11367-016-1104-y

Table 6. Inputs and Outputs required for propane or diesel-driven forklift transport. Inventory is based on the external sources mentioned above and serves to account for tyre wear emissions

Inputs	**Amount and unit**
propane, burned in building machine	71.9 MJ
Outputs	
Transport, forklift, diesel-driven	1.00 t*km
tyre wear emissions, lorry	3.67E-04 kg

Inputs	**Amount and unit**
diesel, burned in building machine	29.5 MJ
Outputs	
Transport, forklift, diesel-driven	1.00 t*km
tyre wear emissions, lorry	3.67E-04 kg

Assumed specific materials and products for generic data provided

As not all primary data was provided in the resolution required for an LCA model, the necessary determination of the specific material was based on the selection of materials provided in other datasets. This way, a table of specific materials for generic data points has been created and applied to further determine materials when necessary. Sometimes, a proxy had to be used as detail if the specific material was not available at all.

Table 7. Datasets from the background database materials used as proxies to fill data gaps

Generic data	**Specific materials and products**
Additives	market for chemical, organic
Wastewater treatment additives	market for chemical, inorganic
Defoamer / Antifoaming agent	market for polydimethylsiloxane
Soap / Detergent / Cleaning agent	cleaning consumables, without water, in 13.6% solution state, with an added flow of completely softened water (see below)
Coagulant	market for polyaluminium chloride
Filler	Talcum powder (see below)
Flotation agent	market for sodium chloride, powder
Colour masterbatch	Both market for chemical, inorganic and market for chemical, organic (see below)
Flocculation agent	market for polyaluminium chloride
Filters	market for air filter, central unit, 600 m3/h

In some cases, data was provided as an aggregate of multiple materials, e.g. ‘polyolefins’ or ‘detergent and defoaming agent’. In these cases, the appropriate materials were modelled in an even mass distribution.

MODELLING POLYAMINE COAGULANT

The production of a polyamine coagulant was modelled based on a generic chemical production process of the background database, here 'polyaluminium chloride', assuming a 5% loss in following ecoinvent's approach[39]. The starting materials 'dimethylamine' and 'epichlorohydrine' were used. Input quantities were stoichiometrically calculated based on standard reactions published in literature[40].

MODELLING CLEANING CONSUMABLES

The background database includes the product 'cleaning consumables, without water, in 13.6% solution state'. The process behind the product averages various cleaning products of five categories but provides data without the water in solution. The needed water to dissolve the active components has been added as completely softened water. This process is used when an unknown cleaning agent is reported in primary data, as seen above.

MODELLING TALCUM POWDER PRODUCTION

To complete the supply chain for mineral filler used in the extrusion of recycled flake, a talcum powder quarrying process has been created based on the background process of 'steatite quarry operation | steatite | Cutoff, U'. Since quarrying locations are unknown, the individual electricity consumptions per country were added up into a single process for global consumption.

Table 8. Inputs and Outputs required for talcum powder production based on ''steatite quarry operation | steatite | Cutoff, U' from the background database, replacing the elementary flow and output according to model requirements

Inputs	**Amount and unit**
Raw slugde	1.00 kg
Electricity, medium voltage	4.13E-3 kWh
Mine, infrastructure, steatite	6.25E-8 items
Talc	1.00 kg
Outputs	
Talcum powder	1.00 kg

MODELLING COLOUR MASTERBATCH

During extrusion, several of the primary data providers reported the use of a colour masterbatch, colours or pigments. Since the composition of a colour masterbatch can contain a complex mixture of additives, pigments and colours as well as a background matrix, composition assumptions can heavily affect the impacts of the used material. As a result, a proxy from the background database products 'chemical, inorganic' and 'chemical, organic' has been constructed, assuming an equal mix on a mass basis.

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[39] Hischier, R., Hellweg, S., Capello, C., & Primas, A. (2005). *Establishing Life Cycle Inventories of Chemicals Based on Differing Data Availability* (9 pp). The International Journal of Life Cycle Assessment, 10(1), 59–67. https://doi.org/10.1065/lca2004.10.181.7

[40] Burkert, H., Hartmann, J., & Herth, G. (2016). Coagulants and Flocculants. In Wiley-VCH Verlag GmbH & Co. KGaA (Ed.), *Ullmann's Encyclopedia of Industrial Chemistry* (pp. 1–14). Wiley-VCH Verlag GmbH & Co. KGaA. https://doi.org/10.1002/14356007.a11_251.pub2

MODELLING EXTRUSION

To improve the coverage of flake EcoProfiles, those covering recyclate flake have been included as an input with a corresponding extrusion process. This process has been modelled off primary data provided on the production of pellets from flakes. An average from three extrusion process requirements has been generated. See Table 9 for a breakdown of specific extrusion impacts used in the processes this proxy is based on. No amount of generated waste was attributed to extrusion, specifically.

Table 9. Average extrusion requirements according to processes with specified extrusion inputs from PET recyclers

Inputs	**Amount and unit**
Electricity, medium voltage	315 kWh
Tap water	0.187 t
Outputs	
Extruded rPET pellets	1.00 t

The energy consumption was in agreement with published data[22].

MODELLING OF WATER

When not specified further, water was assumed to be sourced from the local water supply as tap water.

When specific data on discharged water was lacking, it was assumed that effluent could be calculated following a simple water balance assuming 50% sludge humidity and discharge of the remaining water. Depending on the inclusion of a treatment process in primary data, this discharge was modelled either as average wastewater or as an elementary flow to surface water.

MODELLING OF PARTICULATE MATTER FORMATION DURING RECYCLING

The formation of particulate matter during mechanical recycling had to be estimated through tertiary data: In a report by Franklin Associates[22], unspecified particulate matter formation was disclosed for the mechanical recycling of PET. Due to the specific nature of the PM formation, data was not estimated for the EcoProfiles of rPVC, rABS, rLDPE, rMPO, rHIPS, rHDPE and rPP. This approach has been verified by sensitivity analysis as the PM formation during recycling did not contribute significantly to the overall PM result.

MODELLING WASTE TRANSPORT

In instances where the transport distances of waste from the production site were not known, the country-specific waste transport distances according to the production site location were used as a proxy in accordance with the background database methods[27]. These were aggregated into one average value per European dataset as described in section 6.2.7.1.

MODELLING OF WASTE

As the specificity of available primary data varied a lot regarding waste outputs, generally, diverse wastes were modelled as municipal solid waste outputs, while nonhazardous production wastes were assumed to be chiefly comprised of waste plastic and modelled as such.

Modelling sludge waste treatment

To represent the processes involved in the treatment of sludge generated through recycling operations, a drying process followed by an incineration or landfilling waste treatment process was modelled based upon the background database's process of 'drying, sewage sludge | raw sewage sludge | Cutoff, U'. It was assumed that the same level of moisture remained in dry recycling sludge as in sewage sludge, requiring a reduction in moisture content from 60% to 2%. The produced waste was then assumed to be comprised of waste plastics and modelled further as such.

Table 10. Inputs and outputs of plastic recycling sewage sludge treatment. Based on background database process ' drying, sewage sludge | raw sewage sludge | Cutoff, U'', adapted to an appropriate moisture content from primary data

Inputs	**Amount and unit**
raw sludge	1.00 kg
heat, district or industrial, natural gas	0.128 MJ
heat, district or industrial, other than natural gas	0.128 MJ
Outputs	
wastewater, average	4.80E-04 m3
waste plastic, mixture	0.520 kg

Modelling of by-products

Since useful by-products of the recycling processes require further recycling beyond the state they are sorted out in, a cut-off has been applied to handle these as wastes without requiring disposal and, thus, being burden-free. This follows the same logic as the general modelling approach of the recycled plastic flakes and pellets applied in the EcoProfiles. The raw materials of secondary material production are assumed to not to be associated with upstream impacts, nor is the first life cycle of a product to account for downstream recycling impacts. This also excludes these materials from the applied allocation required in many cases (see section 6.2.7.2 for more information).

Modelling of Fossil Use

Where liquefied petroleum gas or propane was indicated, 'propane burned in building machine' was used as those materials are used in gas-driven forklifts.

