PlastiCircle: *Improvement of the plastic packaging waste chain from a circular economy approach*

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PlastiCircle Deliverable

D7.3 – Environmental Life Cycle Assessment (ITENE)

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Abstract

This deliverable provides analysis on environmental impact of plastic packaging waste management, including the following stages: collection, transport, recycling and end of life options.

Impacts on the project are evaluated using PlastiCircle measurement tools which provide specific information for the comparison of the situation before and after the project evolution on Pilot Cities.

Additionally, products developed from 5 different industries within the project are also environmental evaluated.

Abbreviations

EoL – End of Life
FU – Functional Unit
HDPE – High Density Polyethylene
LCA – Life Cycle Assessment
LCC – Life Cycle Cost
LCI – Life Cycle Inventory
LDPE -- Low Density Polyethylene
LPW – Light Packaging Waste
MAD – Moisture and Dirt
MRF – Material Recovery Facility
MSW – Municipal Solid Waste
PA - Polyamide
PAYT – Pay-As-You-Throw
PE – Polyethilene
PC – PlastiCircle
PET – Polyethilene Terephtlate
PPW – Plastic Packaging Waste
S-LCA – Social LCA
WS – Waste Scenario

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19. PLAST-EU: PLASTICS EUROPE
20. ICLEI: ICLEI EUROPASEKRETARIAT GMBH
21. PICVISA: PICVISA OPTICAL SORTING

21.1. CALAF: CALAF INDUSTRIAL

22. SINTEF AS

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Publishable summary

PlastiCircle aims to develop and implement a holistic process to increase recycling rates of packaging waste in Europe. This will allow to reprocess again plastic waste in the same value chain (i.e. Circular economy; closure of plastic loop). This process is based on four axes: collection (to increase quantity/quality of packaging collected), transport (to reduce costs of recovered plastic), sorting (to increase yield and purity of recovered plastics), and valorisation in value-added products (i.e. foam boards, automotive parts, bituminous roofing membranes, garbage bags, asphalt sheets/roofing felts and urban items such as retention grids).

This deliverable shows a specific evaluation for the waste management systems in Valencia, Utrecht and Alba Iulia throughout LCA methodology, following the baselines set up on previous deliverables (7.1 and 7.2). On parallel LCC and S-LCA are carried out to define other complementary inputs in the whole evaluation of impacts in the PlastiCircle approach. Moreover, this LCA evaluation is extended to five industries/manufacturers working on the project with post-consumer material as the one obtained from PlastiCircle pilots mentioned. Their most remarkable improvement and impacts are referred to one benchmark product per industry.

1. Introduction

Structure of the document and LCA

To structure the environmental assessment, cities and industries are treated separately. The three pilot cities evaluated in PlastiCircle are:

1. Valencia **2. Utrecht** **3. Alba Iulia**

Within the project several technologies and strategies have been developed to improve the waste management of the pilot cities and other aspects in the value chain. Main developments spin around (a) citizens identification through a labelling system integrated on the container on a PAYT basis; (b) route optimization based on filling level sensors integrated on the container and corresponding algorithms for the optimization; (c) Eco-driving app to monitor the transport parameters and suggest efficient driving to the drivers. Moreover, on the sorting stage (d) PICVISA developed different improvement on their sorting equipment to enhance yield and purity on extracted fractions, and as well, a mechanical module to improve film recovery was developed. All these conditions have been evaluated on this report, focusing on the following sections:

1. Collection – Impact of PAYT system on the pilot and quality segregation and IoT infrastructure.
2. Transport – Impact of route optimization and efficient driving
3. Sorting – Impact from yield and purity improvements and development of turbosorter

For the sorting stage a model has been designed for each pilot waste recycling plant, focusing on the energy used per tonne, the yield of each fraction on the plant and the input waste as main parameters, inter alia.

As a bridge between the cities and the final converters, there is a need of a proper pre-treatment/ conditioning of the post-consumer polymer to provide quality standard feedstock to the industries. PlastiCircle, lacks a partner on the consortium undertaking these tasks on an industrial level, however, different lab scale trials and some trials with Sorema have been assessed during the project, also considering broken down processes to evaluate impact on these intermediate stages taking into consideration processes such as the ones used by European industries as Sorema or Herbold, and other processes extracted from literature and commercial solutions:

4. Washing/Pre-treatment – Impact on the pre-conditioning for plastic packaging bales.

Once plastic is ready as flakes or pellets forms, industries within the project use those recycled plastic as raw materials to manufacture their products. Their different processes have been defined analysed, performing specific LCA for each one of their results considering the trials and impacts from the developments done during the project. Thus, we have:

5. Industries/converters

- **CRF/Proplast:** Automotive Parts with r-PP and R-PET Colour from post-consumer waste
- **Interval:** Garbage Bags with post-consumer r-LDPE
- **Hahn:** Injection moulding for from post-consumer flexible r-PP
- **Armacell:** GR-W Foam Board from post-consumer trey/bottle r-PET mix
- **Derbigum:** Bituminous roofing membrane from post-consumer r-PP (iPP/aPP)

Figure 1 (below) lays out a schematic representation of the PlastiCircle approach and main interactions between project WPs and their corresponding steps within the plastic packaging value chain.

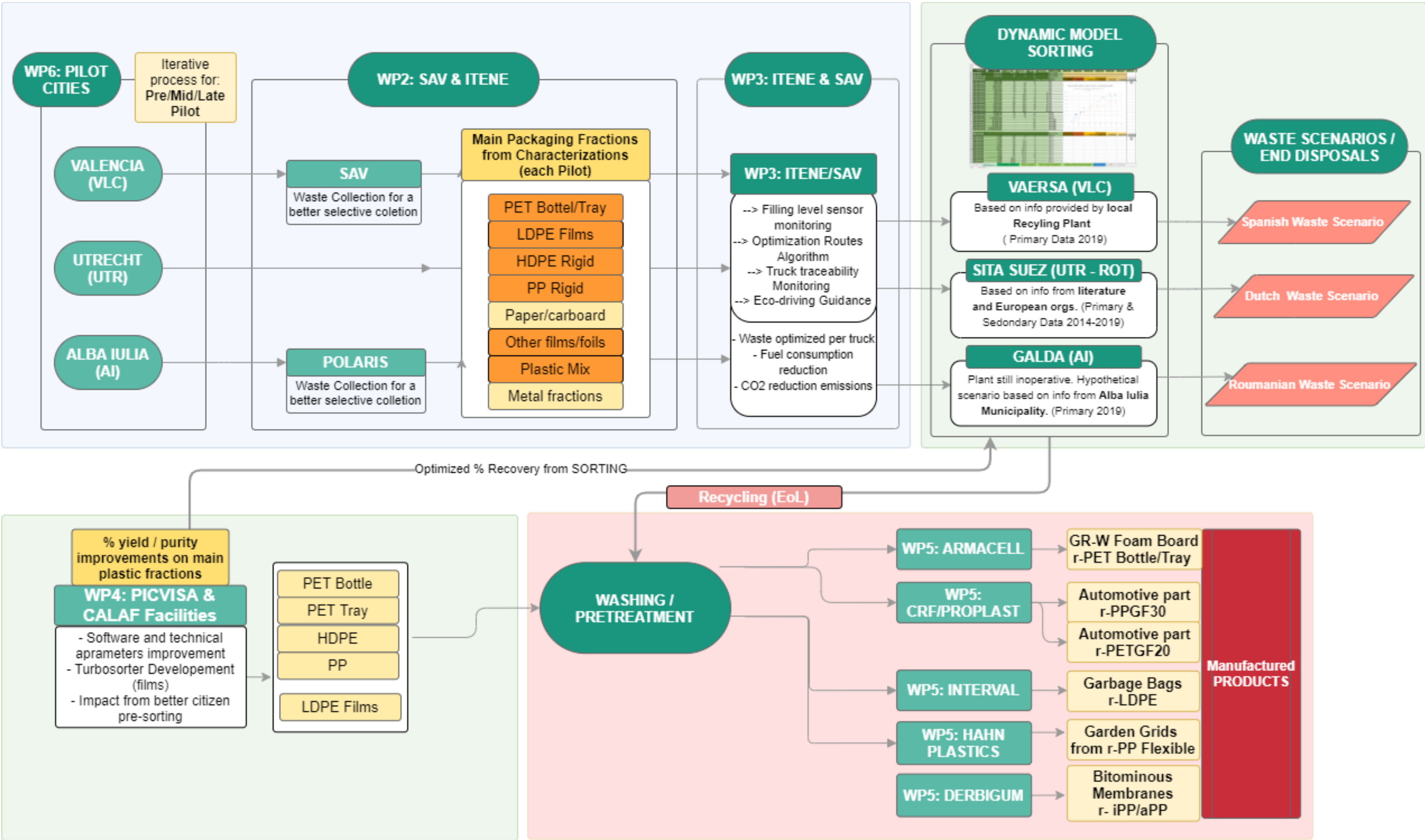


Figure 1 - Flow waste diagram though PlastiCircle WPs. Main considerations and assumptions representation for LCA, own diagram.

Several independent blocks will be used during the document to focus on specific impact. Collection and transport (blue), Sorting (green), Recycling/Converters (red)

2. LCA on Pilot Cities

General Context and Methodology

Pilot cities represent our closest nexus with a potential fully implementation of PlastiCircle on a European context. Valencia and Alba Iulia represent the most relevant case studies since a complete integration of PlastiCircle technology has been executed. Simultaneously, Utrecht will provide us with a good reference benchmark with it up to date collection and transport system. Taking into consideration most critical aspects of each pilot city and also considering developments were already updated prior to PlastiCircle implementation, different scopes are adapted to each city, trying to maintain a coherence with aims and KPIs to be able to acknowledge a reasonable comparison between scenarios.

*As depicted on previous deliverables (7.1, 7.2), the LCA methodology used for this study follows recommendations provided by the ISO 14040 and 14044 standards **[1][2]** and JRC Technical Reports on LCA from EU **[3][4]**, including boundaries, resource inventories and disposal scenarios. As a general structured standard LCA, this LCA study the definition of goal and scope, life cycle inventories (LCI), impact assessment and interpretation of the results.*

On previous deliverable 7.2, the corresponding **Functional Unit (FU)** for the three cases on the cities was defined as: "***the management (collection, transport and end of life options) of the plastic packaging waste collected in each city or Europe in one year***", just to have a general overview of the waste management of the cities. With the intention to enable a comparative assessment, on different scenarios of the three pilot cities, functional unit has been adapted to: "***the management (collection, transport and end of life options) of the plastic packaging waste collected in each city per tonne of waste collected***". Apart from taking into account the impacts per tonne, the impacts per capita were also assessed to be aligned with other waste management studies.

An **attributional approach** has been used to do the calculations. This approach assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product. To refer the different flows on each stage of the value chain **mass flow** has been chosen as main reference.

LCA on pilot cities are carried out on a **cradle-to-grave approach**. Furthermore, the **"zero burden"** hypothesis or **"cut-off"** method is adopted ***[5]***, so that plastic waste carries no burden related to its production and upstream impacts as a product as main consideration, inter alia. Although, this is commonly done for waste management studies, this could also be understood as a limitation since prevention waste is not considered. Details on the specific system boundaries and assumptions are defined for each case study in the following sections.

Table 1 gives details of pilot cities characteristics and main characteristics:

Table 1 - Main characteristics of the pilots for 2019-2020, own table

General Info	Units	CITIES		
Overall numbers		**Valencia**	**Utrecht**	**Alba Iulia**
Inhabitants	u	794.288,00	357.179,00	63,536
Packaging waste generated on selective collection	tons/a	25.899,10	9.819,47	-
Packaging waste per inhabitant	kg/cap.a	32,61	27,49	17.87
Pilot Area	**Name**	**San Marcelino**	**Terwijde**	**Arnsberg-Goldis**
Inhabitants	u	9.923,00	8608,00	7740,00
Packaging waste collected per capita	kg/cap.a	13,12	27,49	17.87
Collection				
Waste collection		Selective collection on Street Containers	Selective collection for Underground containers and Door-to-door	Two main fractions on street containers
Main fractions		LPW, Paper, Glass, Organic Waste, General MSW	LPW, Paper, Glass, Biomass, RDF	Dry (recyclables) and wet (organic and other) fraction
Fraction analysed		LPW on Street Container	LPW on Underground Container	Dry fraction on Street Containers
Technologies used for the pilots				
Individual Characterisation (labelling system)		**X**	-	**X**
Filling level sensor system		**X**	**X**	**X**
Eco-driving		**X**	**X**	**X**
Transport				
Type Trucks	EURO	**EURO 5**	**EURO 6**	**EURO 4/5**
Total Distance per route	km	135	226	63
Sorting				
Recycling Plant		VAERSA (Picassent)	SITA SUEZ (Rotterdam)	Galda Plant (Galda de Jos)
Plant type		Low-Medium Capacity. Semi-automated sorting	High Capacity. High-automated sorting	Middle Capacity – Manual Sorting
Anual Capacity	**tonnes/year**	25.000	120.000	42.000
Recovery Rate	**%**	0,682	0,89	0,4-0.5

City pilots

Valencia Pilot had a duration of 6 months during 2019 initial-mid period and it was performed in San Marcelino area. Total implementation of PC technologies was executed allowing to perform an extensive assessment. Main results extracted from the pilot are as following (extracted from KPIS presented in Deliverable 6.2):

- Increasing % of the amount of valuable materials from the total container on PlastiCircle users: ↑ **12 %**
- Savings on distance and time travelled due to route optimization system: ↓ **32%** and ↓ **28%** respectively.
- Savings on fuel consumption from waste manager trucks: ↓ **22%**

Utrecht pilot was unfortunately not able to implement PlastiCircle's technologies. Furthermore Utrecht policy does not share the strategy of PAYT systems and individual characterization of citizens' waste due to ethic and data protection principles. Main focus was on Eco-driving app technology, however, some delays and great impact from COVID-19 haven't allowed to finish these tasks yet.

Alba Iulia pilot was the last one and had a duration of 4-5 months. This pilot has been the most affected pilot by the pandemic and most of the tasks have suffered delay or unforeseen issues.

Despite of these issues, the pilot had a good acceptance on the pilot area and the following main results can be highlighted (extracted from KPIS on Deliverable 6.4 and SAV calculation on transport routes):

- Increasing % of the amount of plastic packaging waste. Most impact on PET fraction (from 4,9 to 13,22% of the total waste composition for specific PlastiCircle container)
- Savings on distance and time travelled due to route optimization system: ↓ **21%** and ↓ **12%** respectively.
- Savings on fuel consumption from waste manager trucks: ↓ **12%**

A mathematical model for sorting

A big role on environmental impact from packaging around cities is played by the way that waste is sorted, and the infrastructure utilized to do so. In the present report, different sorting scenarios have been drawn for each one of the pilot cities (main characteristics in **Table 1**) addressing mainly the size-efficiency of the plant utilized to sort and the % recovery rate and end-of-life option of the packaging waste. **A specific mathematical model on sorting plant has been developed.** It is based on a Dynamic Excel file in which energy consumption from machinery and their relation to specific fraction are defined. Calculations were based on the Picassent, Valencia (Spain) sorting plant which is used for the treatment of the plastic packaging waste collected in the municipality of Valencia and nearby areas. The model was built to check the differences in power consumption (cost and environmental impacts) and the differences between economy/infrastructure scales (i.e Valencia Recycling Plant with 25.000 tons/year correspond to a small scale while Utrecht or recycling plant in Rotterdam correspond to a high scale with approx. 120-150.000 tons a year, or a more manual sorting approach on the Romanian case). This work has been developed with the support from local sorting plant operation Picassent, Valencia (VAERSA) and advice from PICVISA on some specific machinery behaviours and consumptions. Results obtained from actual PlastiCircle material from pilot cities are also integrated in the model. In this way, a mass flow balance has also been considered for standard recycling plants scenarios, so to consider impacts from a better selective collection on consumption, environmental impacts, and cost of these plants. Furthermore, potential recovered material obtained from the improvements developed during the project have also been estimated.

Full availability of data from sorting processes in MRF is not always possible due to relatively high level of uncertainty on mass flows inside the plants and also non-disclosure information on specific machineries and cost/benefit margins played by main stakeholders in the value chain. To model this uncertainty, ***Table 2*** shows some data, assumptions, and boundary conditions which were considered:

***Table 2** - Parameters, boundary conditions and assumption on the Recycling Plant model, own table*

Known Parameters	Boundary conditions	Assumptions
- % characterized material at entrance. - Output material. - Max nominal and design capacity - Total consumption of the plant. - Specific power installed of the machines. - N shifts - Yield % recovery for Optical sorters (PICVISA)	- Min and Max ranges for power. - Limited energy consumption for specific machinery (not all the time operative or fixed mass flow treated, i.e., balers)	- 20 % of total electricity related to lightning, control, and extras. - Own configuration of the plant based on standard layouts. - 70% machine performance from Power Installed. - N machines per process - Introduction of PICVISA machines on the models

Inside this model, the consumption for each machinery type was included from literature on LCA focused on similar approach ***[6- 7- 8 - 9],*** commercial suppliers (5 M recycling, KOMPTECH, Bianna Recycling, KOMPTECH, STADLER, BRT HARTNER, HSM, JOVISA, MARATHON, Coparm, FELEMANG, Baker Magnetics, TOMRA, PLLENC ST, MSS OPTICAL SORTERS; STAINERT, WAGNER, PRESTO) and own database references. Not all models or specification sheets use mass flow as main parameter, thus, to parametrize every value on the model to the same mass flow reference, data references on European ***[10]*** and US ***[11]*** average values for given specific waste streams have been used, mostly when converting tonnes processes on a plant by the baler (output stage) to throughput of the machine and its specific energy consumption (kWh/m³).

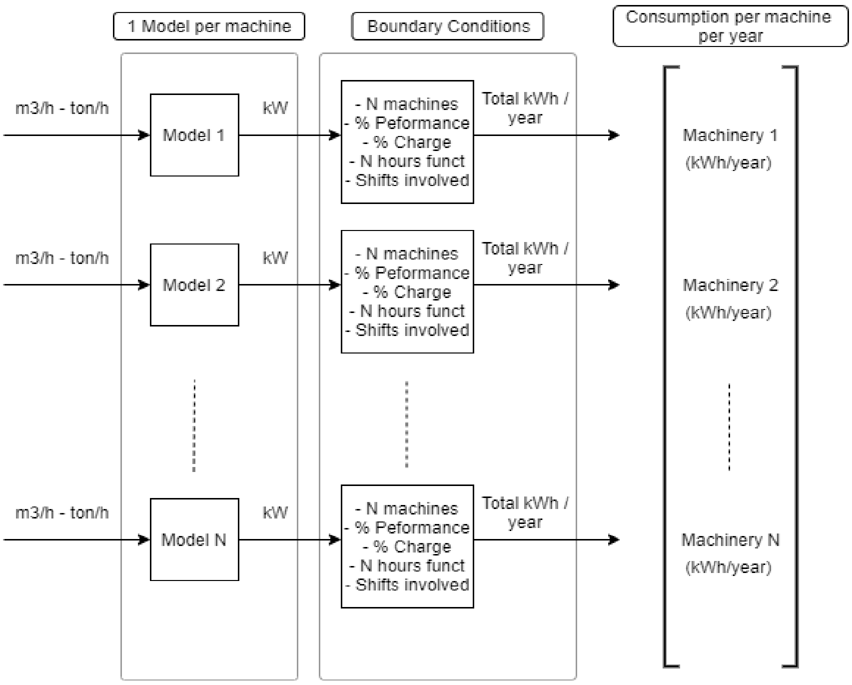


Figure 2 - Scheme on machinery models. Flow mass/volume vs Power. Own figure and model.

Figure 2 represents how energy consumption for each machine (or group of machines) is modelled referring to main characteristic of the machine itself and the configuration of the plant. The allocation of the energy flows in relation to the mass flow is depicted in Eq. [1] where each machine within the plant is referred to the fraction it contributes to the sorting process in a matrix basis.

$$\begin{bmatrix} Fr1_{consumption} \\ Fr2_{consumption} \\ Fr3_{consumption} \\ \vdots \\ \vdots \\ Fr-N_{consumpt.} \end{bmatrix} = \begin{bmatrix} Machinery_1 \\ Machinery_2 \\ \vdots \\ \vdots \\ \vdots \\ Machinery_N \end{bmatrix} * \begin{bmatrix} R_{1-1} & R_{1-2} & R_{1-3} & \dots & R_{1-N} \\ R_{1-2} & R_{2-2} & \dots & \dots & R_{2-N} \\ R_{1-3} & \dots & \dots & \dots & R_{3-N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ R_{1-N} & \dots & \dots & \dots & R_{N-N} \end{bmatrix} * \begin{bmatrix} ^1/_{Fr1_{tons\ per\ year}} \\ ^1/_{Fr2_{tons\ per\ year}} \\ \vdots \\ \vdots \\ \vdots \\ ^1/_{FrN_{tons\ per\ year}} \end{bmatrix} \quad [\ 1\ ]$$

Variable's description:

- ***Fr1, Fr2 … Fr-N*** **|| [kWh/ton-year]**: Recoverable *Packaging fractions (i.e. PET, HDPPE, films…)*
- ***Machinery 1, 2, … N || [kWh/ year]:*** *Consumption associated to each machine typology within the plant.*

- R_{1-1}, R_{1-2}, … R_{1-N} | | ***(1; 0,5; 0)***: *Relation between machinery use and fraction affected for sorting. Respectively, (Machine directly affects the sorting of the fraction; it affects indirectly the purity of the sorted fraction; non-influence)*

From this sorting model, not only energy consumptions have been considered but **also mass flows and losses** for each fraction. From the sorting stage and process different losses factor can be identified until the flake/pellet final product is reached. **Figure 1** schematically describes main stages and its factors for mass losses. During section **2. LCA on Pilot Cities** more details are given for each specific pilot and treatment stage.

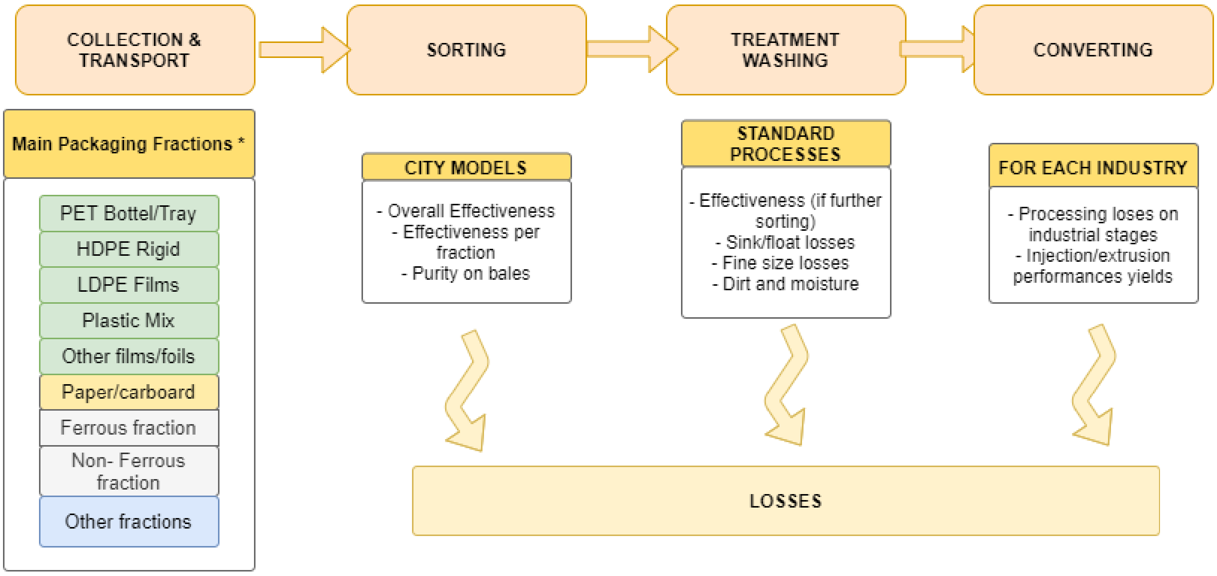


Figure 3 - Schematic representation of mass balance factor for each stage within the recycling chain. Own figure.

WASHING & PRE-TREATMENT

After cities sorting and prior the material is used by converters/manufacturers, material needs to be washed and treated to be in an optimal quality for the corresponding extrusion, injection-moulding, blowing, etc. Thus, the corresponding impacts on this process have been inventoried and developed. As well, mass losses on this stage have been considered as depicted on **Figure 3**

As introductory content for next section, **Table 3** shows main consideration and boundaries on the three pilots so as to gain an overall idea of the pilots and their circumstances. Next section will get deeply into these considerations and further details to understand the work done to evaluate the present LCA.

Table 3 - Main Considerations, boundaries and limitations on city pilot models

			VALENCIA	UTRECHT	ALBA IULIA
PILOT INFO	COLLECTION	Waste collection model	Main selective collection containers (Table 1). Study focused on yellow container (LPW) for PlastiCircle participants.	Main selective collection containers (Table 1). Study focused on underground containers for LPW.	Main waste collection flows (Table 1). Study focused on Dry Fraction and Specific container for plastics (project).
		PlastiCircle Technologies	All PlastiCircle Technologies have been used in this pilot: - Labelling system (Individual characterization) - Filling level sensors	No PlastiCircle technologies have been used. Utrecht already counted with sensorized containers (filling level). No individual characterization allowed due to legal/ethic considerations.	All PlastiCircle Technologies have been used in this pilot: - Labelling system (Individual characterization) - Filling level sensors
		Waste characterisation	Characterisation done on LPW container for Pre- Mid- Late pilot. Characterisation also done for non-user on LPW and general citizens on the general MSW fraction (grey container).	Characterisations of LPW underground containers for Pre- Mid- and Late pilot.	Characterisations done on Dry and Wet fraction for Pre- and Mid- Pilot. PlastiCircle plastic container for mi-pilot.
		Limitations	Representativity for a whole city impact. Pilot was undertaken on an area of 10k inhabitant from a city of 700k population. Thus, impacts are calculated for a pilot approach and then extrapolated to whole city.	PlastiCircle had not so much impact on physical systems from the pilot. Scenario on Utrecht serves just as cooperative model for the rest of the scenarios	Citizen's behaviour towards recycling is uncertain and most individuals use indistinctly dry and wet containers. COVID19 had remarkable impact on pilot performance.
	TRANSPORT	Type of transport	EURO 5 16m³ truck with right-side load	EURO 6 16m³ truck with top load	EURO4/5 16m³ trucks with rear load
		PlastiCircle Technologies	- Route optimization - Eco-driving	- Eco-driving	-Route optimization - Eco-driving
Mechanical	SORTING	Plant Size and configuration	VAERSA Plant (Picassent, Valencia) - 25k tonnes/year. Semi-automated sorting operation. Real data obtained on input, output and consumptions.	SITA SUEZ (Rotterdam) - 120/150k tonnes/year. Advanced-automated sorting. Data from literature and references.	Sorting plant Plant in (Galda de Jos) - (hypothetical scenario, still inoperative) - about 42k tonnes/year. Manual sorting. Data from Alba-Iulia CityCouncil based on project specifications.

		PlastiCircle Technologies	PICVISA improvement on optical sorters and development on the film turbo-sorter are fitted on the sorting model.		PICVISA result and typical sorting efficiencies compared to manual sorting.
	Washing / Pre-treatment		Common Pre-treatment PET, RIGID PO and Flexible Polymers		
EoL	RECYCLING	- Scenario 1. (Local Scenario).	Based on results on recovery rates from real data Plant.	Dutch system manages more than 2/3 of plastic packaging waste on the Rotterdam plant. Thus, local and national scenarios might be quite aligned.	Due to being a hypothetical scenario, national data has been considered to calculat the regional scenario.
	INCINERATION	- Scenario 1. (Local Scenario)	Valencia has no incineration Plant nearby. It is not a common End-of-Life option for this area.		Galda Plant would count with their own landfill, and no incineration alternative.
	LANDFILLING	- Scenario 1 PlastiCircle. (Local Scenario)	Landfilling is main disposal option for non-recycles items on Valencia area.	There is no landfilling as disposal option on the Netherlands	Galda Plant would count with their own landfill, so all rejects from sorting would be landfilled. Organic waste has a separate process.

2.1. Goal and scope

The main objective pursued for this LCA is the environmental impact assessment of PlastiCircle on Valencia and Alba Iulia pilot, comparing the pre- and post- situations after the implementation of the project and consider other scenarios as the Utrecht pilot. To do so, the "cut off" method perspective has been considered[1] [5,12], following the initial evaluation carried out on 7.2 deliverable. In this way, we consider the collection, transport, sorting and recovery option focusing on:

- Acknowledging actual impact from a better selective collection strategy.
- Evidencing the impact from a waste transport optimization.
- Yield recovery fraction of sorting of certain plastics based on PC developed.
- Environmental evaluation of PlastiCircle material on a local Sorting plant (mathematical model)

Primary audience on this deliverable is local councils, solid waste planners, environmental organisations, LCA practitioners as well as municipalities whose interest could result with a potential replicability application. Data has been provided mostly from primary sources (waste manager, council, recycling plant, etc.)

2.2. System Boundaries and Assumptions

a) General Boundaries & Assumptions

- **Valencia Pilot**: Participation in the project was over 500 households and is not a representative of the whole population of Valencia. For that reason, most of the calculation refer to kg per inhabitant, and therefore, some scenarios consider the potential effect of PlastiCircle results to the overall Valencia population.
- **Utrecht Pilot:** Pre- and Post- Situation for Utrecht case has not been considered for the lack of technology testing. Although the results for the improved transport for collection were considered
- **Alba Iulia Pilot**: Participation in Alba Iulia has been up to 254 household. The scenarios and technologies used for this pilots are similar to those used for Valencia's model.

b) Collection Infrastructure and Input Material

- Information regarding **collection and transport** was collected with the help and advice from partners and cities involved in those WPs. This information was provided using questionnaires forms (primary data) developed by ITENE and SINTEF. The full set of questionnaires can be seen on 7.1. **Annex 1: Questionnaires**

b.1) VALENCIA Pilot:

[1] The cut-off method means that primary (first) production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes (source: Eco-invent). So that, in the Plasticircle LCA, only the impacts of the collection and sorting operations are accounted, while the impacts of the primary waste materials not and no credits are provided for the recycling of such materials.

- To build **Waste Scenario for Valencia, primary data obtained from a Recycling Plant** in Picassent Valencia (VAERSA), has been used. In this sense, it cannot be first-hand assumed that material characterization at the entrance of the recycling plant is comparable to the material produced in Valencia Pilot (San Marcelino). In order to know if our disposal recycling scenarios matches PlastiCircle material, next representation shows spectrum of values obtained from own characterization from Pre-Mid and Post Pilot at different packaging fractions throughout Box and Whisker boxes. X red (X) represents the average value of each fraction from the characterization at the entrance of the reference recycling plant. Overall results are remarkably similar, allowing to perform a coherent assumption. For an isolated case (PET fraction) the reference data could be consider as 'outlier data', however, it is evidenced that the specific % of the initial characterization of that fraction was remarkably low compared to the other, and this fact, slightly distorted the representation. Moreover, the rest of fraction values remain inside the main boxes or inside the error margins.

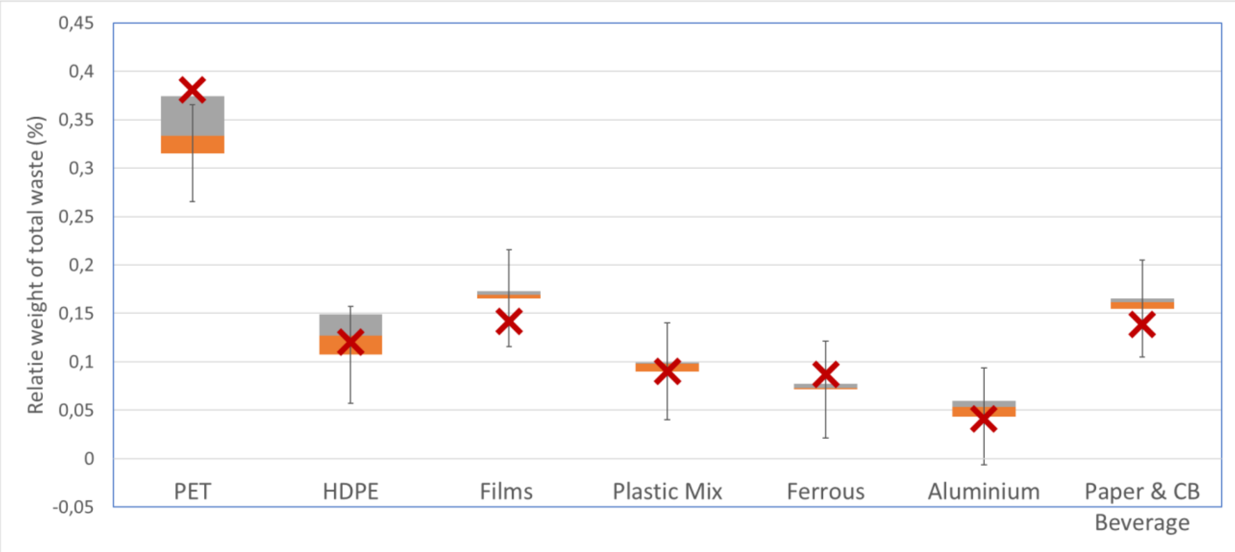


Figure 4 - Characterization comparison: Valencia Pilot vs entrance at the recycling plant.

