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PRIMUS

WP6. 50 EcoProfiles and 200 datasets from the PRIMUS Demo cases

Task 6.3

Applying the Sustainability Assessment for 4 PRIMUS cases, and creation of EcoProfiles for recyclates

Deliverable 6.3

50 Ecoprofiles and 200 datasets from the PRIMUS Demo cases

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DISCLAIMER

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DEFINITIONS/GLOSSARY

Cradle-to-gate – This is a system boundary definition for Life Cycle Assessments that defines the system from raw material extraction, or initial life cycle stages, to factory gate, including transportation and production processes.

Gate-to-gate – This is a system boundary definition for Life Cycle Assessments that defines the system from factory gate to factory gate.

Life Cycle Assessment – A process of evaluating the effects that a product or service has on the environment over the entire period of its life, from raw material extraction until end-of-life, depending on the system boundary.

Primary plastics – referred to usually as virgin plastics. This is the first life cycle of a plastic product.

Recyclates – refers to recycled plastic granulates, pellets, flakes, etc.

Secondary plastics – refers to the second life cycle of a plastic, after recycling.

Primary data – direct data collection for Life Cycle Assessments.

Secondary data – comes from a background database to complete Life Cycle Assessment studies until raw material extraction.

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

EXECUTIVE SUMMARY

The objectives of this work were to refine an all-round and comprehensive sustainability assessment, based on existing solutions, and covering environmental and social aspects, and apply it to the 4 PRIMUS demonstrator cases (Demo cases), arriving to Life Cycle Inventory (LCI) datasets and 4 life cycle models. EcoProfile datasets for recycled plastics were also an objective, representing European industry average.

Primary data was collected from plastic recyclers in Europe with the help of Plastic Recyclers Europe, and further processed by GreenDelta, arriving to 50 EcoProfiles including European averages and regionalised datasets. These are available in PDF format as well as ILCD and JSON-LD, which can be imported in LCA software. The datasets are also available with transparent supply chains, which is a big difference from previously existing eco-profiles.

The LCA datasets here presented entail building blocks that are required to make an LCA for the plastics industry and involves a collection of datasets for fillers and additives, primary plastic production, recycled plastic production, transportation, fuels used, and waste management. The LCA models for the 4 PRIMUS Demo cases is also provided as an example. For this, intensive data collection and workshops were organised with the relevant partners: Cikautxo and Maier for plastic part manufacturing, and Coolrec Plastics for plastic recycling.

The deliverable also provides an analysis of the 4 PRIMUS Demo cases as an example of the applied sustainability methodology.

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PRIMUS PROJECT

PRIMUS project is dedicated to significantly contribute to the goals of the European Strategy for Plastics and enhance the amount of quality and safe recycled plastics that enter the European markets. PRIMUS is a project funded by the Horizon Europe in the following call: *HORIZON-CL4-2021-RESILIENCE-01-10: Paving the way to an increased share of recycled plastics in added value products (RIA)*. PRIMUS is a 3-year project with a total budget of 7 M€. PRIMUS has 10 partners[1], and 2 affiliated entities[2].

PRIMUS will actively engage with the plastics value chain stakeholders and innovatively develop novel methods and technologies to significantly increase the circularity, and production and use of sustainable, safe and quality recyclates in added value products. The main technological focuses are on advanced mechanical recycling coupled with broad analytics and novel pretreatment methods for removal of hazardous substances and counteracting degradation. PRIMUS will produce 4 demonstrations where new added value products will be made from recycled and upgraded non- or underutilized plastic waste streams from waste electronics and electrical equipment (WEEE) and end-of-life vehicles (ELV). The four demo products will be automotive interior parts, automotive cooling circuits and its elements, a food contact application refrigerator, and a closed-loop demonstration of washing machine seals.

The project aims at establishing EU widely accepted and transparent procedures to control quality and safety of recyclates, especially for the waste streams containing hazardous substances like brominated flame retardants. The framework related work will include broad engagement of the European plastics sector and recyclers, but also the society, citizens and communities as well as consumers. Safety and trackability back to origin, traceability, are consistent and overlapping themes in PRIMUS. PRIMUS will not only technically and industrially support the uptake of recyclates in products but will also address and support the concerns of the society and enhance the uptake of products that have recycled content.

INTRODUCTION

The environmental and social implications of an increasing plastic production and disposal pushes for the idea of circularity of plastics, which is often seen as beneficial and something we, as a society, should aim for.

In this project, work package 6 aims to assess the sustainability of mechanically recycled plastics and their integration in plastic products. A full sustainability methodology was developed including Life Cycle Assessment (LCA), social Life Cycle Assessment (sLCA), circularity, criticality, plastic littering risk and an overview with System Dynamics modelling. The methodology was applied to assess the "sustainability" using the indicators collected in the methodology.

Naturally, the processes of performing this task yielded sustainability datasets. This deliverable presents EcoProfile datasets for recycled plastics in Europe, that is, cradle-to-gate and gate-to-gate information for the production of mechanically recycled plastics in Europe. Furthermore, the deliverable presents sustainability datasets to support assessments for recyclates and plastic products with recycled content.

The authors would like to note that there are supporting documents to this deliverable: the PRIMUS Methodology for Sustainability Assessment applied to the 4 Demo cases; and the EcoProfiles Methodology report outlining in detail the work done with EcoProfiles. These are found in the Annex.

Scope

This deliverable outlines the process of making sustainability datasets for the PRIMUS model.

Audience

The audience benefiting from these datasets are plastic recyclers that want to compare their footprint and also the average and LCA practitioners that want to implement the datasets into their assessments. Generally, any party that requires sustainability indicators of recycled plastics (EcoProfiles) or needs tools to calculate the footprint of a plastic part with recycled content (the rest of the datasets).

Contributions of partners

Table 1 depicts the main contributions from participant partners in the development of this deliverable.

Participant short name	Contributions
GD	Work coordination, execution and reporting.
PRE	Data collection from European recyclers.
MAI	Data provision for Demo 1.

CK	Data provision for Demo 2 and 4.
COR	Data provision for Demo 3.
VTT	Data provision for Demo 3.

Table 1. Partners´ contributions

Relation to other activities in the project

Table 2 depicts the main relationship of this deliverable to other activities (or deliverables) developed within the PRIMUS project and that should be considered along with this document for further understanding of its contents.

Deliverable Number	Contributions
D3.5	***PRIMUS Demo case studies report*** provides an overall description of the demonstrator cases that were investigated with the Sustainability Methodology
D6.1	***Open-source tool for developing LCSA for plastic recyclates*** holds the data described in this document.
D7.2	***Best Practice Book*** collects a summary of the PRIMUS Methodology and application to the PRIMUS demonstrator cases.

Table 2. relation to other activities in the project

Structure

The report is divided in two parts. Part A goes through the work to produce the sustainability datasets and Part B contains the methodology for the EcoProfile datasets for recycled plastics developed in PRIMUS.

OBJECTIVES AND EXPECTED IMPACT

WP6 develops and provides a comprehensive and broad perspective sustainability assessment for PRIMUS.

Objective

The objectives of this deliverable are to:

- Develop at least 200 LCA datasets and 4 sustainability life cycle models for plastic recyclates.
- Develop at least 50 Ecoprofiles for primary recyclates from ELV and WEEE recycling. This will include at least 8 core Ecoprofiles, which are representative to the European market for technical plastics.

Expected Impact

These datasets and models will be available for the LCA community and will further disseminate knowledge about the sustainability impacts of recycled plastic along their life cycle.

PART A

1 PRIMUS SUSTAINABILITY METHODOLOGY

The PRIMUS Sustainability Methodology aims to expand the boundaries and perspectives of environmental LCA to include other indicators that help to better understand the sustainability and implications of producing mechanically recycled plastics and to include them in plastic products. This way, social LCA, circularity, plastic littering, criticality and System Dynamics are also included in the analysis. The project further applies the methodology to 4 PRIMUS demonstrator cases (Demo cases).

1.1 Life Cycle Assessment

1.1.1 Goal

The goal of the environmental Live Cycle Assessments (LCAs) is to understand and quantify the environmental sustainability performance of the plastic parts with recycled content developed in the PRIMUS project with respect to their 100% primary counterparts. The results aim to inform plastic recyclers and plastic part producers over the sustainability of these practices, helping assess the uptake of these new materials which can help the Circular Economy.

1.1.2 Scope

This section will present decisions made regarding the functional unit, system boundary, allocation procedures, database use, LCIA Method and choice of indicators.

Functional Unit

Each study's results are reference to the functional unit of the study. In the case for the PRIMUS Demo cases results refer to:

"*a plastic part* at factory gate, performing the usual functionality of the same plastic part with no recycled content"

Results are given for the scenario with recycled content and with 100% primary plastics at the input. **Error! Reference source not found.** has more detailed information on e ach demonstrator case functional unit.

System boundary

The system boundary for the studies includes life cycle stages from cradle-to-gate, that is, from raw material extraction (or recycled material production) to factory gate, not taking into account use phase or end-of-life. Each study compares a plastic part made out of recycled content and its 100% primary material counterpart, see Figure 1 and Figure 2. Both parts are assumed to have the same performance during use phase and end-of life fate, as they both have material properties that pass the same quality assurance tests.

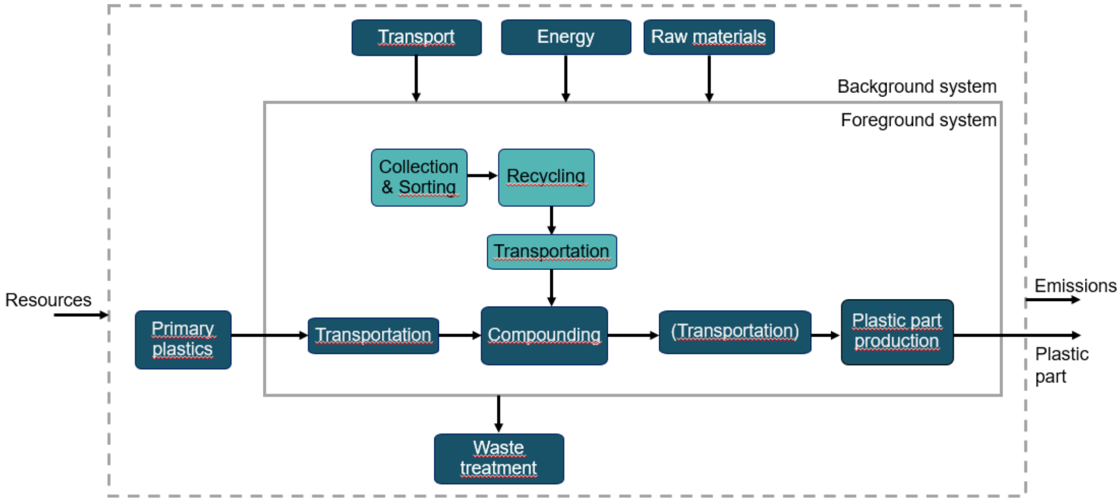


Figure 1. System Boundary for plastic parts with recycled content

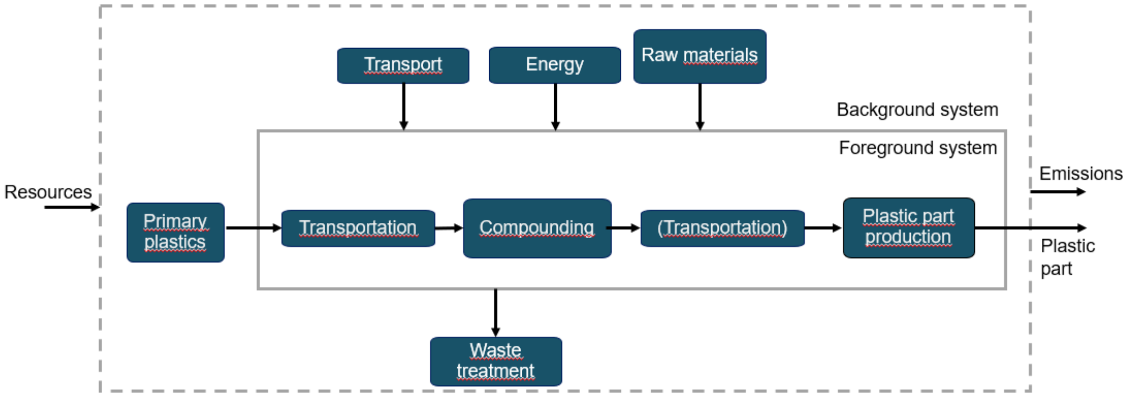


Figure 2. System boundary for plastic parts with 100% primary plastic content

Cut-off criteria

The first life of a plastic product takes the environmental burdens of raw material extraction and further life cycle stages after that. Waste treatments are considered, except if waste is going to recycling, where the system cuts off, see Figure 3. Credits are not given to the first life of the product for energy recovery during incineration neither recycling. The waste collected for recycling starts the second life of the plastic material "burden free", carrying no environmental impacts before it.

Impacts regarding the second life of the plastic are only those involving waste collection, sorting and recycling resulting in the production of recyclates that can substitute primary plastics. Also here, credits are not given to the system.

Multifunctionality in the second life of the plastic is treated with mass allocation. Here, byproducts are considered to be materials ready to substitute a primary material in the market, e.g. other recycled plastics, as it is common in recycling that the processing in the recycling facility produces several plastic recyclates. Other potential byproducts, e.g. the metal fraction, are cut off the system as shown in the bottom right corner of Figure 3. These need further treatment in order to substitute primary material in the market, therefore, they are not yet ready to give credits to the system through allocation or system expansion.

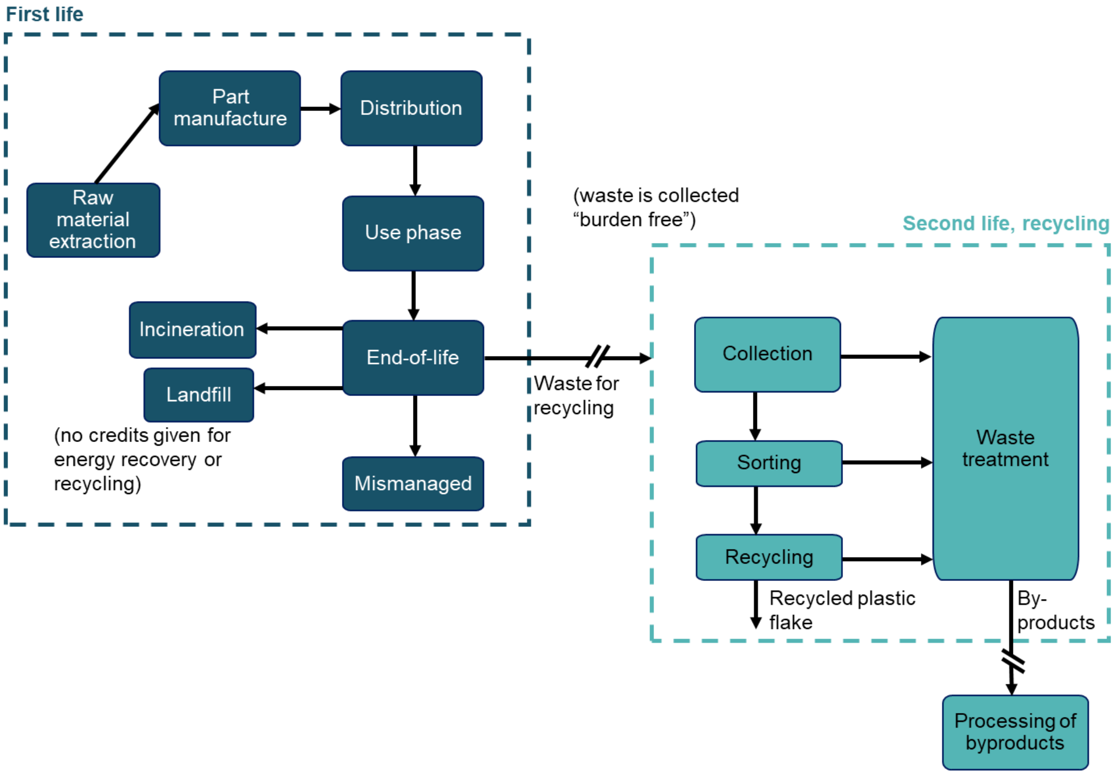


Figure 3. Cut-off criteria between first and second life cycle of plastic products in the PRIMUS LCA methodology

Post-industrial waste

Some PRIMUS Demo cases use post-industrial, or pre-consumer, waste in the recycled scenario. It is important to state that this material shouldn’t be considered as recycled material, nor should we incentivise industry to make a business case out of industrial waste but rather encourage process efficiency and close-loop material circulation of this content, i.e. within the same industrial facility.

For the studies on the Demo cases, it has been assumed that the post-industrial scrap would otherwise be sent to final end-of-life disposal, and therefore could be treated as waste. The efforts considered in this case were grinding the material and transporting it to the compounding facility.

Database, LCIA Method

The LCA database *ecoinvent 3.10 cut-off* [1] was used as a background database that connects to the foreground model and completes supply chains.

Road distances by truck were modelled with the European average for lorry transportation, i.e. “market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U – RER”.

The *Environmental Footprint 3.1* [2] (EF 3.1) Life Cycle Impact Assessment (LCIA) method is used to calculate the environmental impacts from the LCA model, also called product system.

The impact categories chosen for this assessment are outlined in Table 3.

Table 3. Impact Categories shown for the results of the LCA study [2]

LCIA Method name	**Impact indicator**	**Description and importance** [3]
Acidification	Accumulated Exceedance (AE); (mol H+ eq)	Acidification has contributed to a decline of coniferous forests and an increase in fish mortality. The most significant sources are combustion processes in electricity, heat production, and transport. The more sulphur the fuels contain the greater their contribution to acidification.
Climate change	Radiative forcing as Global Warming Potential (GWP100)	Refers to the increase in the average global temperatures as result of greenhouse gas (GHG) emissions.
Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems (CTUe)	This indicator refers to potential toxic impacts on an ecosystem, which may damage individual species as well as the functioning of the ecosystem. Some substances tend to accumulate in living organisms. Based on the USEtox model.
Eutrophication freshwater	Fraction of nutrients reaching freshwater end compartment; (kg P eq)	Eutrophication arises when substances containing nitrogen (N) or phosphorus (P) are released to ecosystems. These nutrients cause a growth of algae or specific plants and thus limit growth in the original ecosystem.
Eutrophication marine	Fraction of nutrients reaching marine end compartment; (kg N eq)	
Eutrophication terrestrial	Accumulated Exceedance (AE); (mol N eq)	
Human toxicity cancer	Comparative Toxic Unit for human (CTUh)	These indicators refers to potential impacts, via the

Human toxicity non-cancer	Comparative Toxic Unit for human (CTUh)	environment, on human health caused by absorbing substances from the air, water and soil. Based on a model called USEtox.
Ionising radiation (human health)	Human exposure efficiency relative to U235	Exposure to radioactivity under normal operating conditions (no nuclear accidents considered).
Land use	Soil quality index	Use and transformation of land for agriculture, roads, housing, mining or other purposes. The impacts can vary and include loss of species, of the organic matter content of soil, or loss of the soil itself (erosion).
Ozone depletion	Ozone Depletion Potential (ODP)	The stratospheric ozone (O3) layer protects us from hazardous ultraviolet radiation (UV-B). Its depletion increases skin cancer cases in humans and damage to plants.
Particulate matter	Disease incidence per kg of PM2.5 emitted.	Measures the adverse impacts on human health caused by emissions of Particulate Matter (PM) and its precursors (e.g. NOx, SO2).
Photochemical ozone formation (human health)	Tropospheric ozone concentration increase; equivalent of kilograms of Non-Methane Volatile Organic Compounds (kg NMVOC eq).	Ozone on the ground is harmful as it attacks organic compounds in animals and plants and increases the frequency of respiratory problems when photochemical smog (summer smog) is present in cities.
Resource use fossils	Abiotic resource depletion fossil fuels (ADP-fossil); (MJ)	Quantifies the amount of materials contributing to resource use, fossil like coal, oil and gas. Extracting those today may lead to non-availability for fossil fuels for future generations.
Resource use minerals and metals	Abiotic resource depletion (ADP ultimate reserve); (kg Sb eq)	Similar to Resource use fossils but applied to minerals and metals

Water use	User deprivation potential (deprivation-weighted water consumption; m3)	Consumption of water from lakes, rivers or groundwater can contribute to the 'depletion' of available water. The impact category considers the availability or scarcity of water in the regions where the activity takes place, if known.

1.2 **Social Life Cycle Assessment**

The goal of the social LCA is to define the social impacts of using mechanical plastic recyclates as part of the European PRIMUS project in comparison to the use primary plastics in the pilot projects. The study adhered to the same goal and scope mentioned in section 1.1.

1.2.1 Selection of social indicators

The PSILCA database [4], a commonly used database for social LCA, holds 70 indicators for the four existing stakeholders of worker, local community, value chain actors, and society. While there is no consumer indicators present yet, they can still be collected and evaluated only on the foreground data level basis. The relevancy of social indicators was evaluated in three ways:

1. Social hotspot screening using PSILCA.
2. Policy relevancy/Literature review.
3. Expert judgement.

A social hotspots screening was performed in PSILCA v3.1.1 for the sectors relating to plastic production in the European region.

There are several policies and directives that promote product recycling in Europe, such as the European Green Deal [5], Circular Economy Action Plan [6], and the Single-Use Plastics Directive [7]. These policies aim to balance the economic and environmental benefits of recycling with the social well-being of workers, communities, and consumers. While the action plan focuses on environmental goals, it also includes important social objectives. Therefore, it shall be used as a reference to learn which social indicators would be relevant to assess to be able to meet these objectives.

To do this, a search for keywords within the directive [8] that related to the social indicators from PSILCA was made. Additionally, text referring to economic and social objective where analysed. The Action Plan emphasizes how circular economy strategies can boost economic growth by creating new jobs and industries and this can be found in the text "*Circularity can be expected to have a positive net effect on job creation provided that workers acquire the skills required by the green transition*" and "*Applying circular economy principles across the EU economy has the potential to* *increase EU GDP by an additional 0.5% by 2030 creating around 700,000 new jobs*". In PSILCA indicators that could help assess that were included and given a score of 5[1]:

1. Contribution of the sector to economic development (score 5)
2. Unemployment rate in the country (score 5)
3. Men in the sectoral labour force (score 5)
4. Woman in the sectoral labour force (score 5)

Other indicators that are not directly measuring the above action plan, but they are more or less related to the above indicators include:

1. Evidence of violations of laws and employment regulations (score 4)
2. Gender wage gap (score 4)

Moreover, the action plan emphasises the importance of consumer protection by stating "*will propose a revision of EU consumer law to ensure that consumers receive trustworthy and relevant information on products at the point of sale*". However, there are no existing indicators found in the PSILCA database relating to consumers. Still, the UNEP methodological social sheets states that the consumer health and safety can be measured by seeing whether "*Presence of a Quality and/or Product Safety management System such as iSO 9001:2015, British retail consortium (brc), Halal, international food Standard (ifS), ISO 10377:2013, etc*" exists. Thus, this information shall be gathered across the manufacturers only but will not exist in the background database i.e. PSILCA

Investment in green transition skills will benefit local economies, with a *"focus on training, advice under the Enterprise Europe Network, and knowledge transfer"*, supporting EU-wide job creation and skill enhancement. In PSILCA, the following indicator reflects a government's priority in fostering educational access and enhancing the skill level across social strata:

1. Public expenditure on education (score 5)

The Circular Economy Action Plan addresses worker safety by promoting a "toxic-free environment" within circular production processes. Key measures include reducing hazardous substances and supporting the development of *"safe-by-design chemicals"* to protect workers and the environment from toxic materials. This aligns with the action to *"progressively substitute hazardous substances to better protect citizens and the environment."* In PSILCA, measuring workers health and safety can be set through:

1. Violations of mandatory health and safety standards (score 5)
2. Rate of non-fatal accidents at workplace (score 5)
3. Rate of fatal accidents at workplace (score 5)
4. Presence of sufficient safety measures (score 5)

[1] A risk assessment system was presented by an evaluation schema (very high risk, no risk, etc.) was converted to numerical scoring system where 1 was "Not important/irrelevant" and 5 was considered " Very important/relevant".

Additionally, there is another indicator that relates to overall environmental management rather than focusing specifically on toxic-free production or hazardous substance substitution:

1. Certified environmental management systems (score 4)

Finally, experts in the study were asked to assess the relevance of each stakeholder to the identified life cycle stages using a scale from 1 (Not important/irrelevant) to 5 (Very important/relevant).

In terms of literature surveying, a comprehensive examination of social impacts within the plastic sector reveals that only a small number of studies exist. A general guideline on social LCA in the plastic sector was presented by Reinales et al. (2020) [9], where various stakeholders were asked to perform a materiality assessment across several plastic-based packaging options. Results indicate that for workers' health and safety, the highest influence is observed with brand owners in plastic bags, food trays, and coffee capsules, as well as packers in food trays and manufacturers in coffee capsules. Consumers' health and safety is highly influenced by brand owners in plastic bags, food trays, and coffee capsules, along with packers and recyclers in absorbent hygienic products. Furthermore, consumers' well-being and community engagement are significantly impacted by brand owners in plastic bags, while community access to material resources is greatly influenced by brand owners in food trays. This strengthens the choice of indicators that score 5.

Table 4 shows the 13 finally selected indicators.

Table 4 Selected social indicators to be evaluated in the Demo cases

Stakeholder	Subcategory	Indicator
Local Community	Access to material resources	Certified environmental management systems
Society	Contribution to economic development	Contribution of the sector to economic development
Value Chain actors	Promoting social responsibility	Membership in an initiative that promotes social responsibility along the supply chain
Workers	Discrimination	Gender wage gap
Workers	Fair salary	Living wage, per month (AV)
Workers	Fair salary	Sector average wage, per month
Workers	Health and safety	Presence of sufficient safety measures
Workers	Health and safety	Rate of fatal accidents at workplace
Workers	Health and safety	Rate of non-fatal accidents at workplace
Workers	Health and safety	Violations of mandatory health and safety standards
Workers	Social benefits, legal issues	Evidence of violations of laws and employment regulations
Workers	Social benefits, legal issues	Social security expenditures
Workers	Working time	Weekly hours of work per employee

The sLCA methodology was applied to the 4 Demo cases, and is part of the Life Cycle Model datasets. The full description and analysis can be seen in section 5.

1.3 Plastic litter risk

Plastic litter is a quantity not usually obtained with Life Cycle Assessment. The plastic littering risk methodology for the PRIMUS project is based on previous work on a database that quantifies plastic litter with a probabilistic approach called *PLEX* [10], also by GreenDelta.

The Plastics Litter Extension database (PLEX), is an extension of the commonly used database for LCA, *ecoinvent APOS*. The extension quantifies the risk of plastic litter by tracing the plastic flows and giving a specific probability of littering per process.

The formula goes as follows:

$$PL_j = P_{litter} * \sum_{i=1}^{n} PC_i$$

Where PL_j is the plastic litter from process j [kg]; P_{litter} is the expected probability of litter from process j [%]; PC_i is the plastic content of flow i [kg]; and n is the number of incoming flows for process j.

The plastic content estimation for flows is done according to different classes, as described in Table 5.

Table 5. Plastic content estimation for flows according to different classes

Class	Plastic content	Example
all plastic	100%	primary plastic flows, e.g. polyethylene
very high	95%	plastic products, waste plastics
high	50%	paints
medium	10%	vehicles
low	0.1%	fibreboards, soaps
very low	0.0001%	e.g. most waste flows with no obvious plastic content
none	0%	metals, electricity

The expected probability of litter is determined per process according to the categories described in Table 6:

Table 6. Expected probability of littering per process type

Category	Probability	Example
None	0	heat and power co-generation
Very low	0.000001	incineration
Low	0.001	construction activities
Medium	0.1	construction activities
High	0.5	-

Very high	0.95	open dump/burning

More details on this methodology can be found in the annex of the PLEX documentation [11].

1.4 Circularity & Criticality

The sustainability assessment was further investigated using Circularity and Criticality indicators.

1.4.1 Circularity

This Circularity assessment aims to further expand the boundaries of an LCA by putting in context how the product is being used, and focuses on assessing the benefits of using and producing recycled material. For example, it can take more environmental efforts to recirculate a material, with recycling, transportation etc., resulting in a higher carbon footprint when looking at end-of-life options for a product. However, it can avoid direct waste and litter into our planet, as well as avoid the extraction of new primary materials from Earth.

A methodology previously developed by GreenDelta for the TRIPLELINK EU project was used to assess the Circularity of each demonstrator case also taking into account the full life cycle of the product. This approach not only looks at the circularity of the materials directly in the product (the mass of the product), but also the amount of material extracted from Earth from the product's supply chain, and the waste produced, including, for example, supply chains of electricity and transport.