Modelling of Infrastructure

The lifetime of the recycling facility has been estimated to be 50 years added with the annual recycling capacity of 10,000 t as stated in the respective process 'waste preparation facility construction (CH)'[41].

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[41] Kellenberger, D., Althaus, H. J., Jungbluth, N., Künniger, T., Lehmann, M., & Thalmann, P. (2007). *Life cycle inventories of building products. Data v2.0*. (ecoinvent report, Report No.: 7). Empa; Swiss Centre for Life Cycle Inventories. https://www.dora.lib4ri.ch/empa/islandora/object/empa%3A34379

6.2.7 Calculation Approach

Data collection provided regional and site-specific data for the mechanical recycling of different polymer and waste streams that have been modelled accordingly. Many waste streams contain not just one but multiple polymer types, which are reprocessed following the allocation approach (section 6.2.7.2). Any recycled plastic outputs were modelled as products of the corresponding recycling processes.

It is evident that a multitude of recycling processes collectively contribute to the total production of a given recycled polymer. As the final EcoProfile describes the European average production of one kilogram recycled polymer, the many sites contribute a fraction of this. The representation of each site's process is modelled based on installed capacity information IC_i of the site i and the share of the polymer in total site i production PS_i, both derived from primary data. This representation is calculated as the product of IC_i and PS_i, it is further be referred to as the specific capacity of XP_i a site i. The contribution $C_{X\text{-}i}$ of a single site i's polymer X output to the 1 kg of polymer produced via the EcoProfile is then calculated via the quotient of an individual site's XP_i and the sum of all XP_i of all sites contributing to a specific EcoProfile, XP_{tot} within openLCA. This calculation is expressed in Equations 1-3.

$$XP_i = IC_i * PS_i \tag{1}$$

$$XP_{tot} = \sum_{i=1}^{n} XP_i \tag{2}$$

$$C_{X-i} = \frac{XP_i}{XP_{tot}} \tag{3}$$

As we obtained data for the production of flakes and pellets, an additional extrusion process was modelled, which is based on the extrusion of rPET (rather high glass temperature). The input of flakes calculated according to Eq. 3 is then modelled to be extruded via this process, assuming no losses of extruded material. The total amount of recycled plastic flakes is part of XP_{tot}, while the rest is contributed by processes that inherently deliver recycled pellets. Through this method, European average production datasets are created for both flake and pellets. The entire method is graphically summarised in Figure 8.

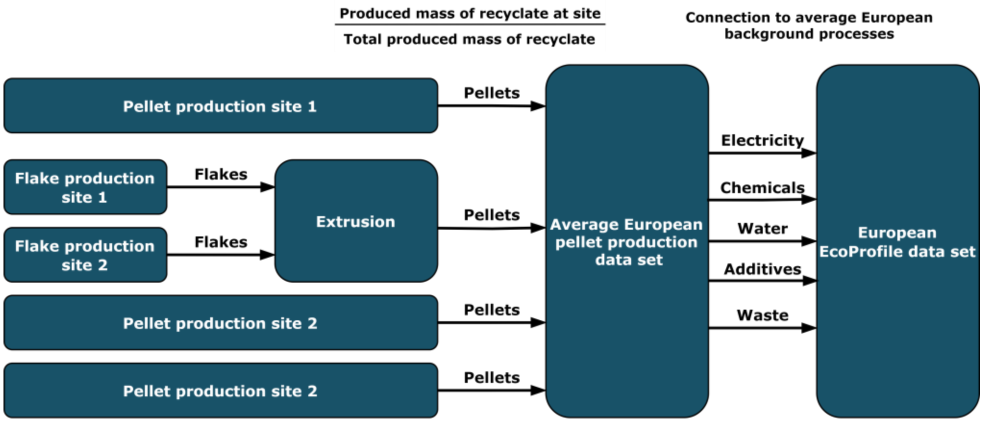

Figure 8. Creation of average European datasets exemplified by generic pellet production process

6.2.7.1 Regionalisation Approach

Since regional primary data is provided, an averaging approach had to be used to create European average EcoProfiles. The approach used here was inspired by the PlasticEurope vertical averaging method in the sense that averages were calculated as weighted means. However, intermediate averaging between production steps has not been performed as a result of lacking data granularity. The weighted means reported in the disaggregated product LCIs were created from site-specific product LCI data modelled off primary data. These site-specific LCIs were averaged to 1 kg of produced plastic flake or pellet according to their share in total reported produced mass and installed recycling capacity as described in the previous section 6.2.7 , thus creating an average weighed by polymer-specific production.

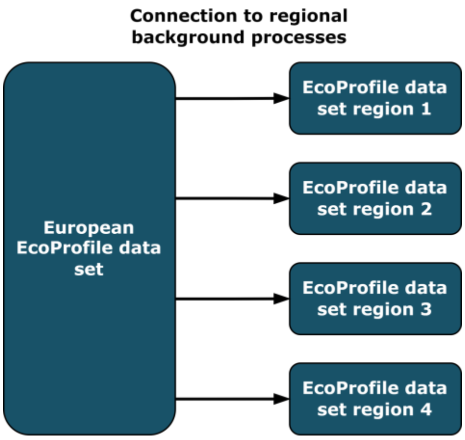

Figure 9. Regionalisation approach for an exemplary generic EcoProfile

Beyond average European EcoProfile datasets, aggregated regionalized datasets have been prepared for gate-to-gate EcoProfiles. These were created based on the European average product LCI datasets by replacing the used background processes with regionally appropriate ones where possible (see Figure 9). Special focus has been placed on waste treatment, energy inputs and transport processes.

Specifically, the following background database processes were regionalised:

- market for electricity, high voltage | electricity, high voltage | Cutoff, U
- market for electricity, low voltage | electricity, low voltage | Cutoff, U
- market for electricity, medium voltage | electricity, medium voltage | Cutoff, U
- market for municipal solid waste | municipal solid waste | Cutoff, U
- market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
- market for waste polyethylene | waste polyethylene | Cutoff, U
- market for waste polyethylene terephthalate | waste polyethylene terephthalate | Cutoff, U
- market for waste polyurethane | waste polyurethane | Cutoff, U

Regionalisation has only been performed for regions that evidently carry out mechanical recycling according to the primary data collected. Regional EcoProfiles have been produced for the EU27+3 countries of Austria, Germany, France, Italy, The Netherlands, and the United Kingdom. See Table 1 for further details.

6.2.7.2 Allocation Rules

Allocation is defined as 'Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems' by ISO 14040. Production processes in recycling industry are usually multi-functional systems, i.e. they have not one, but several valuable product and co-product outputs. For the purposes of the EcoProfiles, only recycled plastic was assumed to be a valuable output of the system. Thus, the impacts of the modelled processes were allocated to plastic outputs alone.

Allocation in the model is needed as recycling can often be a multi-output process. Hence, mass-based physical allocation, accounting only for plastic recyclate in the form of flakes or pellets as useful outputs, is used.

6.2.7.3 Calculation of Uncertainty Values

To enable the expression of modeller confidence in the communicated LCIA results, Monte Carlo simulation (MCS) has been used to compute standard deviations of the calculated results. Hence, the reported LCIA results include a range of uncertainty for each impact category. To calculate the uncertainty values per exchange, the selected Data Quality pedigree values, as outlined in section 6.2.4, were used. Finally, through MCS, using openLCA 2.4 and 1000 iterations, the uncertainty of the foreground model was calculated and is reported in the EcoProfile report.