- When referring to Mixed plastic composition on Ecoinvent data base, this is parametrized on general models for old WRAP characterizations. Plastic waste in UK is indeed quite different from the rest of Europe with a high share of HDPE for instance. Therefore, the Ecoinvent database was customized to the Valencia case, considering the composition of mixed plastic packaging waste in Spain (PP, PS and other plastics not included in their specific fraction or without specific fraction in that order).

b.2) UTRECHT Pilot:

- As main difference with Valencia, waste inputs on the Rotterdam sorting plant were not identified. However, Dutch waste management systems are wide and well reported in the literature [13-19], and packaging waste scenario extracted from literature was compared with characterization made on Utrecht pilot.

Table 4 - Material composition of the separately collection PPW (plastic packaging waste) and the sorted products made thereof. Not differentiating among flexible and rigid material. Extracted from Brouwer, M.T., et al. (2017).

	PET	PP	PE	PS	PVC	Paper	Metal	Glass	Other plastics, black plastics, etc.	Undefined, organic materials, incl. textiles	Moisture and dirt
Separately collected PPW	17%	17%	26%	4%	3%	3%	1%	0%	7%	4%	18%
PET sorted product	69%	6%	7%	0%	0%	1%	0%	0%	0%	0%	15%
PE sorted product	2%	10%	69%	1%	0%	1%	0%	0%	1%	0%	15%
PP sorted product	6%	64%	6%	3%	3%	1%	1%	0%	4%	0%	12%
Film sorted product	3%	10%	54%	2%	2%	2%	0%	0%	4%	0%	24%
Mix sorted product	24%	15%	18%	6%	2%	5%	1%	0%	5%	6%	17%

Similar approach that in Valencia pilot to compare to what level, characterisations done in Utrecht are similar to general plastic packaging waste generated in Netherland and which final destination would be the Rotterdam Plant. On **Figure 5**, it can be seen Box and Whisker boxes in relation to the characterisations done in Utrecht and red X (X), which represent approximate values on the detailed characterisation (based on many studies on Dutch PPW) from *Brouwer, M.T., et al. (2017)*. In general, there are more anomalous values, but main differences could stand for a) categories for each fraction may have not been considered on the same manner and b) studies undertaken on different time references (2017 to 2019).

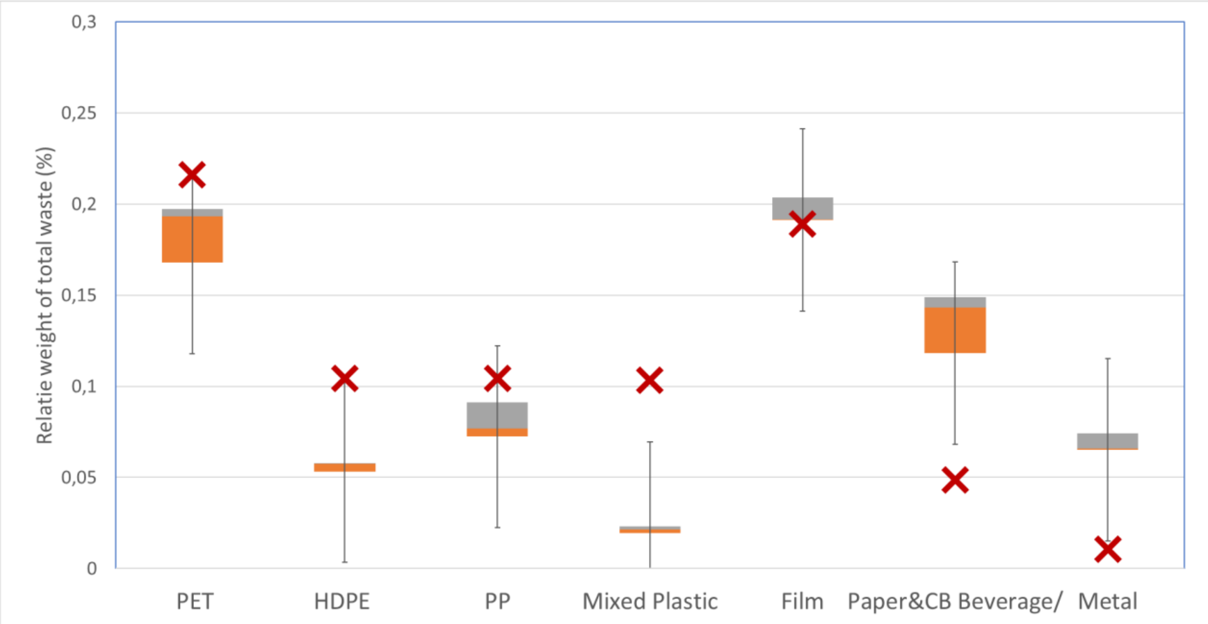


Figure 5 - Characterization comparison: Utrecht Pilot vs literature reference.

b.3) ALBA IULIA Pilot:

In Alba Iulia case, no data has been found in the literature or national documents. Main information about the type of waste generated is the one from PlastiCircle Pilots. Thus, for this case, there is no benchmark, except the pre-pilot situation.

c) Transport Boundaries & Assumptions

- Main parameters considered for transport assessment have been distance and diesel fuel consumption. These have been benchmarked with literature [12,13] and Ecoinvent inventories.

c.1) VALENCIA and ALBA IULIA Pilots:

- When comparing distances from initial and late situation of the pilot, some parts of the route remain constant/fixed. That is why the improvement done on the pilot distance cannot be extrapolated to the whole route distance. Thus, different route segments are differentiated, and the improvements from the project are only applied for the variable distances (the ones that have been and could potentially be improved). The following expressions, represent the above mentioned paragraph:

$$D_{total} = D_{constant} + D_{variable} = (D_{WM-ROUTE} + D_{ROUTE-RecyclingP}) + \Delta_{VLC/ALBA} \quad [2]$$, where:

$\boldsymbol{D_{WM-ROUTE}}$: Distance from Waste Manager location to start of the pilot route.

$\boldsymbol{D_{ROUTE-RecyclingP}}$: *Distance from the end of the route to recycling plant and back to initial site.*

$\Delta_{VLC/ALBA}$: represents variations on the route performed just on the pilot area.

The improvements on the variations are measured referring $\Delta_{VLC/ALBA}$ to the term $(1 - \Delta_{improvement})$ as follows:

$$D_{total} = D_{constant} + D_{variable} * (1 - \Delta_{improvement}) \quad [3]$$

From real performance on the pilots, it was evidenced that not always it is possible to apply the most optimized scenarios due to technical and social reason (e.g., waste cannot remain for more than 5-6 days on the container although that container has not reached the minimum volume to be picked up). $\Delta_{improvement}$ percentages have been assumed down to the results obtained by the optimization algorithm on the deliverable. For that reason, when calculating the potential impact of this technology, we consider two possible scenarios, for pre- and post-pilot situation:

- **Initial scenario** with no improvements.
- **Maximum** optimized scenario from data pilots.

Table 5 - Expressions for different consideration on transport optimization (Valencia and Alba Iulia pilots).

Initial Scenario: non-PC technology implementation	
$D_{total} = D_{constant} + D_{variable} * (1 - \Delta_{improvement})$;	*assuming* $\Delta_{improvement}$
Optimistic Scenario (Maximum Optimization)	
$D_{total} = D_{constant} + D_{variable} * (1 - \Delta_{MAXimprovement})$;	*assuming* $\Delta_{MAXimprovement}$

➔ Like for waste management treatments, the modelling of the transport system, was based on data from Ecoinvent 3 database. Transport datasets in Ecoinvent 3 data include the operation, maintenance of the trucks and their end of life. As infrastructure burdens are not considered when calculating impacts, most of maintenance and impact from truck production are avoided. Capacity for 3 pilots was the same (16 m^3) and EURO emission for each pilot were considered. **Fuel consumption, distances and their values related to the functional unit were modelled consequently.**

d) <u>Treatment Boundaries & Assumptions</u>

- The electricity energy mix consumptions and recoveries have been considered for the Spanish mix. Electricity consumption has a relevant burden on Sorting process and that is why, Ecoinvent inventory for Spanish mix was adapted to consider current sources of electric consumption based on data from "Red Eléctrica Española". Guidelines on

Moreno Ruiz E. et al. (2018) for Ecoinvent energy inventories were also used [21]. Further information on how this calculation was performed and complete inventories can be revised on **7.3 Annex 3: Energy Sources Spanish Case**.

- VAERSA Recycling Plant in Picassent (Valencia) also provided the total energy consumption in 2019 and the total amount of waste treated. The general ratio is **47,278 kWh per kg of waste treated**, which correspond to a coherent reference as it is stated by Cimpan C. and Wenzel H. (2013), explaining that MRF energy consumption rates are in the range between 160-220 MJ (≈52,78 kWh) per tonne of plastic treated [8]. This value varies within the literature, considering the difference on plant typologies, geographic conditions, and other considerations. The table below shows common energy consumption in Light Packaging and Plastics Material Recovery Facilities (MRF) reported in the literature:

Table 6 - Energy Consumption on Light Packaging/plastic MRF. Values gathered from literature (mainly Carolina Liljenström et al. (2015)) and own data.

Value (kWh/tonne)	***Reference***
44.44 – 61.11	Cimpan C. and Wenzel H. (2013) – [8]
44.4	Arena et al. (2003) – [22]
43.9	Swerec (2010) – [22]
37.33	Ren (2012) – [22]
47.278	Primary Data on VAERSA Plant (Valencia)
30	Internal data on Scandinavian Advanced Plant

- Landfill process does not consider carbon storage. This indicator normally covers carbon emissions to air (CO_2, CO, and CH_4) originating from the oxidation and/or reduction of biomass by means of its transformation or degradation (e.g.: combustion, digestion, composting, landfilling) and CO_2 uptake from the atmosphere through photosynthesis during biomass growth. Besides, in the specific case under study, the waste considered is plastic packaging. Consequently, landfill gas and leachate are negligible since only 1-3% of the hydrocarbon content can be degraded during the considered time period of 100 years [24].

2.3. Pre- and Post-Pilot Situation: life cycle inventories (LCI) & waste characterisations

To explain the step-process to analyse the whole cycle from waste on packaging container to end disposals or recovery material, explanatory sequence starts with:

2.3.1 Collection

Following the assumption previously mentioned and gathering all the necessary data to perform the present study on Valencia Pilot impacts. Data are extracted from different sources (noted on the table), trying to prioritize the primary sources. Next parameters are presented on a compacted way, as main variables on LifeCycle Inventory (LCI):

Table 7 - Life cycle inventory data Collection & Transport on pilots

COLLECTION	Units	Pre- Valencia	Post- Valencia	Utrecht	Pre- Alba Iulia	Post- Alba Iulia
General Info						
OVERALL numbers		**Valencia**	**Valencia**	**Utrecht**	**Alba Iulia**	**Alba Iulia**
Inhabitants	u	794.288,00	794.289,00	357.179,00	63,536	63,536
Packaging waste generated on selective collection	tons/a	25.899,10		9.819,47	-	-
Packaging waste per inhabitant	kg/cap.a	32,61		27,49		17.87
PILOT numbers	**Name**	**San Marcelino**		**Terwijde**	**Arnsberg-Goldis**	
Inhabitants	u	9.000,00	9.000,00	7.000,00	7.740,00	7.740,00
Packaging waste collected	tons/a	118,08	-	-	216	
Packaging waste collected per capita (pilot area)	kg/cap.a	13,12		27,49	38,88	
Fraction analysed		LPW on Street Container		LPW on Underground Container	Dry fraction on Street Containers / PlastiCircle street containers	
Collection						
Infrastructure						
Containers in pilot area	u	26	26	40	0	20
Maintenance & Washing						
Water use	l/year	21.600,00				
Water use per tonne	l/ton.a	182,93				
Detergent per tonne (100% pure)	l/ton.a	1,61				
IoT Infrastructure						
PVC from NFC Cards	kg/ton	-	2,50	-	-	2,5
PP Identification labels	kg/ton	-	0,61	-	-	0,61
Energy embedded on IoT system per tonne	kWh/ton	0	0,23	-	0	0,18
Composition of Waste Packaging		**PlastiCircle Pre-Pilot**	**PlastiCircle Late-Pilot**	**Average Utrecht**	**Dry Fraction Pre-**	**PlastiCircle Container**
Unwanted items/Other Waste		**21,59%**	**8,71%**	**26,81%**	**82,00%**	**71,16%**
PET Packaging:		**23,29%**	**30,46%**	**17,71%**	**4,90%**	**13,22%**
PET Bottles		15,49%	23,15%	6,57%	3,20%	12,41%

PET Trays (Mono & Multilayer)	7,81%	7,31%	11,09%	1,70%	0,81%
HDPE Packaging:	**13,40%**	**8,00%**	**5,47%**	**2,80%**	**4,31%**
HDPE Natural	9,34%	6,84%	-	0,80%	1,42%
HDPE Color	3,61%	1,16%	-	2,00%	2,89%
PP rigid	-	-	8,19%	-	-
Mixed Plastic Packaging:	**6,42%**	**9,17%**	**2,11%**	**2,90%**	**2,89%**
Film:	**13,86%**	**15,46%**	**19,92%**	**3,30%**	**4,56%**
Foils - bags & sacks	3,54%	3,84%	1,85%	0,5%	1.67%
Foils - packaging	10,31%	11,62%	18,69%	2,8%	2.89%
Metal Packaging:	**9,85%**	**13,57%**	**7,06%**	**2,40%**	**3,25%**
Aluminium	5,69%	7,51%	-	0,60%	1,62%
Ferrous Packaging	4,16%	6,06%	-	1,80%	1,63%
Paper&CB Beverage/Food:	**11,59%**	**14,63%**	**12,73%**	**1,70%**	**0,61%**

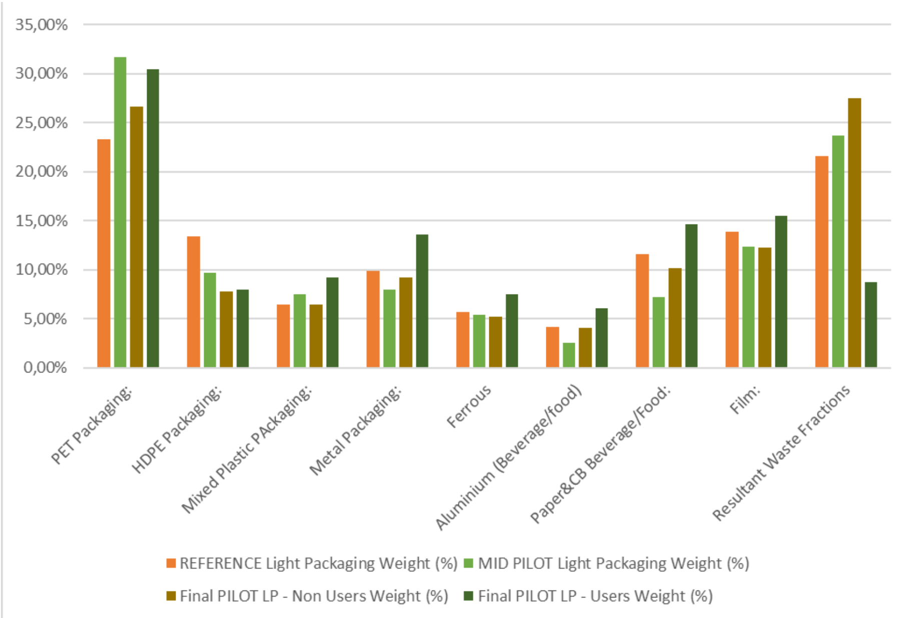


Figure 1 -LPW % fraction evolution during Valencia Pilot, own graphs on information provided by SAV

Main Conclusion from **Valencia characterisations:**

- Reduce resultant waste fraction (non-recyclables) from 20-25% to 8% at the end of the pilot on PlastiCircle participants.
- Increase on PET, film and mixed plastics collection
- Less HDPE (could be due to seasonality)

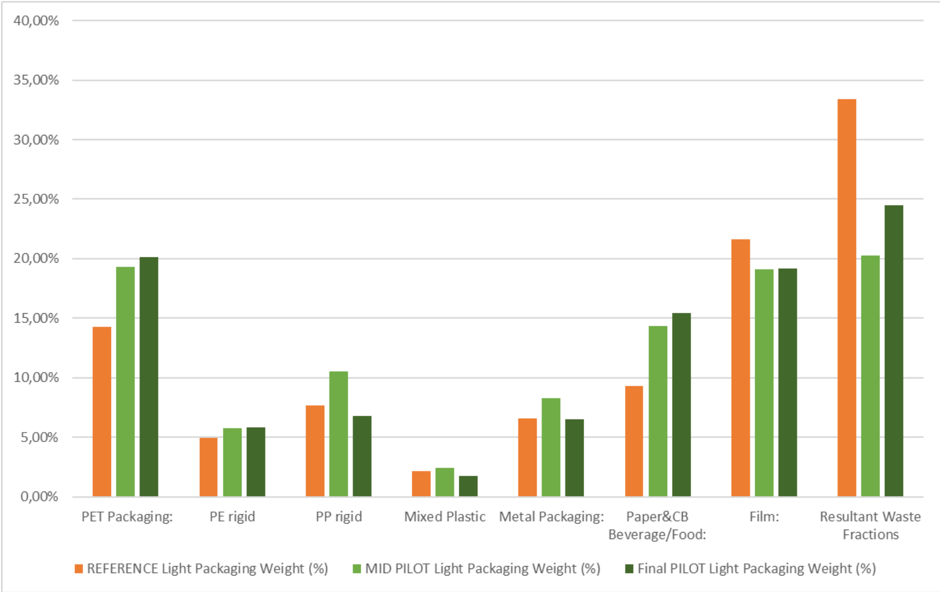


Figure 6- LPW % fraction evolution during Utrecht Pilot, adapted from info provided by Utrecht

Main Conclusion from **Utrecht characterisations:**

- Individual characterizations and the installation of labelling system were not performed due to citizens' ethic requirement. Moreover, low participation and its representativity imply that results on characterization are not direct consequence fromPlastiCircle project,
- However, it is valuable data to know quality from waste on Utrecht underground containers.

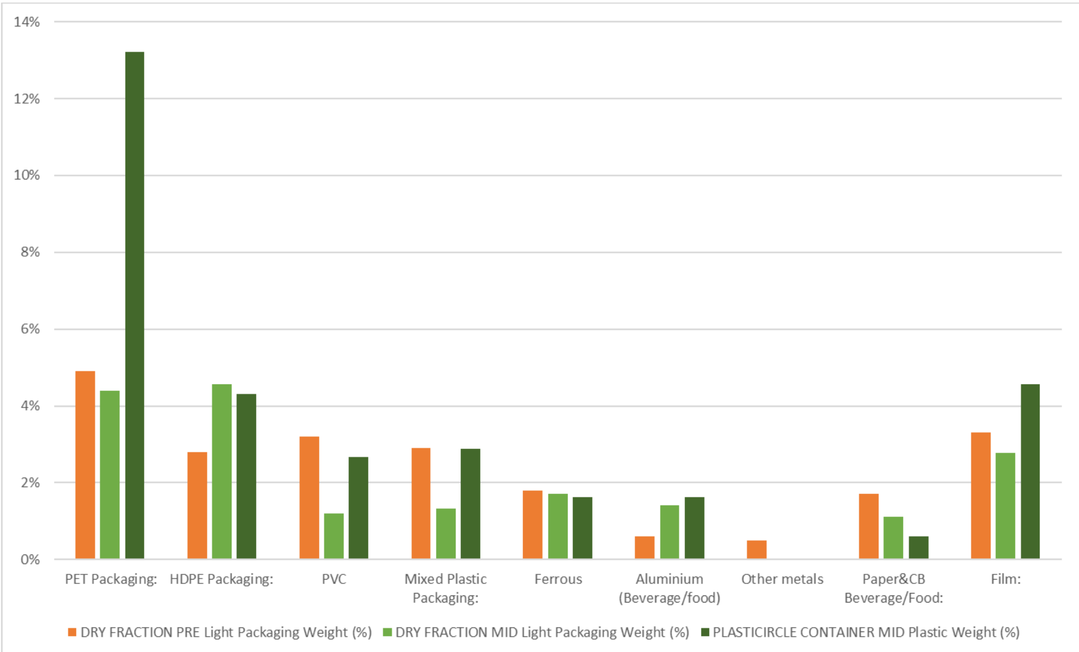


Figure 7 - Dry fraction evolution (in %) during Alba Iulia Pilot comapred with PlastiCircle container. Information from Albalulia/Polaris charactierization.

Main conclusions from **Alba Iulia Characterizations:**

- Alba Iulia Characterisations performed on dry fraction container and specific PlastiCircle one.
- Low presence of plastic packaging in the dry fraction container
- Increase of plastic packaging (mainly PET and films) in the PlastiCircle container in comparison with the dry fraction container.

- High content on PVC while practically no PVC in Valencia and Utrecht was found.
- Other Waste Fractions overcomes scale value on the graphic.

2.3.2. Transport

On this section, information on transport pilot and their main parameters are described. In **Table 8**. A resume of final distance, time and fuel consumption for the 3 pilots are presented. A detailed description of the parameter per track segment and additional data can be found in **Annex 1: Annex 1: City/Waste Managers** Inventories - TRANSPORT:

Table 8 - Main Transport inventories for Pilot Cities

Transport Routes		Pre- Valencia	Post-Valencia	Utrecht	Pre- Alba Iulia	Post- Alba Iulia
Total Distance per route	**km.route**	**135.40**	**106.57**	**226**	**60.05**	**59.314**
Time Average per route	**h.route**	**6.49**	**4.94**	**6.014**	**1.78**	**1.73**
Total Fuel per route	**l/route**	**59.90**	**51.28**	**206.89**	**31.20**	**30.70**
Fuel Consumption per km on a route	**l/km.route**	**0.44**	**0.48**	**0.46**	**0.520**	**0.518**
Tonnes of waste collected	**tonnes**	**3.653**	**3.653**	**3.573**	**9.000**	**9.000**
Tonnes of packaging waste collected	**tonnes**	**3.653**	**3.653**	**3.573**	**2.595**	**2.595**
Distance per functional unit	**tonne*km**	**495**	**389**	**826**	**156**	**154**
Truck Parameters						
Number of trucks for pilot	u.	1	1	1 to 6	1	1
Model	-	EURO 5	EURO 5	EURO 6	EURO 4	EURO 4
Load type		Lateral Right Loader		Top Loader	Rear Loader	
Capacity	m3	16	16	16	16	16
Oil consumption	l	4l/4500km				
Oil usage per distance	L/km	0.0008888				
Tyres usage per distance	km	100000				

* Source of data is detailed in **Annex 1: Annex 1: City/Waste Managers** Inventories - TRANSPORT

VALENCIA

As depicted in Valencia transport assumption's part, constant distance travelled takes a considerable percentage of the total route, however the improvement in the Pilot focuses on the optimization of the containers' pick-up/selection management. The results on these optimization/implementations are depicted on the following table. Second table represents the distances from pilot city to waste manager location (SAV) and local recycling plant (VAERSA).

***Table 9** - Transport KPIs on Valencia Pilot Results, table adapted from ITENE&SAV results on Deliverable 6.2.*

KPIs	Before pilot	During pilot	Final pilot
	Route not optimized	Optimized route	Skipping containers
Distance travelled (Km)	8.6	7.0	5.7
Savings in distance travelled			**2.9 km**
Savings in distance travelled (%)			**34 %**
Time travelled (min)	59.4	48.6	42.78
Savings in duration			**16.61**
Savings in duration (%)			**28 %**
Collection performed (number)	26	26	19
Fuel consumption (l)	7.7	7.3	6.3
Saving in fuel consumption			**1.4 liters**

Saving in fuel consumption (%)	**18 %**

Table 10 - Distances travelled from Valencia Pilot to waste manager (SAV) and recycing Plant (VAERSA)

From SAV to pilot area	3.2 km	9 min	1.0 liters of gasoil
From pilot area to VAERSA	22.5 km	28.2 min	6.3 liters of gasoil
From VAERSA to SAV	24.2 km	23.4 min	5.2 liters of gasoil

Regarding these last considerations and assuming the relation from waste collected and km travelled, the average values of the routes done in the pilot (Pre- Mid- and Late). With that reference and the improvement provided by the route algorithm and the transport systems, we define the following scenarios, applying equation $D_{total} = D_{constant} + D_{variable} * 1 - \Delta_{improvement}$ [3] from the assumptions above an **2.2. System Boundaries and Assumptions** section 2

UTRECHT

As aforementioned, PlastiCircle's technologies have not been used for the pilot in Utrecht. Instead, a theoretical simulation was performed to acknowledge if PlastiCircle optimization was comparable to the commercial system already used by Utrecht. These results are presented in **Table 11**:

Table 11 - Transport results comparison obtained from ITENE results on Deliverable 6.3

Results for average values on 10 routes	Utrecht route simulated		PlastiCircle Route		Difference	
	Time cost (s)	Distance cost (m)	Time cost (s)	Distance cost (m)	Time (%)	Distance (%)
Minimizing Time	12893.1	73649	11297.1	66141	12.34 %	10.10 %
Minimizing Distance			11603.9	62377	9.98 %	15.18%

This is a rough assessment compared to the one performed for Valencia, however, there is no input data to assess PlastiCircle impacts from Utrecht transport pilot.

ALBA IULIA

Regarding Alba Iulia Pilot, route optimization and eco-driving tasks were performed analogously to Valencia case. As general comment, this pilot had less potential to improve on the transport stage, due to the own conditions and situation of containers and fraction collected. The different street containers belong to the whole block buildings and they are relatively near to each other with narrow routes resulting in minor improvement potential. Furthermore, the limited number of containers for the building blocks resulted in frequent collection (daily) as those got exhausted rapidly. Table 12 below displays transport data for Alba Iulia's pilot.

Table 12 - Transport KPIs on Alba Iulia Pilot Results, data from SAV results.

KPIs	Before pilot	During pilot	Final pilot
	Route not optimized	Optimized route	Skipping containers
Distance travelled (Km)	3.551	3.481	2.814
Savings in distance travelled			737 m
Savings in distance travelled (%)			21%

Time travelled (min)	28.25	25.30	24.98
Savings in duration			3.27
Savings in duration (%)			12%
Collection performed (number)	16	16	14
Fuel consumption (l)	4.3	3.9	3.8
Saving in fuel consumption			0.5 liters
Saving in fuel consumption (%)			12%

Table 13 - Distances travelled from Alba Iulia Pilot to waste manager (POLARIS) and recycling Plant (Galda)

From POLARIS to pilot area	3.1km	6.7 min	0.5 liters fuel
From pilot area to Galda Plant	20 km	26 min	35.5 liters fuel
From Galda Plant to POLARIS	19.5 km	25 min	35.5 liters fuel

2.3.3. Sorting

Mathematical simulations for a sorting plant

Scenarios on recycling plants for the 3 cities:

- **VALENCIA** - Light Packaging Plant VAERSA Plant in Picassent, Valencia. (info)
- **UTRECHT** – Light Packaging Plant SITA SUEZ in Rotterdam, Netherlands. (info)
- **ALBA IULIA** – Municipal Solid Waste Treatment Plant in Galda de Jos, Romania (info)

On the sorting model developed, we mainly can vary parameters which are related to the plant capacity, operational hours, fractions to be treated and the relation between the fraction extracted as an output and the energy used on the corresponding machines to do so. All this is controlled with an Excel Dynamic Sheet which gives as results the **energy consumed per tonnes of fraction extracted**, as presented at the beginning of **Section 2.** The specific parameters/characteristics for each situation can be found in **Table 15**. This table also presents the machinery list that would fit on each plant and its corresponding installed power.

In parallel, it is also defined the yield recovery for each fraction on each scenario. This information allows us to predict the potential outputs of a plant with a given input composition. For these definition, different sources have been reached as detailed on **Table 14,** and the one that present more uncertainty is Alba Iulia pilot (they are in a transition of waste management and the plant is not operative yet, and detailed information on Romanian sorting plant or efficiencies have not been identified). On this approach, it has been decided to refer the efficiencies for same packaging categories, however, depending on the plant more fractions can be extracted, as in the case of Dutch Plant which is supposed to extract up to 10 or more different fractions (i.e. PP, PO films, and other which are not differentiated on the Spanish model, for instance).

Table 14 - Sorting Efficiencies per fraction for each pilot city.

	Valencia (VAERSA 2019)	Utrecht (Rotterdam Plant)	ALBA IULIA (Galda)
Source	**Primary Data on Local Sorting Plant// Literature benchmark [25]**	**Primary Data on similar plants// Literature benchmark [17]**	**Hypothetical Data// Literature benchmark [8]**
	0.682	**≈0.89**	**≈0.5**
PET Packaging:	0.845	0.9	0.7
HDPE Packaging:	0.691	0.9	0.7
PP rigid	-	0.8	-
Mixed Plastic Packaging:	0.528	0.85	0.5
Film:	-	0.7	0.5
Aluminium	0.591	0.88	0.6
Ferrous Packaging	0.849	0.97	0.95
Paper&CB Beverage/Food:	0.652	0.88	-

Main assessments on sorting plants **[8,14,17]**, take into account not only the yield/efficiency (material output/material input on a given fraction), but also the purity or correctly targeted consideration (material correctly sorted/material output on a given fraction). For this consideration, information on bales characterisation for each fraction were not available as primary data and thus, it was assumed the minimum content requirement for each bale by Ecoembes[2] on the Spanish case and AFVALFONDS VERPAKKINGEN [3] on the Dutch case.