The Circularity Indicators chosen within the methodology are the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation [12] and the Circularity Index (CI) (Cullen, 2017) [13]. Both take into account material flows but the MCI also takes into account life time and performance of the product whilst CI also takes into account energy used in production processes.

The MCI takes values between 0.1 for a fully linear product, to 1 for a fully circular product. The variables contributing to this indicator are:

- Primary (virgin) material used
- Recycled material used
- Direct waste produced
- Waste from recycling
- Waste from the production of secondary feedstock
- Life time of the product compared to benchmark
- Number of uses of the product compared to benchmark.

The CI can have values ranging from 0 for a fully linear product to 1 for a fully circular product. The variables contributing to this indicator are recovered material over total material demand and it also takes into account the energy required for primary material production in comparison to the energy used in secondary material production.

1.4.2 Criticality

Criticality can be also measured with the Circularity Package for openLCA [14]. It was later seen, in the application of the methodology to the demonstrator cases, that material criticality wasn't of high concern in the study of plastic and recycled plastic products.

2 AVAILABLE DATASETS

The basis of the model, and the big comparison being made, is the environmental performance of primary vs. recycled versions of the same plastic. In this study, primary granulates data comes from available datasets and literature, as collecting data for primary plastics is outside the scope of the project. The state-of-the-art of recycled datasets and literature is also evaluated, but these datasets are also modelled by GreenDelta in the form of EcoProfiles, with primary data collected with Plastics Recyclers Europe, or direct primary data from Coolrec, the recycling partner of the project.

Overall, the following plastics are required in the demonstrator cases of the PRIMUS project:

- ABS
- PC
- EPDM
- PP
- HIPS

2.1.1 Primary granulates

Several common and well-known LCA databases were chosen to investigate the datasets available for plastic granulates and the quality of the data. Three criteria were taken into account to choose the datasets was:

1. **Age of data** – the more recent the data collected, the better.
2. **Representativeness of the data** – how much of the industry is represented by the data collected. Ideally datasets should be market averages.
3. **Compatibility with the model** – is the reference flow system compatible with the one used in the model? Can the dataset calculate all of the impact categories specified in the Goal and Scope (LCIA Method EF 3.1)?

Table 7 shows the summary of the investigation.

It was found that the eco-profiles developed by Plastics Europe [15] have the best data representativeness and data collection process. A lot of care is put on the report of each dataset, and the data is reviewed by a third party. The age of the data is generally very good, with datasets like ABS revised in 2023. However, the PP dataset is from 2014 – it could well be that technology hasn't changed that much though.

Other databases seem to take the EcoProfile datasets to make their own, but not always, e.g. ecoinvent 3.10 in the second row of Table 7. The data collection of the rest of the databases was not as clear as with EcoProfiles, and in some cases even mysterious, like with the Carbon Minds database [16].

This study takes the ecoinvent 3.10 datasets for primary plastics, as they are within the background database chosen for the LCA modelling and they anyhow part from eco-profiles, in some cases have more transparent data, and even cover EPDM, which the eco-profiles are still missing. The data quality of the EPDM dataset, however, could be improved.

Still, a sensitivity analysis was made with all datasets to see how much they differ from one another. Datasets were calculated using the LCIA Method EF 3.1 and clustered with the Single Score provided by the same method, see Figure 4, Figure 5, Figure 6 and Figure 7.

Table 7. Data quality of datasets taking into account collection period, means and representativeness

Database	Background data	Dataset date					Modelling type				
		ABS	PC	EPDM	PP	HIPS	ABS	PC	EPDM	PP	HIPS
EcoProfile (Plastics Europe, n.d.)	ecoprofiles or GaBi | 3rd party verified	2023	2018	X	2014	2018	5 plants | 4 countries | 90% representativeness, **S**	100% representativeness, **S**	X	35 production sites | 7 companies | 76.7% of EU PP production, **S**	7 plants | 6 countries | 80% representativeness, **S**
Ecoinvent 3.10 (Ecoinvent, n.d.)	ecoinvent	EcoP	EcoP	ei legacy	2011	EcoP	based on ecoprofile, **S**	based on ecoprofile, **U**	legacy dataset, >50% representativeness of market, **U**	Coverage 76% capacity, **U**	based on ecoprofile, **S**
Carbon Minds (Carbon Minds, n.d.)	EI background	*	*	X	*	*	unclear how they collect their data	unclear how they collect their data	X	nice production & consumption data	unclear how they collect their data
EF 3.1 (Joint Research Centre, n.d.)	Thinkstep GaBi	?	?	?	?	?	**S**, but has nice ingredients diagr.	**S**, but has nice ingredients diagr.	**S**, but has nice ingredients diagr.	**S**, but has nice ingredients diagr.	**S**, but has nice ingredients diagr.
LCA Commons (US EPA, n.d.)	US LCI database, ecoinvent (adapted to US) and Franklin Associates | internally reviewed	2015	X	X	2015	2015	**U,** 4 plants (3 companies)	X	X	**U**, primary data, but seems not to be too representative, also in technology	**U,** 65% US representation, primary collection

Key: X = no dataset | S = system process (untransparent data) | U = unit process (transparent data) | ? = unsure

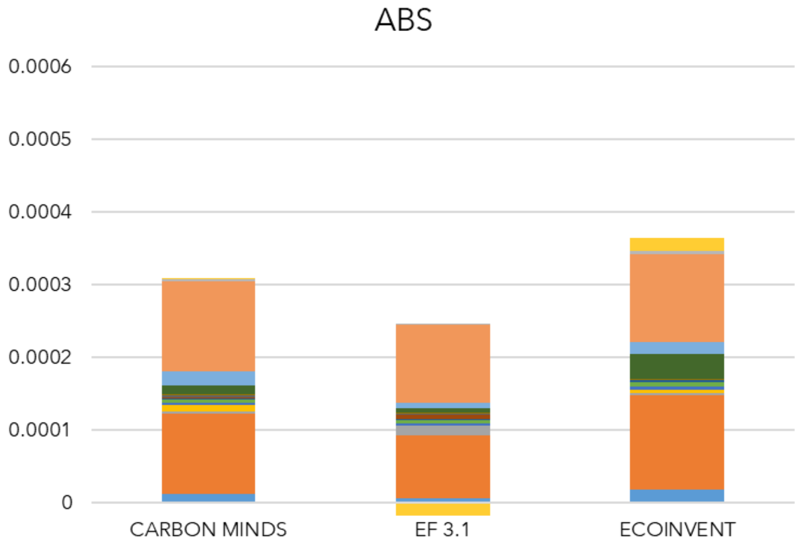


Figure 4. Comparison of EF 3.1 Single Score results using different dataset sources for ABS production

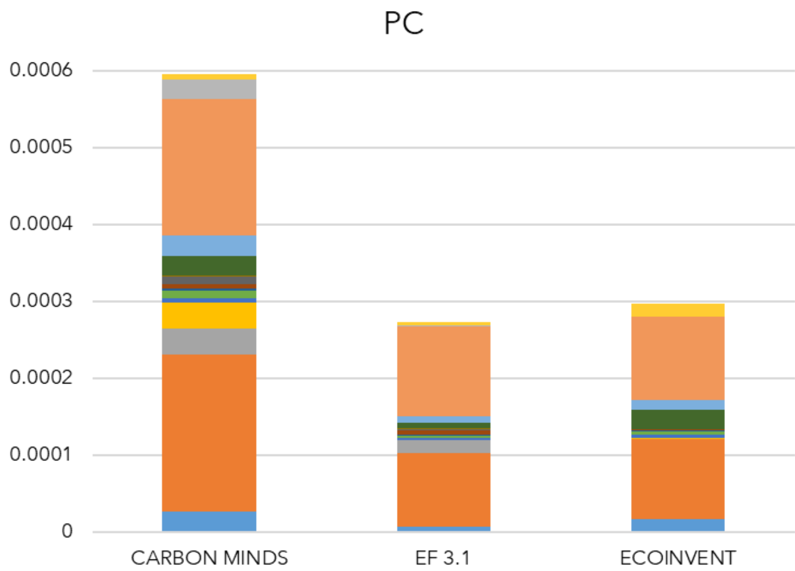


Figure 5. Comparison of EF 3.1 Single Score results using different dataset sources for PC production

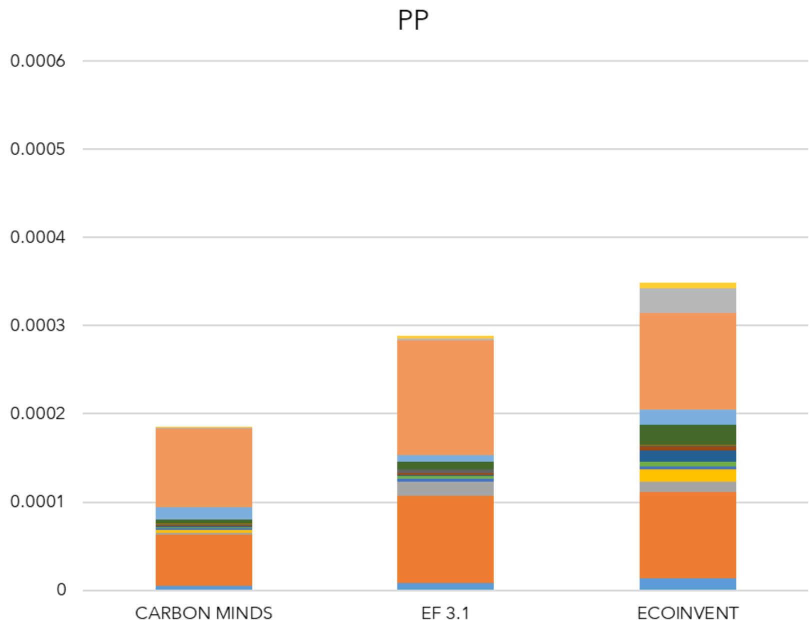


Figure 6. Comparison of EF 3.1 Single Score results using different dataset sources for PP production

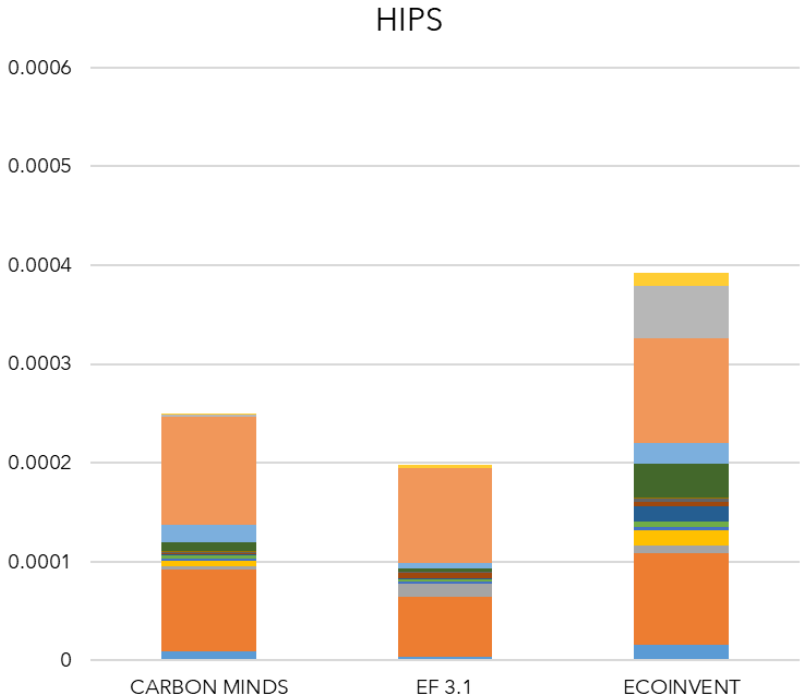


Figure 7. Comparison of EF 3.1 Single Score results using different dataset sources for HIPS production

2.1.2 Recycled granulate

A review of readily available LCI for recycled plastics as well as literature data for mechanical plastic recycling was conducted.

Though data is available for mechanical plastic recycling in many databases, such as ecoinvent 3.10, it is often limited to generic recycling processes. In most cases, polymer-specific data is disclosed for the most widespread types only, such as HDPE and PET in the case of the ecoinvent 3.10. While other databases offer a wider range of data sets, e.g. in the case of the Environmental Footprint 3.1 database many polymer-specific datasets are modelled from literature sources as opposed to primary data. In a similar way, literature data for plastic recyclates is mainly found for plastics with a large market share. More specific recyclate streams, such as EPDM and ABS, were not represented in life cycle literature.

High quality life cycle data was obtained from Franklin Associates (2018) [17] for recycled PET, HDPE and PP, however, the geographical reference of the report is North America. Only the LCI data of PP recycled resin is useful for the PRIMUS demonstrator cases, as PET and HDPE are not used in the production of any of the demo products. The goal and scope of the environmental assessment is defined for a cradle-to-gate production of 1 kg (or 1000 lb) of recycled polymer resin, including the process steps of collecting, sorting, and reprocessing.

A very good source for accessible life cycle data from an established LCA database was found in the Environmental Footprint (EF) 3.1 database, but these are restricted in their application to PEF and OEF studies [18]. Data for several relevant plastic recyclates was obtained from the EF 3.1 database, namely for polycarbonate PC, polypropylene PP, and HIPS production. Out of these, only the PS recycling process was based on primary data collection, whereas PC recycling is based on a publication by Francis (2017) [19], and the PP data set is based upon data from two sources (Leblanc 2019, [20]; SpecialChem 2021, [21]). Furthermore, the data available in the PEF database is limited to system processes, allowing no further analysis beyond the production system level.

Finally, if accessible, the recent ecoinvent update v3.11 provides the most comprehensive and transparent set of recycled plastic data.

As part of the PRIMUS project, a public release of transparent and comprehensive EcoProfile datasets for plastic recyclates is planned for the spring of 2025.

Table 8. Availability of secondary plastics datasets from EcoProfiles and LCA background databases, compared to primary EcoProfiles from Plastics Europe [15]

	Primary EcoProfiles	Franklin Associates	SRP Recyclage	ei v3.10	ei v3.11	EF3.1	PRIMUS EcoProfiles
ABS	✓				✓		✓
PC	✓					✓	
PET	✓	✓	✓	✓	✓	✓	✓
PE	✓	✓	✓	✓	✓	✓	✓
PMMA	✓						
PP	✓	✓	✓		✓	✓	✓
PS	✓		✓		✓		✓
PU	✓						
PVC	✓		✓		✓		✓
PA	✓					✓	

Table 9. Data availability of recycled plastics for the PRIMUS Demo cases

Name	DEMO1			DEMO2					DEMO3	DEMO4
Usage	automotive interiors			automotive cooling circuits					refrigerators' inner linings	washing machine seals
Polymer	**rABS**	rPC		rEPDM	rPP				rHIPS	rEPDM
EF 3.1	Recycling plastic Acrylonitrile-butadiene-styrene (ABS), waste management	Polycarbonate (PC), recycled, **pre-consumer**	Polycarbonate (PC), recycled, **post-consumer**	Recycling of **post-industrial** waste EPDM rubber, production mix	Polypropylene, recycled, post-consumer	Polypropylene, recycled, **pre-consumer**	Recycling of polypropylene plastic (PP), production mix, at plant, from post-consumer waste	Recycling of post-consumer waste polypropylene (PP)	NONE	Recycling of **post-industrial** waste EPDM rubber, production mix
	Mechanical collection, sorting, transport, washing, granulation, pelletization	No collection, shredding, pelletizing, additives	**chemical recycling**, depolymerisation, hydrolysis, Erec/ErecEoL	collection, sorting, transport, washing, granulation, pelletization	No collection, no sorting, washing, drying, shredding, pelletizing, Erec/ErecEoL	No collection, shredding, pelletizing, Erec/ErecEoL	Collection, sorting, transport, washing, granulation, pelletization	Collection, sorting, transport, washing, granulation, pelletization		collection, sorting, transport, washing, granulation, pelletization
	"Cradle-to-gate"	"Cradle-to-gate"	Cradle-to- bisphenol A (BPA) – can be used to synthesize PC again	"Cradle-to-gate"	"Cradle-to-gate"	"Cradle-to-gate"	"Gate-to-gate"	"Gate-to-gate"		"Cradle-to-gate"
	90% recycling rate	98% efficiency assumed	80% efficiency	91.2% recycling rate	efficiency 90% assumed	efficiency 98% assumed	90% recycling rate	48.9% recycling rate		91.2% recycling rate
Primary Cut-off?	material then leaves the primary system "burden free,"*	No burdens	No burdens	No burdens	No burdens	No burdens	No burdens	No burdens		No burdens
Credits?		No credits	No credits	Steam + electricity	No credits	No credits	No credits	Steam + electricity		Steam + electricity
Sample size	-	-	-	-	-	-	-	-		
Year	2016	2018	2016	2020	2016	2016	2015	2016		2020
Post consumer/ industrial	Post-consumer	Post-industrial	Post-consumer	Post-industrial	Post-consumer	Post-industrial	Post-consumer	Post-consumer		Post-industrial
Data provider	GaBi	ecoinvent	ecoinvent	GaBi	ecoinvent	ecoinvent	GaBi	GaBi		GaBi
Comments	Multi-polymer recycling process with mass allocation for separation and cleaning	Seems to be imported from ecoinvent but only literature sources cited	Mechanical recycling is not economically feasible	DATA: PRE	Seems to be imported from ecoinvent but only literature sources cited	Seems to be imported from ecoinvent but only literature sources cited	Multi-polymer recycling process with mass allocation for separation and cleaning	Multi-polymer recycling process; mass allocation for separation and cleaning DATA: PRE		DATA: PRE

3 DATA PREPARATION

3.1 Creating a Master LCA database

In order to execute the PRIMUS Sustainability Methodology, several databases providing different sustainability indicators were fused, this is visually shown in Figure 8.

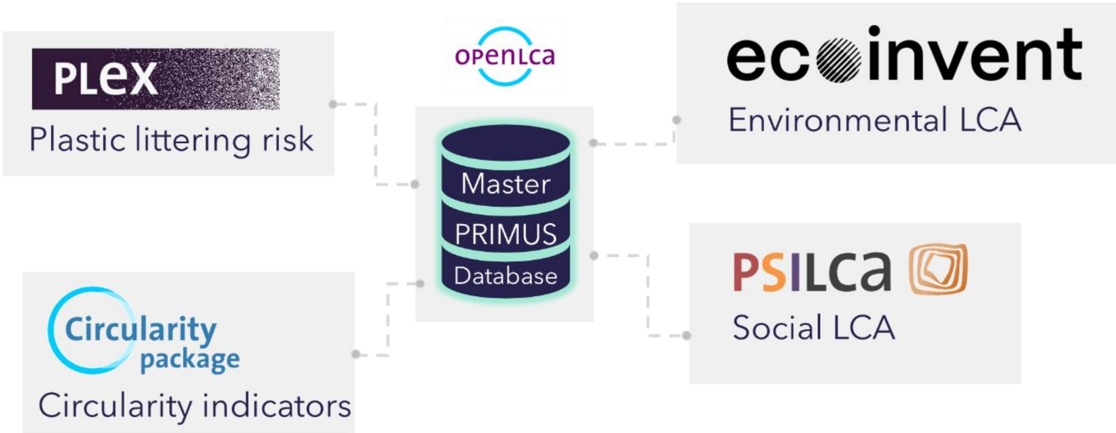


Figure 8. The PRIMUS Master database, visual representation

3.1.1 Environmental LCA

Ecoinvent 3.10 [1] cut-off was used as background LCA database providing background Life Cycle Inventory (LCI). The EF 3.1 LCIA Method [22] from the ecoinvent LCIA Method package was used with its usual Impact Categories to provide environmental results, these are outlined in Table 3.

3.1.2 Social LCA

Social LCA data was added from PSILCA [4], a widely used social LCA input/output database. This was done through the soca database [23], which is already an adaptation of PSILCA to work with ecoinvent cut-off.

3.1.3 Plastic littering risk for PRIMUS

The risk of plastic littering was obtained with a modified version of the PLEX database, aforementioned. The database was adapted to the *Cut-off* (allocation, cut-off by classification) system model of the ecoinvent database, parting from the original *APOS* (allocation, at the point of substitution) system model. More information on how this was done can be seen in Annex A – data adaptation of the PLEX database model to fit cut-off, parting from APOS system model.

3.1.4 Circularity

Circularity and criticality information was added to the database using the Circularity Package for openLCA [14]. Circularity variables trace information for primary (virgin) material, waste produced, recovered material, and energy required for primary and secondary material production. See Figure 9 for a visual representation of where these were placed within the database. This information yields in the calculation of the

Material Circularity Indicator [12] by the Ellen Macarthur Foundation, which looks particularly at material flows, and the *Circularity Index* [13] by Cullen et al., which looks at recovered material vs. primary material used but also at the energy used in primary material production vs secondary material production.

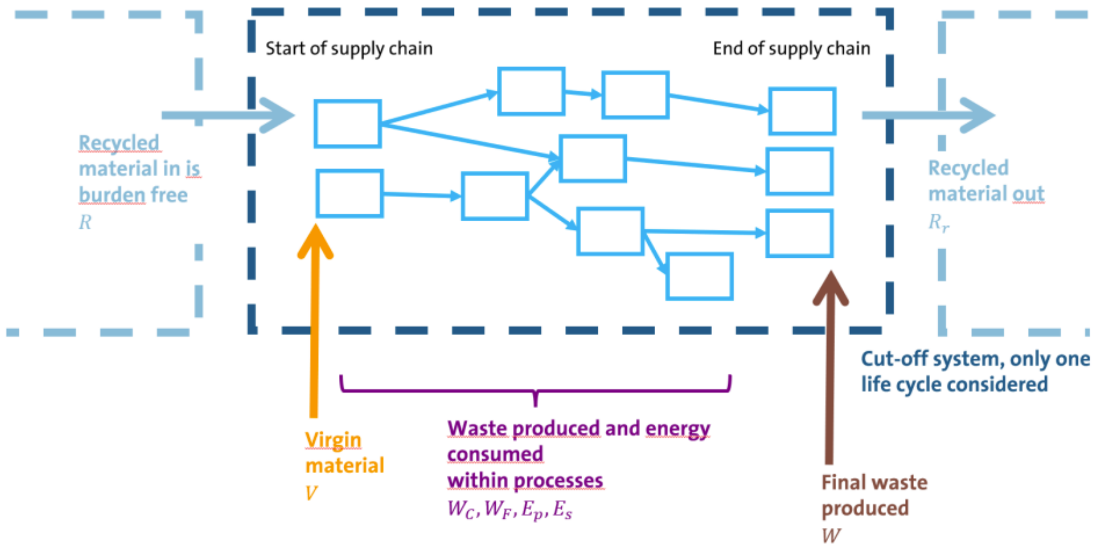


Figure 9. Visual representation of circularity variable placement within the LCA database [24]

3.1.5 Criticality

Circularity and criticality information was added to the database using the Circularity Package for openLCA [14]. Criticality information considers supply risk, material consumption in the EU, import reliance and recycling input rate. The indicator is specifically called *SH2E criticality indicator*, developed in the SH2E project [25], and it is based on the criticality assessment of the European Commission [26]. It was later seen, in the application of the methodology to the demonstrator cases, that material criticality wasn't of high concern in the study of plastic and recycled plastic products.

3.2 **Examples of results**

The database can be found in the PRIMUS Sustainability Expert tool for LCA practitioners, see Figure 10, but also available individually in openLCA Nexus [27]. The database is available for free but is dependent on the database licence of those databases earlier mentioned.

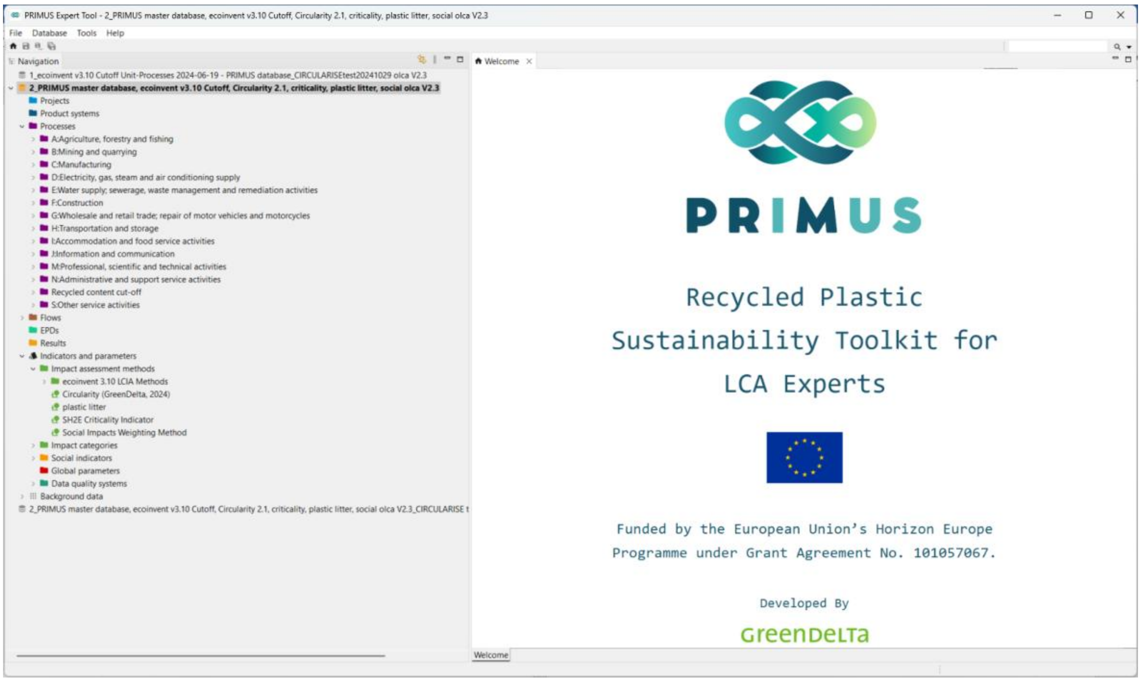


Figure 10. PRIMUS Recycled Plastic Sustainability Toolkit for LCA practitioners

It counts with Life Cycle Impact Assessment (LCIA) Methods for environmental and social LCA, plastic littering risk, circularity and criticality as shown in Figure 11. Furthermore, Figure 13 and Figure 14 show the information for the indicators placed within the database.