6.2.7.4 Calculation of Plastic Littering

Plastic littering can lead to marine plastic and could potentially be calculated by means of LCA.[42] The groundwork for plastic littering estimation was done by GreenDelta[43] and later published as Plastic litter extension (PLEX) for ecoinvent in

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[42] Castelan, G. (2018, September). *How LCA can help reducing plasticsmarine litter a knowledgeable and efficient way: Managing is measuring*. SETAC, Vienna. https://plasticseurope.org/wp-content/uploads/2021/12/LCA_and_Marine_Litter_-_PlasticsEurope_-_SETAC_VIENNA_2018.pdf

[43] Ciroth, D. A., & Kouame, N. (2019, September 2). *Elementary litter in life cycle inventories, approach and application*. LCM, Poznan. https://www.greendelta.com/wp-content/uploads/2019/09/Litter_LCM2019.pdf

2023[44] and updated in 2024[45] respectively. The rationale behind this approach is that the plastic litter generated by a process is determined by multiplying the total expected plastic inflow into that process (calculated by summing the plastic content of all incoming flows) by the process's littering probability (the expected litter quantity), as shown in the equation below:

$$PL_j = P_{litter} * \sum_{i=1}^{n} PC_i \qquad (4)$$

- PL_j = plastic litter from process j [kg]

- P_{litter} = expected probability of litter from process j [%]

- PC_i = plastic content of flow i [kg]

- n = number of incoming flows for process j

The details of this approach are heavily documented and will not be described in detail here. For the foreground system of collection and sorting as well as mechanical recycling following assumptions in line with the PLEX probabilistic logic were done:

- plastic content is all plastic (100%) for the produced recyclates
- plastic content is very high (95%) for the sorted and collected plastic waste
- risk for littering medium (0.1%) for mechanical recycling
- risk for littering medium (0.1%) for collection and sorting

The final plastic litter result was calculated by combination of foreground (mechanical recycling with and without collection and sorting) and background data (transport, waste treatment). However, we hereby want to state, that the plastic litter estimation is only providing insights into a short part of the life cycle of plastic material. Hence, the values should be handled with care.

Despite the absence of a definitive correlation between our plastic littering approach and microplastics emission, the amount of plastic littered can be indicative for the emission of microplastics (as a potential upper limit). Main sources of microplastics in Western Europe are tyre abrasion, road marking, marine coating and primary plastics pellet loss during production.[46] The release of microplastics pollution in wash water and atmospheric discharge from plastics recycling facilities is poorly studied, leaving a research gap in understanding their role in environmental plastic pollution. Estimation of microplastic formation showed that 3.1% of global microplastic production could arise form mechanical recycling[9] using UNEP data[47] as source. Although the use of secondary plastic will strongly reduce the amount of pellets loss

[44] Gutke, J., & Andreas, C. (2023). *Plastic litter extension for ecoinvent: Estimating plastic litter over the life cycle*. https://nexus.openlca.org/ws/files/29729
[45] Cilleruelo Palomero, J., & Ciroth, A. (2024). *PLEX v3 documentation*. https://nexus.openlca.org/ws/files/35714
[46] Main source for primary data in the PRIMUS project's EcoProfiles
[47] Ryberg, M., Laurent, A., & Hauschild, M. Z. (2018). *Mapping of global plastic value chain and plastic losses to the environment: With a particular focus on marine environment*. United Nations Environment Programme. https://backend.orbit.dtu.dk/ws/portalfiles/portal/163092267/UN_2018_Mapping_of_global_plastics_value_chain_and_hotspots_final_version.pdf

during primary production, the processes like shredding, extrusion, and granulation of plastic material potentially generate microplastics. Data supporting this can be found for mechanical PET[48], ELV[49] and mixed plastic recycling[50]. The facilities that reported wastewater treatment information all reported that the wash water was discharged to the local wastewater treatment plant using filters and exhaust air using of air filters of unknown filter size. Microplastic emissions of recycling facilities need to be investigated further while active measures for the reduction of microplastic discharge, which have been recently described by the Association of Plastic Recyclers[51], will need continued deployment. It should be mentioned that, while plastics recycling is a potential source of microplastics, is not among the major contributors to microplastics emissions from an upcoming EU legislation [52] point of view. Moreover, a major contributor of primary plastic production, the loss of pre-production pellets, is commonly not assessed by LCA or our PLEX approach.

As for the first time, characterisation factors for microplastics emissions have been published by MariLCA[53] and by Fraunhofer[54], we want to highlight the potential environmental impacts of microplastics emissions from mechanical recycling. Due to the lack of primary data on key factors, such as polymer type, quantity, size, and shape -critical for assessing the environmental impacts of microplastics, we refrain from performing calculations in this regard. This will be a subject of further studies. However, atmospheric discharge and adverse health effects might be retrievable from the results of the particulate matter formation. Still, as most macro- and microplastic is produced in the Use Phase of plastics, around 39% in Europe[24], and we only cover the production of recyclates, we highly recommend users of the LCI datasets to model the other life cycle stages within the PLEX methodology.

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[48] Guo, Y., Xia, X., Ruan, J., Wang, Y., Zhang, J., LeBlanc, G. A., & An, L. (2022). *Ignored microplastic sources from plastic bottle recycling*. Science of The Total Environment, 838, 156038. https://doi.org/10.1016/j.scitotenv.2022.156038

[49] Wang, R., Wang, H., Zhan, L., & Xu, Z. (2024). Pollution characteristics and release mechanism of microplastics in a typical end-of-life vehicle (ELV) recycling base, East China. Science of The Total Environment, 916, 170306. https://doi.org/10.1016/j.scitotenv.2024.170306

[50] Çolakoğlu, E. B., & Uyanık, İ. (2024). *Plastic waste management in recycling facilities: Intentionally generated MPs as an emerging contaminant*. Waste Management, 181, 79–88. https://doi.org/10.1016/j.wasman.2024.04.005

[51] Association of Plastic Recyclers. (2023). *Microplastics Mitigation/Removal/Treatment in the Plastic Recycling Process*. https://plasticsrecycling.org/wp-content/uploads/2024/08/APR_IssueBrief_Microplastics_2023.pdf

[52] European Parliament. (2025, January 24). Reduction of the release of microplastics in the environment and restriction of microplastics intentionally added to products | Legislative Train Schedule. European Parliament. https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-microplastics

[53] Corella-Puertas, E., Hajjar, C., Lavoie, J., & Boulay, A.-M. (2023). MarILCA characterization factors for microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments. Journal of Cleaner Production, 418, 138197. https://doi.org/10.1016/j.jclepro.2023.138197

[54] Maga, D., Galafton, C., Blömer, J., Thonemann, N., Özdamar, A., & Bertling, J. (2022). Methodology to address potential impacts of plastic emissions in life cycle assessment. *The International Journal of Life Cycle Assessment*, *27*(3), 469–491. https://doi.org/10.1007/s11367-022-02040-1

6.2.8 Inventory, Impact Assessment and Selection of Impact Categories

Although the impact assessment plays a rather limited role compared to the produced LCI data, the CED method[55] and the Environmental Footprint 3.1 method, developed by the JRC[56], have been chosen to analyse the LCI and perform an impact assessment.

The CED inventory method was used to assess the energy demand which in dependent on the energy mix used for the processes. It is based on the method published by ecoinvent for version 1.01 in 1997. It 'assesses primary energy usage, as it aims to investigate the energy use throughout the life cycle of a good or a service. This includes the direct uses as well as the indirect or grey consumption of energy due to the use of, e.g., construction materials or raw materials' (Version 2021).

The EF 3.1 method evaluates the environmental impacts of products, services, and organizations across a wide range of categories, e.g. climate change, resource depletion, and ecosystem quality, providing a holistic view of environmental performance. The method itself represents a compilation of various assessment models and all impact categories have been used for the EcoProfiles. An overview of all impact categories including their description is provided in the annex of this document.

For the comparison of primary polymer production with the EcoProfiles (cradle-to-gate), we selected impact categories which have been identified as critical for the impact assessment after a hot spot analysis using normalisation values: Acidification, climate change, non-renewable energy usage, photochemical oxidant formation and water use which are widely overlapping with the JRC's recommendations[21] on the selection of impact categories for plastics. As we had no primary data on PM formation, we did not include this impact category in the visual comparison. However, it is discussed in the respective sensitivity analysis.

However, with the provided data, LCA practitioners can readily reconstruct the impact assessment with also other methods than the ones applied herein.

[55] VDI. (2012). *Cumulative energy demand (KEA)—Terms, definitions, methods of calculation. Engl. VDI-Gesellschaft Energie und Umwelt*. https://www.vdi.de/richtlinien/details/vdi-4600-cumulative-energy-demand-kea-terms-definitions-methods-of-calculation
[56] European Commission. Joint Research Centre. (2023). *Updated characterisation and normalisation factors for the environmental footprint 3.1 method*. Publications Office. https://data.europa.eu/doi/10.2760/798894

7 LCI RESULTS

LCI datasets were provided in the following aggregation states and formats:

- A short EcoProfile report focusing on the polymer under study
- A fully aggregated dataset in JSON-LD and ILCD format
- A disaggregated dataset in JSON-LD and ILCD format featuring detailed material, service, and energy consumption, as well as waste generation and direct emissions

The report provides a disaggregated LCI focusing on chemical inputs, water and energy consumption, transportation, solid waste, secondary material outputs and wastewater treatment of the foreground system.