Technical Specification on recovered material:
[2]Ecoembes: https://www.ecoembes.com/sites/default/files/etmr_def_v12_0.pdf
[3]AFVALFONDS VERPAKKINGEN: http://www.expra.eu/downloads/book_of_expra_technical_working_grou.pdf

Table 15 - Sorting Model parameters for each city pilot

SORTING	VALENCIA (VAERSA)				UTRECHT (Model on SITA SUEZ or similar German Plant)				ALBA IULIA (Mix Real Data Galda Plant / Model on Western EU Plant)			
	Values	Units	Source	Benchamrk	Values	Units	Source	Benchamrk	Values	Units	Source	Benchamrk
Tons treated a year	25.939	ton/a.	VAERSA	Abejón R. et al. (2020)	120.000	ton/a.		150ktpa is using about 4.5M kWh/year	42200	ton/a.		Alba Iulia Council
Material Recovered	17.684	ton/a.	VAERSA	Abejón R. et al. (2020)	133.500		Own Calculation					
Rejects	8.255	ton/a.	VAERSA	Abejón R. et al. (2020)	16.500		Own calculation					
% Recovery Material	0,682	%	VAERSA	Abejón R. et al. (2020)	0,89	%	Link					
Treatment Capacity	6	ton/h	VAERSA		20	ton/h			9	ton/h		Alba Iulia Council
Number of shifts	2	u	Ecoembes report		3	u			2	u		Alba Iulia Council
Operative hours	4000	h/a.	Calculation from ECOEMBES report		6000		Cimpan C. (2015)		4000			
Number of workers	20	u			50	u	Cimpan C. (2015)		15	u		Own assumption
Number of fractions extracted	6	u	VAERSA		>10	u			>5	u		Alba Iulia Council
% Performance machines	70%		Own assumption base on literature		0,7		Own assumption base on literature		0,7			Own assumption base on literature
% Allocation on non-machine electricity	20%		Own assumption base on literature		20%		Own assumption base on literature		50			Own assumption
Total Annual Energy Consumption	1226334,00	kWh/a	VAERSA		-	kWh/a						
Energy per tonne input	47,28	kWh/ton.a	VAERSA		30	kWh/ton.a	Own Calculation					
Energy per tonne output	69,35	kWh/ton.a	VAERSA		33,70786517	kWh/ton.a	Own Calculation					
Equipment	Number	Nominal Power (kW)	Energy Consumption (kWh.a)	Energy Consumption (kWh/ton.a)	Number	Power (kW)	Energy Consumption (kWh.a)	Energy Consumption (kWh/ton.a)	Number	Power (kW)	Energy Consumption (kWh)	Energy Consumption (kWh/ton)
Bag Opener	1	40	112000	4,31	3	150	630000	4,2	1	50	140000	-
Ballistic separator	1	10	28000	1,07	1	12	50400	0,33	-	-	-	-
Conveyor Belts	20	100	280000	10,79	80	400	1680000	11,2	10	50	1400000	-
Drum Screen	1	15	42000	1,61	3	69	289800	1,932	1		42000	-
Magnetic Separator	2	16,9	47320	1,82	2	54	226800	1,512	1		23660	-
Non-ferrous separator	2	9,5	26600	1,02	3	30	126000	0,84	1		13300	-
Windstifer	1	35	98000	3,77	2	120	504000	3,36	-	-	-	-
Baler Metals	1	36,8	37,52	0,01	1	36,8	154560	1,03	-	-	-	-
Baler Reject	1	44,1	3996,48	0,15	1	44,1	185220	1,23	-	-	-	-
Baler Recoverable	1	44,1	11556,50	3,46	1	44,1	185220	1,23	-	-	-	-
Optical CB	1	2	5600	0,21	1	2	8400	0,056	-	-	-	-
Optical PM	1	2,5	7000	0,26	1	2,5	10500	0,07	-	-	-	-
Optical HDPE	1	2,5	7000	0,26	2	5	21000	0,14	-	-	-	-
Optical PET	1	3	8400	0,32	2	6	25200	0,168	-	-	-	-
Optical PP	-	-	-	-	2	6	25200	0,168	-	-	-	-
Optical PS	-	-	-	-	2	5	21000	0,14	-	-	-	-
Optical PE Film	-	-	-	-	2	7	29400	0,196	-	-	-	-
Optical MPO Film	-	-	-	-	1	7	29400	0,196	-	-	-	-
Optical Paper	-	-	-	-	1	5	21000	0,14	-	-	-	-
Bottle Perforator	1	1,4	3920	0,15	3	6	25200	0,168	-	-	-	-

Based on above explanation on model and parameters, different mass balances have been calculated for each pilot per 1 tonne of waste collected. On this mass balance, losses on effectiveness and due to purity factor have been consider, to potentially calculate the "real" mass for each fraction, mostly focusing on the plastic packaging fractions. These numbers are displayed on the following tables: **Table 16, Table 17** and **Table 18**. These tables indicate the % composition of waste for main packaging waste streams, followed by the influence of effectiveness and purity losses on each stream.

Table 16 - Mass flow balance on main packaging streams for Valencia pilot case. (Pre- and post-pilot compositions, yield and purity for Spanish case)

	EFFECTIVENESS & PURITY MASS LOSSES - VALENCIA							
	Pre-Valencia	Post-Valencia	- Initial Mass flow per 1 ton (kg)		Material extracted per 1 ton (kg) - Effectiveness		Real mass after Purity (kg)	
Composition of Waste Packaging	%	%	Pre-Valencia	Post-Valencia	Pre- Valencia	Post-Valencia	Pre-Valencia	Post-Valencia
Unwanted items	**21,59%**	**8,71%**	215,90	87,10				
PET Packaging:	**23,29%**	**30,46%**	232,90	304,60	196,80	255,86	188,93	245,63
PET Bottles	15,49%	23,15%	154,90	231,50				
PET Trays (Mono & Multilayer)	7,81%	7,31%	78,10	73,10				
HDPE Packaging:	**13,40%**	**8,00%**	134,00	80,00	92,59	69,60	83,33	62,64
HDPE Natural	9,34%	6,84%	93,40	68,40				
HDPE Colour	3,61%	1,16%	36,10	11,60				
PP rigid	-	-						
Mixed Plastic Packaging:	**6,42%**	**9,17%**	64,20	91,70	33,90	66,94	27,12	53,55
Film:	**13,86%**	**15,46%**	138,60	154,60	89,81	100,18	73,65	82,15
Foils - bags & sacks	3,54%	3,84%	35,40	38,40				
Foils - packaging	10,31%	11,62%	103,10	116,20				
Metal Packaging:	**9,85%**	**13,57%**	98,50	135,70				
Aluminium	5,69%	7,51%	56,90	75,10	33,63	44,31	30,27	39,88
Ferrous Packaging	4,16%	6,06%	41,60	60,60	35,32	56,36	31,79	50,72
Paper&CB Beverage/Food:	**11,59%**	**14,63%**	115,90	146,30	75,57	0,12		

Table 17 - Mass flow balance on main packaging streams for Utrecht pilot case. (yield and purity for Dutch case)

	EFFECTIVENESS & PURITY MASS LOSSES - UTRECHT			
		Initial Mass Flow per 1 ton (kg)	Material extracted per 1 ton (kg) - Effectiveness	Real mass after Purity (kg)
Composition of Waste Packaging	%	Utrecht	Utrecht	Utrecht
Unwanted items	26,81%	268,10		
PET Packaging:	**17,71%**	**177,12**	**159,41**	**146,66**
PET Bottles	6,57%	65,70		
PET Trays (Mono & Multilayer)	11,09%	110,86		
HDPE Packaging:	**5,47%**	**54,69**	**49,22**	**46,27**
HDPE Natural	-			
HDPE Color	-			
PP rigid	**8,19%**	**81,868**	**65,49**	**61,56**
Mixed Plastic Packaging:	**2,11%**	**21,057**	**17,90**	**14,32**
Film:	**19,92%**	**199,20**	**139,44**	**114,34**
Foils - bags & sacks	1,85%	18,45		
Foils - packaging	18,69%	186,92		

Metal Packaging:	**7,06%**	**70,60**	**62,13**	**55,92**
Aluminium	1,06%	10,6	10,28	9,25
Ferrous Packaging	6,00%	60	52,80	47,52
Paper&CB Beverage/Food:	**12,73%**	**127,34**	**112,06**	

Table 18 - Mass flow balance on main packaging streams for Alba Iulia pilot case. (Pre- and post-pilot compositions, yield and purity for hypothetical Romanian case)

	EFFECTIVENESS & PURITY MASS LOSSES - ALBA IULIA							
	Pre- Alba Iulia	Post-Alba Iulia	- Initial Mass flow per 1 ton (kg)		Material extracted per 1 ton (kg) - Effectiveness		Real mass after Purity (kg)	
Composition of Waste Packaging	%	%	Pre- Alba Iulia	Post-Alba Iulia	Pre- Alba Iulia	Post-Alba Iulia	Pre- Alba Iulia	Post-Alba Iulia
Unwanted items								
PET Packaging:	**4,90%**	**13,22%**	**49,00**	**132,20**	**34,30**	**92,54**	**32,928**	**88,8384**
PET Bottles	3,20%	12,41%	**32,00**	**124,10**				
PET Trays (Mono & Multilayer)	1,70%	0,81%	**17,00**	**8,10**				
HDPE Packaging:	**2,80%**	**4,31%**	**28,0**	**43,10**	**19,60**	**30,1700**	**17,64**	**27,15**
HDPE Natural	0,80%	0,00%	**8,00**	**0,00**				
HDPE Color	2,00%	2,89%	**20,00**	**28,90**				
PP rigid	-	-						
Mixed Plastic Packaging:	**2,90%**	**2,89%**	**29,00**	**28,90**	**14,50**	**14,45**	**11,60**	**11,56**
Film:	**3,30%**	**4,56%**	**33,00**	**45,60**	**16,50**	**22,80**	**13,53**	**18,70**
Foils - bags & sacks								
Foils - packaging								
Metal Packaging:								
Aluminium	0,60%	1,62%	**6,00**	**16,20**	**3,60**	**9,7200**	3,24	8,75
Ferrous Packaging	1,80%	1,63%	**18,00**	**16,300**	**17,10**	**15,4850**	15,39	13,94
Paper&CB Beverage/Food:	**1,70%**	**0,61%**	**17,00**	**6,10**	**8,50**	**3,0500**		
PVC	**3,20%**	2,66%	**32**	**26,6**	**22,4**	**18,62**	19,04	15,83

Material savings with PICVISA technology based on improvements on hardware/software in the optical sorter system:

Furthermore, PICVISA developed a mechanical module for a stabilization system for films. This would have a direct impact on the quantity/yield of films recovery. But also, on electrical consumption. Energy consumption has been calculated considering throughput, energy of the conveyor and the energy related to valves actioning, as it has previously done not only in waste sorting facilities but also on mining sorting systems [26]. Table 20 shows main characteristics for the system with and without the stabilization system focusing mainly on the Energy per tonne and %PE film yield.

Table 19 - Results on PICVISA trials on Valencia Pilot Material

PET	% PRE-PILOT	% PILOT
Yield	85%	92%
Purity	92%	96%

PET TRAY	% PRE-PILOT	% PILOT
Yield	-	-
Purity	88%	98%

HDPE	% PRE-PILOT	% PILOT
Yield	90%	94%
Purity	91%	95%

PP	% PRE-PILOT	% PILOT
Yield	75%	94%
Purity	92%	95%

Table 20 - Main parameters of PICVISA sorting equipment (with and without stabilization system)

Optical sorter (without film stabilization)		Optical sorter (with film stabilization)	
Installation Power	2,65 – 4,1 **	Installation Power	2,65 – 4,1 ** + 1.1
Energy / ton (kWh/ton)	0,62	Energy / ton (kWh/ton)	0.80
Throughput	5-6 t/h	Throughput	5-6 t/h
Volume of air needed (m3/s)	12x300lpm	Volume of air needed (m3/s)	12x300lpm
Energy needed on valves (J/s, W)	12x9,6W	Energy needed (J/s, W)	12x9,6W
% PE film yield	54%	% PE film yield	81%

The improvement done by PICVISA were also included in the Plant Model for Valencia pilot, as it was the one which suits the most, the overall context of the recycling plant. The main reasons for such decision are: (a)Alba Iulia would have a more manual sorting, and (b) Dutch Plant already counts with a quite advance and high-automated system.

For this particular assessment, PICVISA optical sorting has been assumed to be one of the Valencia Plant model. In this way, the yield/effectiveness on one specific fraction makes reference to the product of all the machines efficiencies on a plant (i.e. ballistic separator, drum screen, optical sorter, etc.). Thus, pre- and post- yield recovery numbers have been used to recalculate the potential mass of plastic packaging that could be recovered. Following next calculation for PET case, the

$$\eta_{PET-PrePICVISA} = \eta_{drumscreen} * \eta_{balistic} * \eta_{opticalPET-PrePICVISAt} * \cdots * \eta_N$$

$$\eta_{PET-PostPICVISA} = [\eta_{drumscreen} * \eta_{balistic} * \eta_{opticalPET-PrePICVISA} * \cdots * \eta_N] * \frac{\eta_{opticalPET-PostPICVISA}}{\eta_{opticalPET-PrePICVISA}}$$

$$\boldsymbol{\eta}_{\mathbf{PET-Post}PICVISA} = \eta_{PET-PrePICVISA} * \frac{\eta_{opticalPET-PostPICVISA}}{\eta_{opticalPET-PrePICVISA}} \quad [4]$$

Table 21 - Comparison on Pre and Post- PICVISA results on main plastic fractions. Yield ($\boldsymbol{\eta}_{FRACTION-Pre/\mathbf{PostPICVISA}}$) improvement

	Post-Valencia	1 ton (kg) - Initial Mass flow	PICVISA SORTING Pre	PICVISA SORTING Post	PICVISA improvement
Composition of Waste Packaging	Composition		Post-Valencia	Post-Valencia PICVISA	% additional material
PET Packaging:	30.46%	304.60	257.39	278.58	8.2%
HDPE Packaging:	8.00%	80.00	55.28	57.74	4.5%
Mixed Plastic Packaging (PP):	9.17%	91.70	48.42	60.68	25.3%
Film:	15.46%	154.60	100.18	125.23	25.0%

2.3. General Washing Pre-Treatment

This process is normally undertaken by a recycler/industry after the sorting stage. It has been a stage considered within the cities section as later on, all the impact from plastic packaging treatment will be allocated into the raw materials as direct inputs on their processes and not add extra stages on their manufacturing. Thus, in this stage we slightly differentiate between PET washing, rigid PO and flexible, focusing mainly on:

- **Electric consumption** (Wet Grinder; friction Washer; Washing Line; Separation; Mechanical dryer; Blower, inter alia)
- **Water used** (fresh and reused)

- **Additives** (Sodium hydroxide, washing agents, antifoams, acid, flocculant)
- **Waste** (landfilling/incineration) **and wastewater** treatments

Focusing on these aspects, data summary are displayed in Table 22, though more detailed information can be found in **7.6 Annex 6 – Washing Conditions**

Table 22 - General parameters for different type of polymer washing (Data from literature, AXION and own database)

	Energy Consumption (kWh/ton)*	General processes for washing	Water use (m3/ton)*	Use of addtitives (l/ton)	Losses (%)**
PET Bottle/Trays	150	**Debaler, Wet Grinder; friction Washer; - Compact Washing Line; - Friction Washer; - Separation; ; -Mechanical dryer; - Blower**	4	**Sodium hydroxide , Washing agent, Antifoam, Acid , Flocculant**	30 to 35%
Rigid PO	136.5		4		20 to 30%
Flexible PE	245		6		22 - 26 %
Additives	Sodium hydroxide , Washing agent, Antifoam, Acid , Flocculant				

*Data from industrial line processes (7.6 Annex 6 – Washing Conditions)
**Data from own trials (7.6 Annex 6 – Washing Conditions

As during this whole LCA, the "cut-off" method is being followed, avoided products or energy consumptions cannot be considered when using recycled materials. However, it is important to express which is the impact of the recycling processes compared to the production of virgin material, and that is why, on the interpretation and conclusions sections, it is laid out main differences and impacts on these two scenarios.

2.5. Interpretation and Conclusions

To lay out the interpretation and conclusions for LCA, firstly a general overview for Valencia pilot is given, comparing the source of the impacts regarding each stage on the waste management. Then, each stage (collection, transport and sorting) is analysed for the cases on Post- pilot for Valencia case and benchmark for Utrecht situation. To finish with the evaluation, the impact from tor the Pre-treatment and Washing are analysed for main plastic packaging fraction (PET, HDPE; Plastic Mix and PE Films). Although we are performing an LCA down "cut-off" method, results from this stage are benchmarked with the results for the process with avoided products burden in order to describe both methodologies effects. Through this chapter, next points can be followed:

- Impacts from PlastiCircle approach in Valencia Pilot.
- Utrecht case scenario.
- Impacts from PlastiCircle approach in Alba Iulia Pilot.
- Impacts from washing/pre-treatment step after sorting. Mass flow balance impact (avoided products).

On this LCA, impacts are calculated with the life cycle impact assessment (LCIA) method ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting. As for this, the impact categories that will be evaluated are enumerated in tables below, with the corresponding units for each category. On some tables/figure on this section, impact categories will refer to the units displayed in the table below:

Table 23 - Impact categories and unit for method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting

Impact Category	Unidad

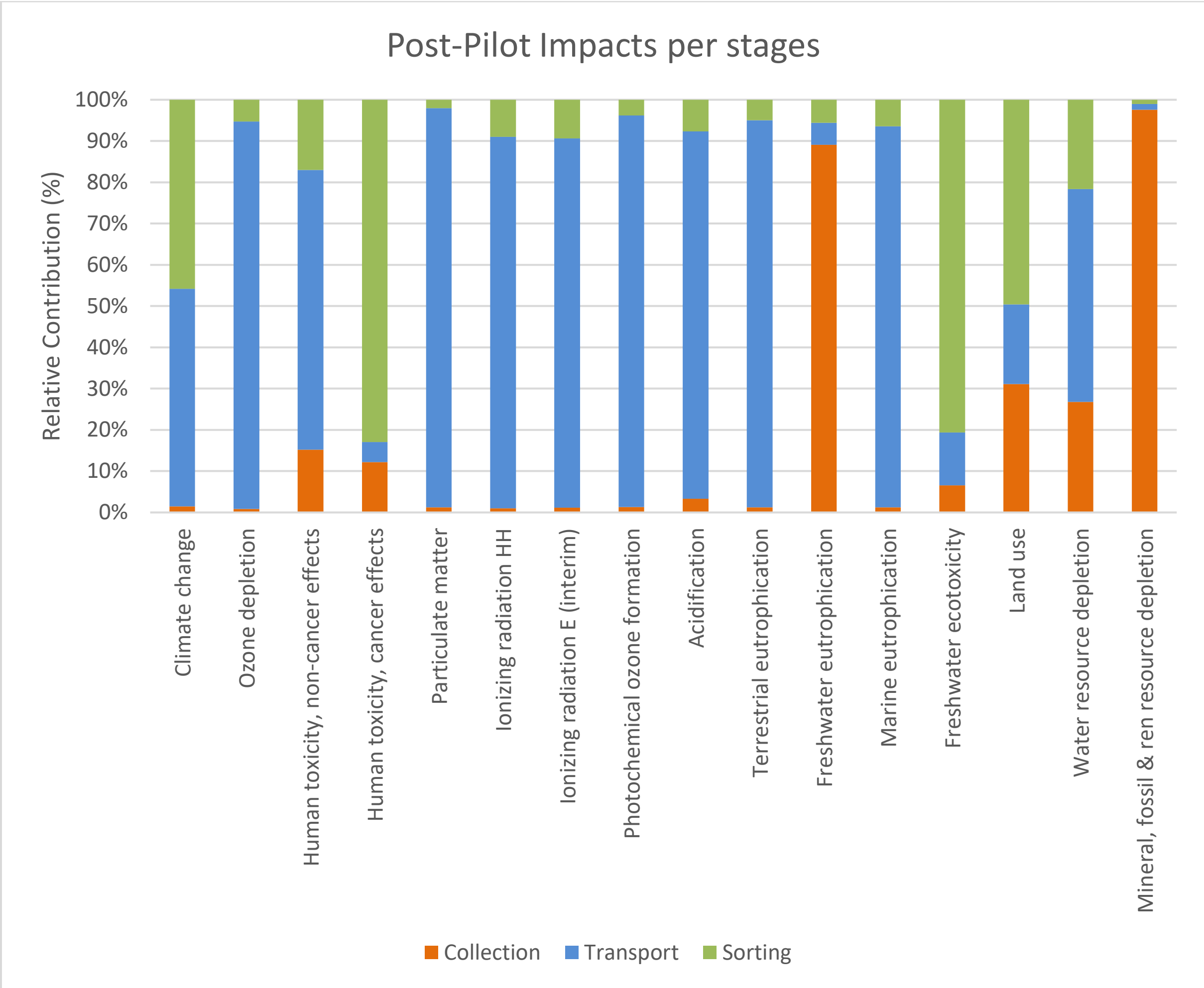
Climate change	kg CO2 eq
Ozone depletion	kg CFC-11 eq
Human toxicity, non-cancer effects	CTUh
Human toxicity, cancer effects	CTUh
Particulate matter	kg PM2.5 eq
Photochemical ozone formation	kg NMVOC eq
Acidification	molc H+ eq
Terrestrial eutrophication	molc N eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Freshwater ecotoxicity	CTUe
Land use	kg C deficit
Water resource depletion	m3 water eq
Mineral, fossil & ren resource depletion	kg Sb eq

Impacts from PlastiCircle approach in Valencia Pilot.

Table 24 - Impacts on Collection, transport and Sorting for Post-Pilot in Valencia. (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)

Impact Category	Acronym	Unit	Collection	Transport	Sorting
Climate change	CC	kg CO2 eq	$1.38\cdot10^{+1}$	$4.98\cdot10^{+02}$	$5.11\cdot10^{+01}$
Ozone depletion	OD	kg CFC-11 eq	$9.62\cdot10^{-07}$	$1.09\cdot10^{-04}$	$3.69\cdot10^{-06}$
Human toxicity, non-cancer effects	HT non-cancer	CTUh	$5.47\cdot10^{-06}$	$2.44\cdot10^{-05}$	$8.40\cdot10^{-07}$
Human toxicity, cancer effects	HT cancer	CTUh	$3.64\cdot10^{-07}$	$1.46\cdot10^{-07}$	$2.91\cdot10^{-08}$
Particulate matter	PM	kg PM2.5 eq	$1.17\cdot10^{-02}$	$8.98\cdot10^{-01}$	$1.15\cdot10^{-02}$
Photochemical ozone formation	POF	kg NMVOC eq	$6.74\cdot10^{-02}$	$4.82\cdot10^{+00}$	$9.62\cdot10^{-02}$
Acidification	AC	molc H+ eq	$1.21\cdot10^{-01}$	$3.24\cdot10^{+00}$	$1.79\cdot10^{-01}$
Terrestrial eutrophication	EU terrestrial	molc N eq	$1.83\cdot10^{-01}$	$1.36\cdot10^{+01}$	$3.14\cdot10^{-01}$
Freshwater eutrophication	EU freshwater	kg P eq	$1.07\cdot10^{-02}$	$6.41\cdot10^{-04}$	$4.92\cdot10^{-04}$
Marine eutrophication	EU marine	kg N eq	$1.62\cdot10^{-02}$	$1.24\cdot10^{+00}$	$6.88\cdot10^{-02}$
Freshwater ecotoxicity	ET freshwater	CTUe	$4.02\cdot10^{+01}$	$7.79\cdot10^{+01}$	$1.32\cdot10^{+01}$
Land use	LU	kg C deficit	$5.42\cdot10^{+00}$	$3.37\cdot10^{+00}$	$1.12\cdot10^{+01}$
Water resource depletion	WRD	m3 water eq	$6.03\cdot10^{-02}$	$1.16\cdot10^{-01}$	$3.64\cdot10^{-02}$
Mineral, fossil & ren resource depletion	MFRRD	kg Sb eq	$7.56\cdot10^{-03}$	$1.06\cdot10^{-04}$	$5.72\cdot10^{-05}$

Figure 8 - Impacts on Collection, transport and Sorting for Post-Pilot PlastiCircle approach in Valencia. (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)



From **Table 24** and **Figure 8**, for each impact category the contribution of each operation (collection, transport and sorting) are provided. These results indicate that **collection** has a large contribution to the **Freshwater eutrophication** and **Mineral, fossil & resource depletion** impact categories. This is due mainly to the use of water for containers washing and material and devices used for the IoT system, respectively. This will be more detailed in each specific section.

Transport stage has a major impact on the rest of categories, representing more than 90% of the impact on **Ozone Depletion, Particle matter** and **Photochemical ozone formation,** inter alia. **Climate change** impacts is mostly generated by the transport and sorting stage.

Sorting stage impacts are mainly related to **Human toxicity, Freshwater Ecotoxicity and Land Use**. More detailed aspects on comparative models between Pre and Post pilot situation will be furtherly developed in following figures.

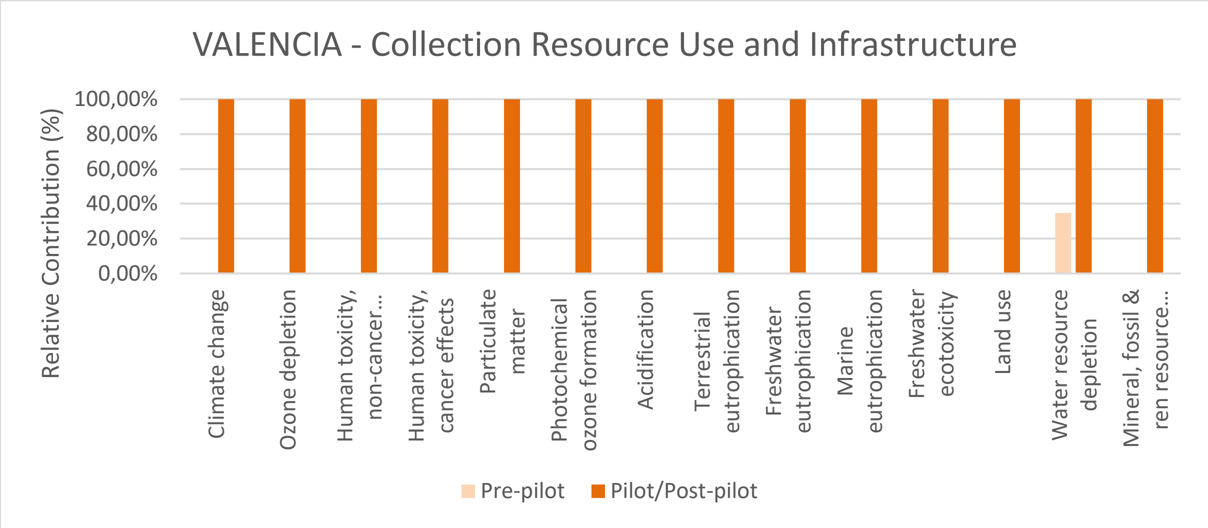
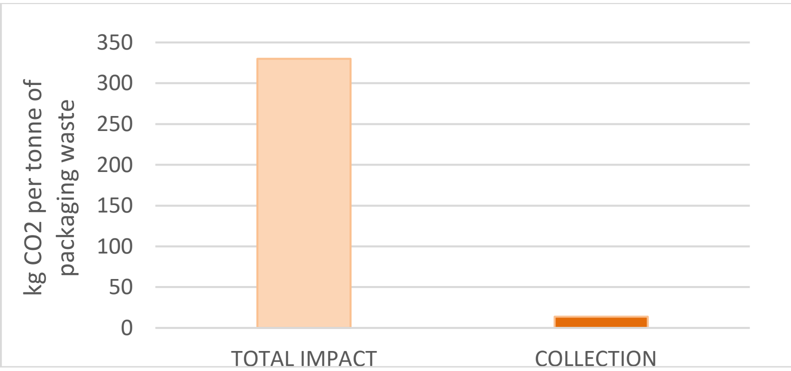


Figure 9 - Impacts for Pre vs Post Pilot COLLECTION in Valencia. (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)

Figure 9¡Error! No se encuentra el origen de la referencia. values mainly show impacts e xtracted from PlastiCircle infrastructure (IoT infrastructure maintenance, batteries, embedded energy and labels and card delivered to the citizens). For the general LCA, infrastructure has not been considered because of being pre-existing built infrastructure and not to disturb direct impacts from the pilot. As a constant input in the system, only water use for cleaning the containers has been considered for this stage and that is the reason for having some impact on the Water resource depletion category for the Pre-pilot case.

In general, the value for PlastiCircle case on this stage looks impactful because there are no items considered before the pilot. However, in the majority of categories, as in the case of Climate Change, the weight of this collection stage compared with the rest of the system is below 5%, which could be assumed as negligible as shown on Figure below:



Mineral, fossil and resources is the unique category which is relevant in comparison to the other stages due to the use of NFC cards, batteries for the devices and other input related to resources. As cut-off method is used during this LCA, no consideration for the production of plastic packaging and therefore, there is no such a considerable impact on other stages.

Tightly connected to the collection infrastructure is the transport stage. Thanks to the different devices developed and installed in the pilot area, improvements on the waste transport time and distances have been achieved.

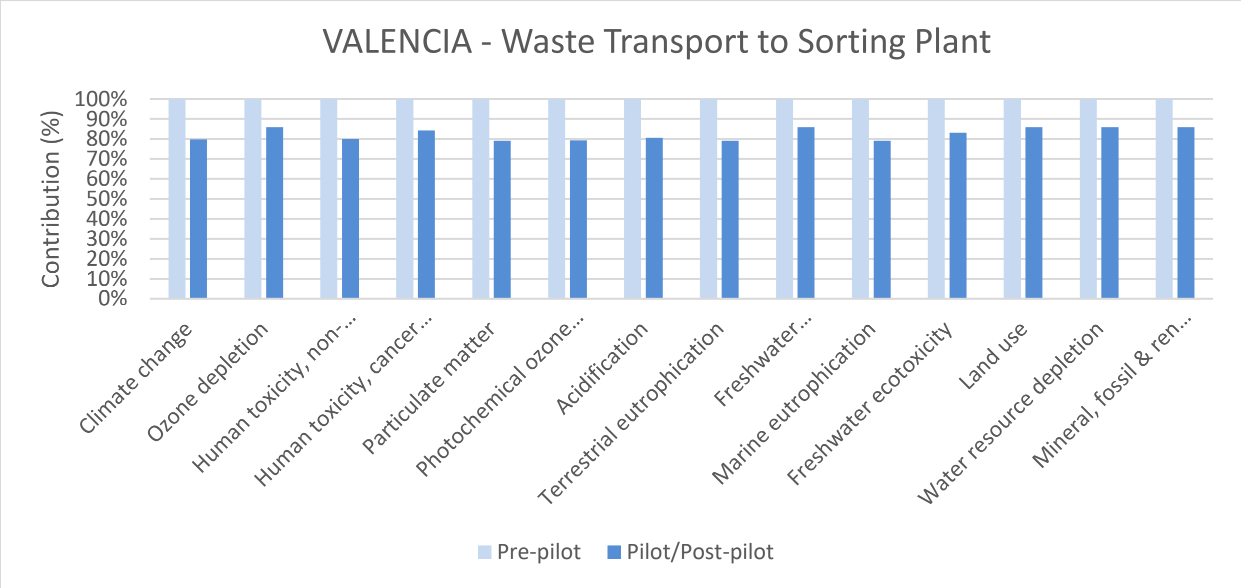


Figure 10 - Impacts for Pre vs Post Pilot TRANSPORT in Valencia. (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)

From **Table 8** on section **2.3.2. Transport**, it can be identified where these improvements come from. Mainly due to not picking up all the containers but only those which are over the 80% of their capacity, the truck is full in advance and thus, it travels less distance per route (135.4 to 106.57km). This result in less fuel consumption (59.9 vs. 51.28 l/route) and reduced time (6,49 to 4,94h) in which the truck is in operation. On LCA terms, this reduction inventoried as distances per tonnes carried and fuels consumption is translated into a 20% reduction on main impact categories such as **Climate change** (-126 kg CO_2 eq. per tonne of waste collected**), Particle matter** (-0.25 kg PM2.5 eq.) or **Acidification** (- 0.78 molc H+ eq.), inter alia.

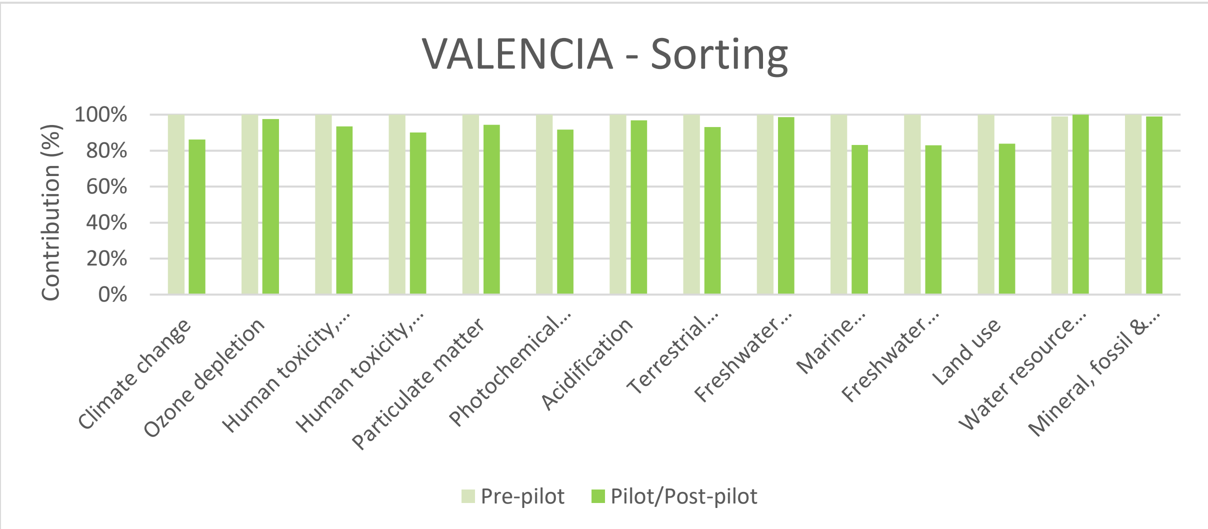


Figure 11 - Impacts for Pre vs Post Pilot SORTING in Valencia . (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)

In this last stage, the assessment considers mainly the impact from having a better input material and less impurities/unwanted material per ton of packaging waste collected. Therefore, on impact network on SimaPro, it is evidenced that the most relevant impacts is are associated with the energy consumption (electricity) and landfilling waste. This factor decreases for the Post scenario with more recoverable material being treated per tonne of collected material and less items being sent to landfilling or final disposal. These factors are translated into a 14 % reduction of the CO_2 eq. emission for the Climate change category and significant decreases for other impact categories such as Freshwater Ecotoxicity, Marine Eutrophication and Land Use (*Figure 11*).