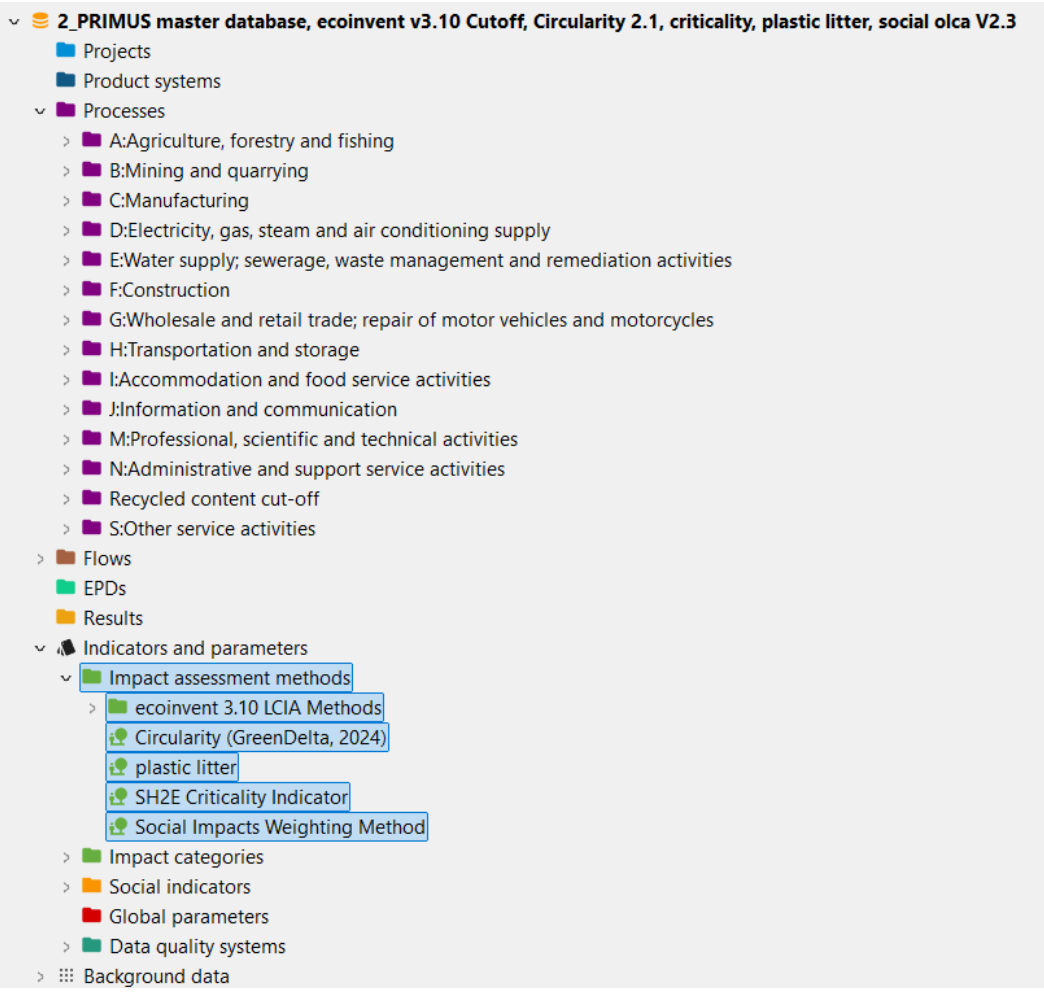
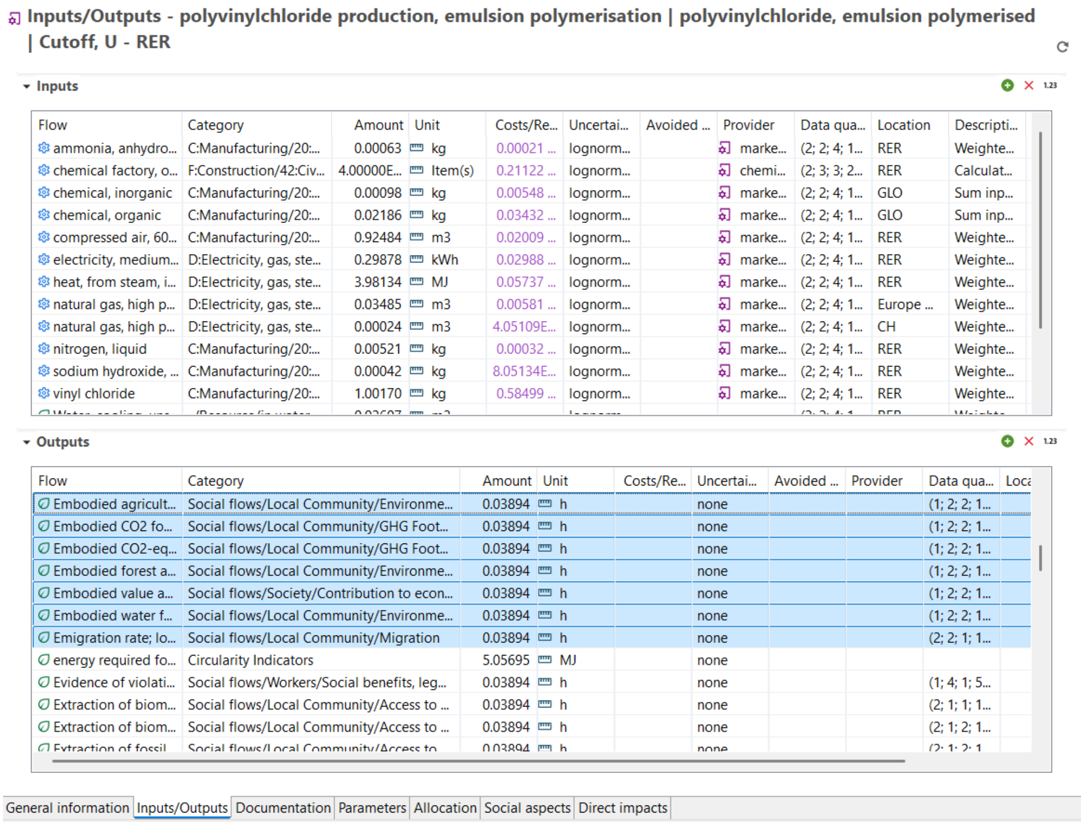


Figure 11. LCIA Methods in the PRIMUS Master database


Inputs/Outputs - polyvinylchloride production, emulsion polymerisation | polyvinylchloride, emulsion polymerised | Cutoff, U - RER

Inputs

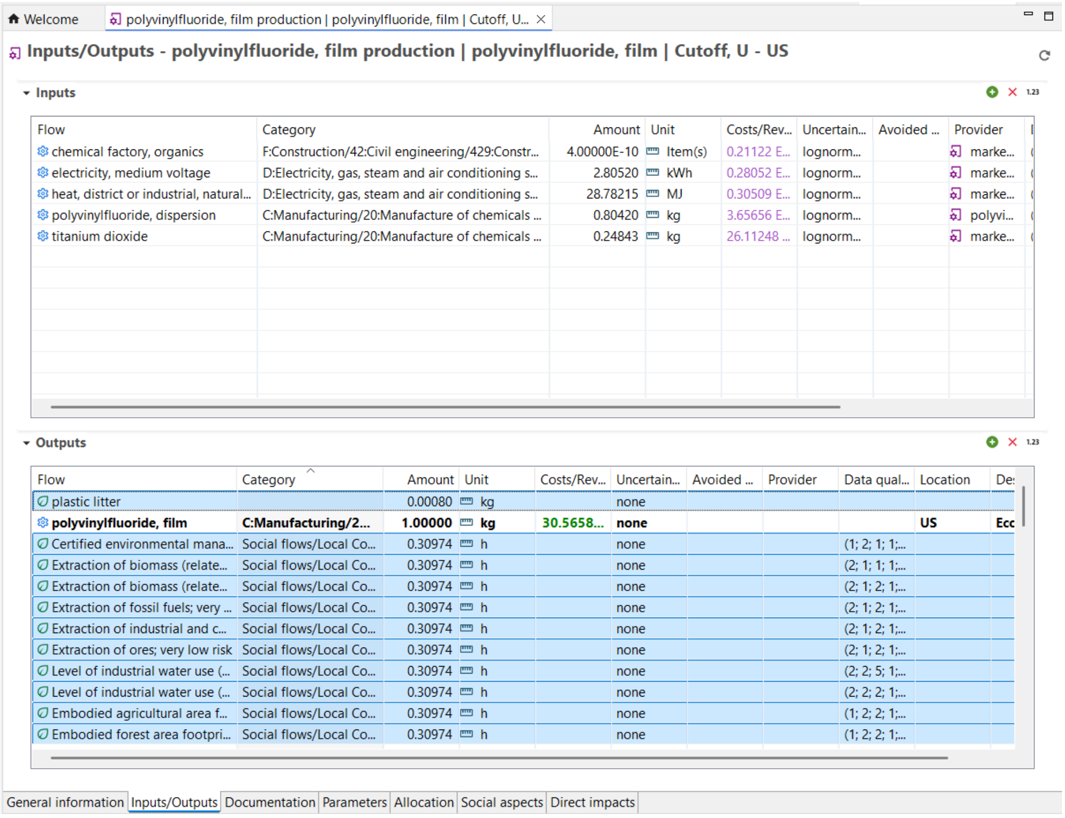
Flow	Category	Amount	Unit	Costs/Re...	Uncertai...	Avoided ...	Provider	Data qua...	Location	Descripti...
ammonia, anhydro...	C:Manufacturing/20:...	0.00063	kg	0.00021 ...	lognorm...		marke...	(2; 2; 4; 1...	RER	Weighte...
chemical factory, o...	F:Construction/42:Civ...	4.00000E...	Item(s)	0.21122 ...	lognorm...		chemi...	(2; 3; 3; 2...	RER	Calculat...
chemical, inorganic	C:Manufacturing/20:...	0.00098	kg	0.00548 ...	lognorm...		marke...	(2; 2; 4; 1...	GLO	Sum inp...
chemical, organic	C:Manufacturing/20:...	0.02186	kg	0.03432 ...	lognorm...		marke...	(2; 2; 4; 1...	GLO	Sum inp...
compressed air, 60...	C:Manufacturing/20:...	0.92484	m3	0.02009 ...	lognorm...		marke...	(2; 2; 4; 1...	RER	Weighte...
electricity, medium...	D:Electricity, gas, ste...	0.29878	kWh	0.02988 ...	lognorm...		marke...	(2; 2; 4; 1...	RER	Weighte...
heat, from steam, i...	D:Electricity, gas, ste...	3.98134	MJ	0.05737 ...	lognorm...		marke...	(2; 2; 4; 1...	RER	Weighte...
natural gas, high p...	D:Electricity, gas, ste...	0.03485	m3	0.00581 ...	lognorm...		marke...	(2; 2; 4; 1...	Europe ...	Weighte...
natural gas, high p...	D:Electricity, gas, ste...	0.00024	m3	4.05109E...	lognorm...		marke...	(2; 2; 4; 1...	CH	Weighte...
nitrogen, liquid	C:Manufacturing/20:...	0.00521	kg	0.00032 ...	lognorm...		marke...	(2; 2; 4; 1...	RER	Weighte...
sodium hydroxide, ...	C:Manufacturing/20:...	0.00042	kg	8.05134E...	lognorm...		marke...	(2; 2; 4; 1...	RER	Weighte...
vinyl chloride	C:Manufacturing/20:...	1.00170	kg	0.58499 ...	lognorm...		marke...	(2; 2; 4; 1...	RER	Weighte...

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertai...	Avoided ...	Provider	Data qua...	Loca
Embodied agricult...	Social flows/Local Community/Environme...	0.03894	h		none			(1; 2; 2; 1...	
Embodied CO2 fo...	Social flows/Local Community/GHG Foot...	0.03894	h		none			(1; 2; 2; 1...	
Embodied CO2-eq...	Social flows/Local Community/GHG Foot...	0.03894	h		none			(1; 2; 2; 1...	
Embodied forest a...	Social flows/Local Community/Environme...	0.03894	h		none			(1; 2; 2; 1...	
Embodied value a...	Social flows/Society/Contribution to econ...	0.03894	h		none			(1; 2; 2; 1...	
Embodied water f...	Social flows/Local Community/Environme...	0.03894	h		none			(1; 2; 2; 1...	
Emigration rate; lo...	Social flows/Local Community/Migration	0.03894	h		none			(2; 2; 1; 1...	
energy required fo...	Circularity Indicators	5.05695	MJ		none				
Evidence of violati...	Social flows/Workers/Social benefits, leg...	0.03894	h		none			(1; 4; 1; 5...	
Extraction of biom...	Social flows/Local Community/Access to ...	0.03894	h		none			(2; 1; 1; 1...	
Extraction of biom...	Social flows/Local Community/Access to ...	0.03894	h		none			(2; 1; 2; 1...	

General information | Inputs/Outputs | Documentation | Parameters | Allocation | Social aspects | Direct impacts

Figure 12. Example of social LCA tracing within the database


Welcome | polyvinylfluoride, film production | polyvinylfluoride, film | Cutoff, U...

Inputs/Outputs - polyvinylfluoride, film production | polyvinylfluoride, film | Cutoff, U - US

Inputs

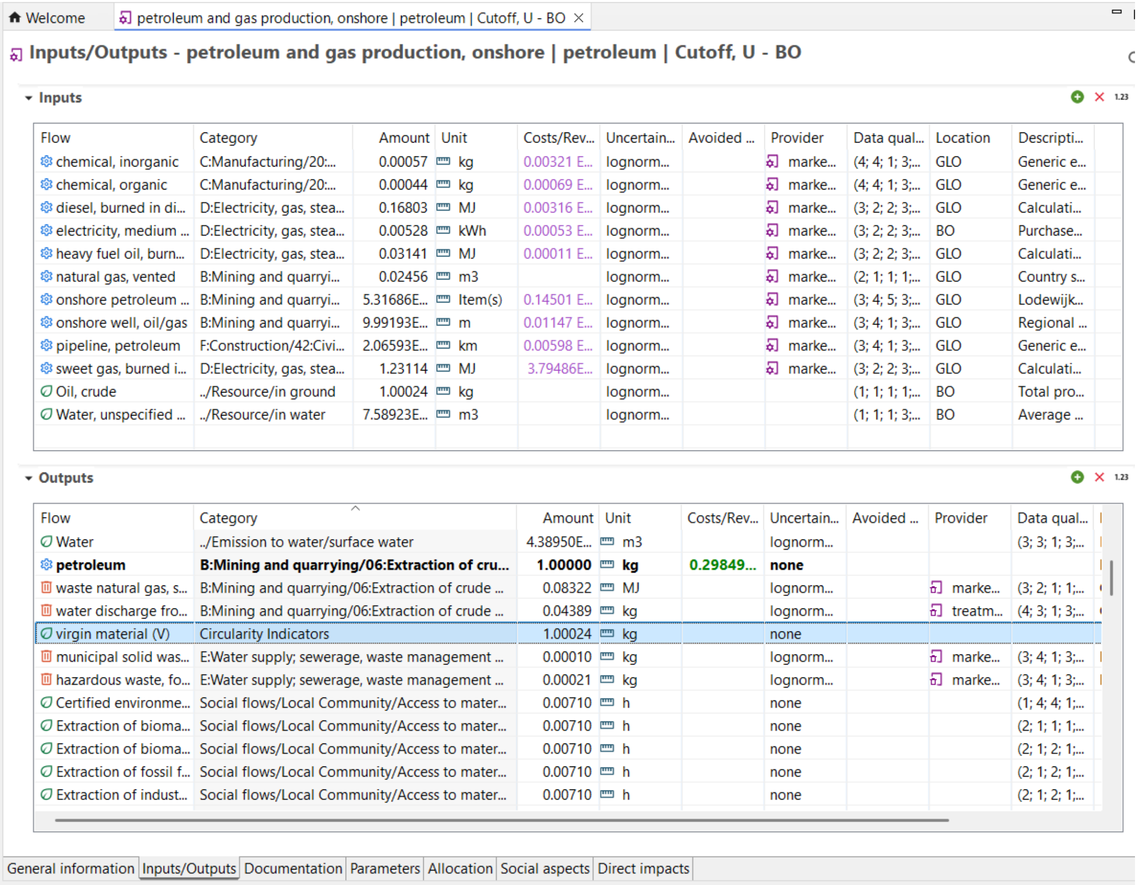
Flow	Category	Amount	Unit	Costs/Rev...	Uncertain...	Avoided ...	Provider
chemical factory, organics	F:Construction/42:Civil engineering/429:Constr...	4.00000E-10	Item(s)	0.21122 E...	lognorm...		marke...
electricity, medium voltage	D:Electricity, gas, steam and air conditioning s...	2.80520	kWh	0.28052 E...	lognorm...		marke...
heat, district or industrial, natural...	D:Electricity, gas, steam and air conditioning s...	28.78215	MJ	0.30509 E...	lognorm...		marke...
polyvinylfluoride, dispersion	C:Manufacturing/20:Manufacture of chemicals ...	0.80420	kg	3.65656 E...	lognorm...		polyvi...
titanium dioxide	C:Manufacturing/20:Manufacture of chemicals ...	0.24843	kg	26.11248 ...	lognorm...		marke...

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertain...	Avoided ...	Provider	Data qual...	Location	De:
plastic litter		0.00080	kg		none					
polyvinylfluoride, film	**C:Manufacturing/2...**	**1.00000**	**kg**	**30.5658...**	**none**				**US**	**Ecc**
Certified environmental mana...	Social flows/Local Co...	0.30974	h		none			(1; 2; 1; 1;...		
Extraction of biomass (relate...	Social flows/Local Co...	0.30974	h		none			(2; 1; 1; 1;...		
Extraction of biomass (relate...	Social flows/Local Co...	0.30974	h		none			(2; 1; 2; 1;...		
Extraction of fossil fuels; very ...	Social flows/Local Co...	0.30974	h		none			(2; 1; 2; 1;...		
Extraction of industrial and c...	Social flows/Local Co...	0.30974	h		none			(2; 1; 2; 1;...		
Extraction of ores; very low risk	Social flows/Local Co...	0.30974	h		none			(2; 1; 2; 1;...		
Level of industrial water use (...	Social flows/Local Co...	0.30974	h		none			(2; 2; 5; 1;...		
Level of industrial water use (...	Social flows/Local Co...	0.30974	h		none			(2; 2; 2; 1;...		
Embodied agricultural area f...	Social flows/Local Co...	0.30974	h		none			(1; 2; 2; 1;...		
Embodied forest area footpri...	Social flows/Local Co...	0.30974	h		none			(1; 2; 2; 1;...		

General information | Inputs/Outputs | Documentation | Parameters | Allocation | Social aspects | Direct impacts

Figure 13. Plastic litter risk and social flows found in PVF film production


Welcome | petroleum and gas production, onshore | petroleum | Cutoff, U - BO

Inputs/Outputs - petroleum and gas production, onshore | petroleum | Cutoff, U - BO

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
chemical, inorganic	C:Manufacturing/20:...	0.00057	kg	0.00321 E...	lognorm...		marke...	(4; 4; 1; 3;...	GLO	Generic e...
chemical, organic	C:Manufacturing/20:...	0.00044	kg	0.00069 E...	lognorm...		marke...	(4; 4; 1; 3;...	GLO	Generic e...
diesel, burned in di...	D:Electricity, gas, stea...	0.16803	MJ	0.00316 E...	lognorm...		marke...	(3; 2; 2; 3;...	GLO	Calculati...
electricity, medium ...	D:Electricity, gas, stea...	0.00528	kWh	0.00053 E...	lognorm...		marke...	(3; 2; 2; 3;...	BO	Purchase...
heavy fuel oil, burn...	D:Electricity, gas, stea...	0.03141	MJ	0.00011 E...	lognorm...		marke...	(3; 2; 2; 3;...	GLO	Calculati...
natural gas, vented	B:Mining and quarryi...	0.02456	m3		lognorm...		marke...	(2; 1; 1; 1;...	GLO	Country s...
onshore petroleum ...	B:Mining and quarryi...	5.31686E...	Item(s)	0.14501 E...	lognorm...		marke...	(3; 4; 5; 3;...	GLO	Lodewijk...
onshore well, oil/gas	B:Mining and quarryi...	9.99193E...	m	0.01147 E...	lognorm...		marke...	(3; 4; 1; 3;...	GLO	Regional ...
pipeline, petroleum	F:Construction/42:Civi...	2.06593E...	km	0.00598 E...	lognorm...		marke...	(3; 4; 1; 3;...	GLO	Generic e...
sweet gas, burned i...	D:Electricity, gas, stea...	1.23114	MJ	3.79486E...	lognorm...		marke...	(3; 2; 2; 3;...	GLO	Calculati...
Oil, crude	../Resource/in ground	1.00024	kg		lognorm...			(1; 1; 1; 1;...	BO	Total pro...
Water, unspecified ...	../Resource/in water	7.58923E...	m3		lognorm...			(1; 1; 1; 3;...	BO	Average ...

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertain...	Avoided ...	Provider	Data qual...
Water	../Emission to water/surface water	4.38950E...	m3		lognorm...			(3; 3; 1; 3;...
petroleum	**B:Mining and quarrying/06:Extraction of cru...**	**1.00000**	**kg**	**0.29849...**	**none**			
waste natural gas, s...	B:Mining and quarrying/06:Extraction of crude ...	0.08322	MJ		lognorm...		marke...	(3; 2; 1; 1;...
water discharge fro...	B:Mining and quarrying/06:Extraction of crude ...	0.04389	kg		lognorm...		treatm...	(4; 3; 1; 3;...
virgin material (V)	Circularity Indicators	1.00024	kg		none			
municipal solid was...	E:Water supply; sewerage, waste management ...	0.00010	kg		lognorm...		marke...	(3; 4; 1; 3;...
hazardous waste, fo...	E:Water supply; sewerage, waste management ...	0.00021	kg		lognorm...		marke...	(3; 4; 1; 3;...
Certified environme...	Social flows/Local Community/Access to mater...	0.00710	h		none			(1; 4; 4; 1;...
Extraction of bioma...	Social flows/Local Community/Access to mater...	0.00710	h		none			(2; 1; 1; 1;...
Extraction of bioma...	Social flows/Local Community/Access to mater...	0.00710	h		none			(2; 1; 2; 1;...
Extraction of fossil f...	Social flows/Local Community/Access to mater...	0.00710	h		none			(2; 1; 2; 1;...
Extraction of indust...	Social flows/Local Community/Access to mater...	0.00710	h		none			(2; 1; 2; 1;...

General information | Inputs/Outputs | Documentation | Parameters | Allocation | Social aspects | Direct impacts

Figure 14. Circularity flow tracing primary (virgin) material extraction

4 DEMONSTRATOR CASESTUDIES

Wherever possible, primary data was obtained directly from the project consortium members involved in the recycling processes and plastic part manufacture.

Primary data for post-consumer ABS, PS and polyolefins was obtained directly from the recycler project partner. The data obtained included collection and other transport distances, processing efforts in terms of energy and other material inputs, and information on byproducts produced, including other recycled plastics and metal fractions. VOC and other emissions were not available.

Data on the specific manufacturing processes was provided by the plastic part producers, including amount and type of energy, raw materials used, efficiency of processes and waste produced and the further treatment type of waste.

A "foreground model" was made with this data.

Other recycled polymers used in the demonstrator cases were either adapted from existing background database or obtained from the recycled plastic EcoProfiles developed in the project, see section 1 of Part B of this report.

4.1 Demo 1, rPC/ABS for automotive interior aesthetic components

The first PRIMUS demonstrator case investigates the use of recycled material in an aesthetic component of the interior of a car. The specific component is shown in Figure 15. The plastic part weights 354.5g and is originally made with 40% ABS and 60% PC. The PRIMUS project achieved a successful 60% rPC coming from post-consumer waste and 20% rABS coming from post industrial waste, see Table 10.

The industrial partner is based in Spain.

Figure 15. Demo 1, an automotive interior aesthetic component

Table 10. Input materials for the recycled content scenario of Demo 1

Input material	Recycled content scenario	Origin
rPC	60%	Post-consumer waste from NL
rABS	20%	Post-industrial waste from ES
ABS	20%	Primary material from ES

4.1.1 Product system description

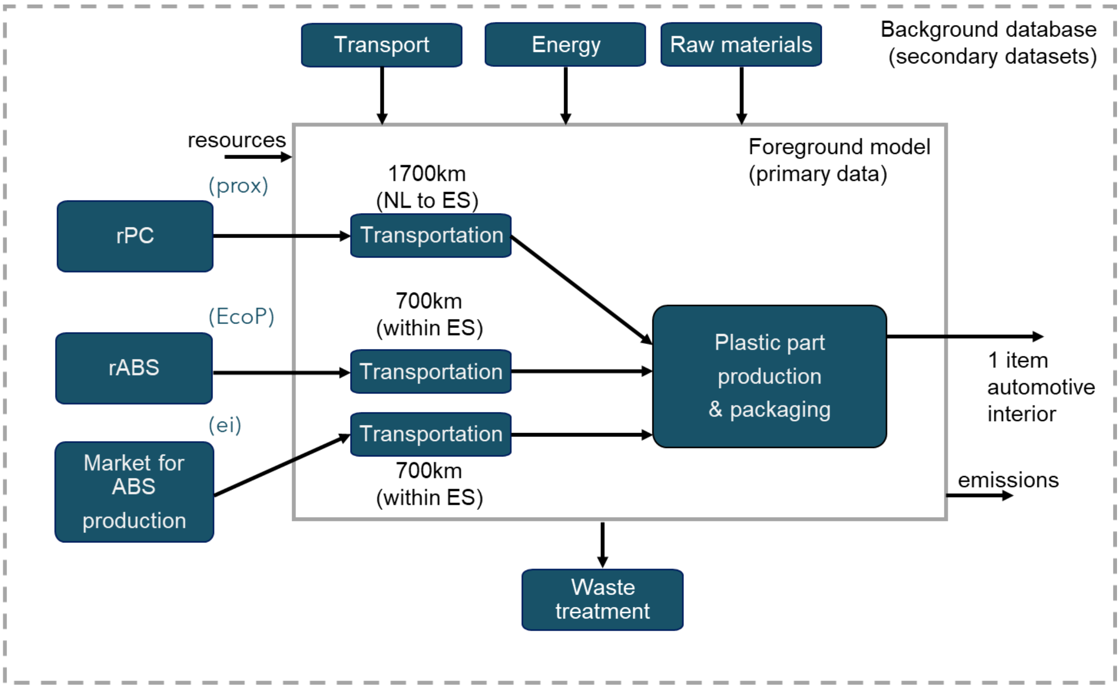
The LCA methodology described in section 1.1 was followed for the environmental sustainability assessment. The functional unit of this demo case is:

"a plastic aesthetic component for an automotive interior at factory gate, achieving aesthetic expectations and passing compliance tests"

The reference quantity is:

"1 unit = 354.5g"

The specific model flow diagram is shown in Figure 16.



(ei) = Ecoinvent dataset
(prox.) = Proxy dataset using ecoinvent
(EcoP) = EcoProfile dataset

Figure 16. Product system flow diagram of Demo 1, automotive interior aesthetic part

rPC is sourced from the Netherlands, however, there was no primary data from the recycler, or an EcoProfile for this specific plastic. Therefore, the production of rPC was modelled as a proxy process using the ecoinvent datasets for collection and sorting of consumer electronic waste that produces PE: "polyethylene production, high density, granulate, recycled | polyethylene, high density, granulate, recycled | Cutoff, U".

rABS is a post-industrial material coming from Spain. However, post-industrial waste is not considered as recycling material, so the dataset used was the rABS EcoProfile (post-consumer).

4.1.2 Results

The sustainability indicator results for Demo 1 can be seen in Table 11 for both the 100% primary and the recycled scenarios. All categories display benefits with the recycled content scenario, see Figure 17.

The electricity used in plastic part production and the plastic mix contribute the most to all LCA impact categories, out of the 100% primary scenario. E.g. 58% of contribution to Climate Change comes from electricity used in plastic part production, followed by the plastic mix with 40% contribution.

The raw material mix is the most contributing input in the categories of Ecotoxicity (87%), Human toxicity (around 60%) and Particulate Matter (52%).

There are big improvements for the environmental footprint of the plastic mix, with a decrease from 5.7 kg CO2 eq. to 1.9 kg CO2 eq. per kg of plastic mix. PC decreased its contribution to the material mix from 3.7kg CO2 eq. to 0.4 kg CO2 eq. And ABS from 1.7 kg CO2 eq. to 1.28 kg CO2 eq. per kg of plastic mix.

Transportation of the recycled pellets proved to be more impactful than the market transportation for the primary materials, with 10% of the Climate Change contribution of the plastic mix with recycled content, compared around 2% in the 100% primary plastic content.

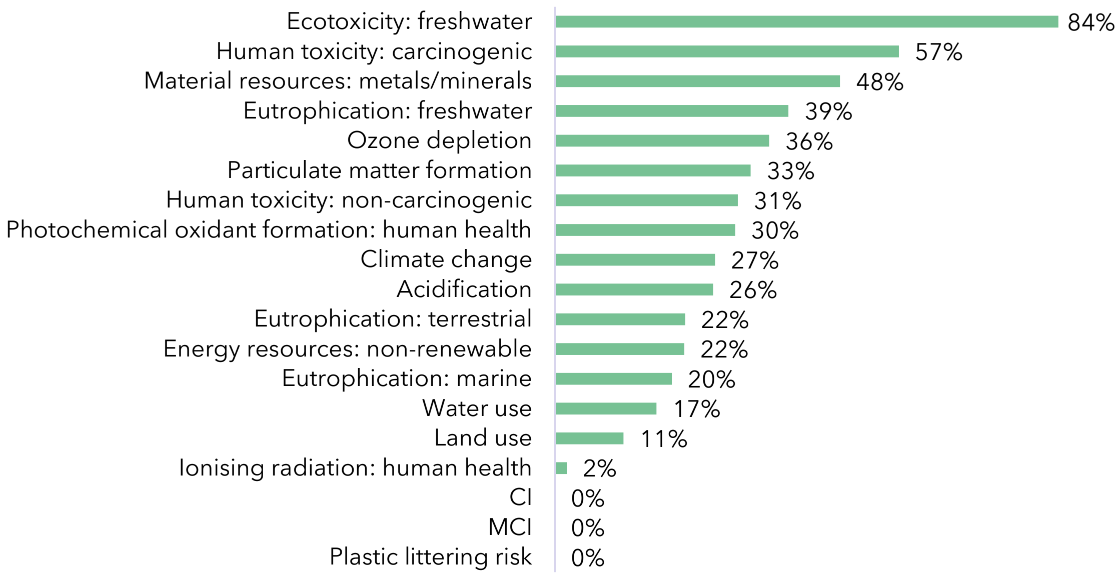


Figure 17. Demo 1 improvements with the recycled material scenario

Table 11. Sustainability indicator results for the primary and recycled scenario of Demo 1

Impact categories	100% primary	Recycled scenario	Unit
Acidification	0.02044	0.01503	mol H+-Eq
Climate change	5.02934	3.68358	kg CO2-Eq
Ecotoxicity: freshwater	73.66383	11.69809	CTUe
Energy resources: non-renewable	140.56532	110.15216	MJ, net calorific value
Eutrophication: freshwater	0.00082	0.0005	kg P-Eq
Eutrophication: marine	0.0042	0.00338	kg N-Eq
Eutrophication: terrestrial	0.04278	0.03347	mol N-Eq
Human toxicity: carcinogenic	3.08E-08	1.31E-08	CTUh
Human toxicity: non-carcinogenic	3.64E-08	2.53E-08	CTUh
Ionising radiation: human health	3.69589	3.62225	kBq U235-Eq
Land use	19.15854	16.95758	dimensionless
Material resources: metals/minerals	2.70E-05	1.41E-05	kg Sb-Eq
Ozone depletion	9.26E-08	5.94E-08	kg CFC-11-Eq
Particulate matter formation	1.70E-07	1.14E-07	disease incidence
Photochemical oxidant formation: human health	0.01787	0.01249	kg NMVOC-Eq
Water use	2.47947	2.05824	m3 world Eq deprived
Plastic littering risk	0.00702	0.05593	kg
MCI	0.2489	0.4749	No units, score from 0.1 - 1
CI	0.1062	0.1969	No units, score from 0 - 1

The circularity assessment shows improvements in all sides of circularity, see Figure 18. The total energy required is reduced to around 36%, as most of the energetic requirements came from the production of primary PC and ABS. The total waste produced is decreased by 32% and the primary (virgin) material use is 64% compared to the 100% primary scenario.