Table 11. Summary of material and energy in- and outputs of an exemplary secondary material production process for recycled ABS pellets with a gate-to-gate boundary

Inputs	**Flow Quantities per 1 kg of rABS**
Mixed plastic waste including impurities[57]	1.70 kg
Material inputs	
calcium carbonate, precipitated	1.15E-03 kg
chemical, organic	4.40E-04 kg
polyaluminium chloride	1.30E-04 kg
sodium chloride, powder	3.43E-02 kg
sodium hydroxide, without water, in 50% solution state	4.96E-05 kg
Talcum powder	7.00E-04 kg
Water consumption	
tap water	0.216 kg
Energy	
electricity, low voltage	1.91 MJ
Infrastructure	
waste preparation facility	2.00E-09
Transportation	
transport, freight, lorry, unspecified	4.24E-02 t*km
Solid Waste	
municipal solid waste	0.133 kg
raw sludge	5.08E-02 kg
waste plastic, mixture	0.377 kg
waste polyurethane	5.76E-02 kg
Secondary material outputs	
Waste fraction - metal - recycling cut-off	6.16E-02 kg
Wastewater treatment	
wastewater, average	2.82E-05 kg
Probability to litter plastic	
plastic litter	1.61E-03 kg

[57] This value expresses an aggregation of all polymer waste streams contributing to the EcoProfile inputs. Please find the disaggregated input values per-waste stream in the disaggregated datasets.

Further details on the subsections of the LCI are provided in the following descriptions.

Input plastic material

The plastic waste is not further defined by its quality or humidity, it is simply an aggregate value of the required waste input for the production of 1 kg of recycled plastic of the quality according to the reported EcoProfile.

Material inputs

Depending on the waste stream under study, further chemicals and products are required to enable the operations to process incoming waste to a usable secondary material product. In many instances, this includes washing and cleaning of the material, sink-float separation and subsequent wastewater treatment. Therefore, usual water treatment processing chemicals are included in this subsection.

Service inputs

On top of chemicals and products, services may be required for plastic wate recycling. These can be found grouped in this category.

Water consumption

The same processes that require chemical inputs also result in significant water consumption. Since this accounts for the majority of water consumption, further processes, such as ‘Steam water’ and ‘Cooling water’ have been disregarded. A disparity between consumed and emitted or treated water may be explained via the water content of incoming plastic waste.

Energy

During the processing of the recyclates, energy is used for the internal transport of materials as well as washing and grinding of the recycled waste. In some cases, drying of the waste may be facilitated through natural gas as well. The required foreground energy demand is reported per energy carrier.

Infrasructure

The infrastructure required for material recycling, both for the recycling process itself, as well as for collection and sorting of the materials, where applicable, can be found in this category.

Transport

Transport is required for incoming materials, generated wastes and internally on the production site. An inventory of transport flows is reported split into the categories of road, marine and rail transport.

Solid Waste

Waste generated in the recycling process is either treated through landfilling or incineration. The total amount of generated wastes is reported per treatment method.

As this reflects a European context, the regionally preferred treatment option may differ greatly.

Secondary Material Output

In the context of recycling, production of recyclates can also lead to the co-production of by-products depending on the waste stream. Some material streams are commonly collected together and later separated by physical means. The reported inventory shows metal scrap specifically while grouping other by-products.

Wastewater Treatment

The treatment of process water is required and does not always occur on-site. Therefore, a mixture of consumed wastewater treatment chemicals and downstream water treatment is reported in the product LCI.

Plastic Litter

The amount of plastic being littered as calculated by the combination of plastic littering probability and plastic content as described in the PLEX documentation[39].

Cumulative Energy Demand

The primary energy demand of the recyclates was calculated using the cumulative energy demand (CED) method.

Table 12. Primary energy demand by carrier using CED method for an exemplary secondary material production process for recycled ABS pellets with a gate-to-gate boundary

Energy carrier	**Total energy input for 1kg of rABS**
Uranium	1.99 MJ-Eq
Gas, natural	1.27 MJ-Eq
Coal, hard	0.59 MJ-Eq
Coal, brown	0.55 MJ-Eq
Oil, crude	0.45 MJ-Eq
Energy resources: non-renewable	4.86 MJ-Eq
Energy resources: renewable	1.15 MJ-Eq
Total	6.01 MJ-Eq

8 LCIA RESULTS

The life cycle impacts were calculated using the Environmental Footprint 3.1 method providing also uncertainties for each value performed by Monte Carlo simulation. They are displayed in the individual EcoProfiles as in the following Table.

Table 13. Life cycle impacts of the gate-to-gate rABS model related to 1 kg of pellets

Impact Category	**Impact assessment**[58]	**Unit**
Acidification	1.54E-03 ± 1.31E-04	mol H+-Eq
Climate change	1.04 ± 0.08	kg CO2-Eq
Ecotoxicity: freshwater	3.79 ± 0.30	CTUe
Energy resources: non-renewable	4.65 ± 0.38	MJ, net calorific value
Eutrophication: freshwater	1.81E-04 ± 1.55E-05	kg P-Eq
Eutrophication: marine	1.27E-03 ± 9.82E-05	kg N-Eq
Eutrophication: terrestrial	3.64E-03 ± 2.72E-04	mol N-Eq
Human toxicity: carcinogenic	1.12E-09 ± 2.41E-10	CTUh
Human toxicity: non-carcinogenic	7.38E-09 ± 6.74E-10	CTUh
Ionising radiation: human health	0.113 ± 0.010	kBq U235-Eq
Land use	2.12 ± 1.10	dimensionless
Material resources: metals/minerals	3.70E-06 ± 5.91E-07	kg Sb-Eq
Ozone depletion	4.05E-09 ± 3.14E-10	kg CFC-11-Eq
Particulate matter formation	9.62E-09 ± 8.84E-10	disease incidence
Photochemical oxidant formation: human health	1.10E-03 ± 7.76E-05	kg NMVOC-Eq
Plastic litter	0.157 ± 0.015	kg
Water use	0.172 ± 0.012	m3 world Eq deprived

[58] The uncertainty value presented here has been calculated on the foreground data. Details are described in 6.2.7.3.

9 DATA QUALITY, COMPARATIVE ANALYSIS AND SENSITIVITY ANALYSIS

9.1 Data Quality

As described in section 6.2.4, a data quality assessment was conducted applying the ecoinvent data quality system. Figure 7 displays the required categories of the data quality system for the calculation of uncertainty values following the ecoinvent methodology[30]. These are: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation. To assess uncertainties associated with primary data quality according to the procedure in section 6.2.7.3, all exchanges of the datasets had to be assigned a value from 1 to 5. The values of each category were set on a per-exchange basis adhering to the following method:

- Reliability: The primary data collection was non-verified, thus a score of 2 has been applied for all exchanges.
- Completeness: According to the number of data providers that included an exchange in their reported inventory. The scoring method is defined in ecoinvent's pedigree matrix approach and has been assigned according to the share of data collection sites from the sample that use a specific substance and therefore contribute to a specific flow's occurrence in the input and output of the unit process ecoprofile. For instance, three out of five data collection sites using sodium hydroxide equates to a 60% occurrence and therefore leads to a score of 2 following ecoinvent's logic.
- Temporal correlation: The difference between the time of primary data collection and the reported EcoProfile dataset should not exceed 3 years. Thus, a score of 1 was assigned to all exchanges.
- Geographical correlation: Since primary data from the reporting regions is extrapolated to a larger region for lack of a complete set of primary data from all EU27+3 countries, a score of 2 would be appropriate considering the matrix in Figure 3.
- Further technological correlation: Since the specific recycling processes covered by primary data may vary between data collection sites, a score between 1 and 4 was assigned following the authors' confidence in the covered processes matching the system boundaries defined in section 6.2.3.