*Utrecht scenario

As explained on previous section, Utrecht did not use all PlastiCircle pilot and thus, not a full comparison between Pre- and Post Pilot could be done, since only the transport improvements were accounted for. Therefore, Utrecht scenario case was calculated but not graphically compared for not being a valid comparison. All values on the impacts for different stages can be found by **Table 25** -

Table 25 -

Impact Category	Unidad	Collection UTR	Transport UTR	Sorting UTR
Climate change	kg CO2 eq	$7.85\cdot10^{-01}$	$1.05\cdot10^{+03}$	$2.77\cdot10^{+02}$
Ozone depletion	kg CFC-11 eq	$1.48\cdot10^{-07}$	$2.22\cdot10^{-04}$	$2.69\cdot10^{-06}$
Human toxicity, non-cancer effects	CTUh	$7.16\cdot10^{-07}$	$5.14\cdot10^{-05}$	$3.76\cdot10^{-06}$
Human toxicity, cancer effects	CTUh	$2.75\cdot10^{-08}$	$3.01\cdot10^{-07}$	$1.61\cdot10^{-06}$
Particulate matter	kg PM2.5 eq	$1.34\cdot10^{-03}$	$1.90\cdot10^{+00}$	$7.62\cdot10^{-03}$
Photochemical ozone formation	kg NMVOC eq	$4.11\cdot10^{-03}$	$1.02\cdot10^{+01}$	$9.46\cdot10^{-02}$
Acidification	molc H+ eq	$1.53\cdot10^{-02}$	$6.80\cdot10^{+00}$	$9.65\cdot10^{-02}$
Terrestrial eutrophication	molc N eq	$1.31\cdot10^{-02}$	$2.88\cdot10^{+01}$	$3.74\cdot10^{-01}$
Freshwater eutrophication	kg P eq	$8.22\cdot10^{-04}$	$1.31\cdot10^{-03}$	$6.72\cdot10^{-04}$
Marine eutrophication	kg N eq	$1.13\cdot10^{-03}$	$2.63\cdot10^{+00}$	$3.49\cdot10^{-02}$
Freshwater ecotoxicity	CTUe	$2.26\cdot10^{+00}$	$1.61\cdot10^{+02}$	$3.15\cdot10+^{02}$
Land use	kg C deficit	$4.86\cdot10^{-01}$	$6.90\cdot10^{+00}$	$6.60\cdot10^{+00}$
Water resource depletion	m3 water eq	$-1.27\cdot10^{-03}$	$2.38\cdot10^{-01}$	$2.11\cdot10^{-02}$
Mineral, fossil & ren resource depletion	kg Sb eq	$2.61\cdot10^{-04}$	$2.17\cdot10^{-04}$	$3.76\cdot10^{-05}$

On this first stage (collection), Valencia situation where label dispenser and sensors on each container were installed. Utrecht has less technology deployment as the city pilot just counted with filling level sensors and no identification cards and labelling dispenser were installed. Thus, this explains the collection stage is more impactful for Valencia situation.

For the Transport stage, several conclusions can be identified mostly analysing the distances between containers and distances to sorting facilities. For this stage, main variables affecting each scenario are distances, tonnes of waste carried and the fuel consumption. We appreciate that impacts on Utrecht Pilot are almost twice as compared to the ones for the Valencia case. This is because for Valencia case, packaging waste are managed by a nearby plant from the pilot while for the Dutch case, packaging waste is not managed in Utrecht but on a Rotterdam Plant which manages most of this kind of waste for the country. This condition adds 100-150 extra km per each route and tonne managed what significantly increasing the impacts on this stage.

Finally for this Sorting stage, impacts are not so evident. There is no common trend for all impact categories, being the results influenced by several factors. Valencia case represented a small-scale sorting plant (25k tonnes a year) while Dutch one represents a big scale sorting plant (120k tonnes a year). This makes electricity consumption optimal for the Dutch case (with 30kWh/tonne against the 47.28 kWh/tonne in Valencia). Moreover, the efficiencies on Dutch Plant are up to 89% while effectiveness for Valencia case is around 69%, having more residual waste ending on landfill/incineration. However, as the assessment considers the „cut-off method":

1. Avoided products mass balance is not considered (Utrecht case having better effectiveness, this would be favourable for its scenario)
2. Energy recovery from incineration is not considered as well (knowing that Valencia scenario is 100% landfilling and Utrecht one 100% incineration, this fact is unfavourable for Dutch case)

Impacts from PlastiCircle approach in Alba Iulia Pilot.

For the **collection stage**, Alba Iulia Pilot presents a very similar impact compared to Valencia case. Specific PlastiCircle containers were used for the collection of plastic packaging, with the associated installation of sensors and devices defining the smart container. Main difference is the LoRa devices needed per module of labelling dispenser, however, it has been noticed that the impacts from these devices and/or its embedded energy is negligible in comparison with other more impactful stages such as transport, sorting or washing step.

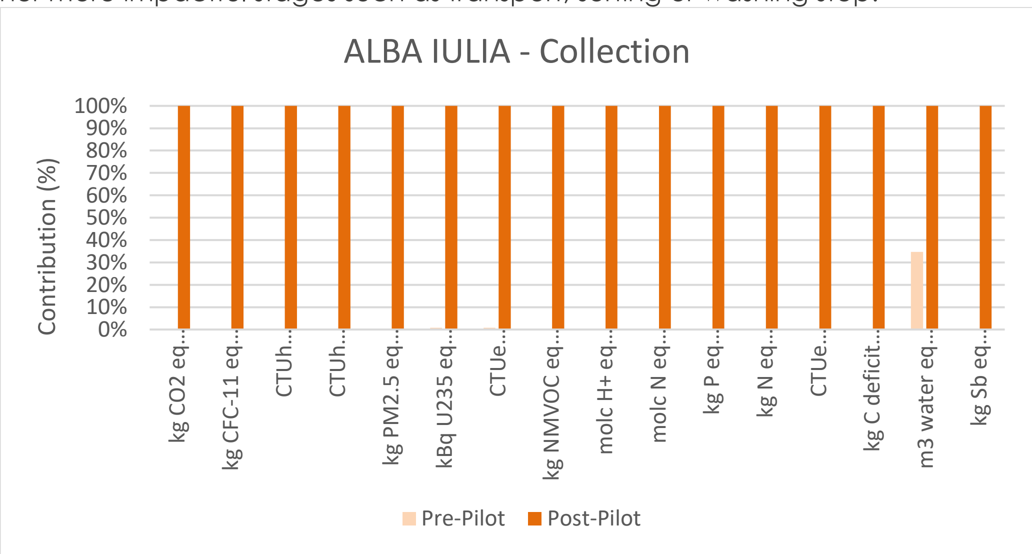


Figure 12 - Impacts for Pre vs Post Pilot COLLECTION in Alba Iulia

For the **transport stage**, the improvement observed is relatively low compared with results from Valencia case. Main reasons are related to the characteristics of the area and the amount of waste collected. PlastiCircle containers were used indistinctly as the dry fraction one, and they were filled rapidly necessitating a daily collection (and no skipping of containers was possible). Furthermore, the characteristics of the streets and traffic ways did not always allow to maximize the route optimization. From the results on Pre- and Post situation in Section 2, one may note that the improvement on the reduction of distances was around 24% and time 12 %. However, the route segment in which the truck is picking up containers is quite short in comparison to the whole route not allowing a significant improvement. When analysing the whole transport route numbers, the improvements in the different impact categories (**Figure 13**)is around 1-2% which is not really significant.

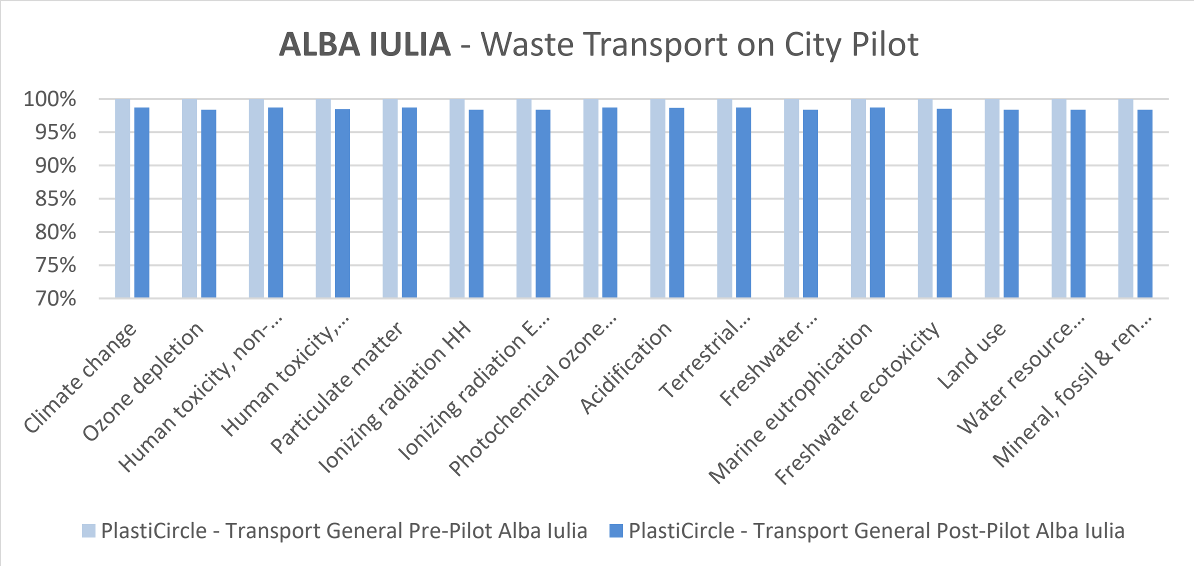


Figure 13 - Impacts for Pre vs Post Pilot TRASNPORT in Alba Iulia

These results might differ for a city pilot with a new collection system fully implemented and when testing the impact from higher areas. Regarding the sorting stage, an evaluation was not performed in Alba Iulia due to difficulties to assess comparative results for environmental impact. On the one hand, Galda Plant is still being setting up and the residue being collected is not purely packaging or plastic but mixed with other dry recyclables and organic matter. Therefore, yield performance presents high level of uncertainty and it was decided to leave a hypothetical scenario based on literature data and approximation but not to extract impact results for this stage.

Impacts of the washing stage and comparison with avoided impacts.

During this whole LCA, "cut off" method has been followed and therefore avoided production of material has not been considered for the different stages of the recycling chain. Furthermore, a comparative evaluation of the washing and pre-treatment processes has been done to appreciate the order of magnitude and benefits for not allowing this material streams ending up in other disposals. Additionally, avoided impact is comparatively shown (green bars) in figure below for Climate change categories. The different among these main fractions are related to the % losses during recycling process (including sorting and washing/pre-treatment), the impact for the production of each type of polymer and their weight in the waste streams (for PlastiCircle case). Approximate avoided impact from these fractions recycling tends to be from 1349 kg CO_2 in the case of PET to 536 in the case of the Plastic Mix depending on above mentioned factors.

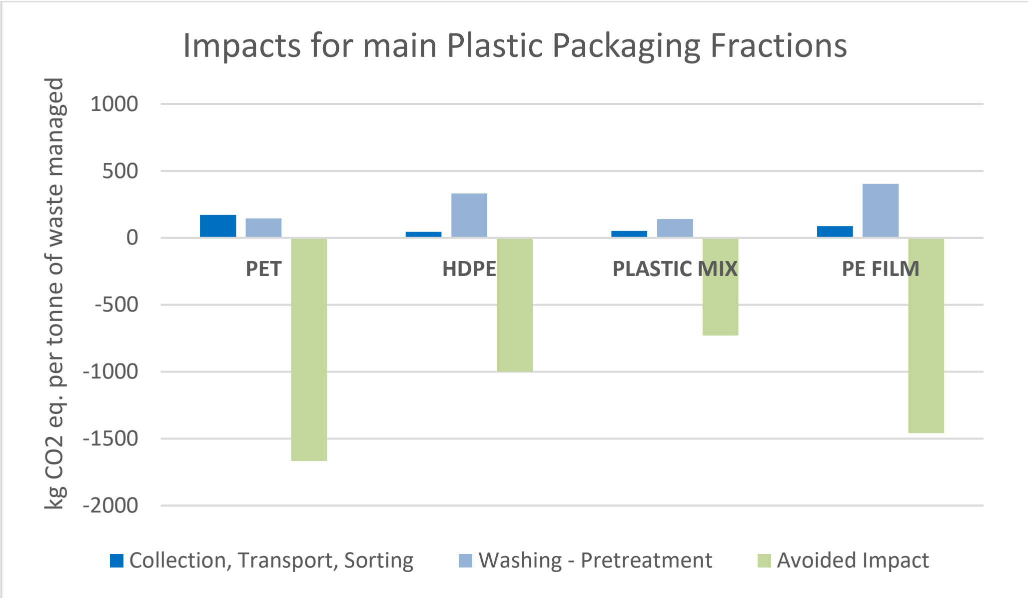


Figure - Impacts from PlastiCircle collection, transport and sorting; washing-pre-treatment stage (blue bars) compared to avoided impact by polymer production (green bars)

2.5. Pilot Cities – Results and Conclusions

PlastiCircle impacts are particularized for 3 pilots, obtaining more representative scenarios for Valencia and Alba Iulia (due to representing the whole implementation of technologies and developments). These pilots have been divided in Collection, Transport and Sorting.

Collection implies the installation and set-up of certain devices and elements for the citizens. The impacts for this stage are related to the use of electronical devices with energy use and the production of PVC cards and PP labels for user's identification. The use of water and detergent for washing containers remains constant for pre-and post-pilot. It has been shown that the impacts from this stage are relatively small compared with the rest of stages (transport and sorting) in categories such as Climate change (2,45% of the total impact on the Collection-Transport-Sorting) and only significant in categories such as **Freshwater eutrophication** and **Mineral, fossil & resource depletion.**

Transport stage presents a remarkable improvement both in Alba Iulia and Valencia pilots, however the type of waste collected makes a difference the potentials improvement to be achieved. Valencia pilots picked up packaging fraction from the packaging container, while Alba Iulia disposed specific containers for PlastiCircle packaging, but the composition of the waste was very similar to the other dry and wet fraction containers (with high content of organic matter). Thus, the truck got full relatively fast after collection the pilot area with not such a big margin to improve. These improvements were important on the pilot site but lose a bit of representativity when considering a whole route. The differences from pre and post situation for the pilot were attributed to a reduction of the distances travelled and the diesel fuel consumed. This meant in a **reduction from 16 to 25% as down and top improvement among the different impact categories** for Valencia pilot, while these improvements where less significant (around 2%) for Alba Iulia pilot due to above mentioned reasons. Utrecht pilot served as validator for PlastiCircle transport optimization algorithms as they were compared to their current software with positive results.

Sorting represents the last stage on cities prior the conditions and pre-treatment process to convert the recovered plastics into new feedstock again. A sorting model based on machinery consumptions and parameters of standardized plants was developed. Valencia case represents the most accurate one as it is based on directly on primary data. Analogously this was developed for Utrecht with literature benchmarking. The model is focused on two main factors: **energy consumed** and **quantities** disposed **to landfill/incineration,** which both depend on the quality of material generated in origin by the citizens (variable improved by PlastiCicle Smart container developments) and the sorting effectiveness yields in the system. Based on Valencia result, it was experimented a decrease of the **14 % reduction for the CO_2 eq. emission for the Climate change** category and significant decreases for other impact categories such Freshwater Ecotoxicity and Land Use.

3. LCA on Industries

For the general LCA evaluation for the industries, it was decided to perform studies the closest to reality as possible using a tangible approach. Thus, it was established to define a benchmark product for each of the industries in order to evaluate the PlastiCircle impacts on the environmental footprint of the products manufactured by the industries within this project.

Main characteristic of the processes to be define is the use of plastic packaging waste to be manufactured on non-packaging application. When the project was initiated (4 years ago), there was no such a pressure on post-consumer feedstocks to be introduced again on close loop packaging applications. However, due to recent European initiatives and legislations, nowadays there is a strong competition among different recycling sectors to obtain these waste streams and to be introduced only in packaging applications again. The project tried to develop solutions to valorise packaging plastic waste which nowadays is still difficult to reuse as food contact packaging applications and is being landfilled/incinerated (i.e., trays or polyolefin films). There is a debate on whether non-packaging applications should use or not packaging inputs and considering the large amount of plastic packaging waste still being disposed on non-recovered streams, new conversion solutions developed within this project are still necessary. Moreover, the research outcomes from the development of PlastiCircle's products can be relevant for other sectors and applications contribution to enhance the possibilities of different plastic streams not being currently considered as technically viable alternatives.

Next, it can be found LCA context and results for the industries analysed:

- **3.1. CRF & PROPLAST – PET & PP Automotive parts**
- **3.2. Interval – PE Film, Garbage Bags**
- **3.3. Hahn Plastics – PP Ground Retention Grids**
- **3.4. Armacell – PET Foam Boards**
- **3.5. Derbigum - PP Construction Roofing Membranes**

3.1. CRF & PROPLAST

3.1.1. Goal and Scope

Product system

On the CRF/Proplast case, two different automotive parts were studied:

- PET (glass fibre reinforced) substituting PA with reinforced fibres.
- Post-consumer as alternative to post-industrial PP

Automotive industry uses high-standard polymers to manufacture these parts such as glass fibres reinforced polyamides. The addition of glass fibres to nylons leads to very significant increases in strength, stiffness, heat distortion temperatures, abrasion resistance and dimensional stability, though properties can be anisotropic - including mould shrinkage, leading to potential distortion. In the case of nylon 6,6, unlike many polymers, this is achieved without loss of impact strength, though elongation to break is, as usual, reduced very substantially.

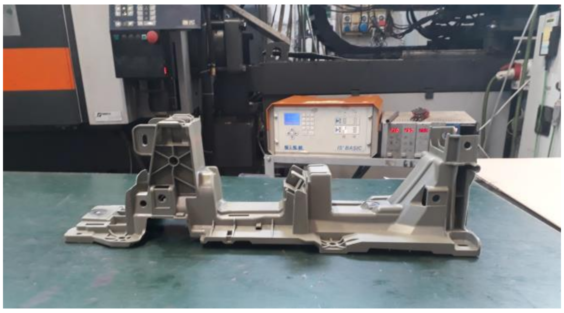


Figure 2 - Injection moulded pieces by CRF/PROPLAST r-PET (left) and r-PP (right)

New European industrial trends regarding the usage of recycled and recyclable materials, stimulated automotive industry to replace virgin materials with recycled materials (PA is not considered a widely recycled stream, even less in packaging sector). Although use of PET is more and more reused as consumer-packaging and food-grade recycled material industry, there is still a gap for this material to fulfil high standards requirements to be reused in automotive parts. Moreover, use of PET in injection-moulded applications is quite challenging, and research done by CRF/Proplast could bring interest from other stakeholders.

- **Manufactured Item:** Automotive piece on r-PETGF20 and r-PP
- **PlastiCircle Development:** Use r-PET on injection-molding application to substitute PA and use PP from post-consumer households' streams instead of post-industrial.
- **Main expected impacts:** Recycled feedstock substitution for virgin polyamide (high impacts on production). Difference on the origin of the material for the r-PP piece (i.e. post-consumer waste streams require more intensive washing than post-industrial)

Goal and scope

Therefore, the **goal** of the study is to compare the performance of the developed solution in PlastiCircle (r-PET), with the PA solution of CRF.
The scope selected for the study is **cradle to gate.**

Functional Unit & Reference flow

As it has been mentioned in D7.1 and D7.2, the functional unit quantifies the performance of a product system and it is used as a reference unit for which the life cycle assessment study is performed, and the results are presented. The **functional unit** of the study is **"to produce 1 ton of injected moulded automotive parts".**
In order to meet the requirements of the above-mentioned Functional Unit, a certain quantity of the different materials for producing 1 ton of injected moulded automotive parts, is required. This quantity is known as **reference flow**, and it is detailed in Table 26.

Table 26. Reference flow for producing 1 ton of injected moulded automotive parts

Material
1 ton of injected moulded automotive parts from PA
1 ton of injected moulded automotive parts from r-PET

3.1.2. System Boundaries and Assumptions

<u>System boundaries</u>

The boundaries specify the unit processes that will be considered in this study. The system boundaries are defined through the stages of the products' life cycle. In this case, a **cradle to gate** approach has been considered, this takes into consideration the steps from the extraction of the raw material to the manufacturing stage. This scope is detailed in Figure 3 and Figure 4.

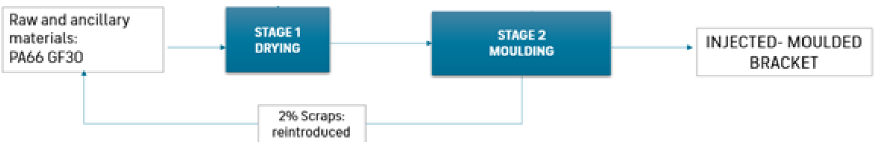


Figure 3. Scheme of the production of the automotive parts from PA

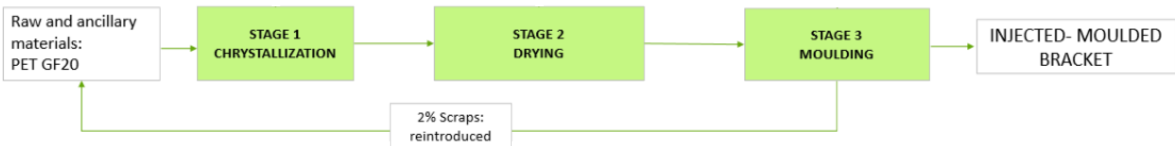


Figure 4. Scheme of the production of the automotive parts from r-PET

<u>Assumptions</u>

The following assumptions for the Life Cycle Assessment of the production of the automotive parts has been made.

- Information regarding **CRF benchmark products** was collected from CRF through meetings and questionnaires forms developed by ITENE and SINTEF. Questionnaires examples can be seen on **Annex 1: Questionnaires**.

- **Energy**: Inventory on energy consumption should be also adapted depending on the material that is extruded, due to noticeable differences within reference taken by Ecoinvent inventory. In this line, references from Elduque A. et al. (2015) were considered to adapt the process. As explained on this study Ecoinvent considers more than 62% of the weight impacts related to energy consumption, the rest are allocated to heat the plant and additives such as colorants, lubricants, stabilizers and pigments…). Main clarification on the assumption for energy consumption on injection-moulding con be found in **8 Annex: Injection-Moulding Consumption**.

- **Transport**: Regarding differences with PA obtention in comparison with PET and its transformation, there are no substantial differences or at least those which could be measured. According to previous transport procedures to convert PET consumer waste into new streams to manufacture automotive parts, it was calculated 1000-1500 km (from south to Northern Italy and vice-versa), which has an impact of 1-2 % of the total process. This transport distance is not significantly different from the ones done to source the virgin pellet material. In addition, due to the fact that density of these two compounds are certainly similar, we can assume that transport will not affect significantly the environmental impacts.

3.1.3 Inventory data

The inventory data for the production of 1 ton of automotive parts from two different raw materials: PA and r-PET is detailed in the ¡Error! No se encuentra el origen de la referencia.

3.1.4. Life Cycle Assessment

<u>Life cycle assessment of PA automotive parts</u>

In Figure 5 the impacts of the production of 1 ton of PA automotive parts are detailed. The life cycle assessment divides the impacts in the production of the polyamide, the use of glass fibre and the injection process.

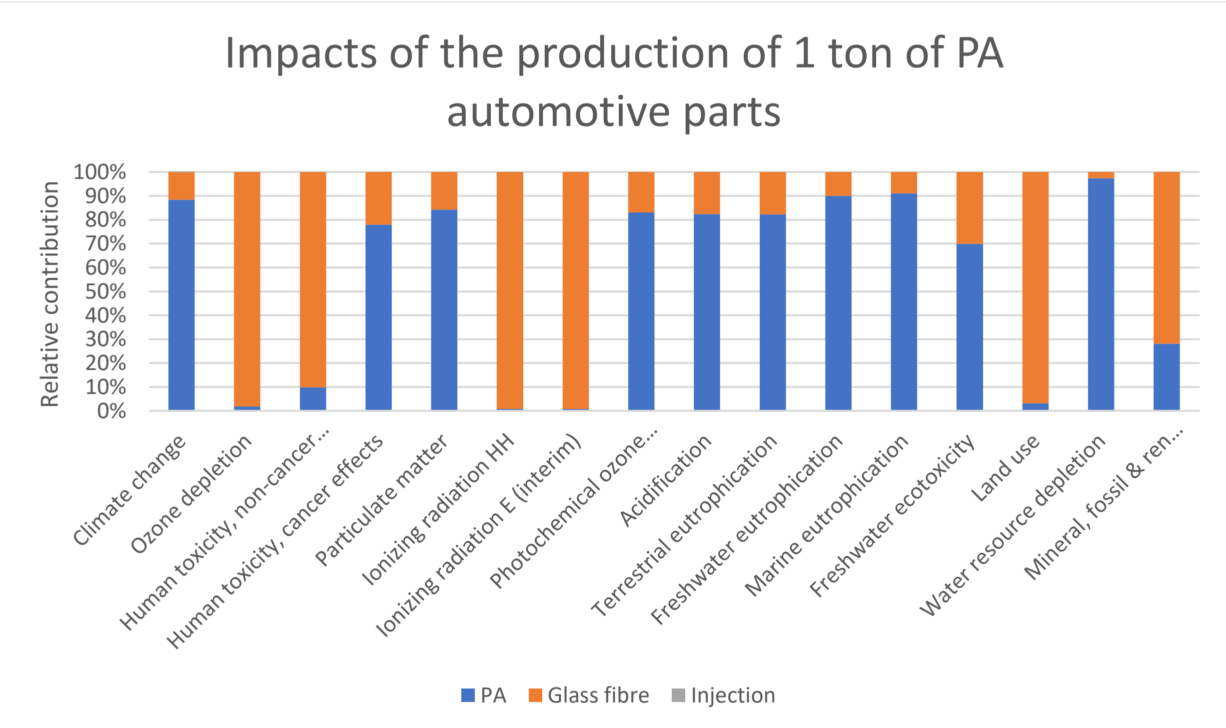


Figure 5. Impacts of the production of PA automotive parts

In the case of the **extraction of the raw materials**, the polyamide and the reinforcing glass fiber accounts for the contribution in the different impact categories. The polyamide has the major contribution in the majority of the impact categories due to the treatment of the waste generated during its production, with values up to 90% in the eutrophication impact categories, as well as in climate change, acidification, photochemical ozone depletion and water resource depletion. On the other hand, the glass fiber has higher value than the PA in the categories of ozone depletion, land use and human toxicity with non-cancer effects, due to its production process.

As it is shown in the figure above, the **injection process** does not have a remarkable contribution to the different impact categories.

Life cycle assessment of the production r-PET automotive parts

In Figure 6 are detailed the impacts of the production of 1 ton of r-PET automotive parts. In this case, the impacts of the raw materials are divided into the process of recycling PET, the reinforcing glass fiber and the additives.

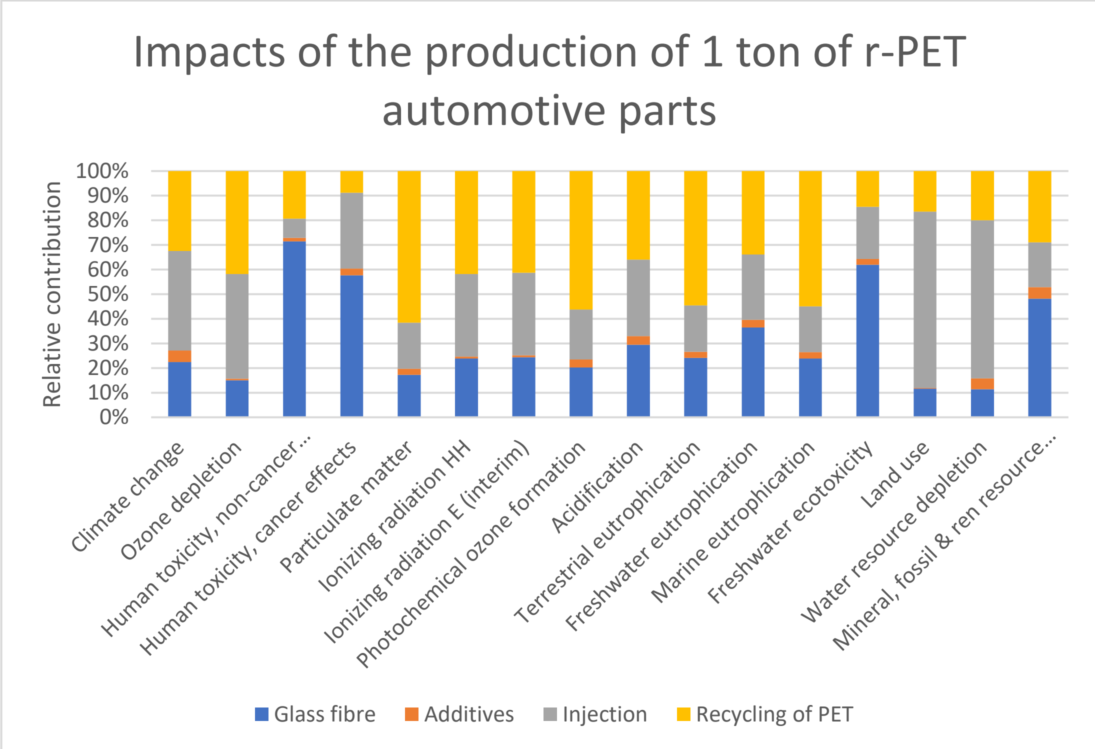


Figure 6. Impacts of the Production of r-PET automotive parts

As it is shown in the figure above, the **recycling of PET** represents the largest contribution in the different impact categories, with values around 60% in categories such as particulate matter, photochemical ozone formation, terrestrial and marine eutrophication. For the rest of the categories, the contribution is down to 40%. The results of this process (Recycling of PET) are described in section 2.3, as it includes the following stages: collection, transport, sorting, washing and pre-treatment.

The **injection process**, the second largest contributor to the overall impacts, has a higher influence in categories such as land use and water resource depletion, due to the ancillary materials and the energy consumption mix used in the process. In these categories, the values of the contribution are around 70%. In climate change and ozone depletion, the contribution is around 40%.

The **glass fiber** has also an important contribution, especially in the categories of human toxicity and freshwater ecotoxicity, where the values of the contribution is 70% and 60% respectively.

These higher values are due to the energy consumption used for the production of the glass fiber. In the category of minerals, fossil resource depletion, the contribution of the glass fiber is around 50%, and is related to the resources used as raw materials such as the boric acid.

Finally, in the case of the **additives,** their contributions to the different impact categories are not significative, as it can be seen in the figure above, the values are around or inferior to 5%.

3.1.5 Conclusions

In this section, a comparison among the values obtained for the different impact categories is made in Table 27. As it is shown in the table below, in the categories of climate change, human toxicity with cancer effects, freshwater and marine eutrophication, freshwater ecotoxicity and water resource depletion, the difference among the values with the same product made with r-PET is superior to minus 65%. In categories such as human toxicity with non cancer effects, particulate matter, photochemical ozone formation, acidification and mineral fossil resource depletion, the values are also inferior for the automotive parts made with r-PET. However, in ozone depletion, land use, the impacts are superior in the product made with r-PET. This is due to the process of recycling PET post-consumer, where the sorting and washing accounts for the majority of the impacts.

Therefore, taken above into consideration, changing the raw material, from polyamide to recycled PET, the impacts for production 1 ton of automotive parts gets reduced for most of the impacts on below table.