The scores for the MCI and the CI are found in the last rows of Table 11. There is a big improvement seen in the MCI when changing the material input to 80% recycled content.

A further sensitivity analysis was made investigating the performance of the part with the recycled content. Performance is measured in terms of life time or number of uses of the part before it reaches the end-of-life phase. Figure 19 shows the results of the indicators varying the performance from 60% worse to 60% better, for both the plastic part with 100% primary material and 80% recycled material.

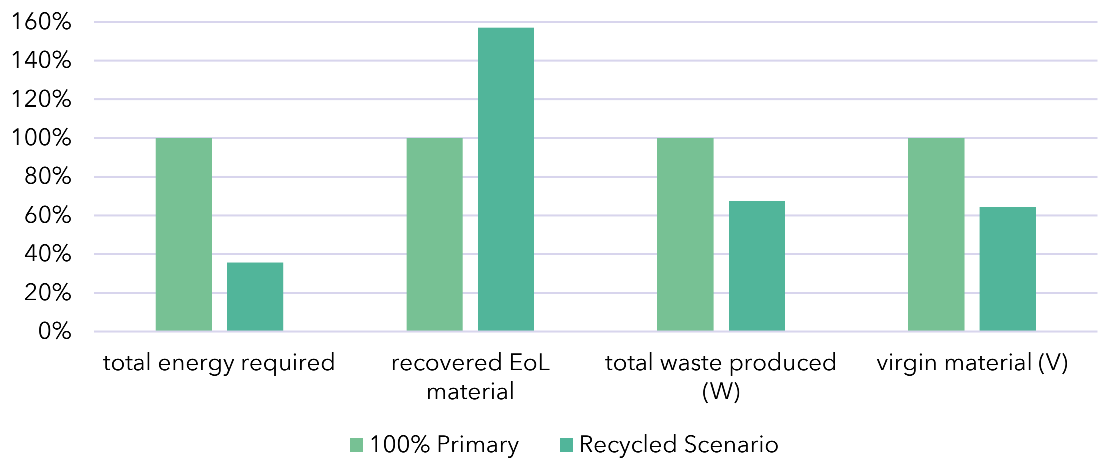


Figure 18. Demo 1 improvements in circularity variables

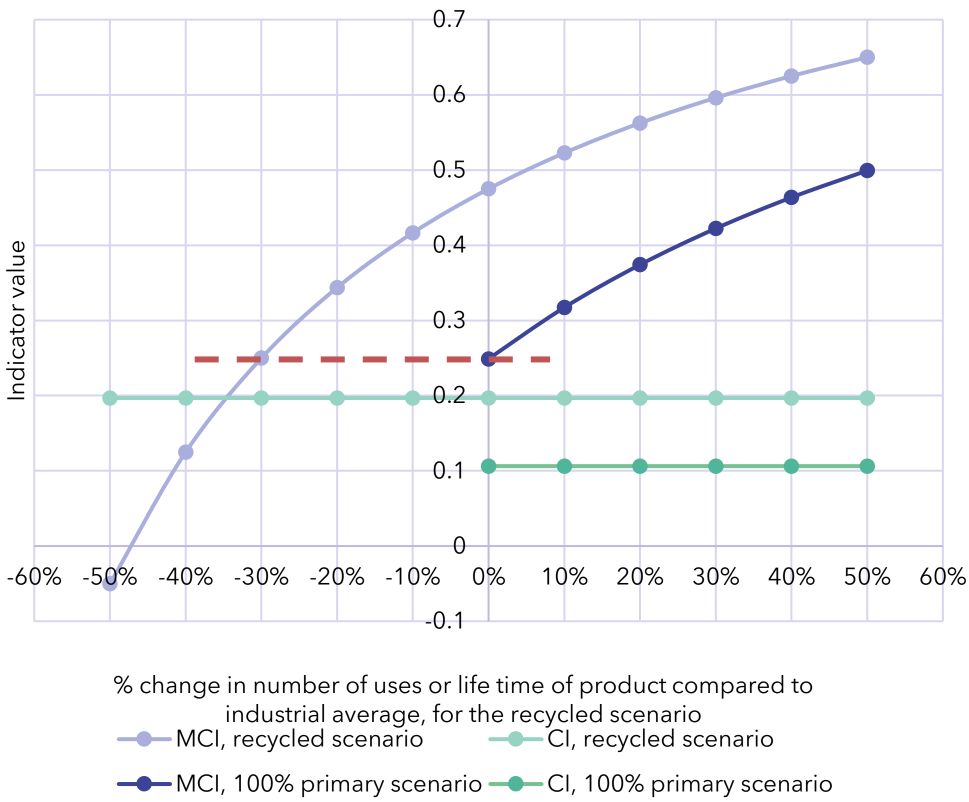


Figure 19. Circularity indicator performance for 100% primary and recycled scenarios, varying the performance of the part

A production with primary material has plastic littering risk hotspots split between the plastic part production processes and electricity supply chain. The amount of plastic littering risk is shown in Table 11. It can be seen that the recycled scenario has nearly

7 times more plastic littering risk than the primary scenario. 70% comes from the recycling of PC and 23% from recycling ABS. This is explained with the assumption made in the database used to calculate plastic littering risk is that there is a probability that 10% of handled plastic flows in recycling processes is littered.

4.1.3 Discussion and Conclusions

All LCA Impact Categories show improvements with the recycled scenario. These go as far as 84% improvement for Ecotoxicity (freshwater). Also worth noting is an improvement of 48% in metals and minerals resource extraction, 27% in Climate Change, 22% fossil resource extraction.

Electricity used in the production of the plastic part is the major contribution to many of the environmental impact categories, including Climate Change (with 58%). Therefore, the use of green energy should be also considered to lower the environmental burdens of the system.

Transport of the recycled content could have a relative high contribution to the plastic mix footprint. Sourcing local recycled contents is preferred.

Looking at circularity, the MCI score improves from 0.25 to 0.48, and the CI score improves from 0.10 to 0.20. A circularity score of around 0.5 is also reached with the full primary plastic part with an improvement of performance of 50%, e.g. increasing life time or number of uses of the part by 50%, see Figure 19. This is not that relevant taking into account that the life of the plastic part is determined by the life of the car.

Figure 19 also shows that even for the part of the recycled scenario, if the performance is decreased by 30%, e.g. by having to change the part earlier or produce more parts at factory gate, the MCI returns back to the same score as the plastic part without recycled content. Having the same or similar performance is therefore important to really see an improvement in the score.

4.2 **Demo 2, rPP/EPDM for automotive cooling circuits**

Demo 2 looks at pipes for automotive cooling circuits, like the one shown in Figure 20. Each unit weighs 170g and is made out of PP, EPDM, paraffinic oil and fillers. The recycled scenario has 23% recycled content, 10.5% rEPDM and 12.5% rPP, see Table 12 for a full disclosure. A higher percentage of recycled content caused unacceptable deformations of the plastic part, as well as failure in the performance test, see Figure 21.

The industrial partner is based in Spain.

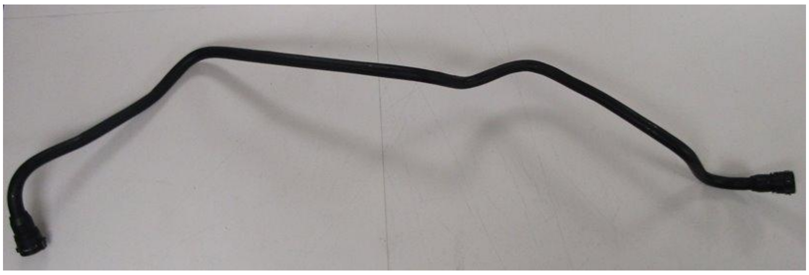


Figure 20. Automotive cooling circuit pipe for DEMO 2

Table 12 . Input materials for the recycled content scenario of DEMO 2

Input material	Recycled content scenario	Origin
EPDM	10.5%	Post-industrial, same company
rEPDM	10.5%	Market average
PP	37.5%	Market average
rPP	12.5%	Post-industrial, another company
Paraffinic oil	22%	
Fillers	7%	

Figure 21. Performance failure (left) and deformations (right) caused by higher percentage recycled content

4.2.1 Product system description

The functional unit of this demo case is:

"a pipe for automotive cooling circuits at factory gate, passing the compliance tests"

The reference quantity is:

"1 unit = 170g"

The flow diagram is shown in Figure 22.

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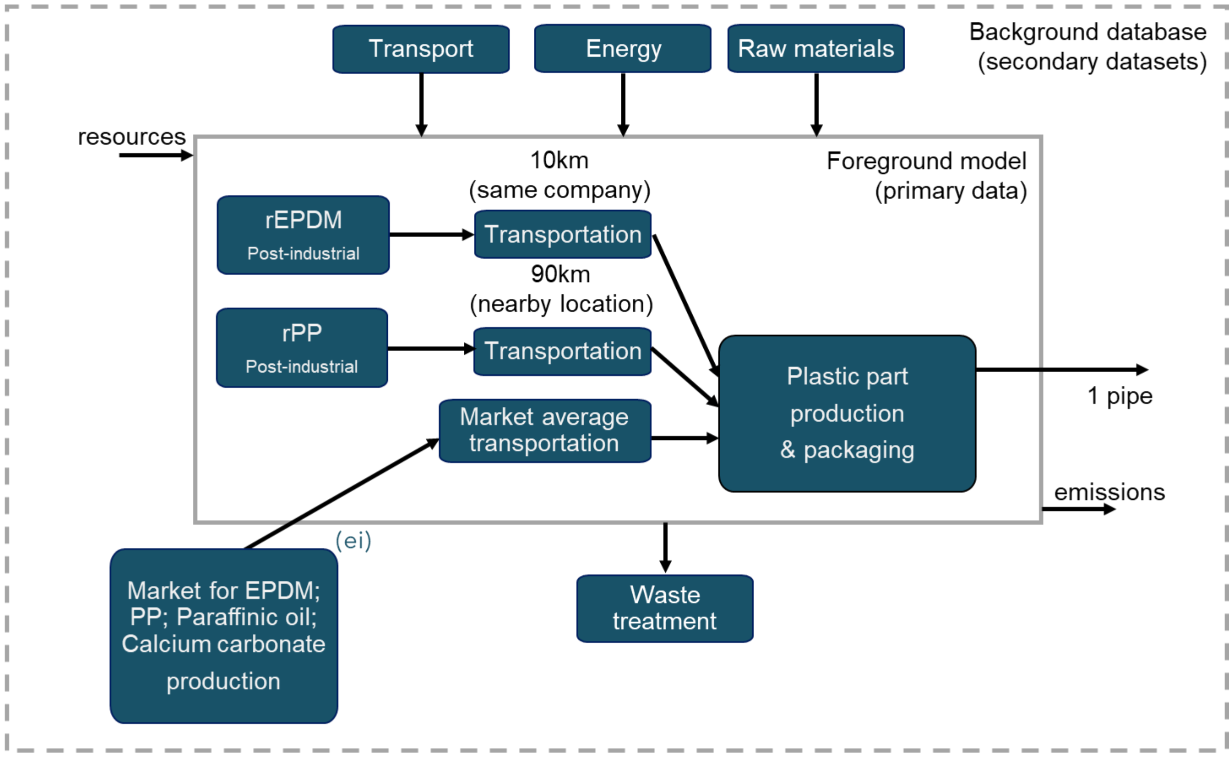


(ei) = Ecoinvent dataset

Figure 22. Product system flow diagram of Demo 2, pipe for automotive cooling circuit

rEPDM and rPP are both from post-industrial waste. These generally carry less burdens than post-consumer recycled material when considering system boundaries described in section 1.1, as less processing is necessary to obtain the material. rEPDM is sourced from the same industrial partner, which provided the efficiency and electricity used, and the same was applied for rPP. 0.5625kWh of electricity required for grinding per kg of post-industrial content made, and 0.0045g of scrap.

The plastic part processing in the industrial partner's facility includes TPV extruder mixer, extrusion, thermoforming and packaging.

4.2.2 Results

Results show improvements in all LCA impact categories, see Figure 23. The plastic part has a carbon footprint of 1.17 kg CO_2 eq. which is improved by 11% to 1.04 kg CO_2 eq., see

Table 13 and Figure 23 for detailed results per impact category.

Table 13. Sustainability indicator results for the primary and recycled scenario of DEMO 2

Impact categories	100% primary	Recycled scenario	Unit
Acidification	0.00409	0.00358	mol H+-Eq
Climate change	1.17768	1.04573	kg CO2-Eq
Ecotoxicity: freshwater	6.06141	4.90362	CTUe
Energy resources: non-renewable	25.52316	22.31881	MJ, net calorific value
Eutrophication: freshwater	0.00024	0.00021	kg P-Eq
Eutrophication: marine	0.00087	0.00077	kg N-Eq
Eutrophication: terrestrial	0.00869	0.00768	mol N-Eq
Human toxicity: carcinogenic	3.19362E-09	2.76572E-09	CTUh
Human toxicity: non-carcinogenic	9.94E-09	8.91E-09	CTUh
Ionising radiation: human health	0.2359	0.23396	kBq U235-Eq
Land use	18.21692	17.76616	dimensionless
Material resources: metals/minerals	8.13575E-06	6.91126E-06	kg Sb-Eq
Ozone depletion	3.18616E-08	2.82594E-08	kg CFC-11-Eq
Particulate matter formation	5.98893E-08	5.27468E-08	disease incidence
Photochemical oxidant formation: human health	0.0041	0.00346	kg NMVOC-Eq
Water use	0.37024	0.32229	m3 world Eq deprived
Plastic littering risk	0.00917	0.00906	kg
MCI	0.1916	0.2616	No units, score from 0.1 - 1
CI	0.0565	0.0991	No units, score from 0 - 1

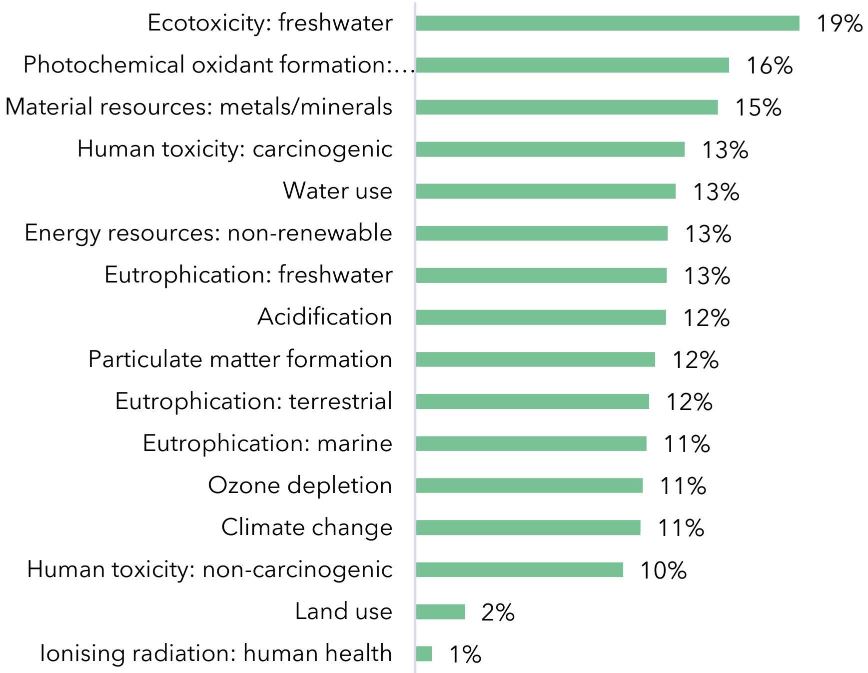


Figure 23. DEMO 2 improvements with the recycled material scenario

The material mix has a carbon footprint of 2.65 kg CO2 eq. per kg of mix, which is improved to 1.89 kg CO2 eq. PP and EPDM contributed 67% and 27% respectively to the footprint, so improving that was important. Even thought the amount of Paraffin oil was 22%, it only contributed 6% to the footprint.

In order to decrease the environmental footprint, packaging and heat during extrusion should also be considered, as they are the other two environmental hotspots.

"market for folding boxboard carton | folding boxboard carton | Cutoff, U – RER", the process used to model carboard packaging, accounts for a high 86% contribution to Land Use, 50% contribution to Particulate Matter Formation and around 40% contribution for Eutrophication and Ecotoxicity of freshwater, and 20% to Climate Change. It must be noted that the primary data collected showed that 0.14kg of carboard box is required per item – this could also be an over estimation.

"heat and power co-generation, natural gas, 160kW electrical, Jakobsberg | heat, central or small-scale, natural gas, Jakobsberg | Cutoff, U – CH" the secondary dataset chosen for the burning of natural gas during thermoforming accounts for 28% in Ozone Depletion, 29% in Climate Change and 19% in Human toxicity.

The recycled scenario generally benefits circularity. Around 12% to 13% decrease is observed in the total energy required, waste produced and virgin material used, see Figure 24. The amount of recovered end-of-life material increases by 77%.

The MCI was run with a 10% decrease in performance, where the recycled scenario was assumed to perform 10% worse than the 100% primary scenario, e.g. by having 10% less number of uses or 10% decrease in life time, on average. This experiment yielded an MCI of 0.1795 which is already worse than the MCI score with 100% primary material, 0.1916.

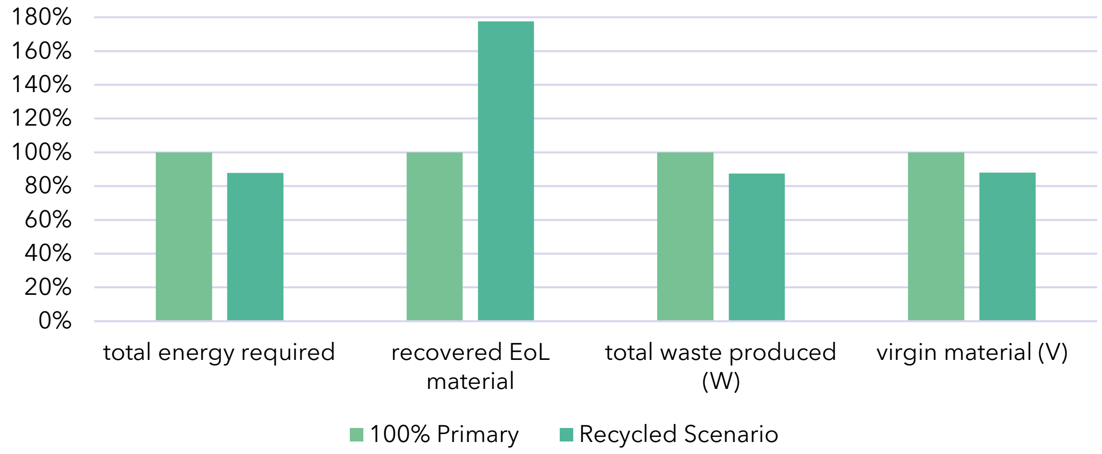


Figure 24. DEMO 2 improvements in circularity variables

There is a small difference in plastic littering risk with both scenarios having a rounded-up littering risk of 0.009kg per item. This is due to the use of post-industrial waste, which doesn't have to be recycled. The only littering risk in this case is from the transportation of post-industrial recyclates. The majority of the plastic littering in this case, over a half, comes from the waste scrap disposed to the bin, a lot of which is further landfilled, followed by the packaging.

4.2.3 Discussion and Conclusions

There are LCA benefits, but these are low, max. 19% improvement in the category Ecotoxicity (freshwater), and 11% improvement in Climate Change.

Other hotspots of the product system are the carboard box used for packaging and the natural gas burned during thermoforming. A more efficient packaging is recommended to be investigated as well as alternative energy sources for thermoforming.

Circularity is benefited from the recycled content scenario, with around 13% decrease in total energy required from cradle-to-gate to produce the part, and around the same decrease for total waste produced and virgin material.

Care should be taken with the performance of the part, as pipe with recycled content with 10% decrease in performance already gives a worse MCI circularity score than the 100% primary counterpart. The efforts of material circulation are counteractive to a smaller life time or number of uses of the material.

Finally, results look positive for plastic littering risk, where there is no apparent increased risk in littering when using recycled content to produce the part. This is explained by the use of post-industrial waste as it doesn't need a lot of processing to achieve high quality material. Plastic littering risk indicator, in this demonstrator, is dominated by plastic scrap waste followed by packaging.

4.3 **Demo 3, rHIPS for refrigerator liners for food-contact**

Demo 3 is a lab-scale demonstrator case that aims to include recycled content in fridge inner linings. The recycled material comes directly from used fridges from the recycler partner company in the PRIMUS project. The recycled material is analysed and further compounded by scientists in VTT, Finland, where a 50g sample is made, see Figure 25.

Figure 25. DEMO 3 plastic part sample, inner fridge lining

The fridge inner lining entails 90% HIPS, 8% impact modifier and 2% antioxidant. The recycled content scenario inputs 70% recycled content. The recycled content formulation is shown in Table 14.

Table 14. Input materials for the recycled content scenario of DEMO 3

Input material	Recycled content scenario	Origin
HIPS	20%	Market average
rHIPS	70%	Post-consumer fridges, primary data
Impact modifier	8%	Proxy modelled dataset, no primary data
antioxidant	2%	Proxy modelled dataset, no primary data

The recycler partner is based in the Netherlands and the compounder and part manufacturing in lab scale is made in Finland.

4.3.1 Product system description

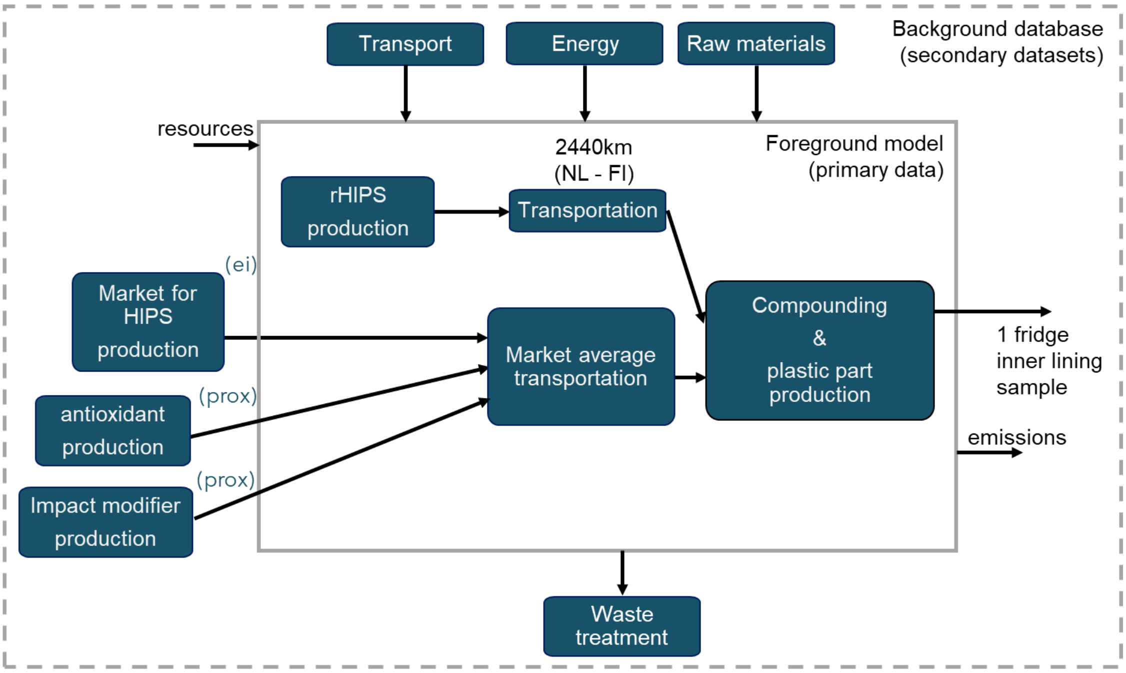
The functional unit of this demo case is:

"1 kg of fridge inner lining at lab scale, achieving food contact regulation standards"

The reference quantity is:

"1 kg"

The specific model flow diagram is shown in Figure 26.



(ei) = Ecoinvent dataset
(prox.) = Proxy dataset using ecoinvent

Figure 26. Product system flow diagram of Demo 3, fridge inner lining sample

rHIPS is obtained directly from fridges in WEEE. The samples used in the demonstrator case were directly coming from the recycler partner, Coolrec Plastics, which also provided primary data for the study. The WEEE is collected and sorted in Coolrec sorting facilities. The sorted plastic fraction is then sent to Coolrec Plastics, which process it further to recycled material, including rHIPS. The data for collection distances, sorting efforts, transportation to Coolrec Plastics facility, and further processing to rHIPS was provided as primary data by Coolrec Plastics. As the facilities deal with other waste fractions other than fridge and handle waste in multiple lines, the efforts for electricity, heat, diesel, propane, water, gas and nitrogen use were allocated through rough estimation provided by the business controllers of each plant.

The antioxidant was modelled according to stochiometric modelling as described by Parvatker and Eckelman (2019)[2].

The impact modifier is a Thermoplastic Elastomer (TPE) who's carbon footprint was known. It was modelled with the synthetic rubber ecoinvent market process as a proxy: "market for synthetic rubber | synthetic rubber | Cutoff, U - GLO" as it proved to have a similar carbon footprint.

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[2] https://pubs.acs.org/doi/10.1021/acssuschemeng.8b03656

4.3.2 Results

The results obtained are shown in Table 15 and the comparison between LCA Impact Categories is clearer seen in Figure 27. This time we see improvements in some cases, but worse performance in other impact category results, and also in the CI circularity indicator, when energy is taken into account.