9.2 Comparative analysis of produced EcoProfiles and secondary Datasets

While a direct comparison with primary plastic is not possible for the gate-to-gate EcoProfiles, we make a comparison of recyclates and primary plastic on a cradle-to-gate level for recyclate pellets. Unfortunately, direct comparison with existing EcoProfiles from PlasticsEurope was not possible, as the presented ILCD data, if present, was not compatible with the used reference flow system. It should be noted that the potentially differing quality of secondary and primary material could not be assessed because of a lack of data. Moreover, the presented data is partly outdated for most primary materials and should be taken with care. Hence, comparison with process for the production of primary material are derived from ecoinvent databases (v. 3.10). The name of the used processes is indicated in the individual EcoProfiles.

The main purpose of the comparison with primary material LCIA results was to benchmark the results of the produced EcoProfiles against a dataset in use by the lifecycle assessment community. For this purpose, secondary polymers available in the background database (ecoinvent, v3.10) were compared to the computed LCIA results from the appropriate EcoProfile dataset of the extended system boundary version, including collection and sorting. The relative results of this comparison are displayed in Figure 10. The specific unit processes used for this comparison are 'polyethylene terephthalate production, flake, amorphous, recycled | polyethylene terephthalate, flake, amorphous, recycled | Cutoff, U - Europe without Switzerland' and 'polyethylene production, high density, flake, recycled | polyethylene, high density, flake, recycled | Cutoff, U - Europe without Switzerland'. To maintain clarity of results, the number of EF 3.1 LCIA impact categories has been reduced.

The lack of available datasets for secondary polymers in commonly used LCA background databases, as mentioned in section 1, was the limiting factor of this modelling verification approach. However, the most robust EcoProfiles of rPET and rHDPE, constructed from 8 and 10 primary datasets, respectively, allowed for this validation approach to be applied. The resulting comparison of selected EF3.1 impact categories is displayed in Figure 10 and Figure 11.

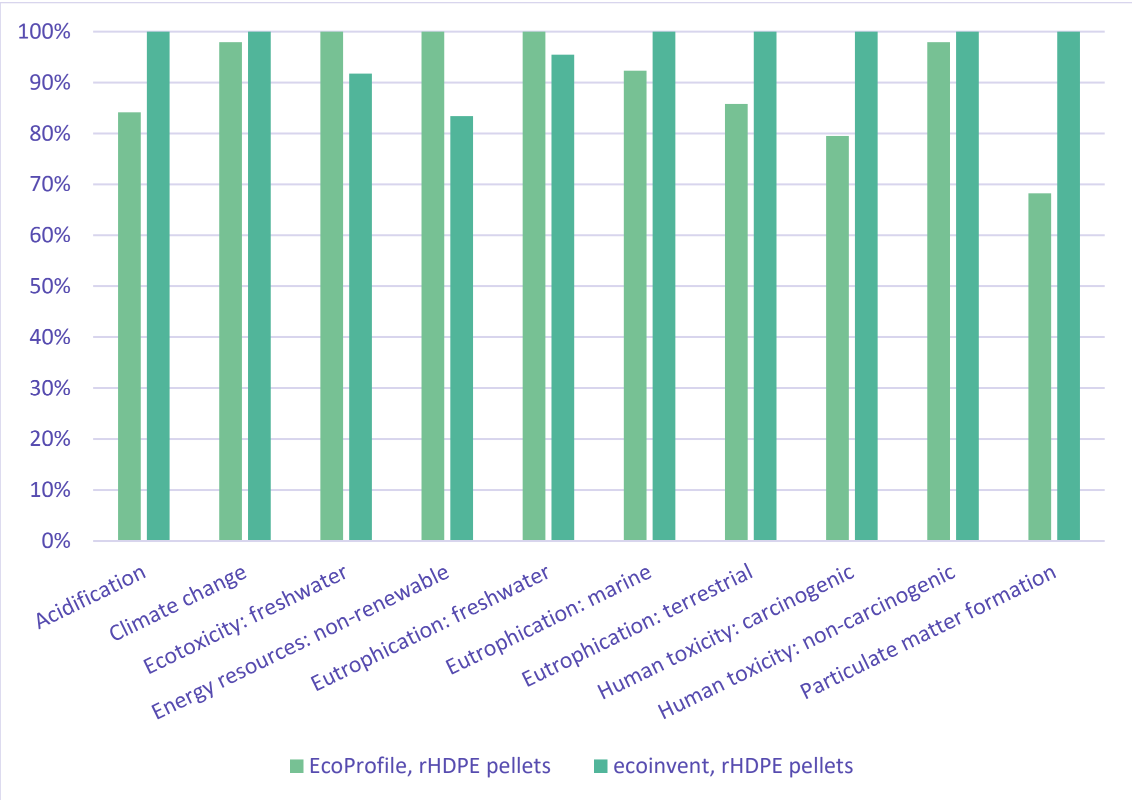

Figure 10. Comparison of EcoProfile and ecoinvent's LCIA results for recycled and extruded rHDPE in selected EF3.1 impact categories

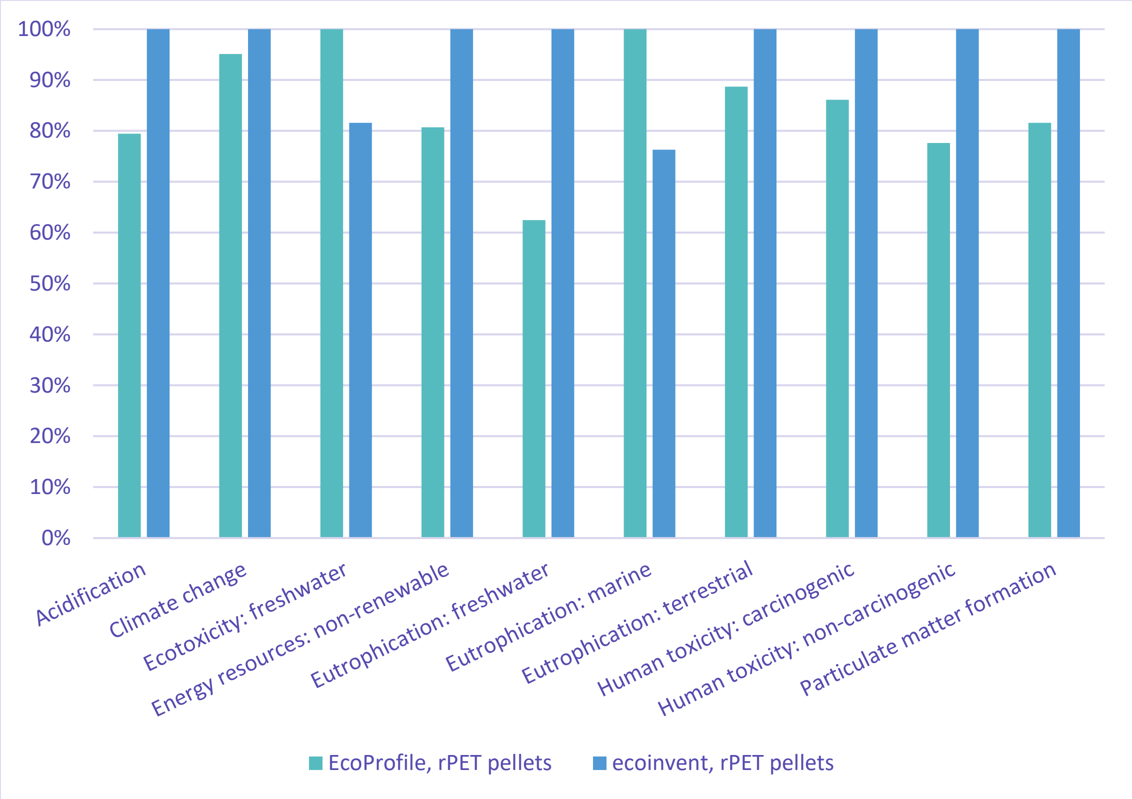

Figure 11. Comparison of EcoProfile and ecoinvent's LCIA results for recycled and extruded PET in selected EF3.1 impact categories

The largest difference between the herein generated LCIA results for rHDPE is present in the impact category for particulate matter formation, with a deviation of 32% of impacts relative to the higher LCIA result of the comparison. The lowest difference has been calculated for the impact category of climate change, where the deviation was only 2.1% of the highest LCIA impact in the category. For rHDPE, the difference was largest in the impact category of freshwater eutrophication at 37.5% and lowest in the impact category of climate change as well, differing only 5.9% from the LCIA results of the ecoinvent dataset. This relatively low range of deviations confirms the viability of the produced EcoProfile models and, thus, the datasets.