Table 27 Comparison among the values for producing 1 ton of automotive parts with PA and r-PET

Impact category	Unit	LCA 1 ton PA automotive parts	LCA 1 ton r-PET automotive parts	Difference %
Climate change	kg CO2 eq	**7,10 ·10³**	**2,18 ·10³**	**-69,30%**
Ozone depletion	kg CFC-11 eq	2,26 ·10⁻⁴	3,71 ·10⁻⁴	64,26%
Human toxicity, non-cancer effects	CTUh	2,86 ·10⁻⁴	2,27 ·10⁻⁴	-20,52%
Human toxicity, cancer effects	CTUh	**5,47 ·10⁻⁵**	**1,30 ·10⁻⁵**	**-76,23%**
Particulate matter	kg PM2.5 eq	2,86 ·10⁰	1,59 ·10⁰	-44,40%
Photochemical ozone formation	kg NMVOC eq	1,86 ·10¹	9,48 ·10⁰	-49,13%
Acidification	molc H+ eq	3,34 ·10¹	1,21 ·10¹	-63,86%
Terrestrial eutrophication	molc N eq	6,16 ·10¹	2,80 ·10¹	-54,45%
Freshwater eutrophication	kg P eq	**2,78 ·10⁻¹**	**4,89 ·10⁻²**	**-82,41%**
Marine eutrophication	kg N eq	**1,09 ·10¹**	**2,62 ·10⁰**	**-75,86%**
Freshwater ecotoxicity	CTUe	**4,16 ·10³**	**1,27 ·10³**	**-69,53%**
Land use	kg C deficit	6,42 ·10²	7,42 ·10²	15,60%
Water resource depletion	m3 water eq	**2,85 ·10¹**	**4,00 ·10⁰**	**-85,96%**
Mineral, fossil & ren resource depletion	kg Sb eq	3,46 ·10⁻²	2,93 ·10⁻²	-15,36%

In the following figures the comparison among the impact categories in absolute values, where the difference between the two products is higher than -65% are described in detail. .

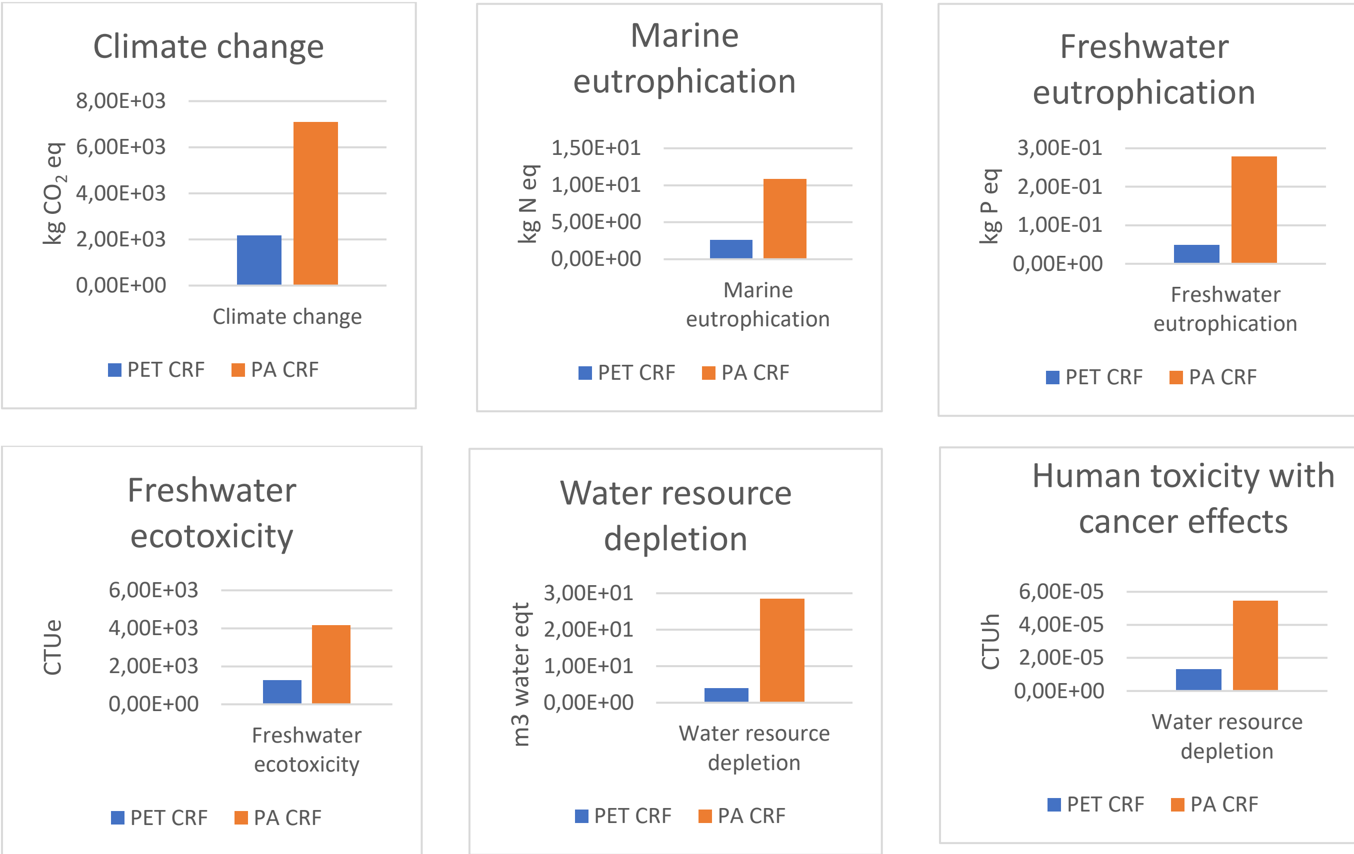


Figure 7. Comparison between the two different products of CRF: PA automive part and R-PET automotive part, in the impact categories with the major difference

3.2. Interval

3.2.1. Goal and Scope

__Product system__

Main goal on Interval´s product LCA is to evaluate the impact of the production of post-consumer PE film garbage bags. During the usual operation Interval produces post-industrial PE pellets and manufactures garbage bags as end-products. PlastiCircle's approach considers PE from post-consumer streams as a replacement to post-industrial PE. Interval is not just a converter but also act as a recycler, since it receives PE film bales, pre-treats the material and then produces granules to be blown-extruded into garbage bags. Therefore, in the first stages of the process, it integrates some burden considered for other feedstocks on the washing/pre-treatment stage (**2.3. General Washing Pre-Treatment**). **Figure 3** shows the produced item by Interval:

Figure 14 - Bags manufactured by Interval using post-consumer feedstock (right image)

- **Manufactured Item:** Garbage bag r-PE (info on Interval's web)
- **PlastiCircle Development:** Blown film extruded PE film from post-consumer streams.
- **Main expected impacts:** Use of a new feedstock material harder to process. Post-consumer material requires a more intensive washing in comparison to post-industrial one, however, it also broadens sources of input material.

__Goal and scope__

The **goal** of the study is to compare the performance of the developed solution in PlastiCircle (made of PE from post-consumer orgigin), with the current garbage bag made of of PE from post-industrial origin .

The scope selected for the study is **cradle-to-gate**.

__Functional Unit & Reference flow__

The **functional unit** of the study is the production of **"1 ton of garbage Bag"**
In order to meet the requirements of the above-mentioned Functional Unit, a certain quantity of the different materials for producing 1 ton of garbage bag, is required. This quantity is known as **reference flow**, and it is detailed in Table 28.

Table 28. Reference flow for producing 1 ton of garbage bag

Material
1 ton of garbage bag from PE post-industrial
1 ton of garbage bag from PE post-consumer

3.2.2. System Boundaries and Assumptions

System boundaries

The boundaries specify the unit processes that will be considered in the studied analysis. The system boundaries are defined through the stages of the products' life cycle. In this case, a **cradle to gate** approach has been considered, this takes into consideration the steps from the extraction of the raw material to the manufacturing stage. In this case, as the raw materials are in both cases from recycled materials, only the impacts of the recycling process are taking into consideration. This scope is detailed in Figure 8 and Figure 9.

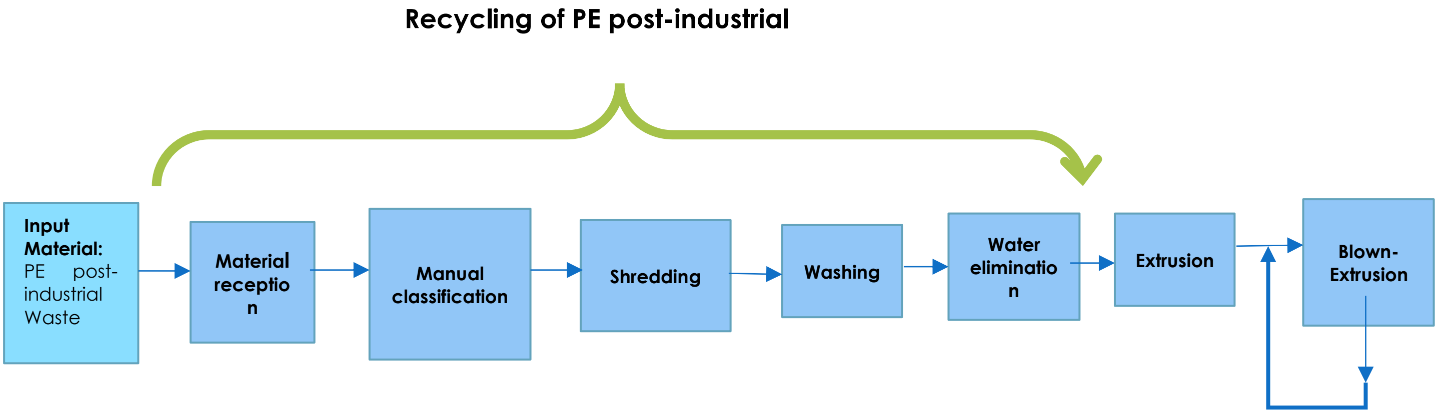


Figure 8. Scheme of the production of garbage bags from PE post-industrial

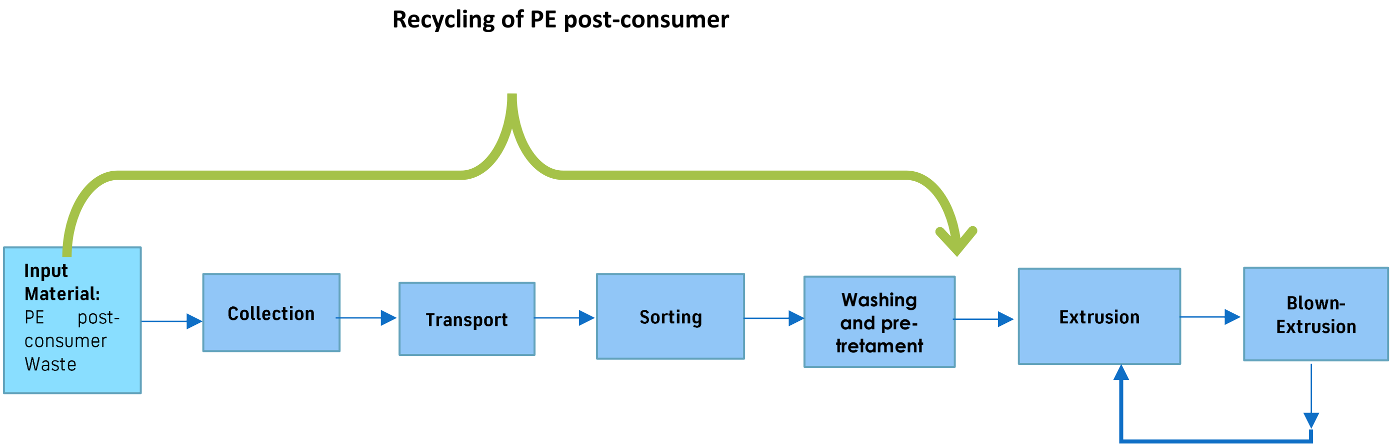


Figure 9. Scheme of the production of garbage bags from PE post-consumer

Assumptions

- Information regarding **Interval benchmark product** was collected from Interval through questionnaires forms developed by ITENE and SINTEF and direct communication. Questionnaires examples can be seen on **Annex 1: Questionnaires.**

- Interval is not just a converter but also a recycler. It receives PE bales and processes into extruded pellet or blown-extruded products. As main difference with the rest of the industries, the washing stage has been considered in the evaluation of Interval system boundaries. It has been compared with a detailed post-consumer washing (differences on chemical additives, use of waste, energy consumptions, etc.)

- Interval receives the PE post-industrial directly from the industries, this transport is not included in the LCA as it is believed that there is no significant difference between the transport of both materials (post-industrial and post-consumer) to Interval.

- In the case of the model of PE post-consumer, this waste requires collection and transport to a sorting plant. After the classification in the sorting plant, it is transported to Interval. This transport is also not included in the LCA.

- ¡Error! No se encuentra el origen de la referencia. **Figure 1**describes Interval processes from bales reception to blown-extrusion of recycled films. Their processes are not described but their specific data has been included in the inventory.

- Energy consumption, water use, fuel/diesel and other resources/waste disposals are based on primary data.

3.2.3. Inventory data

The inventory data used for the life cycle assessment of 1 ton of garbage bag made from PE post-industrial, and 1 ton of garbage made from r-PE post-consumer is detailed in the ¡Error! No se encuentra el origen de la referencia..

3.2.4 Life Cycle Assessment

In the following section, the impacts of producing 1 ton of garbage bag made of PE post-industrial, and from PE post-consumer, are detailed.

Life cycle assessment of 1 ton of garbage bag produced from PE post-industrial

In **¡Error! No se encuentra el origen de la referencia.** the impacts of the production of 1 ton of g arbage bag-PE post-industrial are detailed. The PE post-industrial is directly sent from industries to INTERVAL.

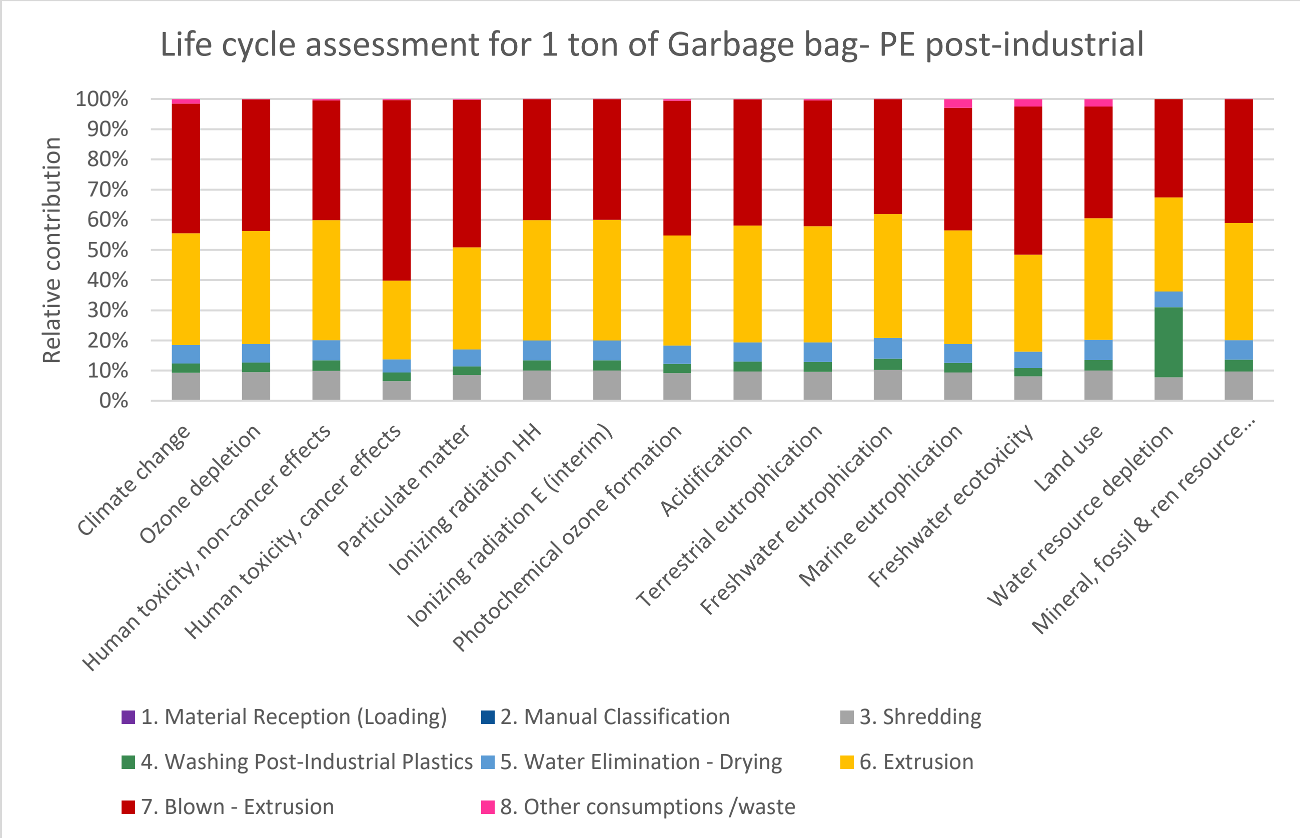


Figure 10. Life Cycle Assessment for 1 ton of garbage bag-PE post-industrial

As it is shown in the figure above, the extrusion and blown-extrusion processes are the major contributors to the impacts in the different categories. In the case of the **extrusion**, the electricity is the input that contributes the most to the different impact categories, whereas the diesel has little contribution. The extrusion process has a relative contribution to the impact categories of around 40-50%.

In the case of the **blown-extrusion process**, electricity is also the input that has the major contribution to the impacts. This process influences in the different impact categories with values around 50-60%.

The **shredding** process contributes also to the different impact categories due in a large extent to the electricity consumption. The values of the contribution of the shredding process to the categories are around 10% in all impact categories.

Finally, the **washing** of the post-industrial plastics influences less than 5% in the different impact categories, except for water resource depletion where the impacts are around 20% because of the water consumption needed for washing of the plastics.

The contribution from the remaining of the stages needed for producing 1 ton of garbage PE post-industrial is not relevant. It should be pointed out that for the stage of other consumption/waste, in the category of water resource depletion, it has a negative impact, which decreases the total value of the category. This value is due to the treatment of the leachate produced in the landfill.

In the annex are the values of the different impact categories.

<u>**Life cycle assessment of 1 ton of garbage bag produced from PE post-consumer**</u>

In Figure 11, the impacts of the production of 1 ton of garbage bag-PE post-consumer are detailed. For the garbage bag produced from PE post-consumer, the waste needs to be collected, transported to the sorting plant and sorted in order to be sent to Interval.

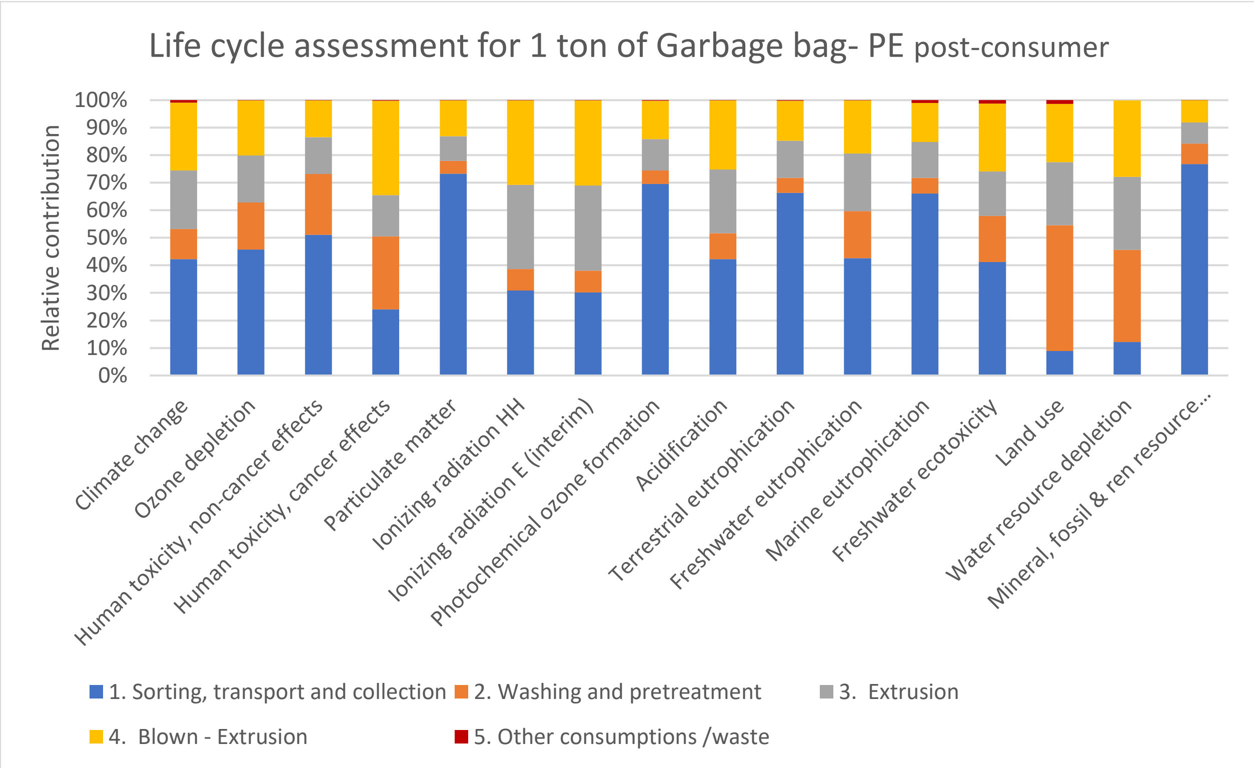


Figure 11. Life Cycle Assessment for 1 ton of garbage bag-PE post-consumer

As it can be seen in the figure above, the stage of **sorting, transport and collection**, has the major contribution to the different impact categories. This stage is detailed in depth in section 3. For the impact categories particulate matter, photochemical ozone formation and mineral fossil resource depletion, this relative contribution has values up to 70%-75%. In this stage, the transport of the waste to the sorting plant is the input that most contributes to the impact categories.

The stages of **extrusion and blown-extrusion**, are in the second place in relation to the contribution to the impact categories analysed. In both cases, the electricity consumption is the input that contributes most to the different impact categories. The values of these stages vary from 10% to 30%.

The **washing and pre-treatment stage** has also an important contribution to the different impact categories, especially in categories such as land use and water resource depletion, with values of 45% and 35% respectively.

Finally, the stage of **other consumptions/waste** it should be pointed out that for the category of water resource depletion, it has a negative impact, which decreases the total value of the category. This value is due to the treatment of the leachate produced in the landfill.

In the annex are the values of the different impact categories

3.2.5 Conclusions

In this section a comparison between the impacts of the two products, a garbage bag with PE post-industrial and PE post-consumer is made in Table 29. As it is detailed, 1 ton of garbage bag with PE post-industrial has lower impacts than 1 ton of garbage PE post-consumer. This is due to the washing treatment of the PE post-consumer as well as the stages needed for recycling this type of plastic (collection, transport and sorting), which is intensive in resources (See section 3.2). In the case of the recycling of PE post-industrial is simpler, as it is directly transported to Interval, and the material reception, shredding and washing stage requires less resources. This is described in Figure 12.

Table 29. Comparison among the values for producing 1 ton of garbage bag with PE post-industrial and PE post-consumer

Impact category	Unit	LCA 1 ton of garbage bag with PE post-industrial	LCA 1 ton of garbage bag with PE post-consumer	Difference %
Climate change	kg CO2 eq	$7{,}66 \cdot 10^{2}$	$1{,}43 \cdot 10^{3}$	46,35%
Ozone depletion	kg CFC-11 eq	$1{,}14 \cdot 10^{-4}$	$2{,}87 \cdot 10^{-4}$	60,48%
Human toxicity, non-cancer effects	CTUh	$2{,}01 \cdot 10^{-5}$	$7{,}13 \cdot 10^{-5}$	71,77%
Human toxicity, cancer effects	CTUh	$1{,}29 \cdot 10^{-6}$	$3{,}18 \cdot 10^{-6}$	59,52%
Particulate matter	kg PM2.5 eq	$3{,}35 \cdot 10^{-1}$	$1{,}33 \cdot 10^{0}$	74,80%
Photochemical ozone formation	kg NMVOC eq	$2{,}24 \cdot 10^{0}$	$7{,}33 \cdot 10^{0}$	69,48%
Acidification	molc H+ eq	$5{,}03 \cdot 10^{0}$	$8{,}85 \cdot 10^{0}$	43,16%
Terrestrial eutrophication	molc N eq	$7{,}47 \cdot 10^{0}$	$2{,}19 \cdot 10^{1}$	65,97%
Freshwater eutrophication	kg P eq	$1{,}42 \cdot 10^{-2}$	$3{,}69 \cdot 10^{-2}$	61,66%
Marine eutrophication	kg N eq	$6{,}99 \cdot 10^{-1}$	$2{,}12 \cdot 10^{0}$	67,01%
Freshwater ecotoxicity	CTUe	$1{,}60 \cdot 10^{2}$	$3{,}41 \cdot 10^{2}$	53,05%
Land use	kg C deficit	$1{,}27 \cdot 10^{2}$	$1{,}72 \cdot 10^{2}$	26,00%
Water resource depletion	m3 water eq	$1{,}49 \cdot 10^{0}$	$3{,}18 \cdot 10^{0}$	53,03%
Mineral, fossil & ren resource depletion	kg Sb eq	$1{,}99 \cdot 10^{-3}$	$1{,}14 \cdot 10^{-2}$	82,53%

In the following figure a comparison among the recycling stages of PE post-industrial, which includes the impacts of: material classification, shredding, washing and elimination of water; with the recycling stages of PE post-consumer: collection, transport, sorting, washing and pre-treatment, is made. As it can be seen, the washing of the PE post- industrial has lower impacts, as usually plastics with an industrial origin are cleaner and have more purity than those whose origin is post-consumer, where the different types of plastic are mixed and are usually dirtier.

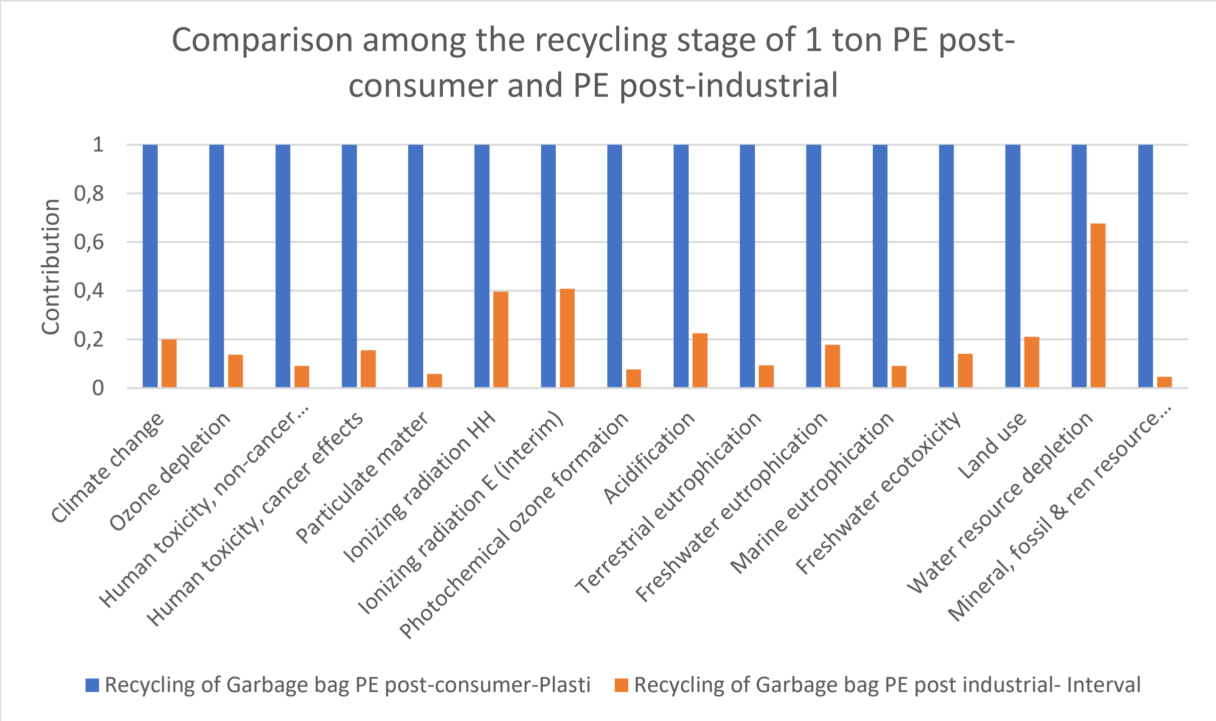


Figure 12. Comparison among the recycling stages of bag PE- post consumer and PE post-industrial

However, if post-consumer films plastics were not recycled, their end of life would be most likely incineration. In the case of climate change, recycling the PE is a better option than the incineration of plastics, as its is depicted on below figure:

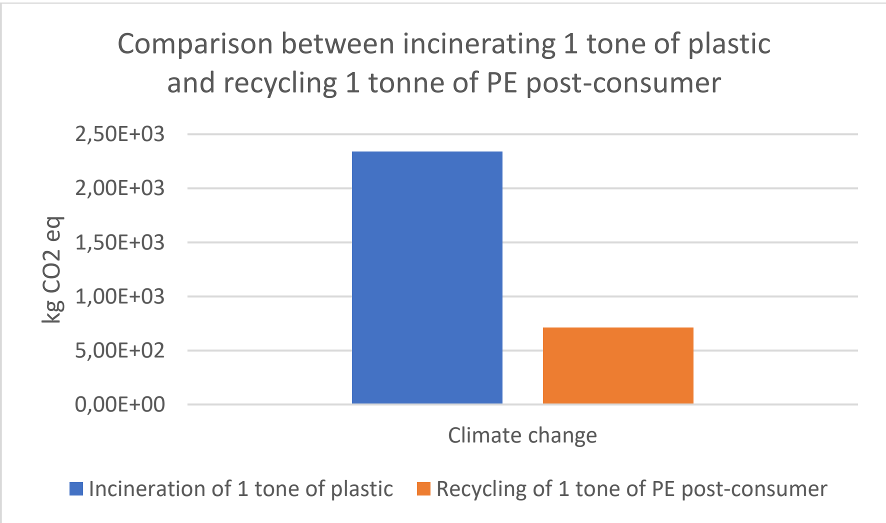


Figure 13. Comparison in climate change among incinerate 1 tone of plastic and recycling 1 tone of PE post-consumer

3.3. Hahn Plastics

3.3.1. Goal and Scope

Product system

Hahn Plastics has been manufacturing post-consumer/post-industrial polyolefins for the last 20-30 years. In order to develop and test new potential applications on PE and PP, flexible PP sources were explored. Nowadays, PP flexible fraction is difficult to source on the one side and not extensively injection-moulded due to the need of specific properties (i.e. MFI) to enable the production of high-value added products.

Figure 14 - Hahnpaive manufacyrured by Hahn Plastics for ground reinforment and surfaces applications.

- **Manufactured Item:** Injection moulded r-PP piece (technical description: Hahn's website)
- **PlastiCircle Development:** Introduction of flexible post-consumer PP for injection molding applications.
- **Main expected impacts:** substitution of PI feedstock for post-consumer one. Might be difference on the washing, pre-treatment steps. Post-consumer material was manufactured directly (without pelletizing) avoiding the energy consumption related to this step.

Goal and scope

The **goal** of the study is to compare the performance of the developed solution in PlastiCircle (PP from post-consumer), with the current solution of PP post-industrial from HANN. In this study four scenarios will be compared, which are detailed in **¡Error! No se encuentra el origen de la referencia.** with different proportion of recycled PP post-consumer and recycled PP post-industrial.

Table 30. Different scenarios to compare

Scenario	% Post-industrial	% Post-consumer
Scenario 1	100	0
Scenario 2	50	50
Scenario 3	30	70
Scenario 4	20	80

The **scope** selected for the study is cradle to gate.

Functional Unit & Reference flow

The **functional unit** of the study is **"to produce 1 ton of Hahn paive"**
In order to meet the requirements of the above-mentioned Functional Unit, a certain quantity of the different materials for producing 1 ton of garbage bag, is required. This quantity is known

as **reference flow**, and it is detailed in Table 28.

Table 31. Reference flow for producing 1 ton of garbage bag

Scenario	Flow reference (ton)
Scenario 1	PP Post-industrial: 1
	PP Post-consumer: 0
Scenario 2	PP post-industrial: 0,50
	PP post-consumer: 0,50
Scenario 3	PP post-industrial: 0,30
	PP post-consumer: 0,70
Scenario 4	PP post-industrial: 0,20
	PP post-consumer: 0,80

3.3.2. System Boundaries and Assumptions

System boundaries

The boundaries specify the unit processes that will be considered in the studied analysis. The system boundaries are defined through the stages of the products' life cycle. In this case, a **cradle-to-gate** approach has been considered, this takes into consideration from the extraction of the raw material to the manufacturing stage. In this case, as the raw materials are in both cases from recycled materials, only the impacts of the recycling process are taking into consideration. This scope is detailed in Figure 15.