Table 15. Sustainability indicator results for the primary and recycled scenario of DEMO 3

Impact categories	100% primary	Recycled scenario	Unit
Acidification	0.01676	0.00899	mol H+-Eq
Climate change	4.07878	2.36349	kg CO2-Eq
Ecotoxicity: freshwater	10.66177	13.7364	CTUe
Energy resources: non-renewable	93.12687	47.9411	MJ, net calorific value
Eutrophication: freshwater	0.00025	0.00047	kg P-Eq
Eutrophication: marine	0.0036	0.00305	kg N-Eq
Eutrophication: terrestrial	0.03106	0.02141	mol N-Eq
Human toxicity: carcinogenic	4.5316E-09	8.2E-09	CTUh
Human toxicity: non-carcinogenic	2.55E-08	3.55E-08	CTUh
Ionising radiation: human health	0.32488	0.60221	kBq U235-Eq
Land use	5.0949	10.9216	dimensionless
Material resources: metals/minerals	8.93929E-06	1.4E-05	kg Sb-Eq
Ozone depletion	1.70023E-08	3.3E-08	kg CFC-11-Eq
Particulate matter formation	1.91713E-07	1.2E-07	disease incidence
Photochemical oxidant formation: human health	0.01331	0.0087	kg NMVOC-Eq
Water use	2.39008	1.31821	m3 world Eq deprived
Plastic littering risk	0.00636	0.05062	kg
MCI	0.1265	0.1778	No units, score from 0.1 - 1
CI	0.0187	-0.0103	No units, score from 0 - 1

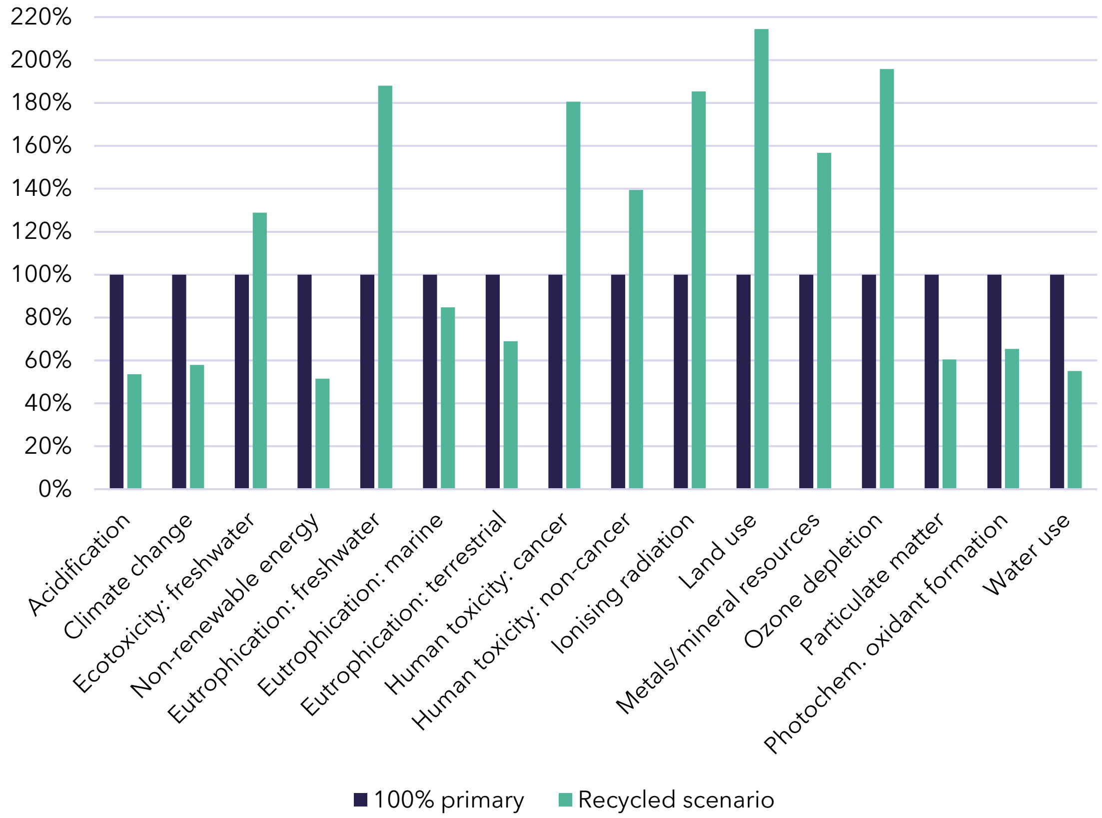


Figure 27. Normalised LCA Impact Category results for DEMO 3

It can be seen from Figure 27 that most Impact Categories benefit from having recycled content. Climate Change, for example, decreases by 42%, where the impact of primary HIPS production already accounted for 86% of the impact, it made sense to substitute this with rHIPS. The compound mix decreases from a value of 3.84 kg CO2 eq. to 2.15 kg CO2 eq. per kg of mix.

Some Impact Categories, however, show an increase in environmental damage. Ecotoxicity, Human Toxicity, and Land Use are specifically affected by the big transport distance of recyclates between the Netherlands (recycler) and Finland ("manufacturer"). Eutrophication (freshwater), Ionising radiation and Ozone Layer Depletion are affected by the large amount of electricity used to produce the recyclates. Also is Resource use (minerals and metals), due to the copper used in the electric grid network. Finally, Eutrophication is affected mainly by the use of nitrogen in the sorting of recycled content, as well as electricity used throughout.

A hidden environmental-burden hotspot of the system is the production of the antioxidant. Only 2% is used to make the formulation to make the plastic part, however the model suggests that it can have very high contributions, i.e. around 40% of contribution to Ecotoxicity (freshwater) and Human Toxicity.

Figure 28 shows the results for the changes of circularity variables. Unlike the other demonstrator cases, the total energy required and waste produced is worse in this scenario. This shouldn't be affected by the lab-scale of the demo case as the contribution mainly comes from the production of recyclates, which is an already an industrialised system. Only 1.63 kWh of energy is required to make a kg of 100% primary inner lining, vs 6.67 kWh required to make the same amount of the recycled scenario inner lining. From here, around half of the energy needed, 3.30 kWh, is coming the sorting facility, and the other half required to produce the nitrogen used also at sorting.

The large amount of electricity required in the production of secondary material is also responsible of the negative Circularity Index (CI) shown in the last rows of Table 15. This indicator shows worse results in the recycled content scenario.

Primary material savings in Figure 28 show a slight decrease which is quantified to 100g less primary material used per kg of fridge inner lining, i.e. a kg of fridge inner lining would require 1.66 kg of primary material, but the recycled scenario needs 1.55 kg.

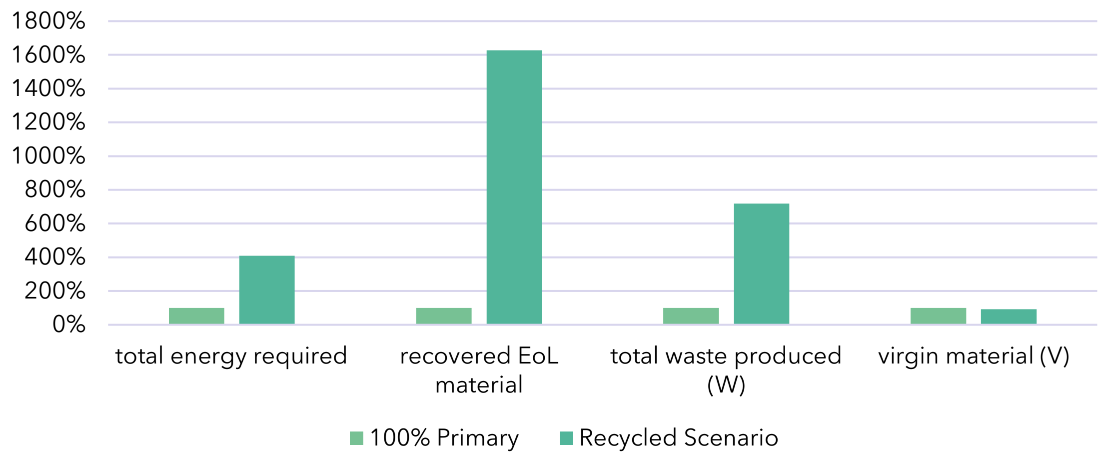


Figure 28. DEMO 3 changes in circularity variables results compared to 100% primary scenario.

The plastic littering risk of the recycled scenario of this demonstrator case is 7 times more than the scenario with 100% primary material. Similarly to Demo 1, the high content of recycled material in Demo 3 (70%) spikes the risk of plastic littering as the methodology assumes a 10% probability of littering in recycling processes. Overall, around 50% of the plastic littering risk comes from rHIPS production and transportation, 7% from HIPS production and transportation and 16% from scrap to waste bin.

4.3.3 Discussion and Conclusions

40% Climate Change impact is saved with the recycled scenario.

There are material savings quantified to 100g (7% lower than the full primary material scenario) saved primary material per kg of fridge inner lining, but this is a small % savings compared to the increased amount of energy used in the recycled scenario, 400% more.

Shorter transportation distance between recyclate production and use, green electricity in recycling processes will help damping higher impacts in Ecotoxicity, Human Toxicity, Land Use, Eutrophication (freshwater), Ionising radiation, Ozone Layer Depletion, Resource use (minerals and metals).

There is a small improvement in the MCI from 0.1265 to 0.1778 but a worse score for the CI, which takes into account energy used, from 0.0187 to -0.0103.

Care should be taken with the amount of antioxidant used, as its production is toxic for the environment and humans.

There is a big change in the risk of plastic littering when the recycled scenario is considered. The highest amount comes from the production and transportation of rHIPS, however HIPS supply chain and the management of the waste from the part production are also relevant. Even thought that these have lower results in the assessment, the methodology is based on littering probability assumptions and factors like the origin of HIPS and location of part production and waste management could influence a lot the amount of plastics that could be leaked into the environment.

4.4 Demo 4, rEPDM, for washing machine food seals

Demo 4 is a rubber washing machine seal made out of EPDM, fillers and paraffinic oil. The demonstrator case manages to include a maximum of 10% recycled content in the plastic part, with the limit established by the performance and tests that the plastic part must pass. In that sense, it ensures that the performance of the rubber seal is kept the same or similar compared to the 100% primary counterpart, but surely acceptable. The specific formulation used for the recycled scenario is shown in Table 16.

Table 16. Input materials for the recycled content scenario of DEMO 4

Input material	Recycled content scenario	Origin
EPDM	23%	Market average
rEPDM	10%	Post-consumer washing machines, primary data
Fillers	39%	Secondary dataset
Paraffinic oil	28%	Secondary dataset

A picture of the rubber seal is shown in Figure 29. The plastic part weighs 1.240 kg. Experiments trying to include more recycled content showed defects in part production, see Figure 30.

Figure 29. DEMO 4 rubber washing machine seal

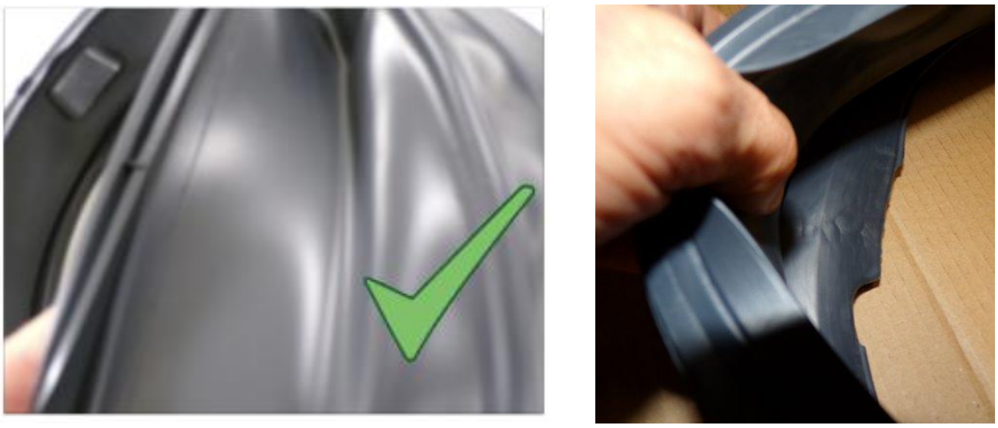


Figure 30. Washing machine seal with no defects (left) and with visual defects (right)

4.4.1 Product system description

The LCA methodology described in section 1.1 was followed for the environmental sustainability assessment. The functional unit of this demo case is:

"a washing machine seal at factory gate, achieving aesthetic expectations and passing compliance tests"

The reference quantity is:

"1 unit = 1240g"

Figure 31 shows the flow diagram.

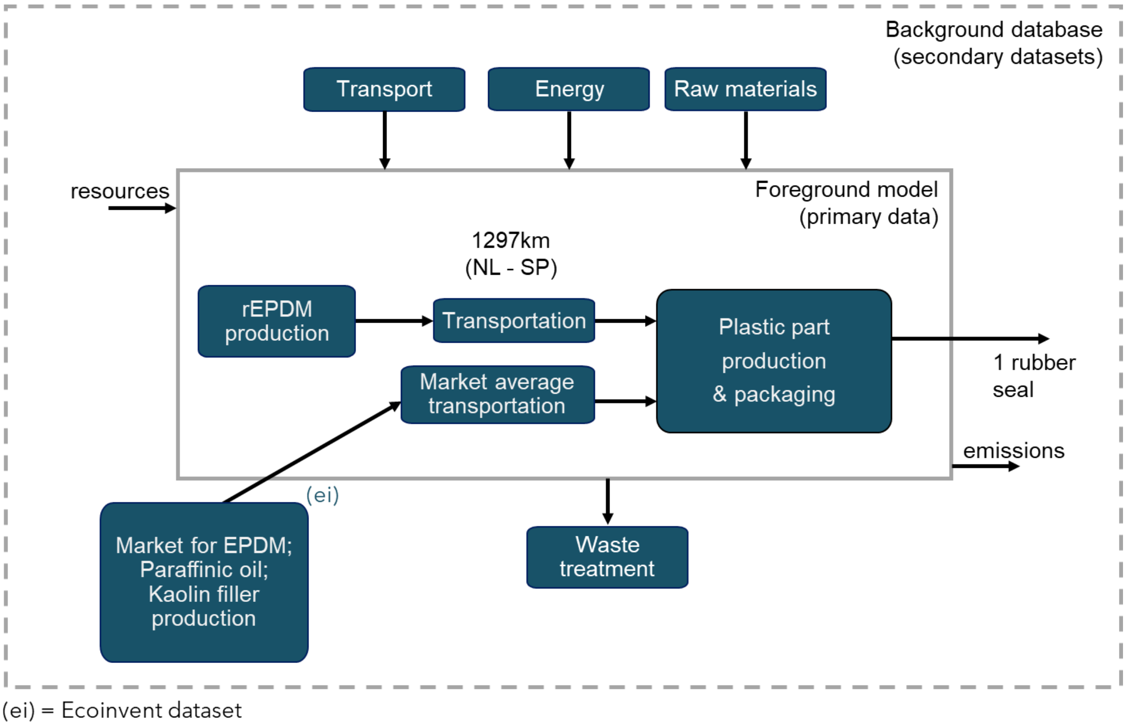


Figure 31. Product system flow diagram of Demo 4, washing machine rubber seal

“rEPDM“ is obtained from used (post-consumer) washing machines, making it not only rEPDM, but a compounded mix of the formulation used for the previous washing machines. These are collected by the recycler partner company in the Netherlands, manually obtained, and sent with a generic truck to the north of Spain, where the part manufacturing partner is located.

Manually sorting is not a usual procedure to obtain the rubber seals from used washing machines. The objective was to try to make a full Circular Economy circle (cradle-to-cradle), and to obtain a recyclate that would best suit the production of new washing machine seals.

As seen in Table 16, 67% of the formulation comes from the paraffinic oil, modelled with “market for paraffin | paraffin | Cutoff, U - GLO”, and kaolin filler, modelled with “market for kaolin | kaolin | Cutoff, U - GLO”.

The processes to make the plastic part involves mixing in a Bambury Mixer where granulates are obtained. These are further injection moulded to make the part. Finally, the parts are packaged in carboard boxes.

4.4.2 Results

Adding 10% recycled content presents benefits in all LCA impact categories, see Figure 32. Table 17 contains the results per impact category for 100% primary and recycled scenarios, with the last two rows dedicated to the circularity indicators. It is also seen that the recycled content scenario improves the circularity score of both indicators.

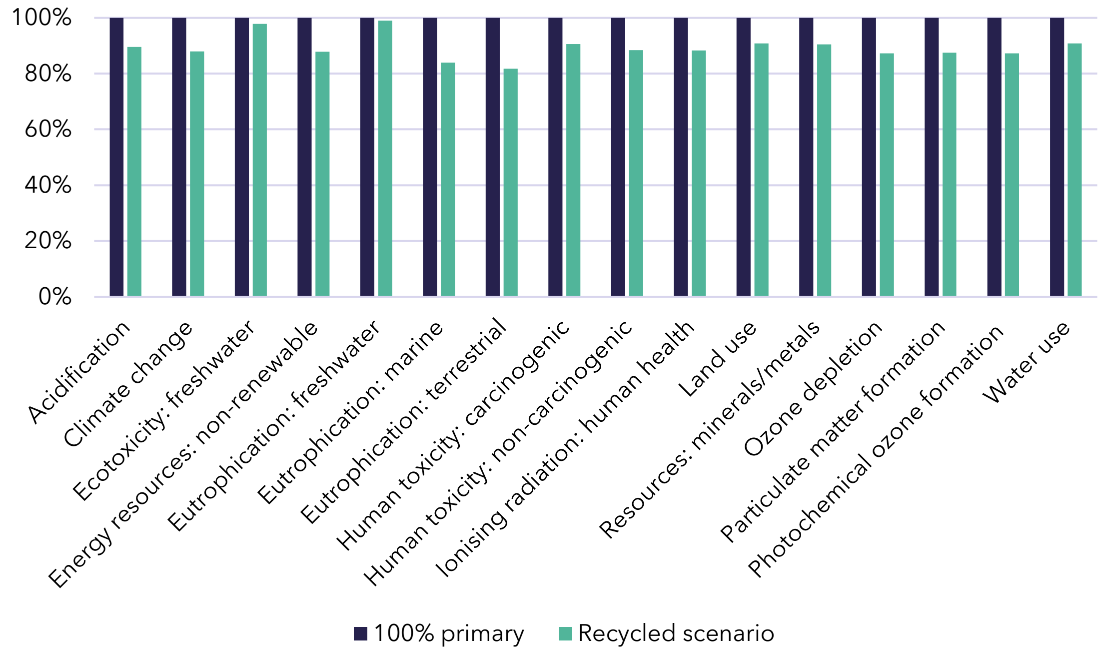


Figure 32. Normalised LCA Impact Category results for DEMO 4

Table 17. Sustainability indicator results for the primary and recycled scenario of DEMO 4

Impact categories	100% primary	Recycled scenario	Unit
Acidification	0.01614	0.01446	mol H+-Eq
Climate change	3.15163	2.77333	kg CO2-Eq
Ecotoxicity: freshwater	0.01544	0.0151	CTUe
Energy resources: non-renewable	3.12472	2.74689	MJ, net calorific value
Eutrophication: freshwater	0.01147	0.01135	kg P-Eq
Eutrophication: marine	17.25259	14.4907	kg N-Eq
Eutrophication: terrestrial	13.00121	10.637	mol N-Eq
Human toxicity: carcinogenic	4.25138	3.8537	CTUh
Human toxicity: non-carcinogenic	84.23559	74.5214	CTUh
Ionising radiation: human health	0.00094	0.00083	kBq U235-Eq
Land use	0.00317	0.00288	dimensionless
Material resources: metals/minerals	0.03199	0.02894	kg Sb-Eq
Ozone depletion	1.02434E-08	8.9E-09	kg CFC-11-Eq
Particulate matter formation	4.70409E-10	4.1E-10	disease incidence
Photochemical oxidant formation: human health	9.77297E-09	8.5E-09	kg NMVOC-Eq

Water use	3.69251E-08	3.4E-08	m3 world Eq deprived
Plastic littering risk	0.02631	0.03885	kg
MCI	0.1796	0.22598	No units, score from 0.1 - 1
CI	0.0494	0.07857	No units, score from 0 - 1

The results for the full primary scenario in the category Climate Change show that the main contributions come from EPDM with 45% of the footprint, followed by the carboard packaging box with 28%. On the other hand, even though paraffinic oil and kaolin make the majority of the compounding formula (67%), these only carry 8% (kaolin filler) and 3% (paraffinic oil) of the carbon footprint impact, so it is good to focus in EPDM to reduce the impacts. In fact, EPDM is a big contributor to most LCA Impact Categories, see Figure 33, therefore, investigating in how to improve the EPDM footprint is therefore interesting.

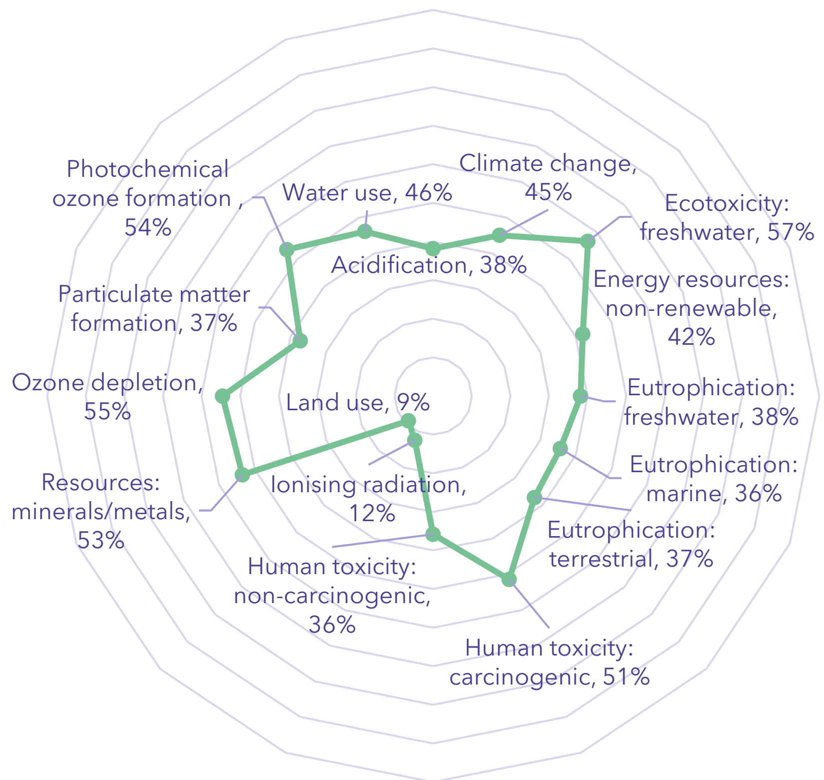


Figure 33. EPDM production contribution per impact category, Demo 4

Adding 10% recycled content changes the compounding formula's impact from 1.79 kg CO2 eq. to 1.41 kg CO2 eq. per item.

Looking at circularity, all circularity variables have an improvement with the recycled scenario, see Figure 34. Around 10% less energy is required, less waste is produced and less primary material is used.

The circularity score of Demo 4 is increased from 0.1796 to 0.2260 for the MCI and from 0.0494 to 0.0786 for the CI for the recycled scenario. Figure 34 shows the improvements in circularity variables that cause this change. To make a 1.240 kg part, 3.672 kg of primary material is required, which decreases to 3.367 kg with the recycled scenario.

Results also show that with a simple 10% decrease in performance, the MCI drops down to 0.1400, which is lower than the 100% recycled case. The performance of the plastic part has to be ensured to be similar to the primary counterpart, in order to have benefits in the MCI score.

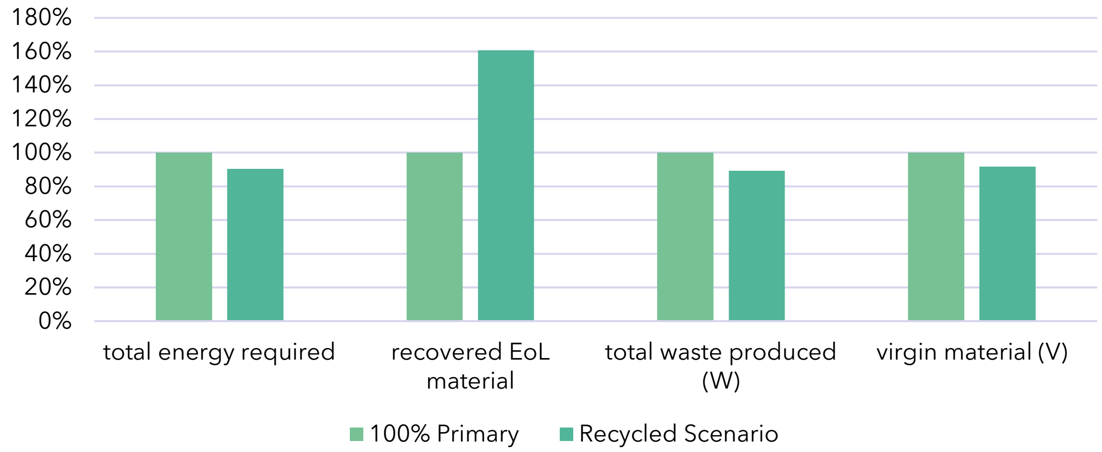


Figure 34. DEMO 4 changes in circularity variables results compared to 100% primary scenario

When no recycled material is present, the plastic littering risk of this demonstrator case is dominated by the waste plastic scrap and also the (carboard) packaging, with a value of 0.0263 kg of estimated plastic litter per plastic part, usually weighing 1.24kg. The recycled scenario, with only 10% rEPDM added, increases the plastic littering risk by nearly a half, adding 0.0153 kg of plastic littering.

5 SOCIAL LCA APPLIED TO THE 4 PRIMUS DEMO CASES

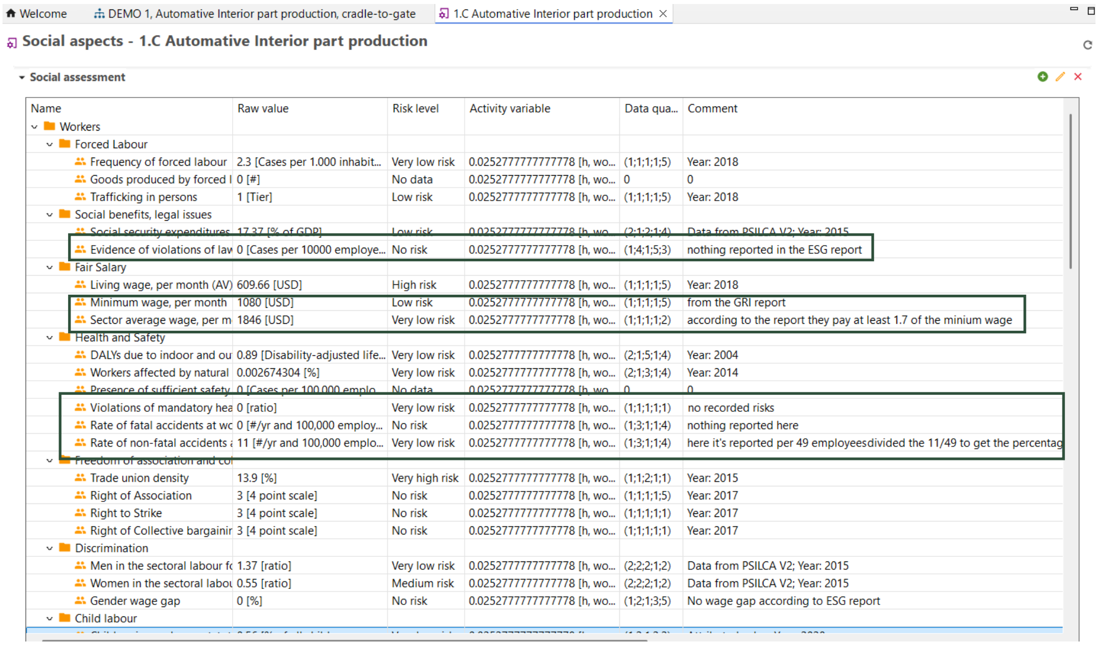
5.1 Foreground and background data (read over this)

For the sLCA study of the demo cases, the background databases PSILCA v3.1.1 and the SOCA v3.0 database [23] were applied. The PSILCA database, developed by GreenDelta, is built upon the multiregional input-output (MRIO) database of EORA with worker hours and social indicator data implemented by GreenDelta. While SOCA is built upon the process-model based LCA database, ecoinvent, with social indicator data taken from PSILCA.

As all demo cases were set up using ecoinvent v3.10, the social indicators evaluation was conducted using the *SOCA* v3.0 database. However, the social indicator data was only available for processes that had a defined location, such as the Coolrec sorting facilities in the Netherlands, France, and Belgium. The recyclates datasets used the average social data from all "recycling" datasets from countries in PSILCA v3.1.1 that are a part of Europe. Additionally, the final (or reference) process for each demo case used social data based on the manufacturing of plastic products in either Spain or Finland, as provided by PSILCA v3.1.1.

For the foreground system, in all cases the activity variable (worker hours) was adjusted based on the available cost data (e.g., recyclates produced by Coolrec). Two companies provided the worker hours needed to produce an item for their main product: Demo 2 required 70 seconds/piece, while Demo 4 required 112 seconds/piece. Because Demo 3 was at a pilot-production phase, a longer time of 30 minutes/piece was assumed. For Demo 1, the required worker hours were taken as the average of Demo 2 and Demo 4.

Other foreground data was attained from the ESG report "CIKAUTXO GROUP" which was following the Global Reporting Initiative (GRI) guidelines and edited under the social aspects tab as indicated in the Figure 35.