9.3 Comparative analysis of EU-27+3-averaged datasets

Another approach requiring model verification is the creation of the European average datasets using average European background data as opposed to average processes created directly from the PRE-member primary data collection with appropriate background datasets. To examine the effect of this aggregation of regional datasets into larger ones with an average supply, the LCIA results of EcoProfiles using data from the primary data collection directly were compared to those making use of average European market processes from the background database. This comparison was performed for the high-value polymers of particular interest in the PRIMUS project, namely rABS, rPP and rHIPS. To achieve a high degree of certainty, only EcoProfile data for pellet production at a gate-to-gate system boundary was compared. Figures 12-14 display the comparison, with the EU production mix on the left and the directly modelled production mix on the right.

The sets of two arranged next to each other in the figure are aligned relatively well for most impact categories; rABS pellets modelled with regional background datasets differed most from European average models in marine eutrophication at a difference of 64.1% and were most aligned in the impact category of terrestrial eutrophication at a difference of 2.5% (Figure 12).

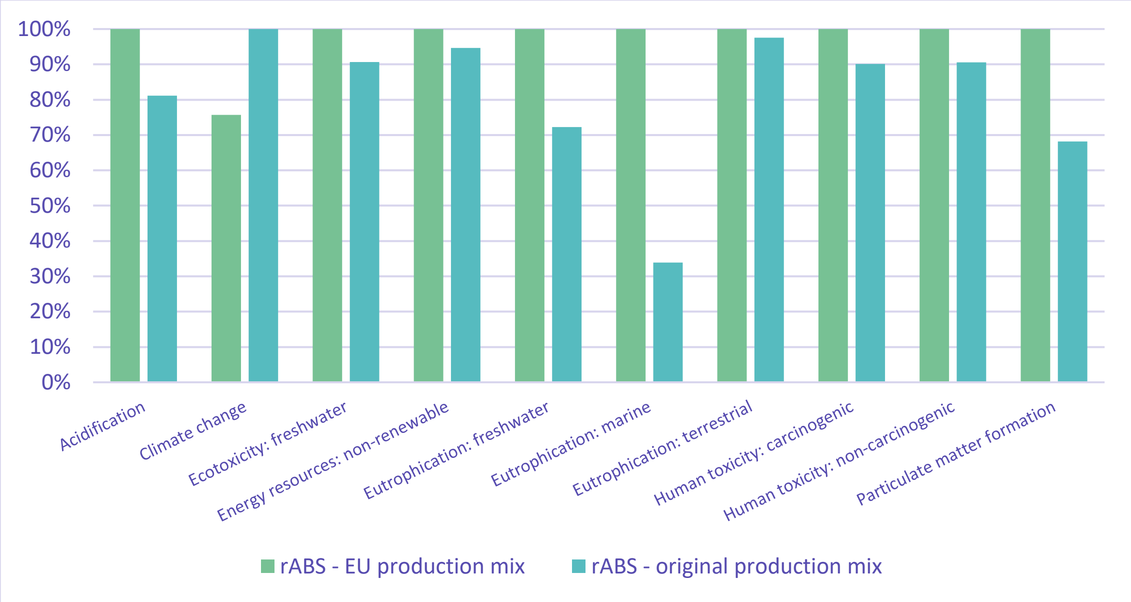

Figure 12. LCIA result sensitivity analysis to regional primary background datasets for rABS. The models are both configured as gate-to-gate rABS pellet production

For the rPP datasets, the largest difference can be observed at 35.0% in freshwater Eutrophication while the lowest one was calculated for freshwater ecotoxicity at 1.1% (Figure 13).

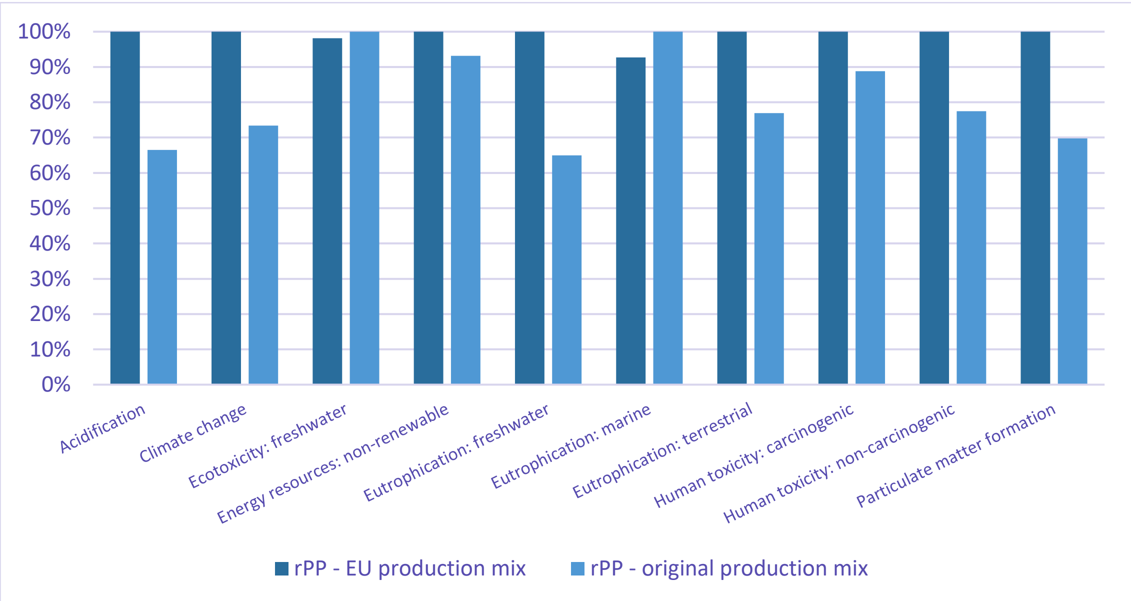

Figure 13. LCIA result sensitivity analysis to regional primary background datasets for rPP. The underlying models are both configured as gate-to-gate rPP pellet production

Lastly, rHIPS' dataset results differed by as much as 40.9% in marine eutrophication impacts and only by 2.9% in fossil fuel resource consumption (Figure 14).

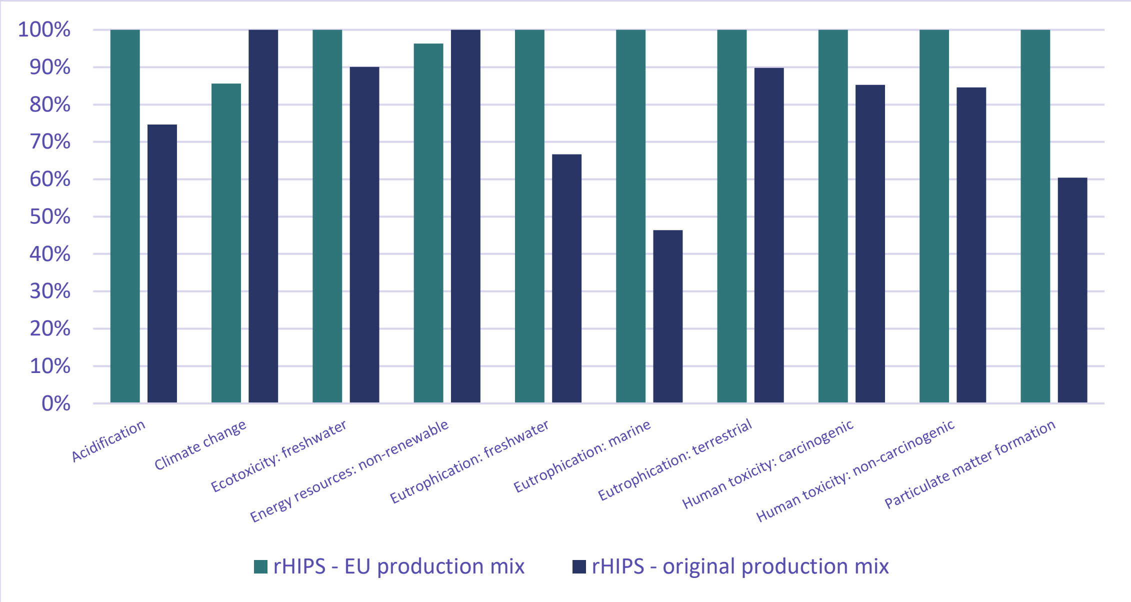

Figure 14. LCIA result sensitivity analysis to regional primary background datasets for rHIPS. The models are both configured as gate-to-gate rHIPS pellet production