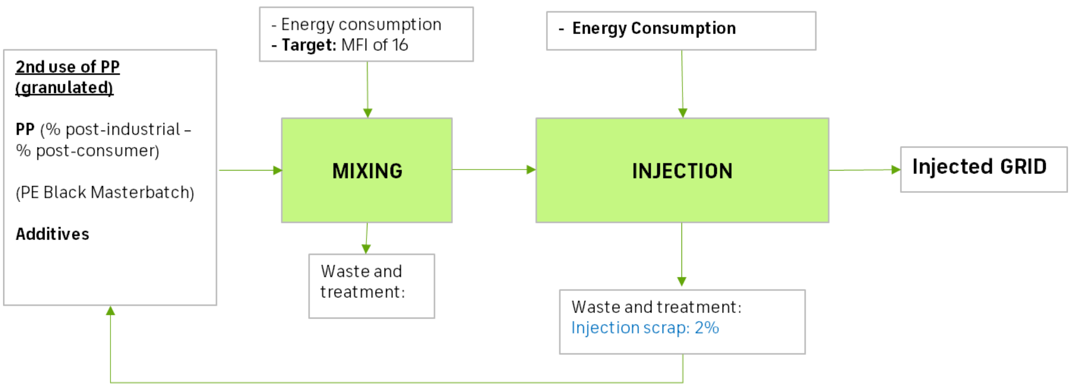


Figure 15. Hahn Process for injection moulding of PP Hahnpaive

➔ Assumptions

- Information regarding **Hahn benchmark product** was collected with the help and advice from Hahn, with close contact and providing information on questionnaires forms developed by ITENE and SINTEF. Questionnaires examples can be seen on **Annex 1: Questionnaires.**
- The information regarding the manufacturing of the product was provided by Hahn.
- Regarding the recycling process of the different types of PP used in Hahn paive, the PP post-consumer inventory data have been provided by the Plasti circleresults of the first part

of this deliverable. The inventory data regarding the PP post-industrial recycling process has been provided by CRF.

- One of the additives in the mixing process has not been modelled, as it represents less than 5% of the mass of this process.

- Main steps on Hahn's process are described on Figure 15
-
- AssumptionsThe injection process has been modelled for specific energy consumption from the process with detail kWh/ton processes (provided by Hahn) together with consideration by [27] as furtherly explained on **7.5 Annex 5** – Inventories for Collection, Transport and Sorting on Valencia Pilot

- The reason for not including the transport of both materials to Hahn, it is because it is an assumption of 500 km and a transported quantity of 1 ton, therefore, the impacts will be equal in both cases.

3.3.3 Inventory data

The information of the data inventory for this process are detailed in the confidential Annex 7.9

3.2.4 Life Cycle Assessment

Life cycle assessment for the production of 1 ton of Hahnpaive from PP post-industrial (including washing and pre-treatment)

In Figure 16 the results of the process of recycling (this step includes washing and extrusion) the PP post-industrial are shown. In Figure 17 are detailed the results of the life cycle assessment for producing 1 ton of Hahnpaive from PP post-industrial.

As it is represented in the first figure, the **electricity consumption** has the major contribution to the different impact categories in the process of recycling PP post-industrial, with values up to 90% in most of the cases. Only in categories such as human toxicity and freshwater and marine eutrophication, this value is lower, because of the contribution of the **wastewater treatment**. This contribution is related to the pollutant substances that could be included in the water flow once treated, which returns to the natural water streams. In the category of water resource depletion, the treatment of the wastewater has a negative impact, which means that the total value of this category decreases as a result of it. The input of **water consumption** especially affects to the category of water resource depletion with a contribution of 40%.

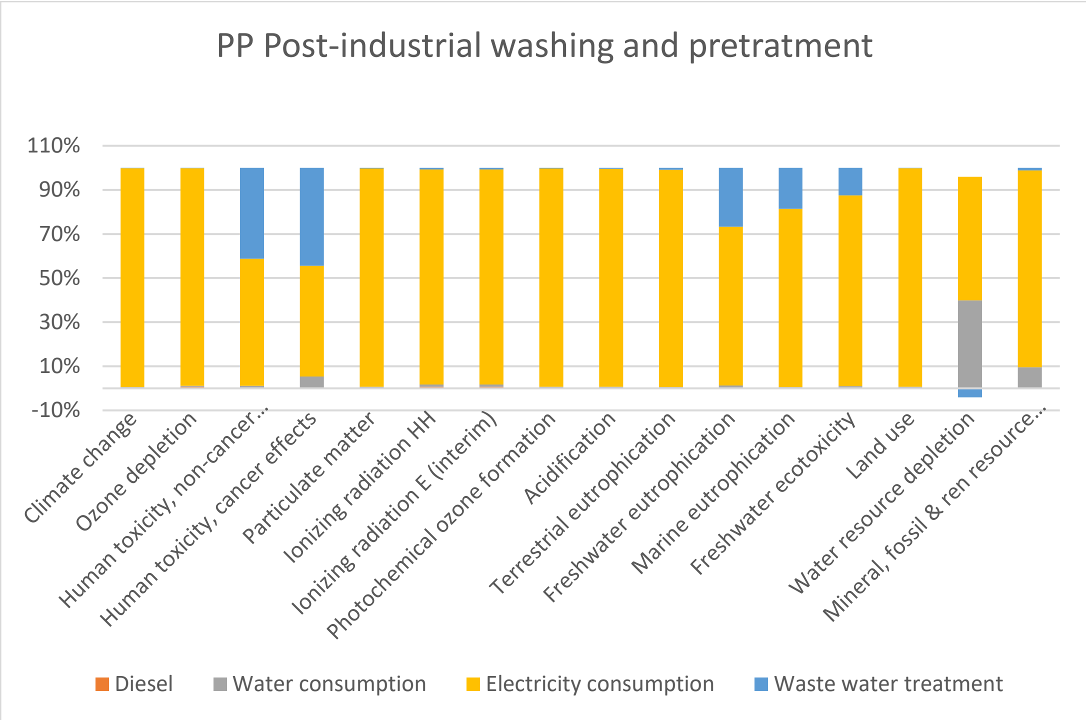


Figure 16. Results of of the assessment of the washing process of PP post-industrial

In Figure 17 the LCA for the production of 1 tone of Hahnpaive made of PP post industrial is represented. The process of **washing the PP post-industrial** has the major contribution to the different impact categories, especially on water resource depletion because of the water consumption (the contribution is higher to 90%). In ozone depletion and land use, the contrbution is among 50-60%., this is due to the electricity mix used by the ecoinvent database and the additives. For the rest of the categories the contribution is inferior to 50%.

In second place, the **injection moulding** process also have an important contribution in the different impact categories, especially freshwater eutrophication, where these contribution values are around 50%. The contribution of the injection moulding to the different categories is related to the electricity. For the rest of the categories the relative contribution is inferior to 40%.

Regarding the **mixing process**, the category with the highest contribution is the human toxicity, with a contribution of 40%, and freshwater ecotoxicity, where this contribution decreases to 30%. This is due to the treatment of the waste produced in obtaining of the ancillary materials. In particulate matter, the relative contribution is also important, as the value are around 30%, this contribution is related to the additive use for mixing the colour masterbatch. For the rest of the impact categories, the contribution is lower than 20%.

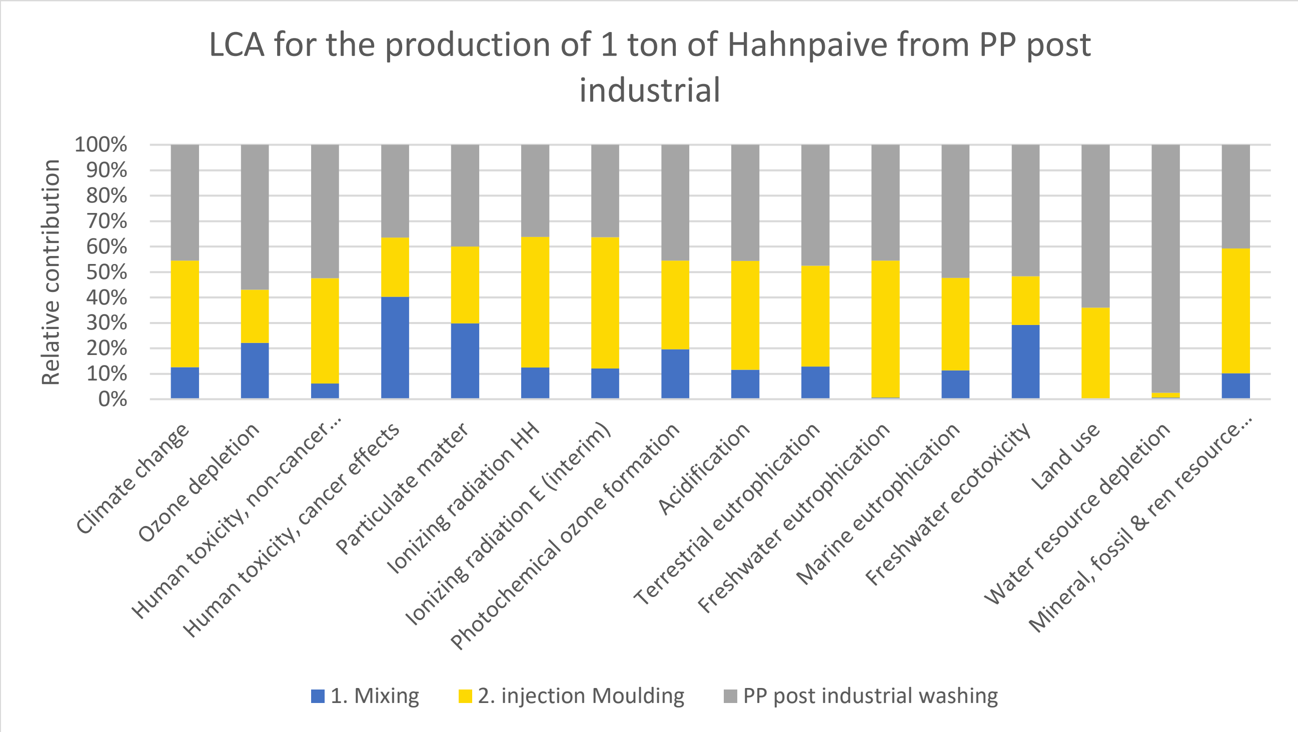


Figure 17. Results of the life cycle assessment of producing 1 ton of Hahnpaive from PP post-industrial

Life cycle assessment for the production of 1 ton of Hahnpaive from PP post-consumer

In Figure 18 is detailed the contribution of the different stages to produce 1 ton of Hahnpaive from PP post-consumer.

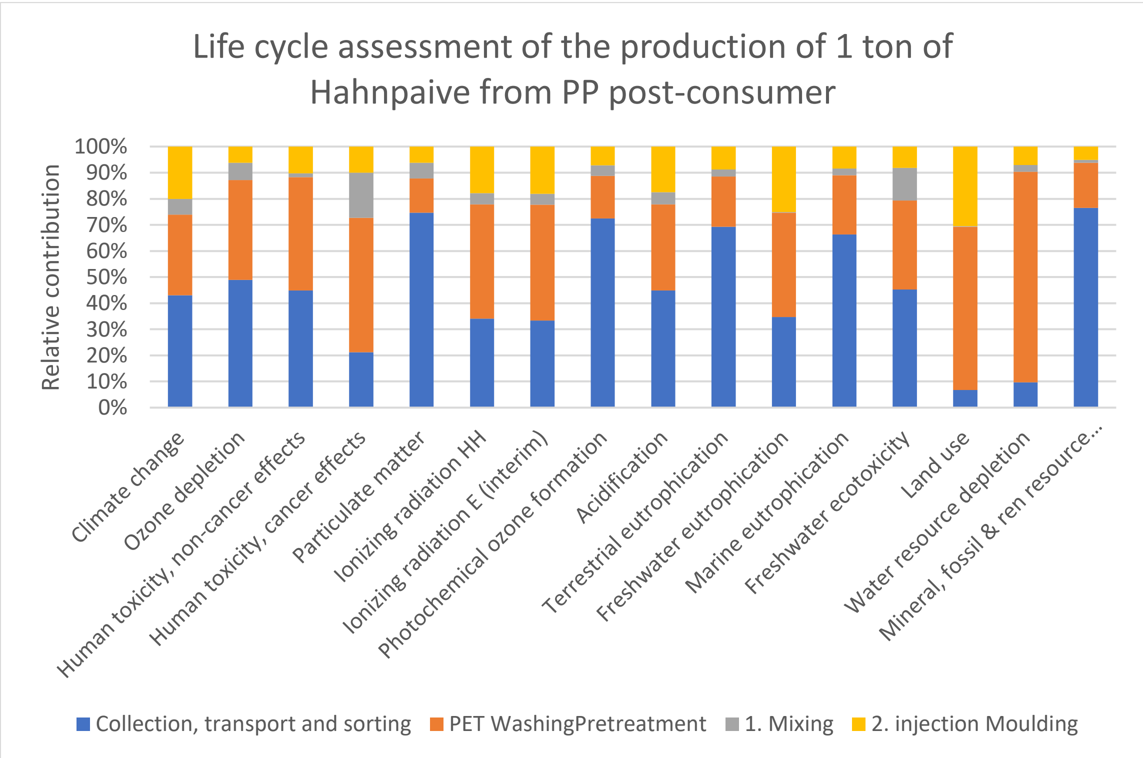


Figure 18. Life cycle assessment of the production of 1 ton of Hanhpaive from PP post-consumer

As it can be seen in the above figure, the **collection, transport and sorting**, accounts for most of the impacts in the different categories. In particulate matter and photochemical ozone formation the contribution is up to 70%, which Is especially due to the transport of the waste to the sorting plant. In mineral, fossil &ren resource depletion, where the contribution is also around 70%, it is related to the collection stage.

The **PET washing and pre-treatment** has the major contribution in categories such as a water resource depletion, and land use, with a contribution f 80% and 60% respectively. In the rest of the categories the contribution is around 35%. A more in deep explanation of the impacts of this process is detailed in **section 2.3** and **7.6 Annex 6 – Washing Conditions**.

The **injection moulding** process has also an important contribution in land use where the value is 30%. This contribution is related to the electricity consumption, For the rest of the categories the values are lower to 25%.

Finally, the **mixing process,** has a lower contribution to the different impact categories, where the maximum value is 15% in human toxicity, and 10% in freshwater ecotoxicity, which is due to the treatment of the waste produced in obtaining of the ancillary materials.

3.3.5 Conclusions

As it can be seen in Figure 17 and Figure 18, in the case of the production of Hahnpaive from PP post-consumer, the recycling process (which includes the collection, transport and sorting, as well as the PET washing and pre-treatment), accounts for almost 80% to 90% of the impacts. Whereas in the PP post-industrial recycling which includes the washing (as the material is directly transported from the industries to the washing plant), accounts for around the 50% of the impacts.

In Table 32 is detailed the comparison between the values in the different categories for producing 1 ton of Hahnpaive made of either post-industrial PP or post-consumer PP. As it can be seen, 1 ton of PP post-industrial has a lower impact than post-consumer, especially because of the differences in its recycling, as it has been commented above. Only in the category of water resource depletion, the recycling of PP post-consumer shows a lower value, as it uses less water during the washing stage.

The values of the completed life cycle are detailed in the annex 7.9

Table 32. Values of the LCA of 1 ton of Hahn paive made from PP post-industrial and 1 ton of Hahn paive made from PP post-consumer

Impact category	Unit	LCA 1 ton of Hahnpaiv from PP post-industrial	LCA 1 ton of Hahnpaiv from PP post-consumer	Difference %
Climate change	kg CO2 eq	$6{,}27\cdot10^{2}$	$1{,}31\cdot10^{3}$	52,12%
Ozone depletion	kg CFC-11 eq	$6{,}88\cdot10^{-5}$	$2{,}32\cdot10^{-4}$	70,30%
Human toxicity, non-cancer effects	CTUh	$1{,}68\cdot10^{-6}$	$6{,}85\cdot10^{-5}$	75,45%
Human toxicity, cancer effects	CTUh	$1{,}09\cdot10^{-6}$	$2{,}54\cdot10^{-6}$	57,09%
Particulate matter	kg PM2.5 eq	$2{,}51\cdot10^{-1}$	$1{,}23\cdot10^{0}$	79,68%

Photochemical ozone formation	kg NMVOC eq	$1,42 \cdot 10^{0}$	$6,87 \cdot 10^{0}$	79,36%
Acidification	molc H+ eq	$3,22 \cdot 10^{0}$	$7,90 \cdot 10^{0}$	59,21%
Terrestrial eutrophication	molc N eq	$4,48 \cdot 10^{0}$	$2,04 \cdot 10^{1}$	78,05%
Freshwater eutrophication	kg P eq	$1,59 \cdot 10^{-2}$	$3,41 \cdot 10^{-2}$	53,47%
Marine eutrophication	kg N eq	$4,62 \cdot 10^{-1}$	$2,00 \cdot 10^{0}$	76,93%
Freshwater ecotoxicity	CTUe	$1,24 \cdot 10^{2}$	$2,90 \cdot 10^{2}$	57,24%
Land use	kg C deficit	$2,53 \cdot 10^{2}$	$2,96 \cdot 10^{2}$	14,59%
Water resource depletion	m3 water eq	$8,47 \cdot 10^{0}$	$2,21 \cdot 10^{0}$	-284,00%
Mineral, fossil & ren resource depletion	kg Sb eq	$1,05 \cdot 10^{-3}$	$1,01 \cdot 10^{-2}$	89,59%

In Figure 19 is detailed the comparison of the results of the different scenarios. It can be concluded that the more post-consumer PP, the more impact the Hanhpaive has. Therefore, the scenario 1(Hahnpaiv made 100% of post-industrial PP), has the best results, except for the water resource depletion category. Whereas the scenario 4, with 80% of the composition being PP post-consumer has the highest impacts, except for the category of water resource depletion, where it has the lowest impact.

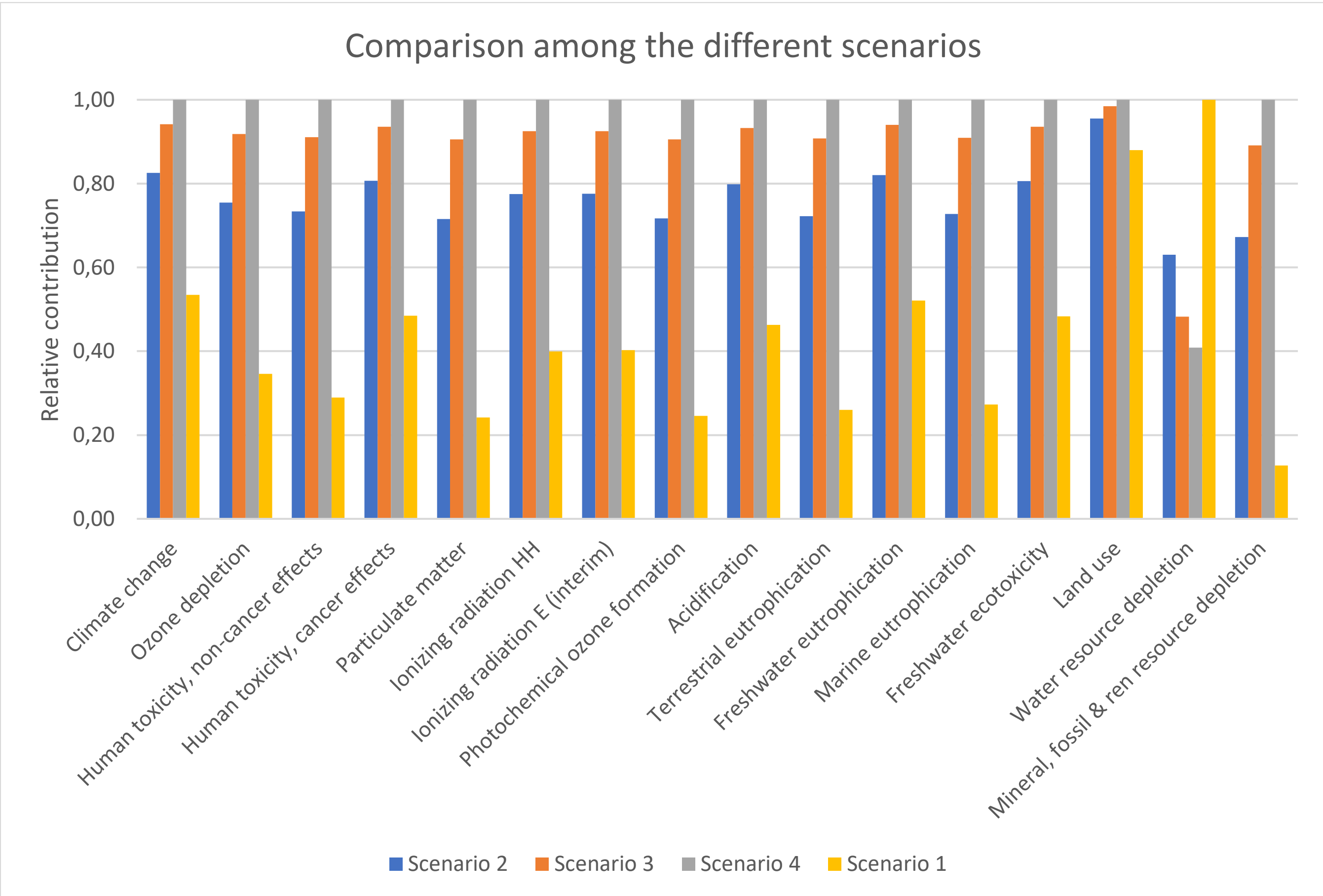


Figure 19. Comparison among the four scenarios defined in the different impact categories

3.4. Armacell

3.4.1. Goal and Scope

Product system

Armacell work within the project has been focused on designing formulations to introduce PET trays content into their foams nowadays manufactured with 100% PET bottle feedstocks. Main applications for these products are related to wind energy turbines blades, transport, building & construction including thermal insulation and general industry. Uprising demand of PET bottle by beverage packaging sector and last push of European legislation boosting bottle-to-bottle and relatively demanding % content on PET bottles [31], pushes to search for new PET feedstocks such us tray alternative which nowadays are not being widely recycled, although it also exists some uprising development on tray-to-tray closed loops driven from tray packaging producers and retailers.

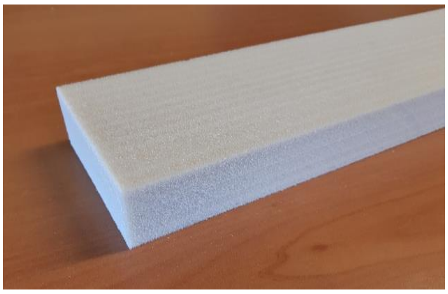


Figure 15 - Foam Board manufactured with 20% of PET tray post-consumer material (left). Sliced sheet product typically starcted from foam board blocks (right)

- **Benchmark product:** r-PET GR-W Sliced Sheet (Technical details on Armacell web)
- **PlastiCircle Development:** Introduction of PET tray from a bottle-tray (80/20 %) mix from post-consumer streams.
- **Main expected impacts:** Need of extra modifier formulation to ensure a stable process and to influence the cell structure.

Goal and scope

The **goal** of the study is to compare the performance of introducing into their foams Pet tray post-consumer (from Plasticircle post-consumer streams), with the current solution of PET bottle post-consumer from Armacell.

The **scope** of the study is gate to gate, as the only difference among the two products that will be compared is in the quantity of themelt modifier package. The impact of recycling PET bottle and PET tray is assumed the same in both cases as they would come from similar streams.

Functional Unit & Reference flow

The **functional unit** of the study is **"to produce 1 ton of foam"**
In order to meet the requirements of the above-mentioned Functional Unit, a certain quantity of the different materials for producing 1 ton of garbage bag, is required. This quantity is known as **reference flow**, and it is detailed in Table 28.

-

- *Table 33. Reference flow for producing 1 ton of garbage bag*

Material
1 ton of foam from PET bottle post-consumer
1 ton of foam from 80% PET bottle post-consumer and 20% PET tray post-consumer

3.4.2. System Boundaries and Assumptions

System boundaries

Information regarding **Armacell's benchmark product** was collected with the help and advice from Armacell, with close contact and providing information on questionnaires forms developed by ITENE and SINTEF. Questionnaires examples can be seen on **Annex 1: Questionnaires.**
General process for the obtention of PET recycled sliced sheets from foam boards is detailed on ***Figure 16*** below:

Figure 16 - Armacell Process for the production of GR-W Sliced Sheet from foam boards.

The scope as it was commented before is gate to gate, including the following stages: granulation, extrusion, welding and slicing.

Assumptions

- Use of PET material has been avoided and no burden is allocated to the production of PET plastic or its corresponding allocation for being a recycling source. Either PET has not burden as "avoided product" as main comparison is thought the same process and not on using virgin versus recycling material.

- Some inputs on the process (mainly modifier package composition) are considered confidential and kept as industrial secret for the manufacturer. However, Armacell has presented own modelled impacts from melt modifier additives on several methods (ILCD Midpoint 2011+ or EPD 2018), which showed no significant change of the total impact.

- The reason for not including the transport of both materials to Armacell, is because it is an assumption of 500 km and a transported quantity of 1 ton, therefore, the impacts will be equal in both cases.

3.4.3. Inventory data

- The inventory data of this product is confidential and will be included in the confidential Annex, section 7.10.

3.4.4. Life Cycle Assessment

In this section the Life Cycle Assessment for the production of the foam with the two different compositions is represented. The values of the LCA have been provided by Armacell and will be included in the annex.

As it can be seen in Figure 20, the differences between the two products with the different composition are minimal, as the modifier additive has little influence in the whole life cycle. The negative impact in the category of water resource depletion is due to the electricity mix used by the Ecoinvent database for Belgium case, where the renewable resources are included.

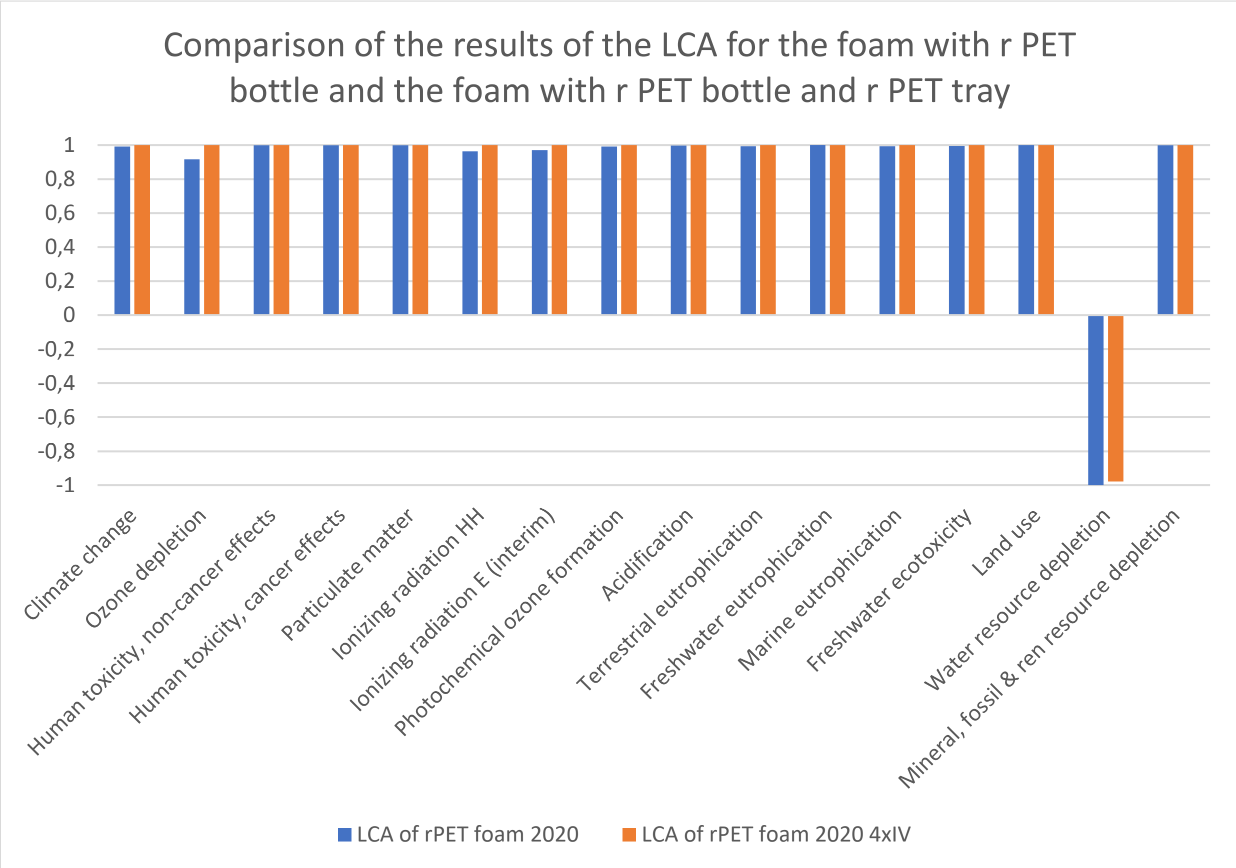


Figure 20. Comparison of the results of the LCA for the foam with r PET bottle (100%) and the foam with r PET bottle (80%) and r PET tray (20%).

3.4.5 Conclusions

As it is detailed in the section above, there is no such a big difference between producing the foam from post-consumer r-PET bottle, or post-consumer r-PET tray, since the only difference is related to quantity of melt modifier package used in the second product mentioned. Even though this quantity is four times than the amount that is used for the foam made with post- consumer r-PET bottle, it does not have a huge influence in the whole life cycle as it can be seen in Figure 20. Besides, this four time (x4) level of modifier was a worst case assumption. It is more likely that it will be in the range of 2x level of standard.

As it can be seen, in Table 34 are detailed the results of the Life Cycle Assessment of both products. This table does not show higher differences between them, only in the category of ozone depletion, the difference is bigger than 5%.

Table 34. Results of the comparison of the Life Cycle Assessment of both products

Impact category	Unit	LCA of rPET bottle foam	LCA of rPET bottle and tray foam 4x melt modifier package	Difference %
Climate change	kg CO2 eq	$2{,}71\cdot10^{3}$	$2{,}73\cdot10^{3}$	0,89%
Ozone depletion	kg CFC-11 eq	$1{,}96\cdot10^{-4}$	$2{,}14\cdot10^{-4}$	**8,48%**
Human toxicity, non-cancer effects	CTUh	$7{,}49\cdot10^{-4}$	$7{,}50\cdot10^{-4}$	0,24%
Human toxicity, cancer effects	CTUh	$1{,}69\cdot10^{-4}$	$1{,}69\cdot10^{-4}$	0,22%
Particulate matter	kg PM2.5 eq	$1{,}54\cdot10^{0}$	$1{,}54\cdot10^{0}$	0,12%
Photochemical ozone formation	kg NMVOC eq	$7{,}93\cdot10^{0}$	$8{,}00\cdot10^{0}$	0,87%
Acidification	molc H+ eq	$1{,}11\cdot10^{1}$	$1{,}11\cdot10^{1}$	0,28%
Terrestrial eutrophication	molc N eq	$2{,}48\cdot10^{1}$	$2{,}50\cdot10^{1}$	0,72%
Freshwater eutrophication	kg P eq	$1{,}16\cdot10^{0}$	$1{,}16\cdot10^{0}$	0,01%
Marine eutrophication	kg N eq	$2{,}07\cdot10^{0}$	$2{,}08\cdot10^{0}$	0,80%
Freshwater ecotoxicity	CTUe	$4{,}56\cdot10^{3}$	$4{,}59\cdot10^{3}$	0,52%
Land use	kg C deficit	$3{,}08\cdot10^{3}$	$3{,}08\cdot10^{3}$	0,00%
Water resource depletion	m3 water eq	$-5{,}18\cdot10^{0}$	$-5{,}06\cdot10^{0}$	-2,32%
Mineral, fossil & ren resource depletion	kg Sb eq	1,28·10-1	1,28·10-1	0,13%

3.5. Derbigum

3.5.1. Goal and Scope

<u>**Product system**</u>

Derbigum produces polymer modified bitumen roofing membranes. The polymer used to modify the bitumen is Polypropylene (PP). The polymer prevents the bitumen from becoming too soft in high temperatures or too brittle in low temperatures.