Welcome | DEMO 1, Automative Interior part production, cradle-to-gate | 1.C Automative Interior part production

Social aspects - 1.C Automative Interior part production

Social assessment

Name	Raw value	Risk level	Activity variable	Data qua...	Comment
Workers					
Forced Labour					
Frequency of forced labour	2.3 [Cases per 1.000 inhabit...	Very low risk	0.0252777777777778 [h, wo...	(1;1;1;1;5)	Year: 2018
Goods produced by forced l	0 [#]	No data	0.0252777777777778 [h, wo...	0	0
Trafficking in persons	1 [Tier]	Low risk	0.0252777777777778 [h, wo...	(1;1;1;1;5)	Year: 2018
Social benefits, legal issues					
Social security expenditures	17.37 [% of GDP]	Low risk	0.0252777777777778 [h, wo...	(2;1;2;1;4)	Data from PSILCA V2; Year: 2015
Evidence of violations of law	0 [Cases per 10000 employe...	No risk	0.0252777777777778 [h, wo...	(1;4;1;5;3)	nothing reported in the ESG report
Fair Salary					
Living wage, per month (AV)	609.66 [USD]	High risk	0.0252777777777778 [h, wo...	(1;1;1;1;5)	Year: 2018
Minimum wage, per month	1080 [USD]	Low risk	0.0252777777777778 [h, wo...	(1;1;1;1;5)	from the GRI report
Sector average wage, per m	1846 [USD]	Very low risk	0.0252777777777778 [h, wo...	(1;1;1;1;2)	according to the report they pay at least 1.7 of the minium wage
Health and Safety					
DALYs due to indoor and ou	0.89 [Disability-adjusted life...	Very low risk	0.0252777777777778 [h, wo...	(2;1;5;1;4)	Year: 2004
Workers affected by natural	0.002674304 [%]	Very low risk	0.0252777777777778 [h, wo...	(2;1;3;1;4)	Year: 2014
Presence of sufficient safety	0 [Cases per 100.000 emplo...	No data	0.0252777777777778 [h, wo...	0	0
Violations of mandatory hea	0 [ratio]	Very low risk	0.0252777777777778 [h, wo...	(1;1;1;1;1)	no recorded risks
Rate of fatal accidents at wc	0 [#/yr and 100,000 employ...	No risk	0.0252777777777778 [h, wo...	(1;3;1;1;4)	nothing reported here
Rate of non-fatal accidents a	11 [#/yr and 100,000 emplo...	Very low risk	0.0252777777777778 [h, wo...	(1;3;1;1;4)	here it's reported per 49 employeesdivided the 11/49 to get the percentag
Freedom of association and co					
Trade union density	13.9 [%]	Very high risk	0.0252777777777778 [h, wo...	(1;1;2;1;1)	Year: 2015
Right of Association	3 [4 point scale]	No risk	0.0252777777777778 [h, wo...	(1;1;1;1;5)	Year: 2017
Right to Strike	3 [4 point scale]	No risk	0.0252777777777778 [h, wo...	(1;1;1;1;1)	Year: 2017
Right of Collective bargainir	3 [4 point scale]	No risk	0.0252777777777778 [h, wo...	(1;1;1;1;1)	Year: 2017
Discrimination					
Men in the sectoral labour fc	1.37 [ratio]	Very low risk	0.0252777777777778 [h, wo...	(2;2;2;1;2)	Data from PSILCA V2; Year: 2015
Women in the sectoral labou	0.55 [ratio]	Medium risk	0.0252777777777778 [h, wo...	(2;2;2;1;2)	Data from PSILCA V2; Year: 2015
Gender wage gap	0 [%]	No risk	0.0252777777777778 [h, wo...	(1;2;1;3;5)	No wage gap according to ESG report
Child labour					

Figure 35. Social data collected from ESG report

5.2 Results of the sLCA methodology applied to the Demo cases

The results, in medium risk hours, show differences in social impact indicators across the Demo cases and material choices. Concerning the access to material resources impact category, the social indicator *Certified environmental management systems* are highest in Demo 4, with 10.37 for primary and 8.38 for recycled, while Demo 1 drops sharply from 9.42 to 2.13 in the recycled scenario, possibly due to company policies or lack of data availability. Concerning the Discrimination impact category, the gender wage gap is highest in Demo 1 at 14.10 for the primary and 6.11 for recycled, and in Demo 4 at 13.26 for primary and 11.33 for recycled, showing slight improvements in pay equity when using recycled materials. The Fair salary category is highest in Demo 4, with 31.98 for primary and 27.14 for recycled. Workplace safety measures are highest in Demo 4, with 3.29 for primary and 3.25 for recycled, while the rate of fatal accidents is also highest in Demo 4, at 0.07 for primary and 0.06 for recycled, indicating possible risks in this sector. Violations of employment laws are highest in Demo 4, with 9.27 for primary and 7.81 for recycled, which reflects more recorded violations and may also reflect stronger labor protections. Weekly working hours are highest in Demo 4, with 6.29 for primary and 5.30 for recycled, showing that this sector demands longer work shifts. Overall, Demo 4 stands out for higher wages and social security but also longer working hours and higher workplace risks, while Demo 1 shows strong environmental and social commitments but a shows a drop in its recycled scenario.

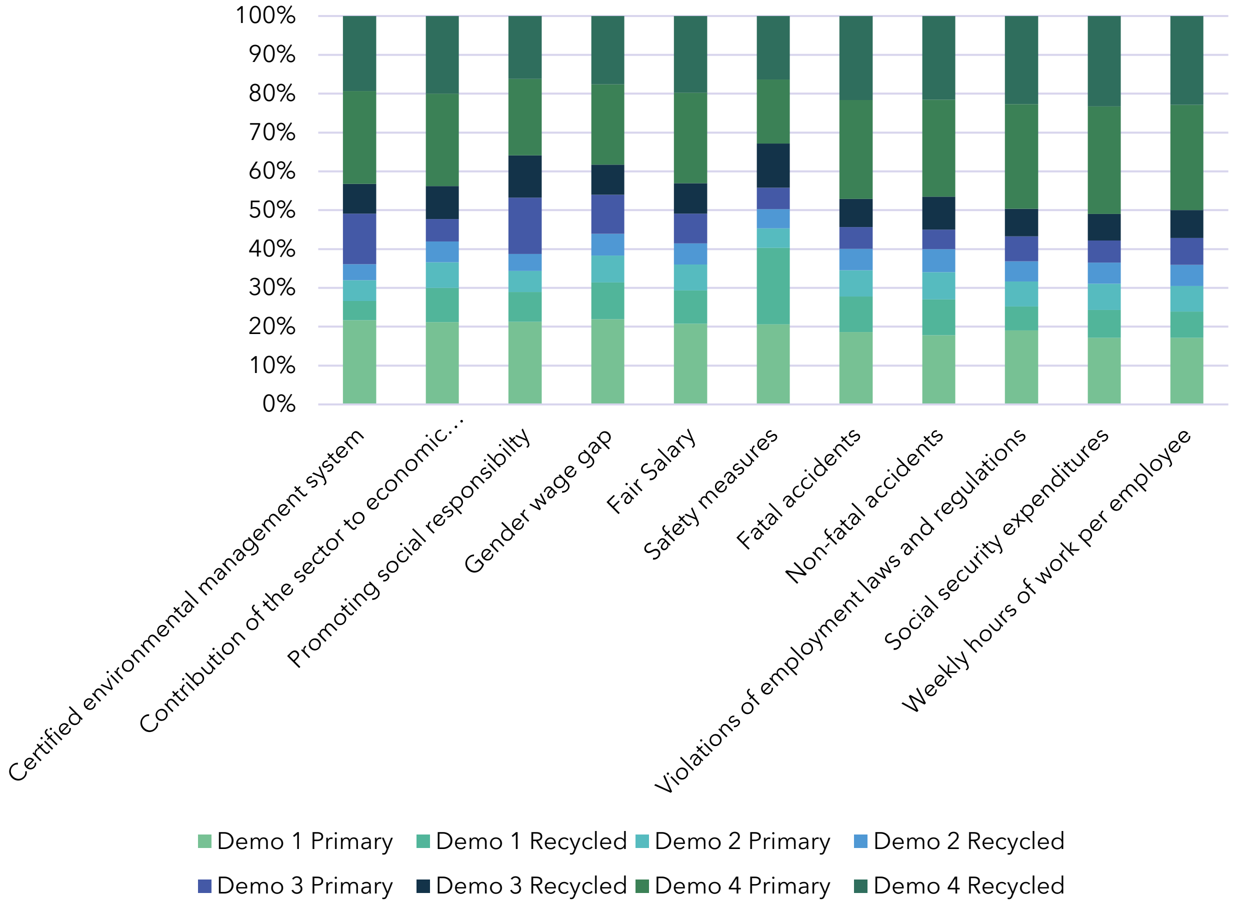


Figure 36. Overall social LCA results medium risk hours

In the following subsections, we will take a closer look at the stakeholders along the life cycle for each demonstrator, the corresponding social themes or categories that concern them and the raw values of the chosen social indicators used to represent and quantify these categories.

5.2.1 Local community

The Certified Environmental Management Systems (CEMS) indicator assesses sectoral commitment to environmental protection using ISO 14001 certifications per 10,000 employees as the unit of measurement. The results show that Demo 1 shows a slightly lower CEMS adoption in the recycled scenario compared to 100% primary, suggesting a marginally reduced sectoral commitment. Demo 2 and Demo 4 display identical CEMS levels across both scenarios, indicating that incorporating recycled content does not impact certification rates in these cases. Demo 3, a lab-scale project, has the lowest CEMS levels, with no significant variation between scenarios, possibly due to its early-stage implementation. Overall, Demo 4 has the highest CEMS levels, reflecting a well-established environmental certification system in that sector. These findings suggest that CEMS adoption is influenced by industry sector and company policies rather than the choice between recycled and virgin plastics.

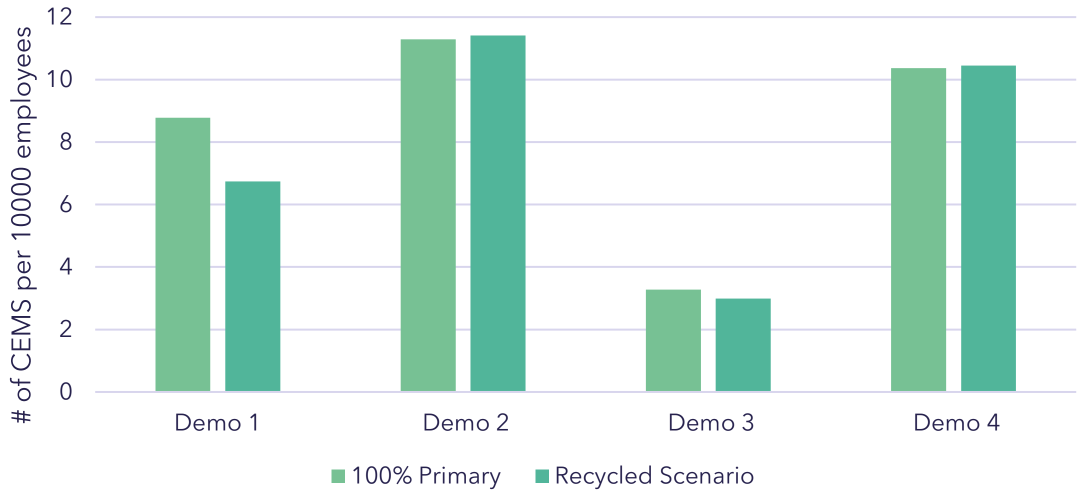


Figure 37. Certified Environmental Management Systems for each demo scenario

5.2.2 Society

The Contribution of the Sector to Economic Development category, represented by an indicator with the same name and measured in percentage (%), measures a sector's impact on GDP, job creation, education, training, and investments. Results indicate that Demo 3 (fridge inner linings in Finland) has the highest contribution to economic development: 14.11% for primary materials and 14.38% for recycled content. Demo 1 (automotive interior in Spain) shows a minor increase in contribution from 9.81% (primary) to 9.99% (recycled). The contribution of Demo 2 (cooling pipes in Spain) rises slightly from 8.84% to 8.87%, while Demo 4 (washing machine seal in Spain) has the lowest contribution at 8.26% (primary) and 8.29% (recycled). Overall, recycled material scenarios contribute comparably or slightly more to the GDP than primary material scenarios, suggesting that integrating recycled plastics supports economic performance with marginal benefits.

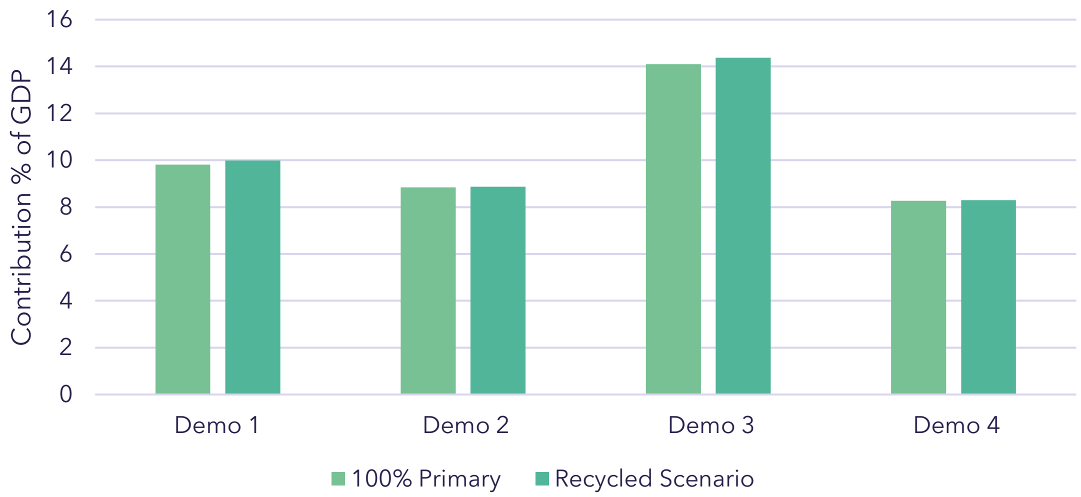


Figure 38. Contribution of the Sector to Economic Development for each demo scenario

5.2.3 Value Chain Actors

The membership of value chain actors in a social responsibility initiative indicator measures how committed sectors are to sustainability programs like the UN Global Compact, which focuses on human rights, labour rights, the environment, and anti-corruption, it is measured based on number of initiatives per sector in a particular country on sector specific country data can be recorded by counting the number of initiatives in the company. A larger number of initiatives implies a higher level of commitment to social responsibility along the value chain. Demo 1 (automotive interior in Spain) has the highest engagement, rising from 10.76 (primary) to 12.28 (recycled), likely influenced by data from the company ESG report "CIKAUTXO GROUP." Demo 2 sees a small decrease in engagement from 9.15 to 9.07, showing stable but slightly lower participation. Demo 3 has the lowest engagement, with 5.68 (primary) and 5.80 (recycled), indicating more limited commitment than the other demos. Demo 4 remains steady, with a minor increase from 10.26 to 10.35, reflecting moderate engagement within the demos compared. Overall, Demo 1 shows the biggest improvement, while Demo 3 lags behind, highlighting differences in how sectors engage with social responsibility programs.

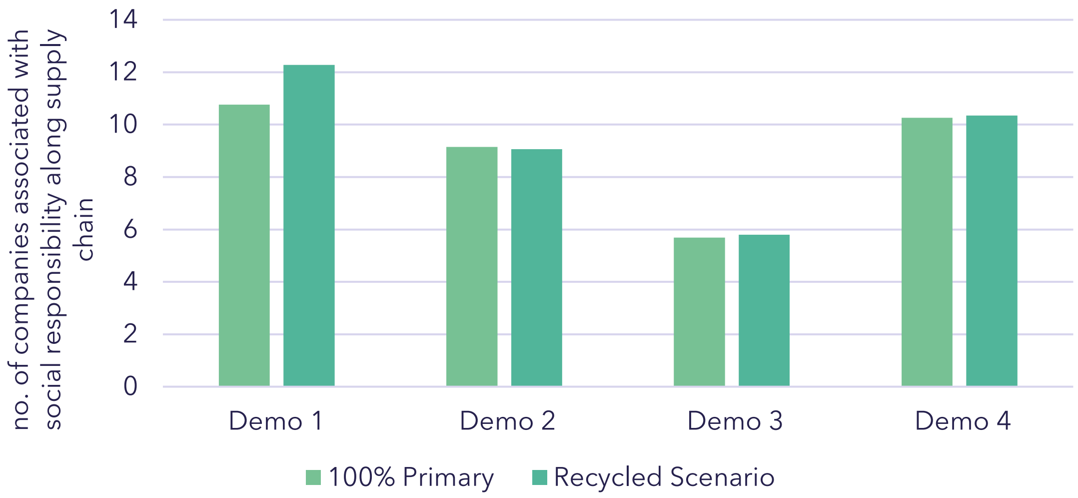


Figure 39. Promoting social responsibility per each demo

5.2.4 Workers

Three themes are covered that are relevant to workers : (1) discrimination (2) fair salary and (3) health and safety. The discrimination theme is represented by the inidcators gender wage gap and gender participation in the sectoral labour force. The gender wage gap indicator shows that pay differences between men and women exist across all cases, with Demo 3 (fridge inner linings in Finland) having the highest gap at 11.12% for primary materials and 10.29% for recycled, likely because men hold more high-paying technical roles. Demo 1 remains stable at 8.94%, Demo 2 sees a slight increase from 8.42% to 8.52%, and Demo 4 has the lowest wage gap, rising slightly from 6.80% to 6.96%, possibly due to more standardized wages in this sector. To compliment this indicator, the ratio of men in the sectoral labour force was also investigated. The ratio of men in the sectoral labour force also confirms a discrepancy in the participation of men and women in the labour force in the sectors involved in the life cycle, with more male employees in general as well as in roles with higher wages.

Table 18. Gender wage gap and men in sectoral labour force for each demo scenario

Demo Set	Scenario	Gender Wage Gap (%)	Men in Sectoral Labour Force
Demo 1	Primary	8.94	1.23
	Recycled	8.93	1.29
Demo 2	Primary	8.42	1.23
	Recycled	8.52	1.23
Demo 3	Primary	11.11	1.37
	Recycled	10.28	1.37
Demo 4	Primary	6.8	1.21
	Recycled	6.95	1.21

The fair salary category is represented by the Indicators sector average wage and living wage in this study, both measured in USD. The sector average wage indicator shows that wages vary across demos. Demo 3 has the highest wages, at 3075 USD (primary) and 2944 USD (recycled), reflecting Finland's higher wage standards. Demo 1 follows with around 1084 USD, while Demo 2 and Demo 4 have the lowest, at around 980 USD. In order to determine the fairness of wages and whether they offer the worker a dignified life, the living wage indicator is assessed as well and the difference between the sector wage and the living wage is accounted for, Demo 3 shows that earnings are 2000 USD higher than the 1335.82 USD living wage raw value of Finland, suggesting better financial security, while the other demos exceed their respective country specific living wages by a smaller margin. Wages remain mostly stable between primary and recycled scenarios, showing that material choice does not significantly impact salaries. These differences may also be influenced by country-specific labour policies, with Finland generally offering higher wages than Spain.

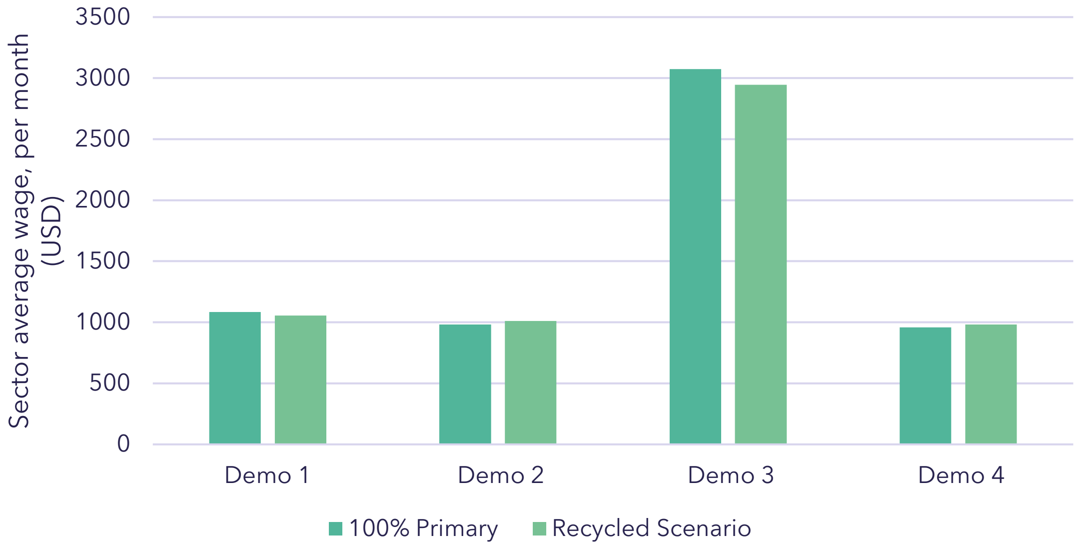


Figure 40. Sector average wage, per month for each demo scenario

The health and safety theme is represented by accident rates in this study. Rate of accidents indicates workplace safety, with non-fatal accidents causing injuries and fatal accidents leading to death within a year. The results show that Demo 3 has the highest non-fatal accident rate, with 511 per year (primary) and 496 (recycled), highlighting significant workplace safety concerns in this sector. Demo 1, Demo 2, and Demo 4 report much lower accident rates, with Demo 1 increasing from 56 to 96, Demo 2 from 61 to 70, and Demo 4 from 72 to 82 per 100,000 employees in the recycled scenario, indicating minor variations in accident rates. The relatively high accident rates in Demo 3 may be influenced by industry-specific risks or stricter reporting standards in Finland, while the other demos maintain more stable figures. Overall, the switch to recycled materials does not show a major impact on accident rates, suggesting that sectoral risks and workplace policies play a bigger role in safety outcomes.

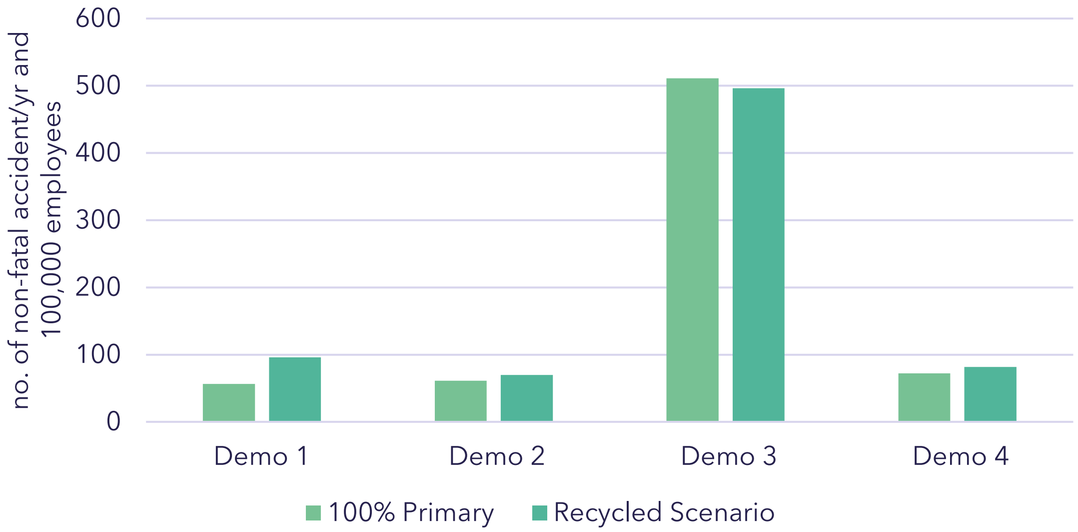


Figure 41. Rate of non-fatal accidents for each demo scenario

5.3 Discussions sLCA

The results suggest that social impacts in plastic recycling are shaped more by industry characteristics, national labor policies, and governance structures than by material type. While some indicators show slight improvements with recycled content, broader systemic factors appear to be the main drivers of social sustainability in the sector.

One key finding is the variation in CEMS adoption, with Demo 4 maintaining high certification levels and Demo 1 showing a sharp decline in the recycled scenario. This could be due to differences in company policies, data availability, or industry-wide commitments to certification tracking. Since Demo 1's recycled scenario included actual ESG data, this may have influenced the results, making them more reflective of real industry practices rather than database background information.

Economic contribution remains relatively the same across all scenarios, with Demo 3 (Finland, recycled scenario) showing the highest GDP contribution, reflecting how industrial applications of recycled plastics can support economic growth without lowering output[3]. Social responsibility along supply chain engagement varies, with Demo 1 (recycled scenario) showing the highest participation in initiatives, likely due to ESG data inclusion, while Demo 3 is lower, reflecting a lower corporate focus on social sustainability.

Gender disparities persist across all cases, with higher male employee participation in technical roles and a limited representation amongst informal waste workers, a group often underreported in formal labor statistics. In fact, the PSILCA database may not fully capture female participation in informal plastic collection, which is significant in lower-income regions[4].

Overall, the findings suggest that the recycled scenarios generally align with the EU Circular Economy Action Plan's goal of maintaining economic stability while promoting sustainability. However, the plan also emphasizes social equity and worker protection, areas where the results indicate persistent challenges, such as workplace risks, gender imbalances, and sectoral differences in social responsibility adoption. Sectoral policies and national labor conditions have a greater influence on social outcomes than the use of recycled materials alone. Future improvements in social sustainability should focus on worker safety, gender inclusion, and unique labor policies in high-risk recycling industries.

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[3] Jayawardane, H., Davies, I.J., Gamage, J.R. et al. Additive manufacturing of recycled plastics: a 'techno-eco-efficiency' assessment. *Int J Adv Manuf Technol* 126, 1471–1496 (2023). https://doi.org/10.1007/s00170-023-11169-8

[4] Aparcana, S., & Salhofer, S. (2013). Development of a social impact assessment methodology for recycling systems in low-income countries**.** *The International Journal of Life Cycle Assessment, 18*(5), 1106–1115. https://doi.org/10.1007/s11367-013-0559-3

5.4 Comparison with PSILCA

As SOCA is based on the bottom-up process based supply chain curated by ecoinvent, PSILCA on the other hand, is based on the input-output EORA database[5] which consists of a multi-region input-output table. Thus, the supply chain of PSILCA is more localized than SOCA. A comparision was thus made between both database for the Demo 1 and presented in The comparison between SOCA and PSILCA for Demo 1 highlights differences due to their methodological approaches. PSILCA, based on the EORA MRIO model, provides higher estimates for sectoral indicators such as GDP contribution. It also reports higher workplace risks, with non-fatal accident rates nearly 25 times higher than SOCA, reflecting its broader regional sectoral approach. Since SOCA derives data from PSILCA but integrates it into ecoinvent's bottom-up process model based supply chain, its results reflect the same in its calculations, leading to differences in the magnitude of reported impacts. While PSILCA provides a macro-level sectoral perspective, SOCA aligns social data with the process model based environmental LCA, making it more applicable to product-specific assessments. Both databases serve different purposes, and their combined use can enhance the strength of sLCA studies.

Table 19 below.

The comparison between SOCA and PSILCA for Demo 1 highlights differences due to their methodological approaches. PSILCA, based on the EORA MRIO model, provides higher estimates for sectoral indicators such as GDP contribution. It also reports higher workplace risks, with non-fatal accident rates nearly 25 times higher than SOCA, reflecting its broader regional sectoral approach. Since SOCA derives data from PSILCA but integrates it into ecoinvent's bottom-up process model based supply chain, its results reflect the same in its calculations, leading to differences in the magnitude of reported impacts. While PSILCA provides a macro-level sectoral perspective, SOCA aligns social data with the process model based environmental LCA, making it more applicable to product-specific assessments. Both databases serve different purposes, and their combined use can enhance the strength of sLCA studies.

[5] World MRIO. (n.d.). *Multi-regional input-output databases and analysis*. Retrieved March 17, 2025, from https://worldmrio.com/

Table 19 Comparing SOCA to PSILCA for Demo 1

Indicator	Unit	Demo 1_Primary_SOCA	Demo 1_Recycled_SOCA	Demo 1_Primary_PSILCA	Demo 1_Recycled_PSILCA
Certified environmental management systems	# of CEMS per 10000 employees	8.78	6.74	80.87	72.05
Contribution of the sector to economic development	% of GDP	9.82	9.99	18.35	18.35
Membership in an initiative that promotes social responsibility along the supply chain	number of companies	10.76	12.28	12.28	13.90
Gender wage gap	%	8.94	8.94	13.63	13.39
Living wage, per month (AV)	USD	428.33	372.38	653.86	657.34
Sector average wage, per month	USD	1084.04	1056.32	2388.20	2450.23
Presence of sufficient safety measures	Cases per 100.000 employees	0.01	0.01	0.01	0.01
Rate of fatal accidents at workplace	#/yr and 100,000 employees	0.64	0.51	2.57	1.98
Rate of non-fatal accidents at workplace	#/yr and 100,000 employees	56.26	96.05	1304.55	1396.63
Violations of mandatory health and safety standards	ratio	0.00	0.00	0.00	0.00
Evidence of violations of laws and employment regulations	Cases per 10000 employees	7.49	11.31	6.42	6.60
Social security expenditures	% of GDP	6.01	7.26	13.72	13.73
Weekly hours of work per employee	h	30.53	33.24	39.95	40.07

5.5 Limitations

The sLCA study faced limitations primarily related to data availability during the data collection process. It relied mainly on the PSILCA database for secondary data, with limited primary data sourced from the GRI reporting by a single company. Ideally, monetary data for all inputs and primary social data from the end-of-line supply chain companies should be collected, to more accurately reflect the reality of the selected social indicators. Additionally, the study used LCA practitioners in the stakeholder dimension during the selection of social indicators for the materiality assessment. A broader pool of industry experts should be engaged in the selection, to enhance the social indicator selection for the assessment.