As every comparison exemplifies, the greatest difference between the original production mix and the EU production mix lies in the impact categories of eutrophication. This finding warranted an investigation of the underlying model differences, which yielded a considerable difference in the impacts of waste treatment processes. Resulting from the use of average EU data sets for the EU production mix, a larger fraction of polyurethane, plastic and municipal solid waste is landfilled, leading to increased landfill emissions.[23]

Though the largest deviations are significant, most impact categories deviate less than 20% for each set, showing that, although there is a difference in results, it can be argued that the aggregation of a larger set of technologies covered by the EU datasets as opposed to regional background data allows for a better representation of the EU mechanical recycling market covered by these EcoProfiles. It should also be noted that the difference in the impact categories of climate change and non-renewable energy resource consumption is relatively low, peaking at 24.3% in the case of climate change when comparing the primary data-based EcoProfile and the average EcoProfile for rABS. As plastic products are inherently fossil materials, these impact categories are particularly useful for benchmarking of related datasets.

9.4 Sensitivity Analysis for VOC and PM

In contrast to primary produced polymers, mechanical recycling produces intrinsically particulate matter (PM) but is also prone to emit VOCs during processing and extrusion. In particular, the formation of PM is a critical impact category as described in a JRC report on plastic waste management[21]. While the formation of PM has its own impact category within the EF 3.1 method, the emission of VOC contributes to various impact categories: Ecotoxicity (freshwater), human toxicity (non-cancerogenic) and photochemical oxidant formation (human health).

Since the primary data did not include polymer-specific PM or VOC data for mechanical recycling, we conducted a sensitivity analysis to evaluate the impact of this data gap. The latest version of ecoinvent (v3.11) provides polymer-specific data and constant flake pelletising (extrusion and cutting) on VOC and PM emissions. Although ecoinvent was contacted regarding the source of this data, no conclusion on the origin of this data could be made beyond it being described as "dust". Hence for the waste treatment processes, VOC and PM data per polymer type and waste stream was present. In case of multiple processes per polymer, values had been averaged. Interestingly, the value for PM below 10 µm for pelletising was constant irrespective of the polymer type, indicating an assumption on the part of ecoinvent.

Finally, to assess the sensitivity of our models' results, those respective emissions per process have been added to our EcoProfiles for rABS, rHIPS and rPP and the results have been compared to identify potential differences in the overall results. Data availability limited the comparison to rABS flakes, rHIPS flakes, rPP flakes and rPP pellets. The relative LCIA results for the impact categories with characterisation factors for VOC, NMVOC and PM elementary flows are displayed in below (Figure 15).

For rABS flakes and rHIPS flakes, no noticeable differences were observed in any category for the VOC/PM-added EcoProfiles. Similarly, rPP flakes showed only negligeable changes in particulate matter formation. The most pronounced differences were observed for rPP pellets, where particulate matter formation increased by 0.81%, photochemical oxidant formation (human health) rose by 1.56% but human toxicity (non-carcinogenic) and ecotoxicity (freshwater) showed no increase respectively. These findings suggest that the inclusion of polymer-specific emissions barely influences the impact assessment results. However, the updated version of the EcoProfiles should include primary data on PM and VOC, which will then be integrated into the final results.

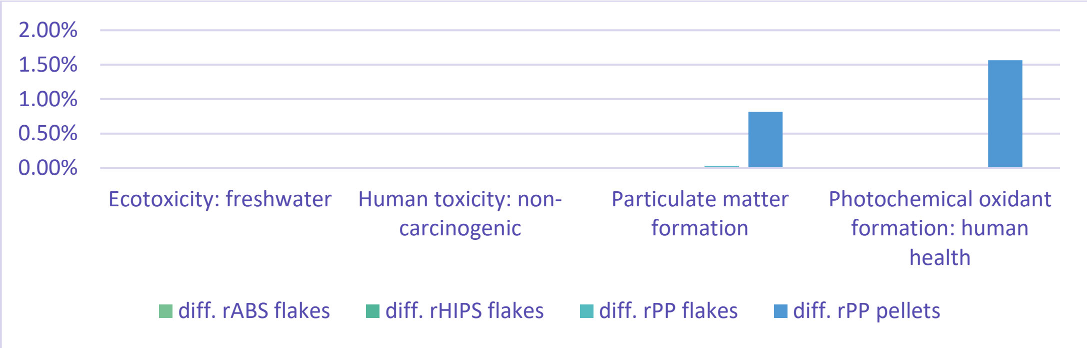

Figure 15. Relative LCIA result changes of the PM and VOC sensitivity analysis, calculated using the EF3.1 LCIA method as described above. Emission data extracted from ecoinvent processes corresponding to the recyclates in question: rABS flakes[59], rHIPS flakes[60], rPP flakes[61] and rPP pellets[62]

[59] Direct emissions were extracted from the processes "treatment of waste plastic, small domestic appliances, recycling | acrylonitrile-butadiene-styrene, flakes, recycled | Cutoff, U", "treatment of waste plastic, WEEE, recycling | acrylonitrile-butadiene-styrene, flakes, recycled | Cutoff, U", "treatment of waste plastic, refrigerator, flakes, recycling | acrylonitrile-butadiene-styrene, flakes, recycled | Cutoff, U" and "treatment of waste plastic, television, recycling | acrylonitrile-butadiene-styrene, flakes, recycled | Cutoff, U"

[60] Emission data was extracted from the background processes "treatment of waste plastic, television, recycling | polystyrene, flakes, recycled | Cutoff, U", "treatment of waste plastic, small domestic appliances, recycling | polystyrene, flakes, recycled | Cutoff, U", "treatment of waste plastic, refrigerator, flakes, recycling | polystyrene, flakes, recycled | Cutoff, U " and "treatment of waste plastic, WEEE, recycling | polystyrene, flakes, recycled | Cutoff, U"

[61] Emission data was extracted from the background processes "treatment of waste plastic, mixed, recycling | polypropylene, flakes, recycled | Cutoff, U", "treatment of waste plastic, WEEE, recycling | polypropylene, flakes, recycled | Cutoff, U ", "treatment of waste plastic, refrigerator, flakes, recycling | polypropylene, flakes, recycled | Cutoff, U", "treatment of waste plastic, small domestic appliances, recycling | polypropylene, flakes, recycled | Cutoff, U", "treatment of waste polypropylene, packaging, flakes, recycling | polypropylene, flakes, recycled | Cutoff, U" and "treatment of waste plastic, television, recycling | polypropylene, flakes, recycled | Cutoff, U"

[62] Emission data was extracted from the background processes "pelletising of polypropylene | polypropylene, pellets, recycled | Cutoff, U", "treatment of waste polypropylene, recycling | polypropylene, pellets, recycled | Cutoff, U", "treatment of waste plastic, consumer electronics, recycling | polypropylene, pellets, recycled | Cutoff, U", "treatment of waste polypropylene, packaging, pellets, recycling | polypropylene, pellets, recycled | Cutoff, U" and "treatment of waste plastic, refrigerator, pellets, recycling | polypropylene, pellets, recycled | Cutoff, U"

10 REVIEW

Experts from VTT (Noora Harju, Silvia Forin) which have not been previously involved in the PRIMUS project review the methodology and the documentation of one exemplary EcoProfile.

The datasets made available to the public represent a consistent contribution to the assessment of recycled plastics in LCA studies. This report provides a clear and transparent documentation of the calculation procedures carried out within the project and can be taken as a baseline for future dataset production processes.