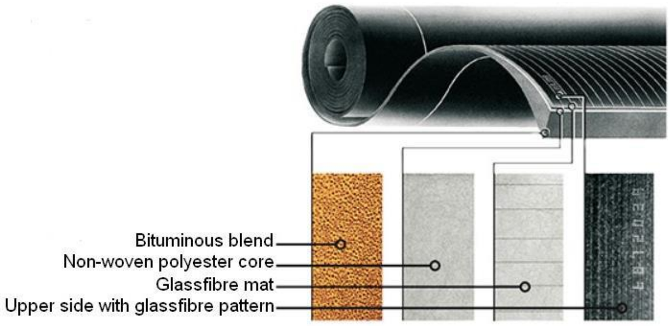


Figure 21 -- Layer structure of the finished membrane product

Derbigum use a mixture of amorphous (or atactic) PP (aPP) and crystalline (or Isotactic) PP (iPP). The amount of polymer used in the bitumen blend is approximately 20%. aPP is the predominant component in the blend.

Derbigum has analysed PP and PE samples from the market, so that more recycled content can be incorporated into the product. In PlastiCircle, the replacement of virgin iPP by recycled iPP has been tested in pilot scale. The product is currently usable for base sheets formulations and the bituminous blend and the finished product have properties in their range.

- **Benchmark product:** 100% virgin-base Polymer (PP) modified bitumen roofing membranes.
- **PlastiCircle Development:** introduction of PP post-consumer and PP post-industrial in the bitumen roofing membranes
- **Main expected impacts:** concerning the top sheepts, Derbigum needs to work on the formulation, because the recycled polymer increases significantly the viscosity and prevent us to reach the range of the required cold flexibility.

<u>**Goal and scope**</u>

The **goal** of the study is to compare the performance of introducing PP post-consumer and PP post-industrial(both materials from Plasti circle development) into their bitumen roofing membrane.
The **scope** of the study is **cradle to gate**, which takes into account the impacts of the recycling process of PP post-consumer and PP post-industrial.

<u>**Functional Unit & Reference flow**</u>

The **functional unit** of the study is **"to produce 1 ton of polymer modified bitumen roofing membrane"**
In order to meet the requirements of the above-mentioned Functional Unit, a certain quantity of the different materials for producing 1 ton of roofing membrane, is required. This quantity is

known as **reference flow**, and it is detailed in Table 35

Table 35. Reference flow for producing 1 ton of garbage bag

	Material	Amount (kg)
Benchmark product	11% of PP virgin	110
Plasti circle development	4% PP post-consumer	40
	7% PP post-industrial	70

3.5.2. System Boundaries and Assumptions

<u>**System boundaries**</u>

- ➔ Information regarding **Derbigum benchmark product** was collected with the help and advice from Derbigum, with close contact and providing information on questionnaires forms developed by ITENE and SINTEF. Questionnaires examples can be seen on **Annex 1: Questionnaires.**
- ➔ As it was mentioned before, the scope is **cradle to gate**, as it represented in Figure 22, which includes the recycling process of the inputs material: from PP post-consumer and PP post-industrial, and the production of PP virgin; as well as the production stage in Derbigum for producing the bitumen roof membrane.

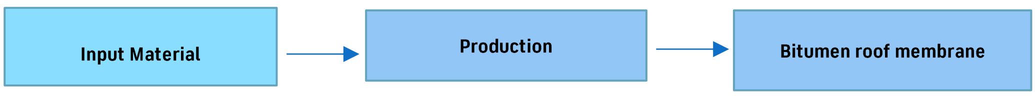


Figure 22. Production of the roofing membrane

<u>**Assumptions**</u>

- The reason for not including the transport of the PP to Derbigum factory, is because it is an assumption of 500 km and a transported quantity of 1 ton, therefore, the impacts will be equal in both cases.
- In the case of the raw materials, only 11% of the inventory has been provided by Derbigum, the rest of the inventory is confidential. Nevertheless, the rest of the raw materials, are identical for both products that will be compared, only the PP is different, therefore, this will not affect the results of the comparison.

3.5.3. Inventory data

The inventory data is confidential and is included in the confidential Annex 7.11

3.5.4. Life Cycle Assessment

In this section the results of the Life Cycle Assessment for both products are detailed.

<u>**Life Cycle Assessment of the production of 1 ton of PP virgin modified bitumen roofing membrane**</u>

In Figure 23 are shown the results of the Life Cycle Assessment of 1 ton of PP virgin modified bitumen roofing. As it can be seen,

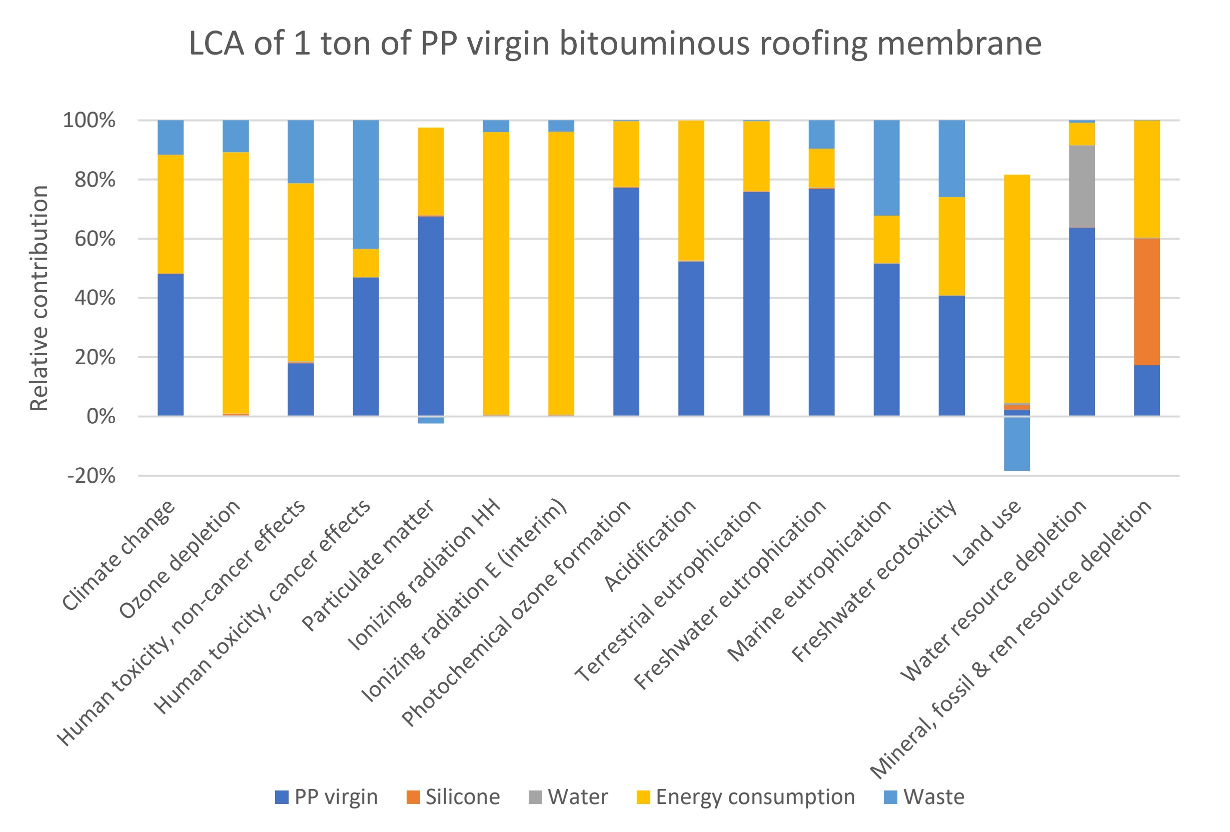


Figure 23. Life Cycle Assessment of 1 ton of PP virgin bitouminous roofing membrane

As it is shown in the figure above, the production of the **PP virgin** has an important contribution to impact categories such as photochemical ozone formation, terrestrial and freshwater eutrophication, where the impact values are around 75%, this is related to the treatment of the waste generated during the production of the PP virgin. In other categories, water resource depletion and particulate matter the value of the contribution is 65%. In climate change, the PP virgin also has an important contribution of 50%.

In second place, the **energy consumption** of the process has a higher contribution in categories such as ozone depletion, and land use, where the relative contribution is among 85% to 90%. The electricity is the type of energy that most contributes to the different impacts.

In the case of the **waste**, it has an important contribution, especially in the category of human toxicity (with a value of 40%), related to the incineration of the process waste. In marine eutrophication the contribution is of 30%, and this is due to the process waste that is landfilled.

The use of **water** has an influence in the category of water resource depletion of 30% due to the water consumption of this stage. Finally the **silicone** has a high contribution in mineral and fossil resource depletion, of around 40%, especially due to the zinc used for producing the silicone.

The values of the different stages for the different impact categories are detailed in Annex 7.11

Life Cycle Assessment of the production of 1 ton of PP post-consumer and PP post-industrial bitumen roofing membrane

In Figure 24 are detailed the impacts of producing 1 ton of PP post-consumer and PP post-industrial bitouminous roofing membrane.

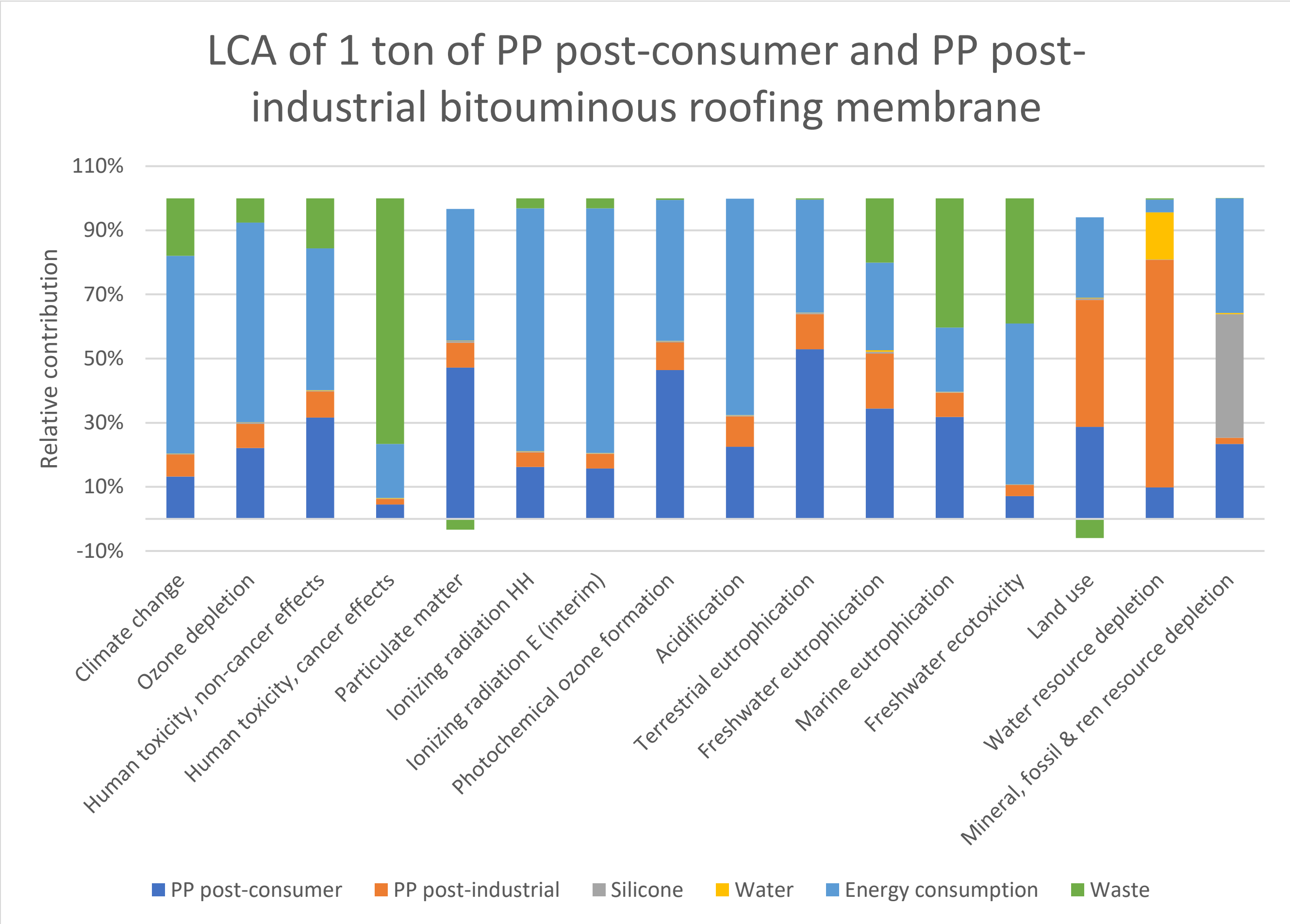


Figure 24. Life Cycle Assessment of 1 ton of PP post-consumer and PP post-industrial bitouminous roofing membrane

As it can be seen in the figure above, the **energy consumption** accounts for most of the impacts, such as climate change, ozone depletion, and acidification, where the contribution is around 60% to 75%. The electricity is the type of energy that most contributes to the different impact categories.

The second most relevant contribution to impact is the **recycling of the PP post-consumer**, which includes the collection, transport, sorting, and washing stage. has importance regarding its contribution, to the categories of particulate matter, photochemical ozone formation, and the eutrophication categories. This contribution is especially due to the transport and the washing of the PP post-consumer.

The **recycling of the PP post-industrial**, that only includes the washing stage, has an important contribution to the category of water resource depletion, because of the water consumption for washing, with a contribution of 70%.

The **waste treatment** has an important contribution to categories such as human toxicity, because of the emissions produced by the process waste that is incinerated, with a value around 80%. In the eutrophication categories, the contribution is between 20% and 30%, and it is related to the process waste that is landfilled. It should be highlighted than in the category of land use, the impact is negative, which results in a decrease of the value of the total category. This is due to the recycling of the steel and iron,where for its extraction as virgin material it requieres a certain amount of surface, therefore, by its recycling, this land it is not needed.

Finally, in the case of the **water** used, the value is around 15% in the category of water resourced depletion, for the rest of the categories, the impact contribution of the water is negligible.

The values of the different stages for the different impact categories are detailed in ¡Error! No se encuentra el origen de la referencia..

3.5.5 Conclusions

In Table 36 are detailed the results of both LCA for the bituminous roofing membrane. As it can be seen, the product made with PP virgin has a higher impact than the product with 7% of PP post-industrial and 4% PP post-consumer. The differences are high especially in the categories of particulate matter, photochemical ozone formation, terrestrial and marine eutrophication, where the values decrease up to 77%. In Figure 25, are represented the impacts of both products in the different categories in parts per unit.

Table 36. Comparison of the results for 1 ton of PP virgin modified bituminosr roofing membrane and 1 ton of PP post-consumer and PP post-industrial bitouminous roofing membrane

Impact category	Unit	LCA 1 ton of PP virgin modified bitouminous roofing membrane	LCA 1 ton of PP post-consumer and PP post-industrial modified bitouminous roofing membrane	Difference %
Climate change	kg CO2 eq	$4{,}50\cdot10^{2}$	$2{,}33\cdot10^{2}$	-48,19%
Ozone depletion	kg CFC-11 eq	$2{,}57\cdot10^{-5}$	$2{,}57\cdot10^{-5}$	-0,34%
Human toxicity, non-cancer effects	CTUh	$5{,}62\cdot10^{-6}$	$4{,}61\cdot10^{-6}$	-18,00%
Human toxicity, cancer effects	CTUh	$2{,}90\cdot10^{-6}$	$1{,}54\cdot10^{-6}$	-46,89%
Particulate matter	kg PM2.5 eq	$1{,}21\cdot10^{-1}$	$3{,}52\cdot10^{-2}$	**-70,91%**
Photochemical ozone formation	kg NMVOC eq	$1{,}04\cdot10^{0}$	$2{,}36\cdot10^{-1}$	**-77,27%**
Acidification	molc H+ eq	$1{,}56\cdot10^{0}$	$7{,}40\cdot10^{-1}$	-52,46%
Terrestrial eutrophication	molc N eq	$2{,}04\cdot10^{0}$	$4{,}93\cdot10^{-1}$	**-75,83%**
Freshwater eutrophication	kg P eq	$6{,}19\cdot10^{-3}$	$1{,}44\cdot10^{-3}$	**-76,82%**
Marine eutrophication	kg N eq	$2{,}81\cdot10^{-1}$	$1{,}36\cdot10^{-1}$	-51,59%
Freshwater ecotoxicity	CTUe	$1{,}95\cdot10^{2}$	$1{,}16\cdot10^{2}$	-40,73%
Land use	kg C deficit	$5{,}88\cdot10^{0}$	$5{,}66\cdot10^{0}$	-3,60%
Water resource depletion	m3 water eq	$4{,}33\cdot10^{-1}$	$1{,}57\cdot10^{-1}$	-63,81%
Mineral, fossil & ren resource depletion	kg Sb eq	$1{,}46\cdot10^{-3}$	$1{,}21\cdot10^{-3}$	-17,27%

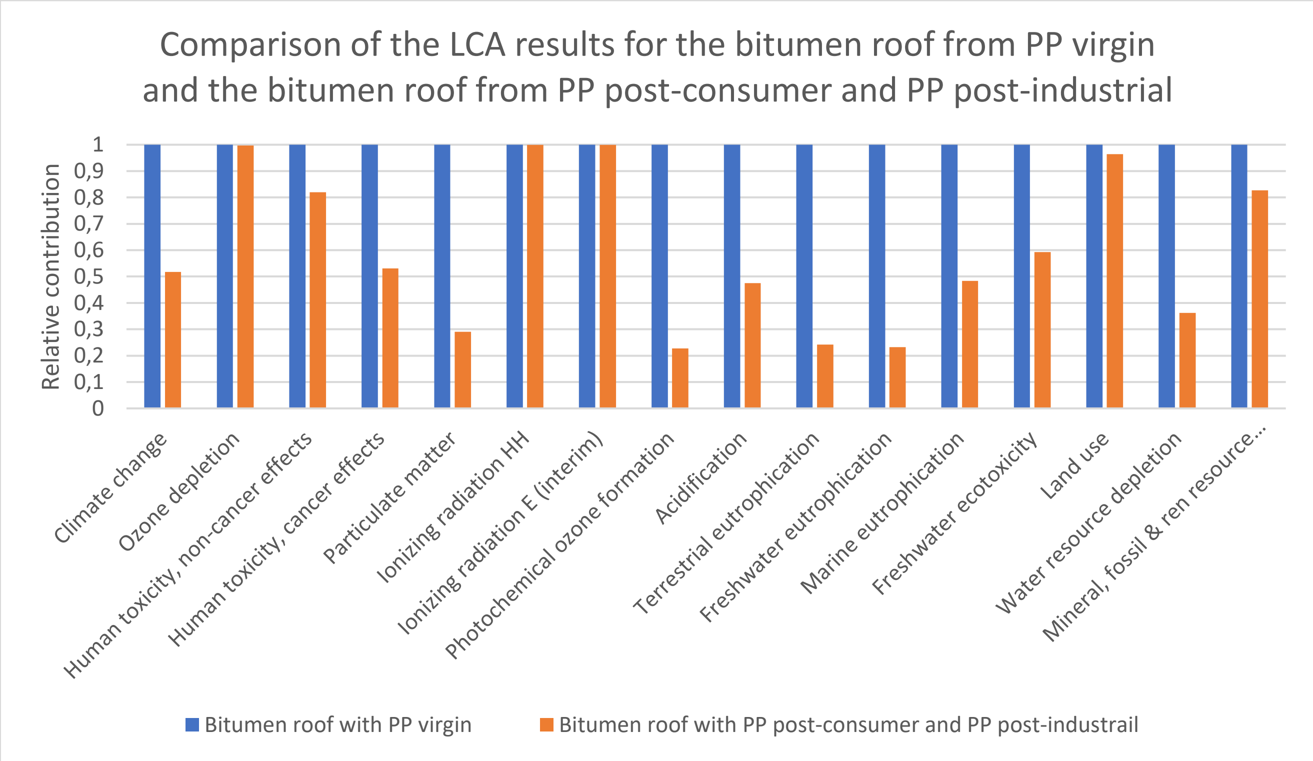


Figure 25. Results of the comparison fot the bitumen roof made from PP virgin and the bitumen roof made from PP post-consumer and PP post-industrial

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7. Annexes

7.1. Annex 1: Questionnaires/Inventories

Annex 1: City/Waste Managers Questionnaires/Inventories – COLLECTION

COLLECTION	Units	Pre- Valencia	Post-Valencia	Utrecht	Pre- Alba Iulia	Post- Alba Iulia			
General Info							SOURCE		
OVERALL numbers		Valencia	Valencia	Utrecht	Alba Iulia	Alba Iulia			
Inhabitants	u	794.288,00	794.289,00	357.179,00	63,536	63,536	Las Naves	Utrecht	Alba Iulia
Packaging waste generated on selective collection	tons/a	25.899,10		9.819,47	-	-	SAV data	Utrecht	-
Packaging waste per inhabitant	kg/cap.a	32,61		27,49	17.87		SAV data	Utrecht	
PILOT numbers	Name	San Marcelino		Terwijde	Arnsberg-Goldis				
Inhabitants	u	9.000,00	9.000,00	7.000,00	7740,00	7.740,00	Las Naves	Utrecht	Alba Iulia
Packaging waste collected	tons/a	118,08	-	-	216	*	SAV data on pilot		Own calculation (tonnes collected daily and characterizations)
Packaging waste collected per capita (pilot area)	kg/cap.a	13,12		27,49	38,88				
Fraction analysed		LPW on Street Container		LPW on Underground Container	Dry fraction on Street Containers		SAV	Utrecht	Alba Iulia
Collection									
Infrastructure									
Containers in pilot area	u	26	26	40	0	20			
Maintenance & Washing									
Water use	l/year			21.600,00					
Water use per tonne	l/ton.a			182,93					
Detergent (10% diluted)	l / year			1.900,00					
Detergent per tonne (100% pure)	*l/ton.a*			*1,61*					
IoT Infrastructure									

NFC Card	u/ton	-	540,00	-	-	540	Own Calculation	Own Calculation	Own Calculation
PVC from NFC Cards	kg/ton	-	2,50	-	-	2,5	Own Calculation	Own Calculation	Own Calculation
Identification Labels	u/ton	-	9.146,00	-	-	9146	Own Calculation	Own Calculation	Own Calculation
PP Identification labels	kg/ton		0,61	-	-	0,61	Own Calculation	Own Calculation	Own Calculation
Filling level Sensors (F.L.S.)	u/u container	0	1	1	0	1	Own Calculation	Own Calculation	Own Calculation
Energy embedded on F.L.S.	Wh/u container	0	72	100	0	72	Own Calculation	Own Calculation	Own Calculation
Label Dispenser Devices (L.D.D.)	u/u container	0	1	-	0	1	Own Calculation	Own Calculation	Own Calculation
Energy embedded on L.D.D	Wh/u container	0	979,2	-	0	979,2	Own Calculation	Own Calculation	Own Calculation
LoRa Nodes	u/u container	0	0,19	-	0	0,55	Own Calculation	Own Calculation	Own Calculation
Energy consumed by LoRa	Wh/u container	0	0,74	-	0	2,12	Own Calculation	Own Calculation	Own Calculation
Energy embedded on IoT system per tonne	kWh/ton	0	0,23	-	0	0,18	Own Calculation	Own Calculation	Own Calculation
Composition of Waste Packaging		**PlastiCircle Pre-Pilot**	**PlastiCircle Late-Pilot**	**Average Utrecht**	**Dry Fraction Pre-**	**PlastiCircle Container**			
Unwanted items/Other Waste		**21,59%**	**8,71%**	**26,81%**	**82,00%**	**71,16%**	SAV Charact	EURECO (UTR)	POLARIS (AI)
PET Packaging:		**23,29%**	**30,46%**	**17,71%**	**4,90%**	**13,22%**	SAV Charact	EURECO (UTR)	POLARIS (AI)
PET Bottles		15,49%	23,15%	6,57%	3,20%	12,41%	SAV Charact	EURECO (UTR)	POLARIS (AI)
PET Trays (Mono & Multilayer)		7,81%	7,31%	11,09%	1,70%	0,81%	SAV Charact	EURECO (UTR)	POLARIS (AI)
HDPE Packaging:		**13,40%**	**8,00%**	**5,47%**	**2,80%**	**4,31%**	SAV Charact	EURECO (UTR)	POLARIS (AI)
HDPE Natural		9,34%	6,84%	-	0,80%	1,42%	SAV Charact	EURECO (UTR)	POLARIS (AI)
HDPE Color		3,61%	1,16%	-	2,00%	2,89%	SAV Charact	EURECO (UTR)	POLARIS (AI)
PP rigid		-	-	**8,19%**	-	-	SAV Charact	EURECO (UTR)	POLARIS (AI)
Mixed Plastic Packaging:		**6,42%**	**9,17%**	**2,11%**	**2,90%**	**2,89%**	SAV Charact	EURECO (UTR)	POLARIS (AI)
Film:		**13,86%**	**15,46%**	**19,92%**	**3,30%**	**4,56%**	SAV Charact	EURECO (UTR)	POLARIS (AI)
Foils - bags & sacks		3,54%	3,84%	1,85%	-	-	SAV Charact	EURECO (UTR)	POLARIS (AI)
Foils - packaging		10,31%	11,62%	18,69%	-	-	SAV Charact	EURECO (UTR)	POLARIS (AI)
Metal Packaging:		**9,85%**	**13,57%**	**7,06%**	**2,40%**	**3,25%**	SAV Charact	EURECO (UTR)	POLARIS (AI)
Aluminium		5,69%	7,51%	-	0,60%	1,62%	SAV Charact	EURECO (UTR)	POLARIS (AI)
Ferrous Packaging		4,16%	6,06%	-	1,80%	1,63%	SAV Charact	EURECO (UTR)	POLARIS (AI)
Paper&CB Beverage/Food:		**11,59%**	**14,63%**	**12,73%**	**1,70%**	**0,61%**	SAV Charact	EURECO (UTR)	POLARIS (AI)

Annex 1: City/Waste Managers Inventories - TRANSPORT

Transport Routes		Pre- Valencia	Post-Valencia	Utrecht	Pre- Alba Iulia	Post- Alba Iulia	SOURCE		
Total Distance per route	km.route	135,40	106,57	226	60,05	59,314	Own calculations	Own calculations	Own calculations
Time Average per route	h.route	6,49	4,94	6,014	1,78	1,73	Own calculations	Own calculations	Own calculations
Total Fuel per route	l/route	59,90	51,28	206,89	31,20	30,70	Own calculations	Own calculations	Own calculations
Fuel Consumption per km on a route	l/km.route	0,44	0,48	0,46	0,520	0,518	Own calculations	Own calculations	Own calculations
Tonnes of waste collected	tonnes	3653	3653	3573	9000	9000	SAV	Utrecht D6.3	Alba Iulia
Tonnes of packaging waste collected	tonnes	3653	3653	3573	2595,6	2595,6	SAV	Utrecht D6.3	Alba Iulia and characterisations
Distance per functional unit	tonne*km	495	389	826	1	119	Own calculations	Own calculations	Own calculations
Start to pilot area	km	3,2	3,2	7,7	3,4	3,4	SAV data	SAV data	SAV data
Time	h	0,15	0,15	-	0,13	0,13	SAV data	SAV data	SAV data
Fuel	l	1	1	6,31	0,6	0,6	SAV data	SAV data	SAV data
Average distance on pilot area	km	8,6	5,7	60,8	3,55	2,814	SAV data	SAV data	SAV data
Time	h	0,99	0,71		0,47	0,42	SAV data	SAV data	SAV data
Fuel	l	7,7	6,3	77,63	4,3	3,8	SAV data	SAV data	SAV data
Collected containers	u	26	19	40	16	14	SAV data	SAV data	SAV data
Packaging waste collected (pilot) per route	kg/route	820	820	3573	9000	9000	SAV data	Utrecht D6.3	Alba Iulia
Average distance on other areas (until truck full)	km	76,9	50,97	-	-	-	SAV data	-	-
Time	h	4,49	3,22	-	-	-	SAV data	-	-
Fuel	l	39,7	32,48	-	-	-	SAV data	-	-
Packaging waste collected	kg	2833	2833		-	-	SAV data	-	-
Pilot area to management plant/transfer plant	km	22,5	22,5	150	50	50	SAV data	Own assumption	Own assumption
Time	h	0,47	0,47	1,25	1	1	SAV data	Own assumption	Own assumption
Fuel	l	6,3	6,3	122,95	25	25	SAV data	Own assumption	Own assumption
Back to initial point	km	24,2	24,2	7,5	3,1	3,1	SAV data	Own assumption	Own assumption

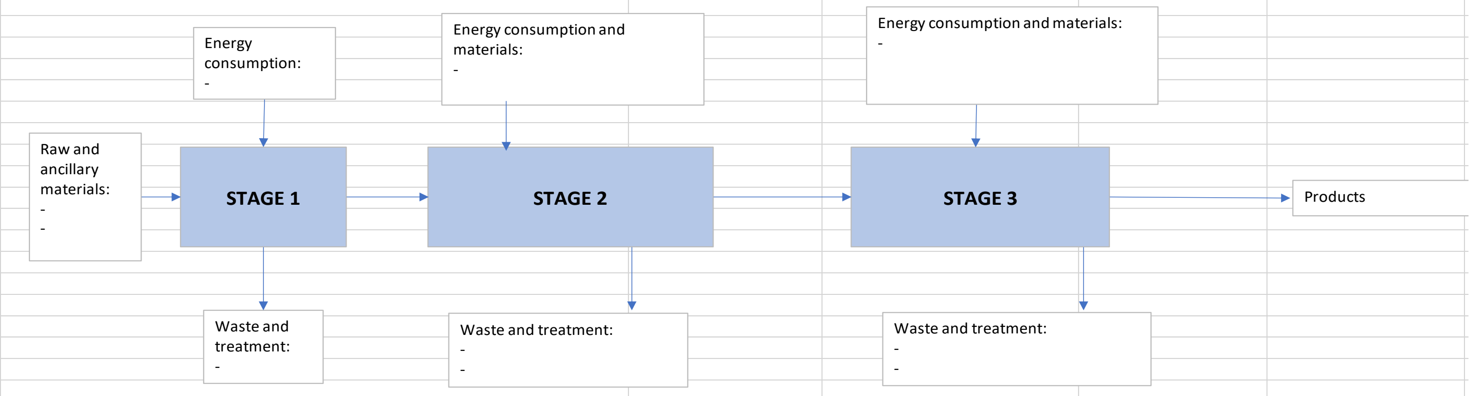
Time	h	0,39	0,39	-	0,18	0,18	SAV data	Own assumption	Own assumption
Fuel	l	5,2	5,2	-	1,3	1,3	SAV data	Own assumption	Own assumption
Truck Parameters									
Number of trucks for pilot	u.	1	1	1 to 6	1	1	**SAV**	Utrecht	Alba Iulia
Model	-	EURO 5	EURO 5	EURO 6	EURO 4	EURO 4	**SAV**	Utrecht	Alba Iulia
Load type		Lateral Right Loader		Top Loader	Rear Loader		**SAV**	Utrecht	Alba Iulia
Capacity	m3	16	16	16	16	16	**SAV**	Utrecht	Alba Iulia
Oil consumption	l	4l/4500km					SAV data and internal database		
Oil usage per distance	L/km	0,0008888					SAV data and internal database		
Tyres usage per distance	km	100000					SAV data and internal database		

Annex 1: Recyclers/Industries Questionnaire

RECYCLERS (HAHN PLASTICS & INTERVAL)	BEFORE THE PILOT	units	AFTER THE PILOT	units
process diagram				
energy consumption per tonne of waste recycled		kWh/tonne		kWh/tonne
water consumption per tonne of waste recycled		l/tonne		l/tonne
Ancillary materials (detergents, compatibilizers, colorants, additives, etc.) per tonne of waste recycled		kg/tonne		kg/tonne
Amount of plastic waste received		tonnes		tonnes
Electricity consumed (equipments)		kWh/tonne treated		kWh/tonne
Cost Electricity consumed (equipments)		€/tonne treated		€/tonne
Cost Diesel consumed (forklift)		€/tonne treated		€/tonne
Labour		€/tonne treated		€/tonne
Capital cost recycling unit		€		
Life time recycling unit		years		
Recycled plastics				
PET		tonnes		tonnes
PE-HD		tonnes		tonnes
PE-LD		tonnes		tonnes
PP		tonnes		tonnes
PS		tonnes		tonnes
PVC		tonnes		tonnes
Other plastic resins		tonnes		tonnes
Disposal				
Amount to landfill		tonnes		tonnes
Distance to landfill		km		km
Cost disposal in landfill		€/tonne		