6 PRIMUS DATASETS

The PRIMUS datasets are found in the PRIMUS Master database. This database is prepared to be able to calculate environmental and social LCA, plastic littering risk, criticality and circularity indicators. The development of the database was explained in section 3.

Furthermore, the PRIMUS Master database contains:

a) 4 example life cycle models of the PRIMUS Demonstrator cases,
b) Folders that aim to aid modellers in making life cycle models of plastic recyclates or plastic parts with recycled content, and
c) Disaggregated EcoProfile datasets for recycled plastics.

6.1 4 PRIMUS Demonstrator case sustainability models

The PRIMUS Sustainability Methodology described in section 1 was applied to the 4 PRIMUS Demonstrator cases:

1. **Demo 1** – rPC/ABS for automotive interior aesthetic components
2. **Demo 2** – rPP/EPDM for automotive cooling circuits
3. **Demo 3** – rHIPS for refrigerator liners for food-contact
4. **Demo 4** – rEPDM for washing machine door seal

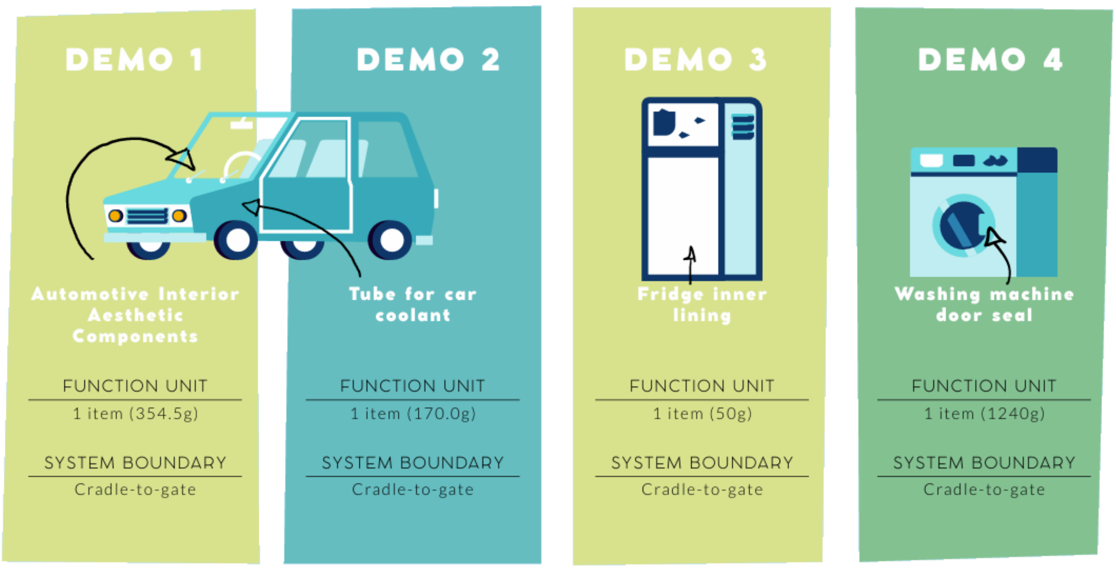

Figure 42. The 4 PRIMUS Demonstrator cases

The LCA models are found within the PRIMUS Master database, as shown in Figure 43 and Figure 44.

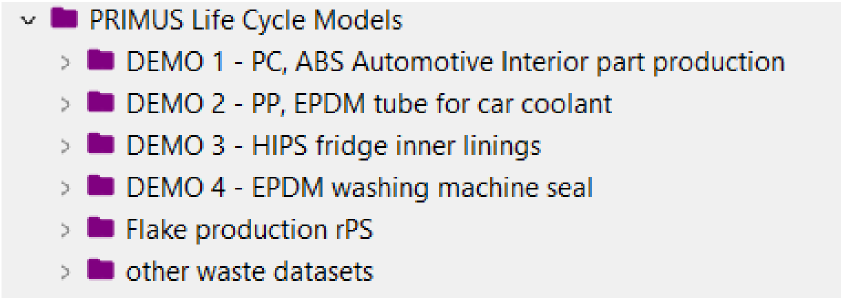

Figure 43. 4 Demonstrator cases in openLCA

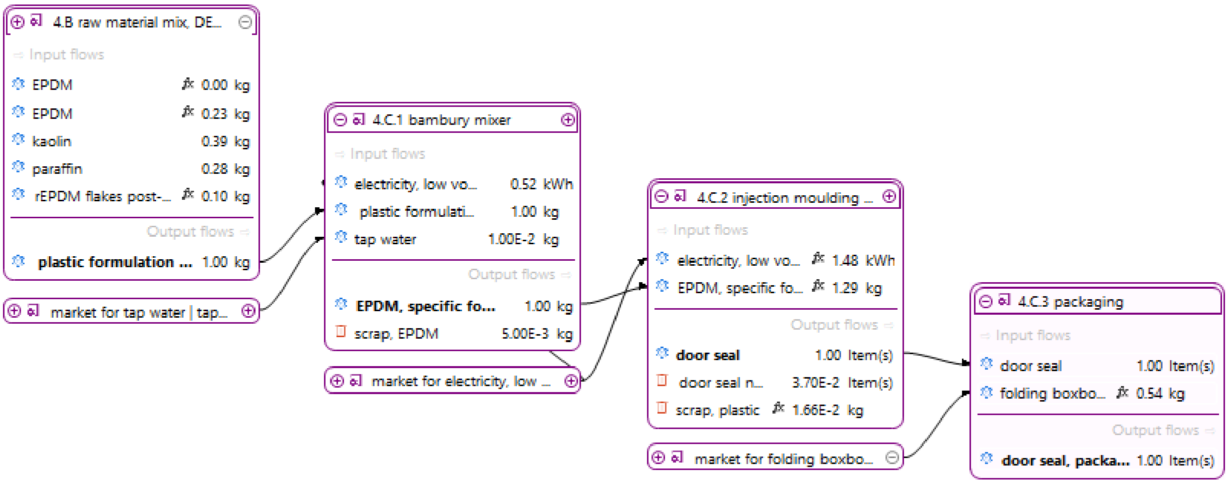

Figure 44. Demo 4 life cycle model in openLCA

6.2 PRIMUS datasets

The primary data collection, and workshops within the project allowed to put together standard datasets that will fit into life cycle models for recycled content production or plastic part production with recycled content. These datasets are used in the PRIMUS non-expert sustainability tool to aid non-LCA practitioners to make a model and calculate environmental results.

Generic datasets are laid up as shown in Figure 45 to help the LCA practitioner create a life cycle model from waste collection to plastic part production. Furthermore, there are specific folders with datasets for fillers and additives commonly used by industry (Figure 46), fuels like natural gas or nitrogen (Figure 47), recycled plastic datasets in a disaggregated format (disaggregated EcoProfiles, Figure 48), average plastic production datasets (Figure 49), a post-industrial waste dataset (Figure 50) and typical end-of-life disposal datasets (Figure 51).

- PRIMUS 200 datasets
  - 0 datasets
  - 1_Waste collection for plastic recycling
  - 2_Sorting plastics, at factory gate
  - 3_Production of recycled material, plastic A at factory gate
  - 3_Production of recycled material, plastic B at factory gate
  - 3_Production of recycled material, plastic C at factory gate
  - 3_Production of recycled material, plastic D at factory gate
  - 4_Recycled plastic distribution
  - 5_Compounding
  - 6_Plastic part production

Figure 45. Set up to make your own life cycle model in openLCA

- additives, fillers and other
  - antioxidant production, with distribution - RER
  - calcium carbonate, precipitated, with distribution - RER
  - calcium carbonate, precipitated, with distribution - RoW
  - carbon black production, with distribution - GLO
  - caustic soda, average production, without distribution - RER
  - caustic soda, with distribution - RER
  - caustic soda, with distribution - RoW
  - colour masterbatch production, with distribution - GLO
  - hydrochloric acid, without water, in 30% solution state, with distribution - RER
  - hydrochloric acid, without water, in 30% solution state, with distribution - RoW
  - kaolin, at factory gate - RER
  - kaolin, at factory gate - RoW
  - kaolin, with distribution - GLO
  - lubricating oil, at factory gate - RER
  - lubricating oil, at factory gate - RoW
  - lubricating oil, with distribution - RER
  - lubricating oil, with distribution - RoW
  - neutralising agent, sodium hydroxide eq., with distribution - RER
  - neutralising agent, sodium hydroxide eq., with distribution - RoW
  - salts, with distribution - GLO
  - sodium chloride, brine solution, at factory gate - RER
  - sodium chloride, brine solution, at factory gate - RoW
  - sodium chloride, brine solution, with distribution - GLO
  - sodium chloride, powder, at factory gate - RER
  - sodium chloride, powder, at factory gate - RoW
  - sodium chloride, powder, with distribution - GLO
  - sodium hydroxide, without water, in 50% solution state, with distribution - RER
  - talc production - CA-QC
  - talc production - RoW
  - Talcum powder production - GLO
  - talk production, with distribution - GLO
  - washing detergent - RER

Figure 46. Additive, fillers and other datasets available

- fuels and transport
  - diesel burned in truck - RER
  - diesel used in facility - GLO
  - gas burned in processing machine - Europe without Switzerland
  - gas burned in processing machine - RoW
  - nitrogen, at factory gate - RER
  - nitrogen, with distribution - RER
  - nitrogen, with distribution - RoW
  - nitrogen, with distribution - RoW
  - propane burned in forklift - GLO

Figure 47. Typical fuels and transport required in the LCA model

- mechanically recycled plastic datasets (PRIMUS EcoProfiles)
  - European averages
    - ctg
      - Eco Profile, ABS flakes - 1kg - ctg - disaggregated - RER
      - Eco Profile, ABS pellets - 1kg - ctg - disaggregated - RER
      - Eco Profile, HDPE flakes - 1 kg - ctg - disaggregated - RER
      - Eco Profile, HDPE pellets - 1 kg - ctg - disaggregated - RER
      - Eco Profile, HIPS flakes - 1kg - ctg - disaggregated - RER
      - Eco Profile, HIPS pellets - 1kg - ctg - disaggregated - RER
      - Eco Profile, LDPE pellets - 1kg - ctg - disaggregated - RER
      - Eco Profile, MPO flakes - 1 kg - ctg - disaggregated - RER
      - Eco Profile, MPO pellets - 1 kg - ctg - disaggregated - RER
      - Eco Profile, PET flakes - 1 kg - ctg - disaggregated - RER
      - Eco Profile, PET pellets - 1 kg - ctg - disaggregated - RER
      - Eco Profile, PP flakes - 1 kg - ctg - disaggregated - RER
      - Eco Profile, PP pellets - 1 kg - ctg - disaggregated - RER
      - Eco Profile, PVC pellets - 1 kg - ctg - disaggregated - RER
    - gtg
  - other datasets required to make EcoProfiles
  - Regionalised

Figure 48. Transparent (disaggregated) PRIMUS EcoProfiles for recycled plastics

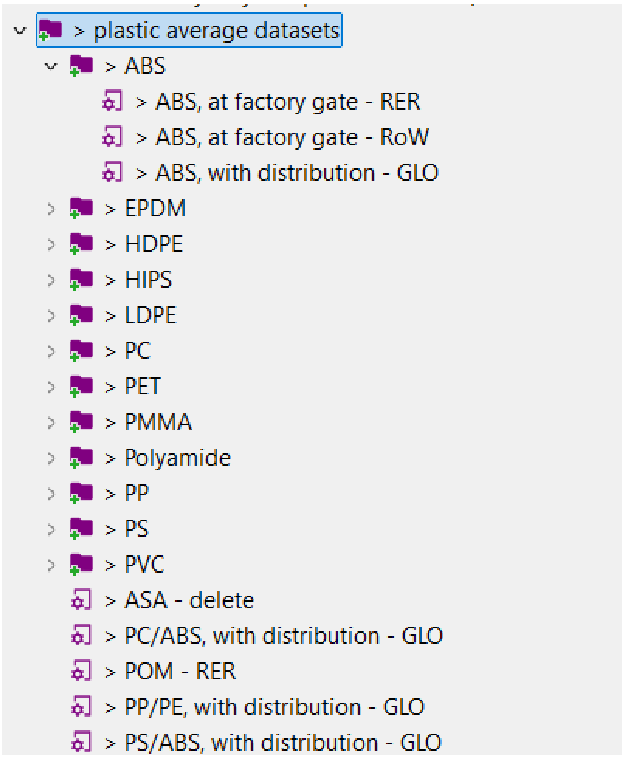

Figure 49. Datasets for plastic manufacturing

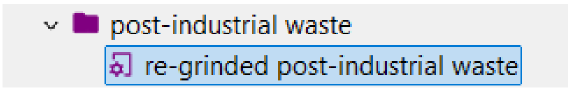

Figure 50. Dataset for post-industrial waste

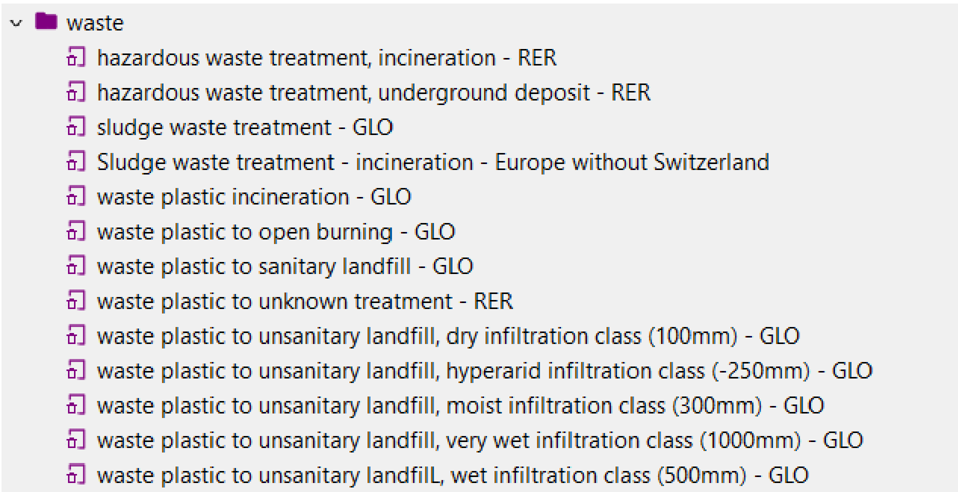

Figure 51. Datasets for waste and end-of-life options for plastic LCA models

7 CONCLUSIONS AND DISCUSSION

A full sustainability framework was developed as part of the PRIMUS Sustainability Methodology involving Life Cycle Assessment (LCA), Social LCA, Circularity, plastic littering risk and System Dynamics. The methodology was applied to the 4 PRIMUS demonstrator cases in a cradle-to-gate analysis, resulting in LCI datasets that can help LCA practitioners with recycled plastic sustainability models.

Furthermore, a wide array of sustainability datasets for recycled polymers, EcoProfiles, were developed. They allow to assess and compare environmental impacts within the recycling industry average but also to primary production. Hence, decision for recyclates will be backed up from now on with transparent and comprehensive LCA data derived from the PRIMUS project.

Sustainability assessments show general environmental improvements when using recycling content, where impacts like Climate Change always show a decrease in emissions. Only Demo 3 on the production of fridge inner lining with rHIPS shows a mix between improvements and worse environmental results, mainly due to the large transportation distance of recycled content from recycler to compounder and intensive energy and nitrogen use in the specific demo recycling process.

Furthermore, a higher plastic littering risk is generally seen in the recycled plastic scenarios. However, results would change if a full cradle-to-grave rather than cradle-to-gate analysis was considered, as e.g. landfilling plastic products is considered to have higher plastic littering risk than recycling them.

Circularity assessments showed improvements in the MCI and CI indicator scores, except for Demo 3 due to the large amount of electricity required in recycling. The MCI analysis reminded that a compromise of 10-30% in performance of the plastic part with recycled content can defeat the aim of a circular economy by placing recycled content in the first place.

Regarding social LCA, differences between primary and recycled scenarios do not drastically shift overall social metrics. Meanwhile, national context remains a dominant factor in shaping social outcomes, as country-level differences, such as living wages, average weekly work hours (46 h vs. 30 h), and accident rates (496-511 vs. 56-96 per 100,000 employees), are far greater than the relatively modest variations observed between primary and recycled plastics.

All in all, recycled plastic use is a more sustainable option compared to primary plastics. It is recommended that these are sourced locally to avoid big transportation efforts that can counter act sustainability improvements from recycling. Plastic litter risk can seem to be higher on the production of recycled plastics when speaking about cradle-to-gate perspective. This would change in a cradle-to-grave perspective and it should be made clear that the cause of plastic litter is the production of primary plastics to start with. In a System Dynamics perspective, the supply of recyclates seems to be a struggle, and the increasing amount of plastic production a concern.

7.1 Summary of achievements

The deliverable contains a summary of the PRIMUS Sustainability Methodology, explanation of data preparation and LCI datasets and EcoProfiles made, and extra information on assessment analysis of the application of the Methodology to the 4 PRIMUS Demo cases.

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ANNEX A – DATA ADAPTATION OF THE PLEX DATABASE MODEL TO FIT CUT-OFF, PARTING FROM APOS SYSTEM MODEL

Both the Cut-off and APOS databases are the same, contain the same information, and only differ in the way that they treat waste and recyclable materials[6]. In the cut-off system model, the waste producer is responsible for waste treatment for recycling (ecoinvent terms this "polluter pays"), and recyclable products are available burden free (cut-off). For example, recycled paper only bears impacts related to collection, sorting and recycling of the paper, but not on the forestry activity or primary production. On the other hand, the APOS system shares impacts of the first life cycle also with subsequent ones, similar to waste treatments.

The steps to pass from the PLEX Cut-off to the PLEX APOS database were as follows:

1. All plastic littering risk information were obtained from the processes of the APOS database,
2. These processes were matched from the APOS to the Cut-off database (process names are the same),
3. The plastic littering risk information was finally inserted into the Cut-off database.

Only 639 out of the 9835 processes with plastic littering risk didn't find a direct match between databases. These were processes specific to the cut-off system model, e.g. those that produce or sort scrap.

A check was made to see the difference between the implementations. Dataset results for plastic littering risk were mapped between APOS and Cut-off and the total results are shown in Figure 52 with a closer look up of plastic littering values from [0, 1.0] kg in Figure 53, with an R-squared in the regression line of 0.915208063.

There is a correlation of Cut-off and APOS processes having the same littering values, with some differences due to the intrinsic differences of the Life Cycle Inventory of both databases.

[6] https://support.ecoinvent.org/system-models

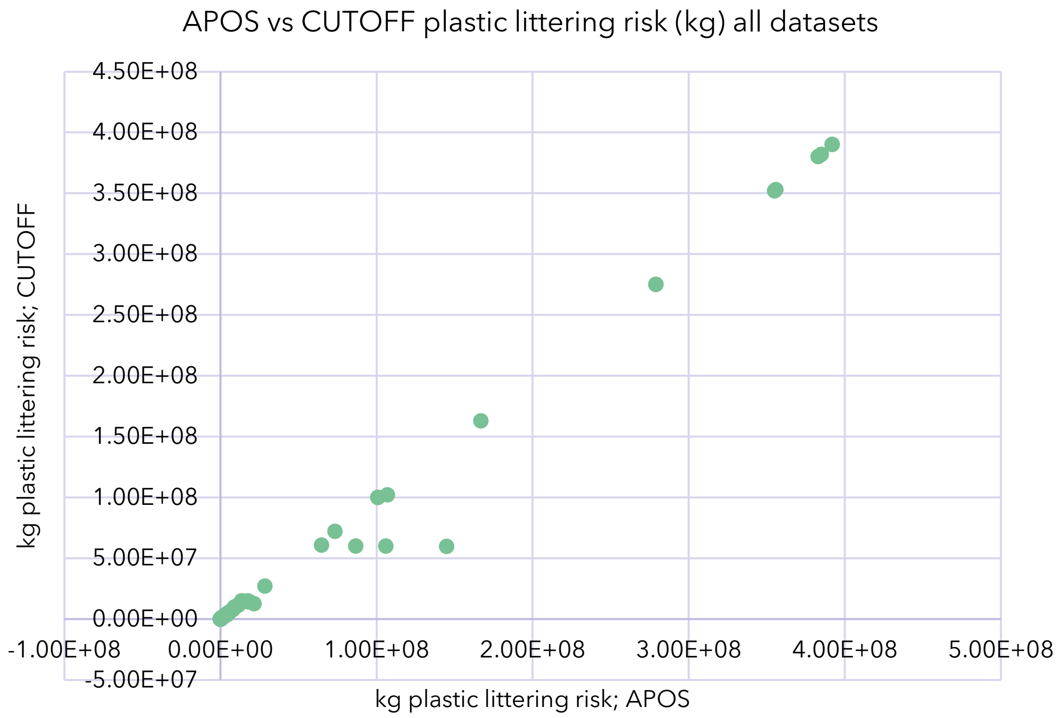
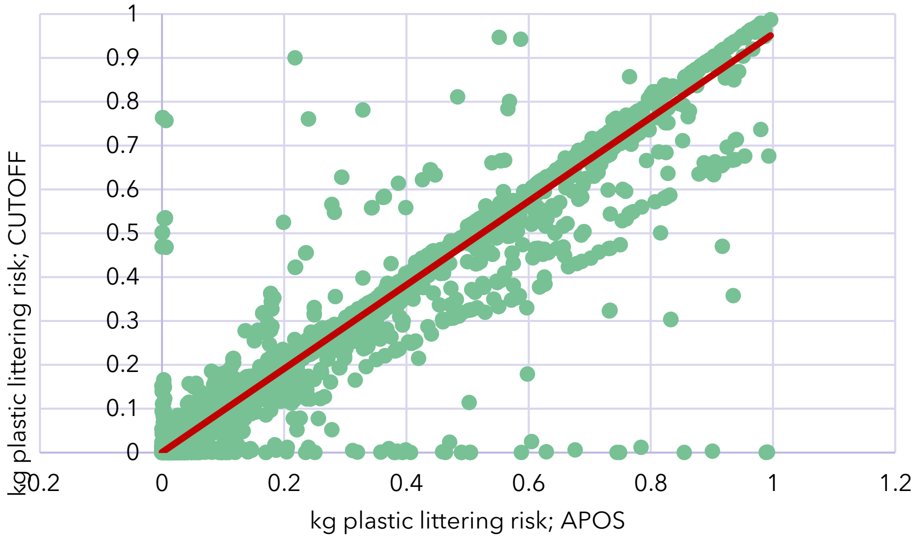


Figure 52. Plastic littering risk (kg) of the same dataset in APOS and Cut-off system models



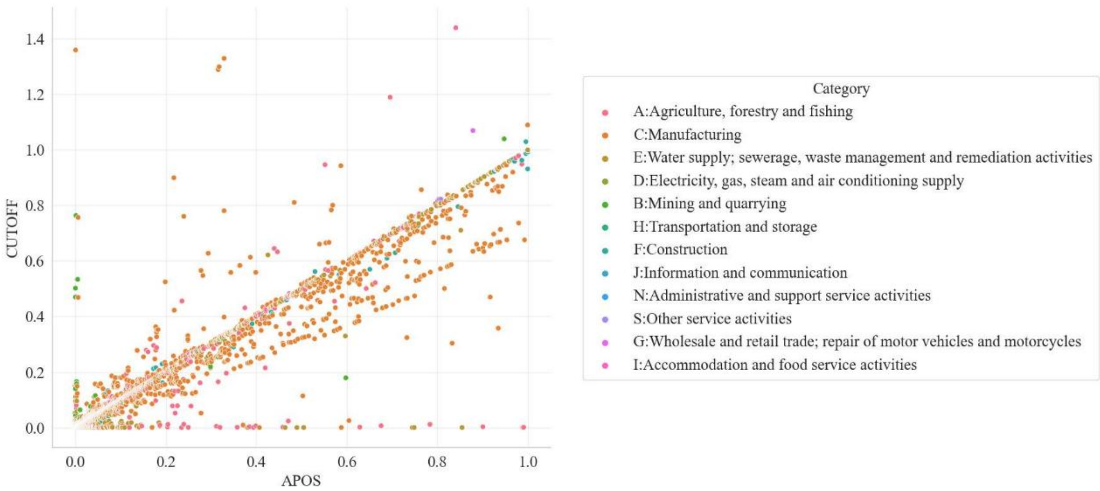


Figure 53. Close up of Plastic littering risk (kg) of the same dataset in APOS and Cut-off system models

PART B - EcoProfiles

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[7] (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[8]. 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.[9]

Currently, more than 70 EcoProfile reports and LCI datasets have been published for high-volume commodity chemicals and primary polymers by PlasticsEurope[10]. 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 54, left).

Recently, data for the production of rPS, rPVC, rLDPE, rHPDE, rPET, rPP have been presented by Syndicat national des Régénérateurs de matières Plastiques[11] (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.

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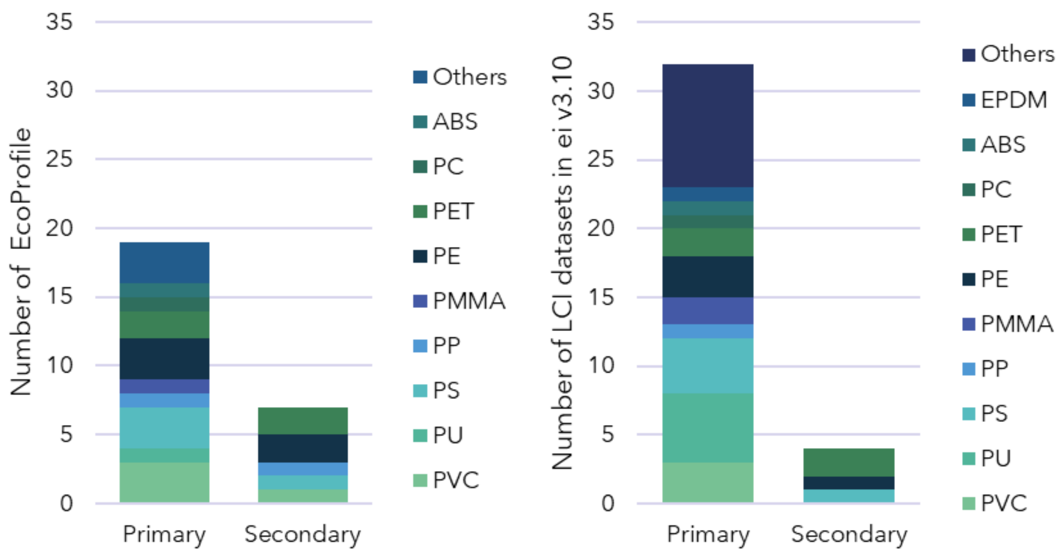

Figure 54. Comparison of available EcoProfiles (PlastEu vs. SRP) and LCI datasets in ecoinvent v3.10 for primary and secondary produced plastics

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 54**Error! Reference source not found.**, right), highlighting the need to advance LCI data on recycled material.

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[12] in the plastics value chain, in line with the focus of the PRIMUS project. See Table 20**Error! Reference source not found.** for an overview of datasets that were published along with this

[12] 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

report and their respective EcoProfile reports. Regionalised EcoProfile reports and datasets were be published in six versions, one for each region.

Table 20. 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[13] 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

[13] 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 55) and shows that the majority of these sites were concentrated in western Europe, thereby excluding northern and eastern Europe from the primary data collection.