Goal and Scope

The goal and scope of the study are displayed in a clear and detailed way. The declared unit and the reference flow are in line with the goal of the study. The choice of the system boundaries underscores the focus on mechanical recycling processes, considering the material to be recycled as burden-free. The data quality requirements encompass reliability, completeness, temporal, geographical and technological representativeness and are in line with the main criteria laid out by ISO 14044.

Data collection, modelling assumptions and calculation approach

The collection procedure for primary data is displayed transparently. Collected primary data is not reported in a disaggregated way for confidentiality reasons, which limits the reproducibility of the datasets. Still, the rationale behind the calculation of both national and EU-level averages is made transparent, thus providing a guidance for future dataset creation. The use of secondary (Ecoinvent) datasets is displayed transparently in the report.

Life cycle inventory and impact assessment

Life cycle inventory results are provided for different parts of the cradle-to-gate boundary, i.e. fully aggregated and tier-1 only. Besides standard inventory categories, also the probability to plastic litter is included, thus filling a relevant gap in the consideration of the elementary flows related to plastics. For impact assessment, one of the most updated consensus methods available, the Environmental Footprint 3.1, is used, thus ensuring a holistic approach.

Data quality analysis

The quality of the datasets was analysed in detail according to the data quality requirements declared in the goal and scope of the study. Moreover, a juxtaposition with existing datasets, used a plausibility check, located the newly developed datasets in the same ballpark as existing datasets for recycled plastics.

Data sets and EcoProfile reports

The developed datasets were reviewed along with the report, and the accuracy of the data contained in the product-specific EcoProfile reports was verified at the highest aggregation level (14 documents and datasets a geographical scope at EU level and cradle-to-gate system boundary). For these datasets, the assumptions and background LCI data selection documented in the EcoProfile reports were compared with the dataset content to ensure their correspondence. Additionally, the reviewers performed the impact assessment calculation using the openLCA software, version 2.4, and verified the related content of the EcoProfile reports.

11 ANNEX

ENVIRONMENTAL FOOTPRINT IMPACT ASSESSMENT CATEGORY SELECTION AND DESCRIPTION

The Environmental Footprint 3.1 method is a LCIA method developed by the European Commission's Joint Research Centre (JRC). The individual impact categories are described below.

Table 14. Explanation of the LCIA categories and their underlying models used in the EF3.1 LCIA method, excluding subcategories

Name	**Unit**	**Model**
Acidification	mol H+ eq.	Accumulated Exceedance method (combination of models)
This EF impact category addresses impacts due to acidifying substances in the environment. Emissions of NOx, NH3 and SOx lead to releases of hydrogen ions (H+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.		
Climate change	kg CO2 eq.	Baseline model of 100 years of the IPCC
EF impact category considering all inputs and outputs that result in greenhouse gas (GHG) emissions. The consequences include increased average global temperatures and sudden regional climatic changes. Climate change is an impact affecting the environment on a global scale.		
Ecotoxicity, freshwater	CTUe	USEtox 2.1
EF impact category that addresses the toxic impacts on an ecosystem, which damage individual species and change the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem.		
Eutrophication		
EF impact category related to nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland that accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of substances emitted into a common measure expressed as the oxygen required for the degradation of dead biomass. Three EF impact categories are used to assess the impacts due to eutrophication: eutrophication, terrestrial; eutrophication, freshwater; eutrophication, marine.		
Eutrophication, freshwater	kg P eq.	Accumulated Exceedance method (combination of models)
Eutrophication, marine	kg N eq.	Accumulated Exceedance method (combination of models)

Eutrophication, terrestrial	mol N eq.	Accumulated Exceedance method (combination of models)
Human toxicity, cancer.	CTUh	USEtox 2.1
EF impact category that accounts for adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to cancer.		
Human toxicity, non-cancer.	CTUh	USEtox 2.1
EF impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.		
Ionising radiation (human health)	kBq U-235 eq.	ExternE
EF impact category that accounts for the adverse health effects on human health caused by radioactive releases.		
Land use	dimensionless	
EF impact category related to use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in soil quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in soil quality multiplied by the area).		
Resource use, fossils	MJ	Abiotic resource depletion (ADP fossil)
EF impact category that addresses the use of non-renewable fossil natural resources (e.g. natural gas, coal, oil).		
Resource use, metals/minerals	kg Sb eq	Abiotic resource depletion (ADP fossil)
EF impact category that addresses the use of non-renewable abiotic natural resources (minerals and metals).		
Ozone depletion	kg CFC11 eq	
EF impact category that accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substances, for example, long-lived chlorine and bromine-containing gases (e.g. chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons).		
Particulate matter formation	disease inc.	EF-particulate matter
EF impact category that accounts for the adverse effects on human health caused by emissions of particulate matter (PM) and its precursors (NOx, SOx, NH3).		
Photochemical oxidant formation	kg NMVOC eq	LOTOS-EUROS
EF impact category that accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight.		
Water use	m3 depriv.	AWARE 100 (Available water Remaining)

EF impact category that represents the relative available water remaining per area in a watershed, after demand from humans and aquatic ecosystems has been met. It assesses the potential for water deprivation, to either humans or ecosystems, based on the assumption that the less water remaining available per area, the more likely it is that another user will be deprived.		
Plastic litter	kg littered	PLEX methodology[39]
This methodology provides an estimate of how much plastic litter is generated, considering the specific littering risk associated with different processes.		

Estimation of polymer-Specific recycling efficiencies

Based on a Material Flow Analysis (MFA) study published by the JRC in 2023[63], polymer-specific recycling efficiencies have been estimated. The mean transfer coefficient per polymer, i.e. the approximate recycling efficiency, was calculated by multiplying the values of the polymer-specific recyclate contribution of the sectors with the polymer-specific transfer coefficient of that sector.

Table 15. Transfer coefficients of specific polymers from input material to be recycled to recyclate. Mean transfer coefficient computed according to recyclate contribution of sectors

P = Packaging, C = Construction T = Transport, E = Electrical and Electronic Equipment, A = Agriculture		Sector					Mean transfer coefficient scaled by recyclate contributions, recycling effic.
		P	C	T	E	A	
Polymer-specific transfer coefficients [%]	LDPE	59%	56%	70%	50%	58%	59%
	HDPE	84%	71%	70%	50%	77%	82%
	PP	69%	56%	70%	50%	63%	66%
	PS	56%	56%	70%	50%	59%	55%
	PVC	82%	55%	70%	50%	59%	59%
	PET	76%	56%	70%	50%	59%	76%
	ABS	71%	56%	70%	50%	59%	61%
P = Packaging, C = Construction T = Transport, E = Electrical and Electronic Equipment, A = Agriculture		Sector					Sum of sector contributions
		P	C	T	E	A	

[63] Amadei, A. M., Rigamonti, L., & Sala, S. (2023). *Exploring the EU plastic value chain: A material flow analysis*. Resources, Conservation and Recycling, 197, 107105. https://doi.org/10.1016/j.resconrec.2023.107105

P = Packaging, C = Construction T = Transport, E = Electrical and Electronic Equipment, A = Agriculture		Sector					Sum of sector contributions
		P	C	T	E	A	
Polymer-specific recyclate contributions of each sector [%]	LDPE	82%	2%	1%	2%	13%	100%
	HDPE	93%	4%	2%	2%	0%	101%
	PP	66%	6%	12%	5%	11%	100%
	PS	56%	18%	3%	19%	3%	99%
	PVC	14%	76%	2%	4%	5%	101%
	PET	98%	1%	0%	0%	0%	99%
	ABS	7%	12%	44%	37%	0%	100%

The sector- and polymer-specific transfer coefficients from 'Recycling' to 'Recyclate' in table SM13 of the JRC study have been assumed to be equivalent to the recycling efficiency of each polymer. To estimate total cross-sector recycling efficiencies of each polymer, mean transfer coefficients were computed from sector-specific values of each polymer published as part of the supplementary information's table SM13 and weighed by the "Polymer-specific contribution of each sector regarding the total recyclates produced" from Figure 3 of the JRC report. In Table 15, we only display extracted and calculated values for polymers that are also represented by an EcoProfile within the PRIMUS project.