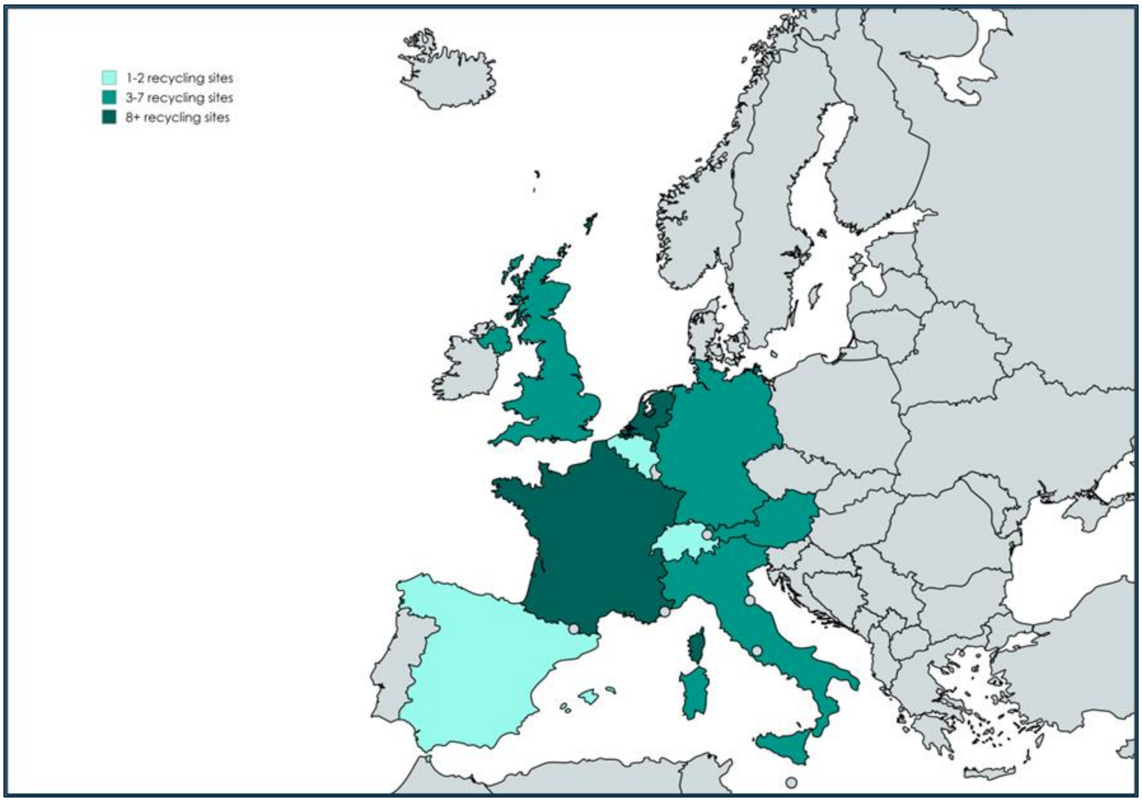

Figure 55. Recycling site coverage per country contributing data to the EcoProfile primary data collection

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 56.

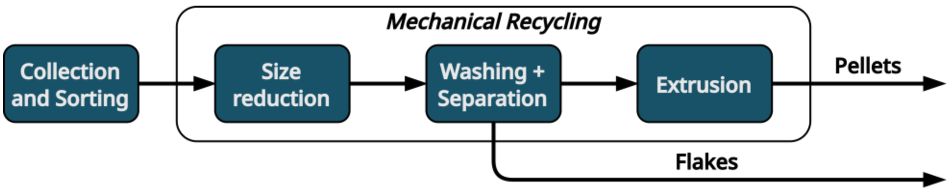

Figure 56. Waste management steps associated with mechanical recycling of general plastics waste;

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 56 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.[14] In pursuit of this objective, the European Plastics Strategy[15], a cornerstone of the EU's Circular Economy Action Plan[16], 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[12] 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

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[14] 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

[15] 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

[16] 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. [17]

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[18], UNEP[17], JRC[19] and publications of PRE[20].

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 57). 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.[21] 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.[20]

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.

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[17] 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

[18] 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

[19] 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

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

[21] 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

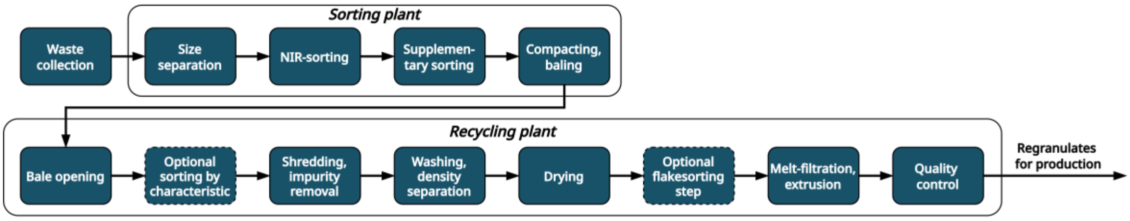

Figure 57. Sorting and mechanical recycling scheme for packaging plastics, from waste collection to final recycled pellets material for thermoforming of products. Based on EU BAT reference document[22] for waste treatment

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.[23]

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

[22] 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

[23] 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.[19,24] See Figure 58 for a visual representation of the process.

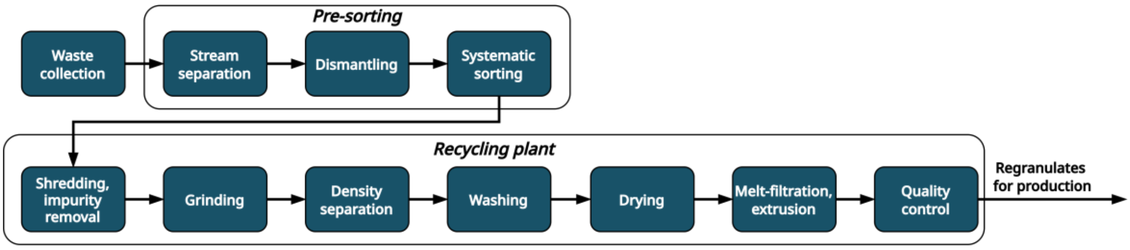

Figure 58. Sorting and mechanical recycling scheme for WEEE plastics, from waste collection to final recycled pellets material for thermoforming of products. Based on PRE WEEE recycling factsheet[24]

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).[25]

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.[26] 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.[11,27] 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

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24 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

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

26 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

27 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

being used in lower-value applications, e.g. rPET fibres for textiles or rMPO for plastic lumber.

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.[28] Thus, prioritizing recycling as the preferred end-of-life (EoL) option becomes essential.[26] Currently, the highest EoL recycling rates in the EU are found amongst PET (23%), LDPE (18%) and PVC (17%),[29] 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

[28] 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

[29] 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

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 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.[30] 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 34).

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

[30] 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

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 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 34).

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.[31] The Recycling efficiency of PVC in Europe across all sectors was calculated as 59% (see Table 34).

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.[32] 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[33]. Increasing the recycled content in primary PVC generally results in higher

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[31] 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

[32] 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

[33] 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

melt viscosity, hardness, and density. High-quality PVC recyclate can be reused in similar applications as primary material.

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)[34] 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.[35] Recycling efficiencies have been calculated as 59% for LDPE and 82% for HDPE across all sectors within the EU (see Table 34).

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

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

[35] 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

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 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.[18]

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[36] 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.[37] The PET recycling efficiency in Europe was calculated as 76% across all sectors (see Table 34 Annex).

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[36] 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

[37] 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

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 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.[36]

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.[18]

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[38] 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[39] 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).

[38] 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

[39] 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 59).

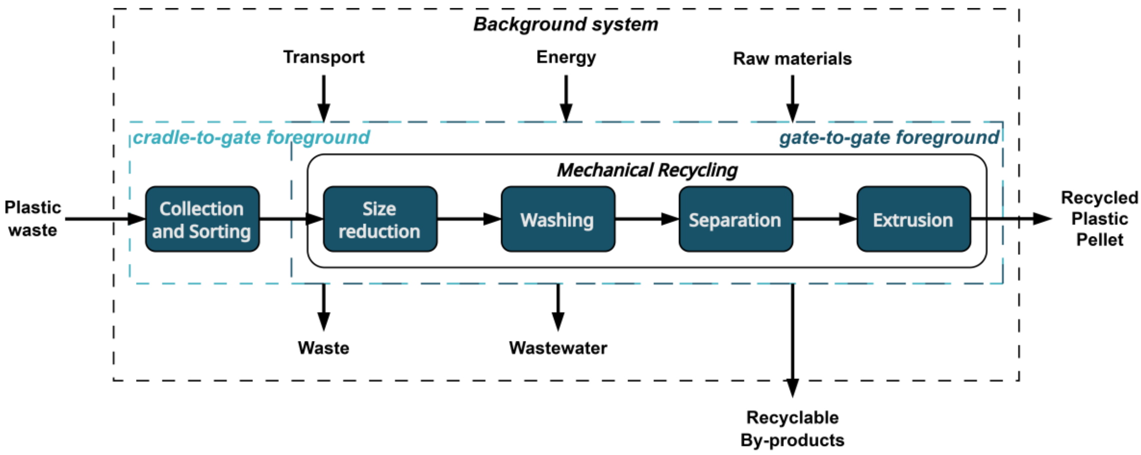

Figure 59. Exemplary system boundaries for polymer flakes including cradle-to-gate scope with collection and sorting as well as gate-to-gate scope encompassing only the mechanical recycling processes

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[40] (Figure 60):

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	

[40] 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 60. 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 21 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 21. 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.[41] 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.

[41] 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 22. Collection and sorting approach by waste stream used in the model. See Table 23 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 23. 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 24. 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[42] 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[43].

[42] 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

[43] 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 25. 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 26. 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[44]. The starting materials 'dimethylamine' and 'epichlorohydrine' were used. Input quantities were stoichiometrically calculated based on standard reactions published in literature[45].

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 27. 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.

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[44] 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

[45] 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

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.

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 28 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 28. 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[27].

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[27], 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 29. 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)'[46].

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[46] 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).

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 61.

Empa; Swiss Centre for Life Cycle Inventories. https://www.dora.lib4ri.ch/empa/islandora/object/empa%3A34379

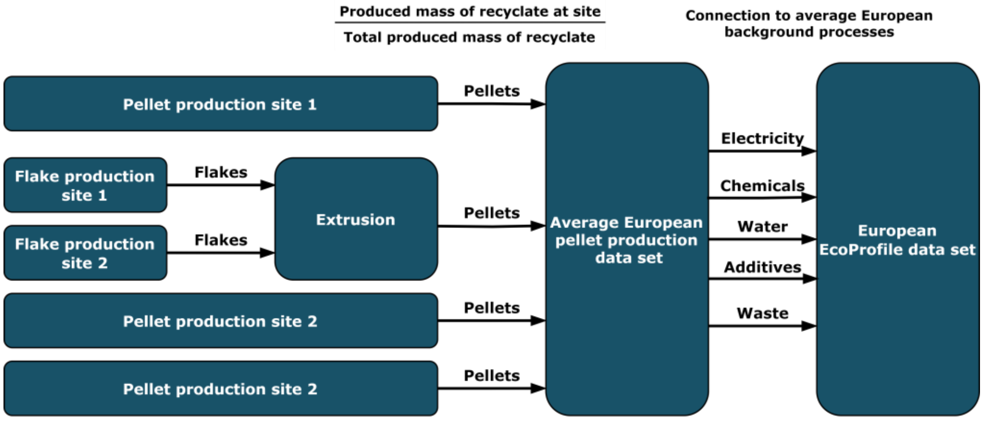

Figure 61. Creation of average European datasets exemplified by generic pellet production process

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.

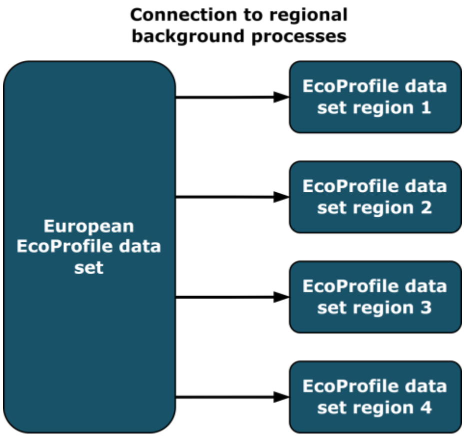

Figure 62. Regionalisation approach for an exemplary generic EcoProfile

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 62). 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.

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.[47] The groundwork for plastic littering estimation was done by

[47] 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

GreenDelta[48] and later published as Plastic litter extension (PLEX) for ecoinvent in 2023[49] and updated in 2024[50] 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:

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

- 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.[51] 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[52] as source.

[48] 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
[49] Gutke, J., & Andreas, C. (2023). *Plastic litter extension for ecoinvent: Estimating plastic litter over the life cycle*. https://nexus.openlca.org/ws/files/29729
[50] Cilleruelo Palomero, J., & Ciroth, A. (2024). *PLEX v3 documentation*. https://nexus.openlca.org/ws/files/35714
[51] Main source for primary data in the PRIMUS project's EcoProfiles
[52] 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

Although the use of secondary plastic will strongly reduce the amount of pellets loss 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[53], ELV[54] and mixed plastic recycling[55]. 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[56], 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 [57] 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[58] and by Fraunhofer[59], 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[29], 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.

Programme. https://backend.orbit.dtu.dk/ws/portalfiles/portal/163092267/UN_2018_Mapping_of_global_plastics_value_chain_and_hotspots_final_version.pdf

[53] 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

[54] 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

[55] 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

[56] 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

[57] 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

[58] 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

[59] 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[60] and the Environmental Footprint 3.1 method, developed by the JRC[61], 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[26] 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.

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[60] 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

[61] 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 30. 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[62]	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

[62] 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 31. 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 32. Life cycle impacts of the gate-to-gate rABS model related to 1 kg of pellets

Impact Category	**Impact assessment[63]**	**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

[63] 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 60 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 56.
- 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 63. 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 63 and Figure 64.

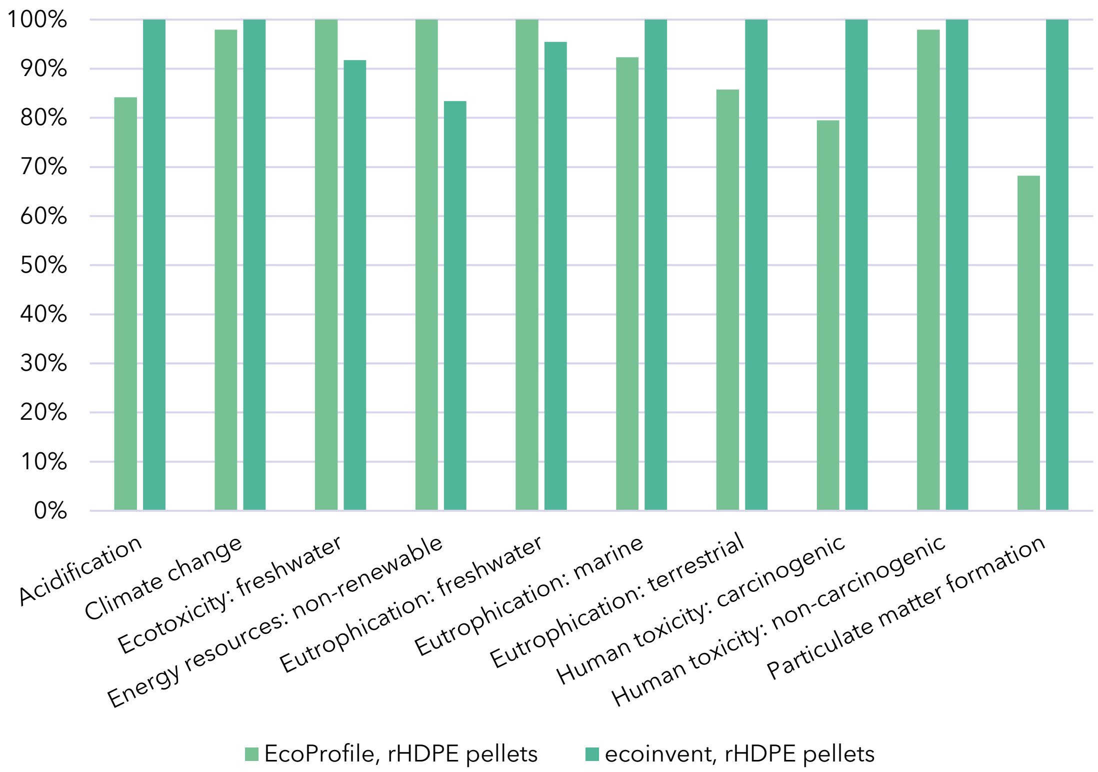

Figure 63. Comparison of EcoProfile and ecoinvent's LCIA results for recycled and extruded rHDPE in selected EF3.1 impact categories

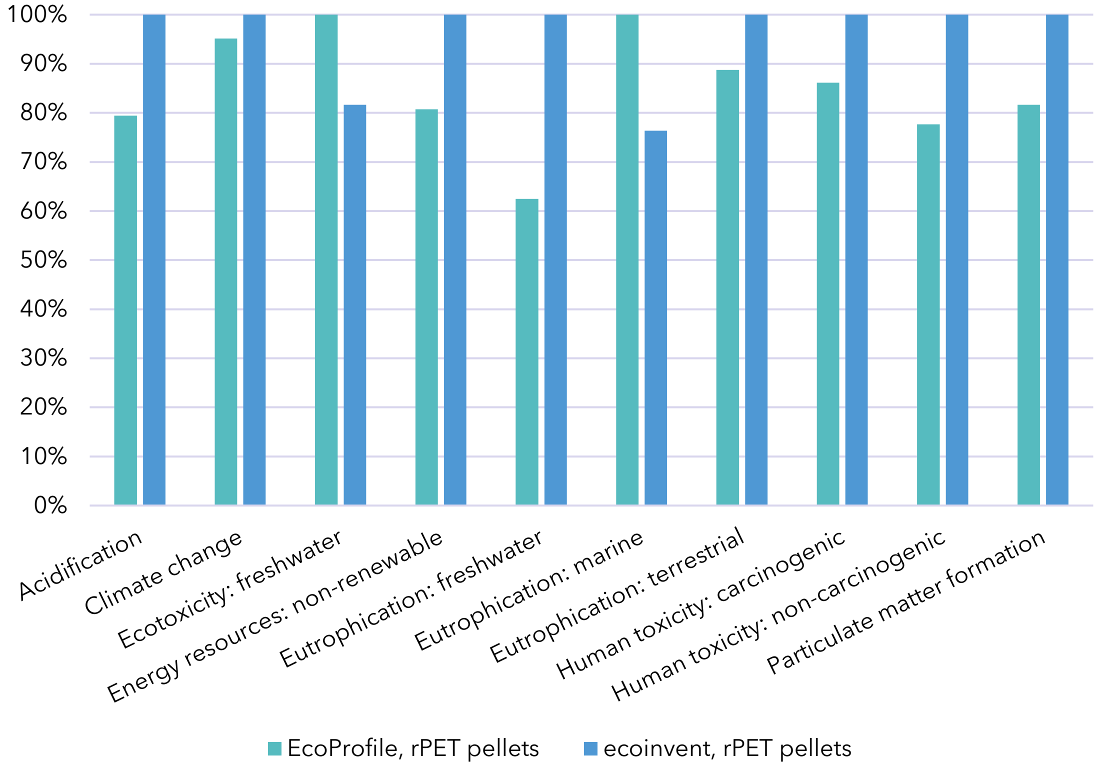

Figure 64. Comparison of EcoProfile and ecoinvent's LCIA results for recycled and extruded PET in selected EF3.1 impact categories

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. Figure 65, Figure 66 and Figure 67display 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 65).

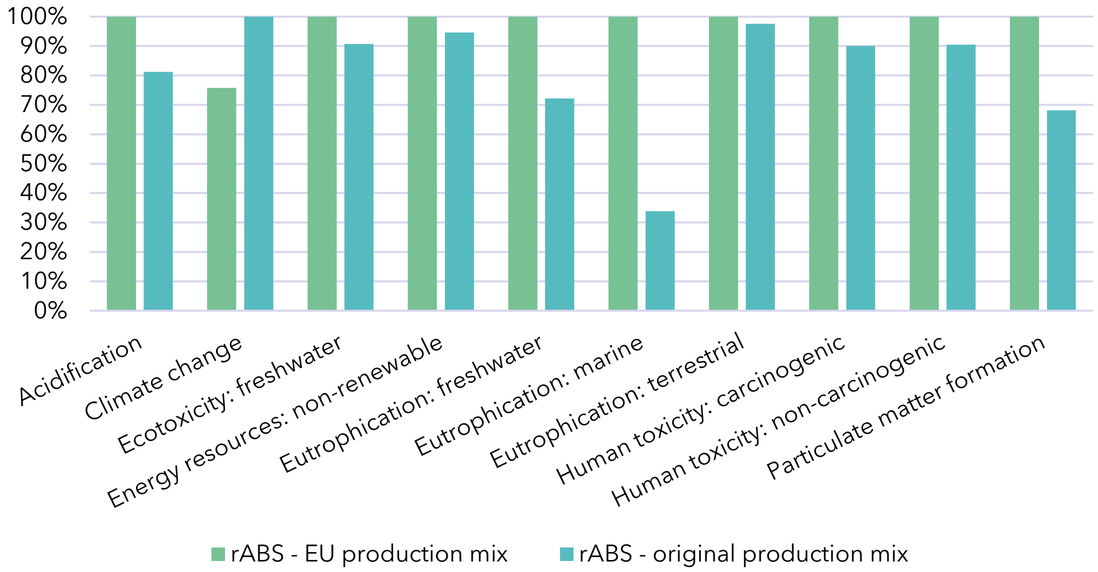

Figure 65. LCIA result sensitivity analysis to regional primary background datasets for rABS. The models are both configured as gate-to-gate rABS pellet production

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 66).

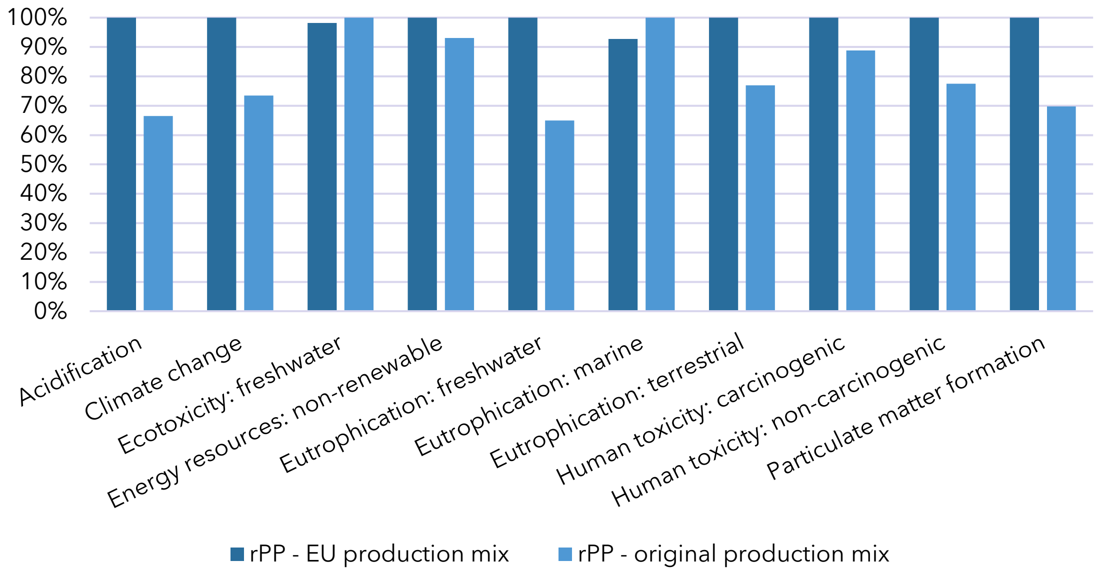

Figure 66. LCIA result sensitivity analysis to regional primary background datasets for rPP. The underlying models are both configured as gate-to-gate rPP pellet production

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 67).

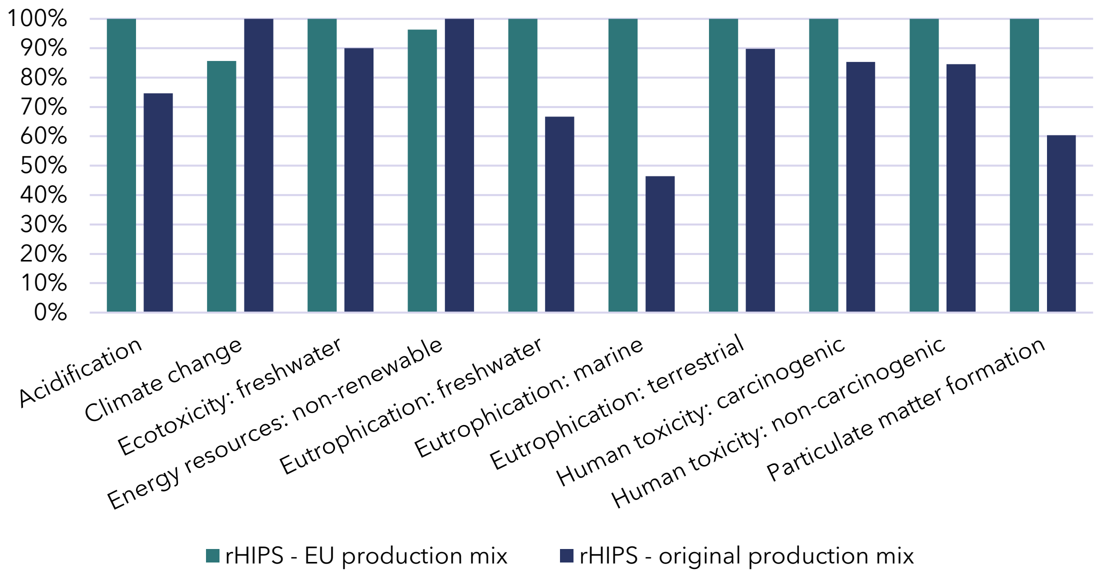

Figure 67. LCIA result sensitivity analysis to regional primary background datasets for rHIPS. The models are both configured as gate-to-gate rHIPS pellet production

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.[28]

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[26]. 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.

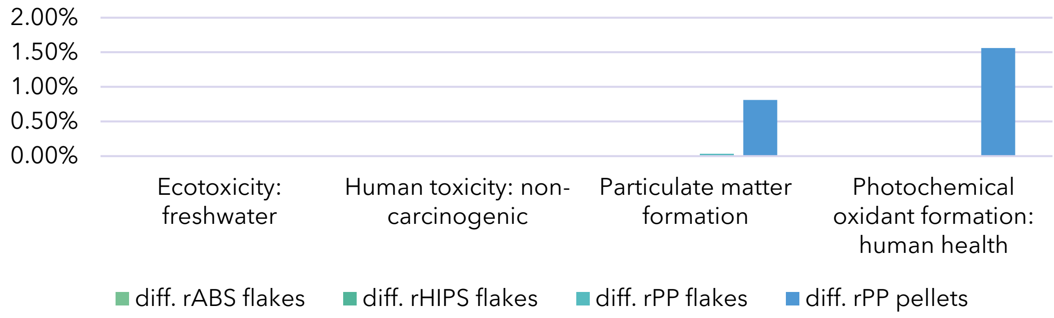

Figure 68. Relative LCIA result changes of the PM and VOC sensitivity analysis, calculated using the EF3.1 LCIA method as described above. Emission data extracted from ecoinvent processes corresponding to the recyclates in question: rABS flakes[64], rHIPS flakes[65], rPP flakes[66] and rPP pellets[67]

[64] 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"

[65] 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"

[66] 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"

[67] 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 33. 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[68], 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 34. Transfer coefficients of specific polymers from input material to be recycled to recyclate. Mean transfer coefficient computed according to recyclate contribution of sectors

<table>
<tr><td colspan="2" rowspan="2">P = Packaging, C = Construction
T = Transport, E = Electrical and
Electronic Equipment,
A = Agriculture</td><td colspan="5">Sector</td><td rowspan="2">Mean transfer coefficient scaled by recyclate contributions, recycling effic.</td></tr>
<tr><td>P</td><td>C</td><td>T</td><td>E</td><td>A</td></tr>
<tr><td rowspan="7">Polymer-specific transfer coefficients [%]</td><td>LDPE</td><td>59%</td><td>56%</td><td>70%</td><td>50%</td><td>58%</td><td>59%</td></tr>
<tr><td>HDPE</td><td>84%</td><td>71%</td><td>70%</td><td>50%</td><td>77%</td><td>82%</td></tr>
<tr><td>PP</td><td>69%</td><td>56%</td><td>70%</td><td>50%</td><td>63%</td><td>66%</td></tr>
<tr><td>PS</td><td>56%</td><td>56%</td><td>70%</td><td>50%</td><td>59%</td><td>55%</td></tr>
<tr><td>PVC</td><td>82%</td><td>55%</td><td>70%</td><td>50%</td><td>59%</td><td>59%</td></tr>
<tr><td>PET</td><td>76%</td><td>56%</td><td>70%</td><td>50%</td><td>59%</td><td>76%</td></tr>
<tr><td>ABS</td><td>71%</td><td>56%</td><td>70%</td><td>50%</td><td>59%</td><td>61%</td></tr>
<tr><td colspan="2" rowspan="2">P = Packaging, C = Construction
T = Transport, E = Electrical and
Electronic Equipment,
A = Agriculture</td><td colspan="5">Sector</td><td rowspan="2">Sum of sector contributions</td></tr>
<tr><td>P</td><td>C</td><td>T</td><td>E</td><td>A</td></tr>
</table>

[68] 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

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

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.