MANUFACTURERS (before and after the pilot if there are changes on the process) (ARMACELL, CRF. DERBIGUM, INTERVAL & HAHN PLASTICS)

Process diagram with inputs (raw and ancillary materials, energy) and outputs (waste, products) of every stage with units



7.2. Annex 2: Machinery Models and Energy Consumption/Fraction – Excel Calculator

							Function Regression (Nominal Power vs Max Volume Capacity)								
Machinery	**Model**	**Max Vol Capacity (m3/h)**	**Mass flow (ton/h)**	**Consumption (kW)**	**Caracteristic Dimension**	**Source**	**a5**	**a4**	**a3**	**a2**	**a1**	**a0**	**R2**	**Number of machin**	**Global Consum**
Baler Metals	CHB-1500/110	1600 m3	90 packs/h	36,8		Piloto Valencia								1	36,8
Baler Reject	JS-1000VL/75	156	7,8	44,1		Piloto Valencia								1	44,1
Baler Recoverable	JS-1000VL/75	156	7,8	44,1		Piloto Valencia								1	44,1
Baler(Horizontal)				50		Reference								1	50
Baler(Horizontal)				50	Regula. Frecuencia	Reference	-4,45893E-12	9,74606E-09	-7,64446E-06	0,002493603	-0,083291201	5,307163565	0,962768689	1	50
Baler (Horizontal)	HSM VK 1206	92	-	9,2	-	HSM							#N/D		
Baler (Horizontal)	HSM VK 2306	62	3,08	9,2	-	HSM							#N/D		
Baler (Horizontal)	HSM VK 2307	113	5,63	15	-	HSM									
Baler (Horizontal)	HSM VK 4812 P	151	7,57	15	-	HSM									
Baler (Horizontal)	HSM VK 4812 P	204	10,21	22	-	HSM									
Baler (Horizontal)	HSM VK 6015	128	6,41	30	-	HSM									
Baler (Horizontal)	HSM VK 6016	145	9, 19	45	-	HSM									
Baler (Horizontal)	HSM VK 6017	231	11,55	55	45	HSM									
Baler (Horizontal)	HSM VK 6018	291	14, 53	75	55	HSM									
Baler (Horizontal)	HSM VK 8818	417	20,85	90	75	HSM									
Baler (Horizontal)	HSM VK 8819	643	32, 14	135	90	HSM									
Baler (Horizontal)	HSM VK 8820	417	20,85	90	75	HSM									
Baler (Horizontal)	HSM VK 8821	643	32, 14	135	90	HSM									
Baler (Horizontal)	HSM VK 12018	540	27,02	90	75	HSM									
Baler (Horizontal)	HSM VK 12019	786	39,32	142	90	HSM									
Baler (Horizontal)	HSM VK 12020	887	44,36	145	110	HSM									
Baler (Horizontal)	HSM VK 15020	557	27,86	110	90	HSM									
Baler (Horizontal)	HSM VK 15021	767	38,35	150	110	HSM									
Baler (Horizontal)	HSM VK 15022	873	43,64	-	150	HSM									
Baler (Horizontal)	JS-1000VL/45	133	6,60	22		JOVISA									
Baler (Horizontal)	JS-1000VL/60	153	7,70	36,8		JOVISA									
Baler (Horizontal)	JS-1000VL/75	156	7,80	44,1		VAERSA									
Baler (Horizontal)	JS-1000/Contenedor	144	7,2	44,1		JOVISA									
Baler (Horizontal)	SE-504842-830	-	-	22,4		MARATHON									
Baler (Horizontal)	SE-504242-830	-	-	22,4		MARATHON									
Baler (Horizontal)	SE-503042-830	-	-	22,4		MARATHON									
Baler (Horizontal)	SE-503042-720	-	-	14,9		MARATHON									
Baler (Horizontal)	SE-604842-830	-	-	22,4		MARATHON									
Baler (Horizontal)	SE-504230-950A UBC	-	-	37,3		MARATHON									
Baler (Horizontal)	SE-503042-950A UBC	-	-	37,3		MARATHON									

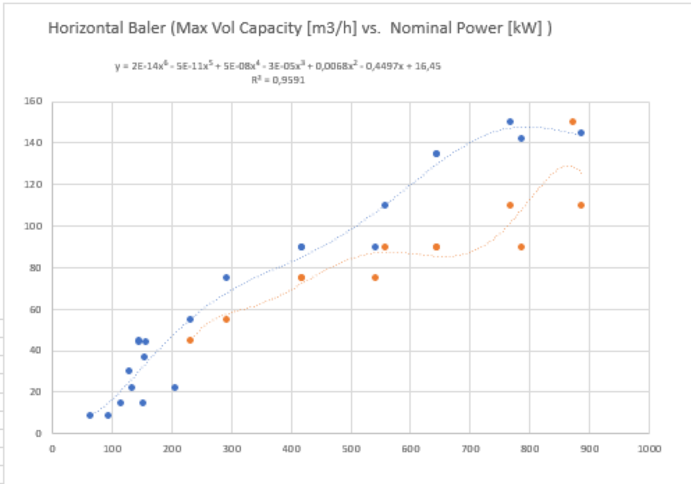


Figure 26 - Example of machinery modelled (baler). Power consumption (kW) vs. Max Volume capacity of the machine.

Source	Piloto Valencia	
Etiquetas de fila	**Suma de Number of machines needed**	**Suma de Global Consumption (kW)**
Bag Opener	**1**	**40**
Baler (vertical)	**0**	**0**
Ballistic separator	**1**	**10**
Conveyor Belts	**20**	**100**
Drum Screen	**1**	**15**
Magnetic Separator	**2**	**8**
Non-ferrous separator	**2**	**10**
Optical separators	**0**	**0**
Windstifer	**1**	**35**
Baler Metals	**1**	**36,8**
Baler Reject	**1**	**44,1**
Baler Recoverable	**1**	**44,1**
Optical CB	**1**	**2**
Optical PM	**1**	**2,5**
Optical HDPE	**1**	**2,5**
Optical PET	**1**	**3**
Total general	**35**	**353**

Etiquetas de fila	kWh	kWh (distributed)
Bag Opener	**112000**	**14000**
Baler (vertical)	**0**	**0**
Ballistic separator	**28000**	**3500**
Conveyor Belts	**280000**	**35000**
Drum Screen	**42000**	**5250**
Magnetic Separator	**22400**	**22400**
Non-ferrous separator	**28000**	**28000**
Optical separators	**0**	**0**
Windstifer	**98000**	**98000**
Baler Metals	**103040**	**51520**
Baler Reject	**123480**	**123480**
Baler Recoverable	**123480**	**24696**
Optical CB	**5600**	**5600**
Optical PM	**7000**	**7000**
Optical HDPE	**7000**	**7000**
Optical PET	**8400**	**8400**

SORTING PLANT VARIABLES		
Operational Hours	4000	
Performance Machine Rates	0,7	
% Global Consuption Rate	0,2	
Consuption associated to PRESS	15590,48427	kWh
ANUAL CONSUMPTION VAERSA (Pic	1226334	MWh
1a ESTIMACIÓN MODELO	1233666,8	MWh
	-0,60%	

Piloto Valencia

Suma de PET	Suma de HDPE	Suma de Films	Suma de Mix Plastic	Suma de Ferrous	Suma de Aluminium	Suma de Brick	Suma de Rejection	Number of influeced machines
1	1	1	1	1	1	1	1	8
0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	8
1	1	1	1	1	1	1	1	8
1	1	1	1	1	1	1	1	8
0	0	0	0	1	0	0	0	1
0	0	0	0	0	1	0	0	1
1	1	0	0	0	0	1	0	3
0	0	1	0	0	0	0	0	1
0	0	0	0	1	1	0	0	2
0	0	0	0	0	0	0	1	1
1	1	1	1	0	0	1	0	5
0	0	0	0	0	0	1	0	1
0	0	0	1	0	0	0	0	1
0	1	0	0	0	0	0	0	1
1	0	0	0	0	0	0	0	1
7	**7**	**6**	**6**	**6**	**6**	**7**	**5**	

GENERAL CALCULATOR

OUTPUTS (material recovered/reject)								
5967,9	**1544,46**	**3960,15**	**2500,36**	**1573,3**	**467,67**	**1670,04**	**8255,188**	25939,068
PET	**HDPE**	**Films**	**Mix Plastic**	**Ferrous**	**Aluminium**	**Brick**	**Rejection**	**TOTAL**
2,345883812	9,064656903	3,535219626	5,599193716	8,898493612	29,93563838	8,383032742	1,695903231	69,45802202
0	0	0	0	0	0	0	0	0
0,586470953	2,266164226	0,883804906	1,399798429	2,224623403	7,483909594	2,095758185	0,423975808	17,3645055
5,864709529	22,66164226	8,838049064	13,99798429	22,24623403	74,83909594	20,95758185	4,239758077	173,645055
0,879706429	3,399246339	1,32570736	2,099697644	3,336935105	11,22586439	3,143637278	0,635963712	26,04675826
0	0	0	0	14,23758978	0	0	0	14,23758978
0	0	0	0	0	59,87127675	0	0	59,87127675
0	0	0	0	0	0	0	0	0
0	0	24,74653738	0	0	0	0	0	24,74653738
0	0	0	0	32,74645649	110,1631492	0	0	142,9096057
0	0	0	0	0	0	0	14,9578665	14,9578665
4,138139044	15,99005478	6,236127419	9,876977715	0	0	14,78766976	0	51,02896871
0	0	0	0	0	0	3,353213097	0	3,353213097
0	0	0	2,799596858	0	0	0	0	2,799596858
0	4,532328451	0	0	0	0	0	0	4,532328451
1,407530287	0	0	0	0	0	0	0	1,407530287
15,22244005	57,91409295	45,56544575	35,77324865	83,69033242	293,5189343	52,72089291	21,95346732	**606,3588544**
								VERDADERO

Figure 27 - Excel capture - Dynamic Calculator based on (1) Machine models, (2) Relation matrix Fraction/Machinery), (3) Data inputs/outputs on Local Recycling Plant (4) Own assumptions.

7.3 Annex 3: Energy Sources Spanish Case

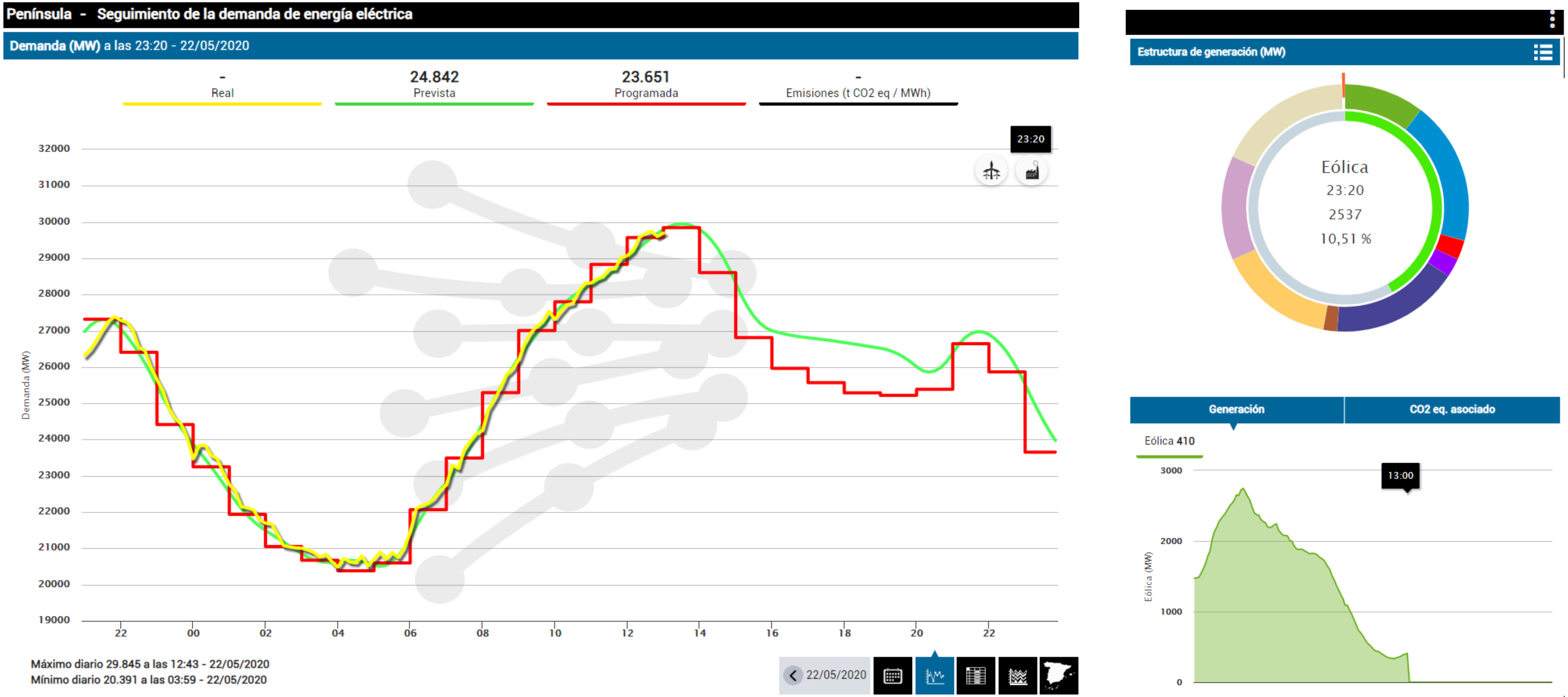


Figure 28 - Representation on real-time data from Power Demand (kW) on 22nd May 2020. Yellow (real), red (programmed), green(foreseen). Right figure: % of power sources (wind, hydro, nuclear, etc.). With this tool information can be obtained for an exact period of time.

(Site: https://demanda.ree.es/visiona/peninsula/demanda/total)

Table 37 - Sources of Energy (%) average values from 01/01/2019 to 01/01/2020 for Spanish peninsule. Own adaptation to Ecoinvent Inventories

Source of Energy	% relative	% absolute	Value (MWh)	Ecoinvent Reference
Measured generation Biogas	0,32%	**0,31%**	787.362,38	Electricity, high voltage {ES}| heat and power co-generation, biogas, gas engine | Alloc Def, U
Measured generation Biomass	1,13%	**1,11%**	2.808.674,98	N.A.
Measured generation Combined cycle*	20,69%	**20,24%**	51.240.902,02	Electricity, high voltage {RoW--> ES - PlastiCircle}| electricity production, natural gas, combined cycle power plant | Alloc Def, U - Modified for ES - Natural Gas .
Measured generation Oil or coal derivatives	1,18%	**1,15%**	2.913.854,06	Electricity, high voltage {ES}| electricity production, oil | Alloc Def, U
Measured generation Residual energy**	0,01%	**0,01%**	20.376,37	N.A
Measured generation Onshore wind	21,45%	**20,98%**	53.114.858,50	Electricity, high voltage {ES}| electricity production, wind, >3MW turbine, onshore | Alloc Def, U Electricity, high voltage {ES}| electricity production, wind, 1-3MW turbine, onshore | Alloc Def, U
Measured generation Fuel	0,00%	**0,00%**	0,00	----
Measured generation Natural Gas Cogeneration*	10,78%	**10,55%**	26.704.354,11	Electricity, high voltage {ES}| electricity production, natural gas, at conventional power plant | Alloc Def, U – Modified for ES - Natural Gas .
Measured generation Hydraulic UGH	7,88%	**7,71%**	19.518.093,46	Electricity, high voltage {ES}| electricity production, hydro, run-of-river | Alloc Def, U
Measured generation Non UGH Hydraulics	2,16%	**2,11%**	5.342.282,85	Electricity, high voltage {ES}| electricity production, hydro, reservoir, non-alpine region | Alloc Def, U
Measured generation Anthracite coal	1,77%	**1,73%**	4.372.562,69	Electricity, high voltage {ES}| electricity production, hard coal | Alloc Def, U
Measured generation Sub-bituminous coal	2,55%	**2,49%**	6.308.707,61	Electricity, high voltage {RoW}| electricity production, lignite | Alloc Def, U
Measured Nuclear Generation	22,61%	**22,12%**	55.994.960,05	Electricity, high voltage {ES}| electricity production, nuclear, pressure water reactor | Alloc Def, U Electricity, high voltage {ES}| electricity production, nuclear, boiling water reactor | Alloc Def, U
Measured generation Ocean and geothermal	0,01%	**0,01%**	18.879,05	Electricity, high voltage {DE}| electricity production, geothermal | Alloc Def, U
Generation measured Household and similar waste	0,60%	**0,59%**	1.482.146,75	Electricity, high voltage {ES}| treatment of municipal solid waste, incineration | Alloc Def, U
Measured generation Miscellaneous waste	0,43%	**0,42%**	1.059.295,46	Electricity, high voltage {ES}| treatment of municipal solid waste, incineration | Alloc Def, U
Measured generation Solar photovoltaic	3,58%	**3,50%**	8.855.075,54	Electricity, low voltage {ES}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Alloc Def, U
Measured generation Solar thermal***	2,09%	**2,04%**	5.171.742,44	N.A. (burden allocated on Solar Photovoltaic and Spanish Mix | market for 1:1)
Generation measured Mining by-products	0,11%	**0,11%**	275.124,51	N.A.
Measured generation Turbination pumping	0,67%	**0,65%**	1.650.969,55	Electricity, high voltage {ES}| electricity production, hydro, pumped storage | Alloc Def, U
TOTAL SPAIN		**97,81%**	**247.640.222,37**	
Dependence Portugal****		**2,19%**	5.545.490,00	Electricity, high voltage {ES}| import from PT | Alloc Def, U
Dependence France****		0,00%	-266.745,00	
AL CONSUMPTIONS			**253.185.712,37**	
Import France			7.006.269,00	Electricity, high voltage {ES}| import from FR | Alloc Def, U
Import Portugal			28.725.922,00	Electricity, high voltage {ES}| import from PT | Alloc Def, U
Export France			7.273.014,00	
Export Portugal			23.180.432,00	

7.4 Annex 4: Lay out Configuration Plant for Sorting Model

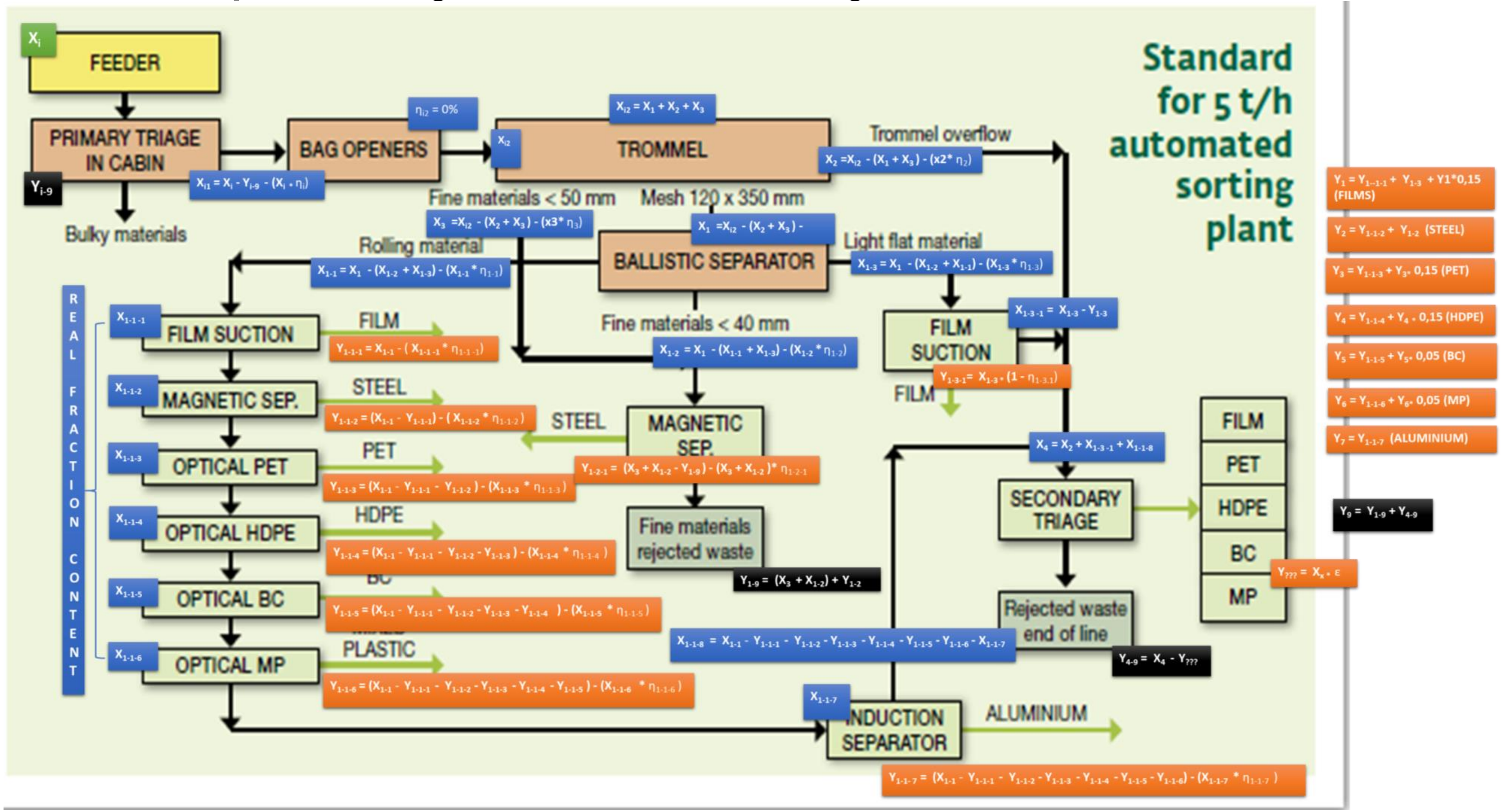


Figure 29 -- Mass Flow Model on standard Spanish Recycling plant for 5 to 6 ton/h capacity. Diagram extracted from Ecoembes manuals. Own mathematical development on mass flow.

7.5 Annex 5 – Inventories for Collection, Transport and Sorting on Valencia Pilot

Table 38 - Impacts on Collection, transport and Sorting for Post-Pilot in Valencia. (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)

Impact Category	Unit)	Collection	Transport	Sorting
Climate change	kg CO2 eq	$1.38\cdot10^{+1}$	$4.98\cdot10^{+02}$	$5.11\cdot10^{+01}$
Ozone depletion	kg CFC-11 eq	$9.62\cdot10^{-07}$	$1.09\cdot10^{-04}$	$3.69\cdot10^{-06}$
Human toxicity, non-cancer effects	CTUh	$5.47\cdot10^{-06}$	$2.44\cdot10^{-05}$	$8.40\cdot10^{-07}$
Human toxicity, cancer effects	CTUh	$3.64\cdot10^{-07}$	$1.46\cdot10^{-07}$	$2.91\cdot10^{-08}$
Particulate matter	kg PM2.5 eq	$1.17\cdot10^{-02}$	$8.98\cdot10^{-01}$	$1.15\cdot10^{-02}$
Photochemical ozone formation	kg NMVOC eq	$6.74\cdot10^{-02}$	$4.82\cdot10^{+00}$	$9.62\cdot10^{-02}$
Acidification	molc H+ eq	$1.21\cdot10^{-01}$	$3.24\cdot10^{+00}$	$1.79\cdot10^{-01}$
Terrestrial eutrophication	molc N eq	$1.83\cdot10^{-01}$	$1.36\cdot10^{+01}$	$3.14\cdot10^{-01}$
Freshwater eutrophication	kg P eq	$1.07\cdot10^{-02}$	$6.41\cdot10^{-04}$	$4.92\cdot10^{-04}$
Marine eutrophication	kg N eq	$1.62\cdot10^{-02}$	$1.24\cdot10^{+00}$	$6.88\cdot10^{-02}$
Freshwater ecotoxicity	CTUe	$4.02\cdot10^{+01}$	$7.79\cdot10^{+01}$	$1.32\cdot10^{+01}$
Land use	kg C deficit	$5.42\cdot10^{+00}$	$3.37\cdot10^{+00}$	$1.12\cdot10^{+01}$
Water resource depletion	m3 water eq	$6.03\cdot10^{-02}$	$1.16\cdot10^{-01}$	$3.64\cdot10^{-02}$
Mineral, fossil & ren resource depletion	kg Sb eq	$7.56\cdot10^{-03}$	$1.06\cdot10^{-04}$	$5.72\cdot10^{-05}$

*Table 39 - Impacts for Pre vs Post Pilot **COLLECTION** in Valencia. (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)*

Impact Category	**Unit (per ton of LPW managed)**	**PrePilot - Collection Resource Use and Maintenance**	**PostPilot - Collection Resource Use and Maintenance**
Climate change	kg CO2 eq	$2.64\cdot10^{-02}$	$1.38\cdot10^{+01}$
Ozone depletion	kg CFC-11 eq	$3.02\cdot10^{-09}$	$9.62\cdot10^{-07}$
Human toxicity, non-cancer effects	CTUh	$8.99\cdot10^{-10}$	$5.47\cdot10^{-06}$
Human toxicity, cancer effects	CTUh	$3.96\cdot10^{-11}$	$3.64\cdot10^{-07}$
Particulate matter	kg PM2.5 eq	$9.01\cdot10^{-06}$	$1.17\cdot10^{-02}$
Photochemical ozone formation	kg NMVOC eq	$5.34\cdot10^{-05}$	$6.74\cdot10^{-02}$
Acidification	molc H+ eq	$1.37\cdot10^{-04}$	$1.21\cdot10^{-01}$
Terrestrial eutrophication	molc N eq	$1.86\cdot10^{-04}$	$1.83\cdot10^{-01}$
Freshwater eutrophication	kg P eq	$2.15\cdot10^{-06}$	$1.07\cdot10^{-02}$
Marine eutrophication	kg N eq	$1.73\cdot10^{-05}$	$1.62\cdot10^{-02}$
Freshwater ecotoxicity	CTUe	$3.81\cdot10^{-03}$	$4.02\cdot10^{+01}$
Land use	kg C deficit	$7.74\cdot10^{-03}$	$5.42\cdot10^{+00}$
Water resource depletion	m3 water eq	$2.09\cdot10^{-02}$	$6.03\cdot10^{-02}$
Mineral, fossil & ren resource depletion	kg Sb eq	$1.02\cdot10^{-07}$	$7.56\cdot10^{-03}$

Table 40 --- Impacts for Pre vs Post Pilot TRANSPORT in Valencia . (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)

Impact Category	**Unit (per tonne of waste collected)**	**Pre-pilot**	**Pilot/Post-pilot**
Climate change	kg CO2 eq	$6.25\cdot10^{+02}$	$4.98\cdot10^{+02}$
Ozone depletion	kg CFC-11 eq	$1.26\cdot10^{-04}$	$1.09\cdot10^{-04}$
Human toxicity, non-cancer effects	CTUh	$3.05\cdot10^{-05}$	$2.44\cdot10^{-05}$
Human toxicity, cancer effects	CTUh	$1.73\cdot10^{-07}$	$1.46\cdot10^{-07}$
Particulate matter	kg PM2.5 eq	$1.13\cdot10^{+00}$	$8.98\cdot10^{-01}$
Photochemical ozone formation	kg NMVOC eq	$6.07\cdot10^{+00}$	$4.82\cdot10^{+00}$
Acidification	molc H+ eq	$4.02\cdot10^{+00}$	$3.24\cdot10^{+00}$

Terrestrial eutrophication	molc N eq	$1.72\cdot10^{+01}$	$1.36\cdot10^{+01}$
Freshwater eutrophication	kg P eq	$7.47\cdot10^{-04}$	$6.41\cdot10^{-04}$
Marine eutrophication	kg N eq	$1.57\cdot10^{+00}$	$1.24\cdot10^{+00}$
Freshwater ecotoxicity	CTUe	$9.36\cdot10^{+01}$	$7.79\cdot10^{+01}$
Land use	kg C deficit	$3.93\cdot10^{+00}$	$3.37\cdot10^{+00}$
Water resource depletion	m3 water eq	$1.35\cdot10^{-01}$	$1.16\cdot10^{-01}$
Mineral, fossil & ren resource depletion	kg Sb eq	$1.24\cdot10^{-04}$	$1.06\cdot10^{-04}$

Table 41 -- Impacts for Pre vs Post Pilot SORTING in Valencia . (Method: ILCD 2011 Midpoint+ V1.06 / EU27 2010, equal weighting)

Impact Category	Unit (per tonne of waste collected)	Pre- Pilot Sorting GENERAL Landfill	Post- Pilot Sorting GENERAL Landfill
Climate change	kg CO2 eq	$5.93\cdot10^{+01}$	$5.11\cdot10^{+01}$
Ozone depletion	kg CFC-11 eq	$3.78\cdot10^{-06}$	$3.69\cdot10^{-06}$
Human toxicity, non-cancer effects	CTUh	$8.99\cdot10^{-07}$	$8.40\cdot10^{-07}$
Human toxicity, cancer effects	CTUh	$3.22\cdot10^{-08}$	$2.91\cdot10^{-08}$
Particulate matter	kg PM2.5 eq	$1.22\cdot10^{-02}$	$1.15\cdot10^{-02}$
Photochemical ozone formation	kg NMVOC eq	$1.05\cdot10^{-01}$	$9.62\cdot10^{-02}$
Acidification	molc H+ eq	$1.84\cdot10^{-01}$	$1.79\cdot10^{-01}$
Terrestrial eutrophication	molc N eq	$3.37\cdot10^{-01}$	$3.14\cdot10^{-01}$
Freshwater eutrophication	kg P eq	$4.98\cdot10^{-04}$	$4.92\cdot10^{-04}$
Marine eutrophication	kg N eq	$8.26\cdot10^{-02}$	$6.88\cdot10^{-02}$
Freshwater ecotoxicity	CTUe	$1.59\cdot10^{+01}$	$1.32\cdot10^{+01}$
Land use	kg C deficit	$1.33\cdot10^{+01}$	$1.12\cdot10^{+01}$
Water resource depletion	m3 water eq	$3.60\cdot10^{-02}$	$3.64\cdot10^{-02}$
Mineral, fossil & ren resource depletion	kg Sb eq	$5.78\cdot10^{-05}$	$5.72\cdot10^{-05}$

Table 42 - Values for Post-Pilot VLC and Utrecht scenarios

Categoría de impacto	Unidad	Collection PostPilot VLC	Collection UTR	Transport Post-Pilot VLC	Transport UTR	Post- Pilot Sorting VLC	Sorting UTR
Climate change	kg CO2 eq	$1.38\cdot10^{+01}$	$7.85\cdot10^{-01}$	$4.98\cdot10^{+02}$	$1.05\cdot10^{+03}$	$5.11\cdot10^{+01}$	$2.77\cdot10^{+02}$
Ozone depletion	kg CFC-11 eq	$9.62\cdot10^{-07}$	$1.48\cdot10^{-07}$	$1.09\cdot10^{-04}$	$2.22\cdot10^{-04}$	$3.69\cdot10^{-06}$	$2.69\cdot10^{-06}$
Human toxicity, non-cancer effects	CTUh	$5.47\cdot10^{-06}$	$7.16\cdot10^{-07}$	$2.44\cdot10^{-05}$	$5.14\cdot10^{-05}$	$8.40\cdot10^{-07}$	$3.76\cdot10^{-06}$
Human toxicity, cancer effects	CTUh	$3.64\cdot10^{-07}$	$2.75\cdot10^{-08}$	$1.46\cdot10^{-07}$	$3.01\cdot10^{-07}$	$2.91\cdot10^{-08}$	$1.61\cdot10^{-06}$
Particulate matter	kg PM2.5 eq	$1.17\cdot10^{-02}$	$1.34\cdot10^{-03}$	$8.98\cdot10^{-01}$	$1.90\cdot10^{+00}$	$1.15\cdot10^{-02}$	$7.62\cdot10^{-03}$
Photochemical ozone formation	kg NMVOC eq	$6.74\cdot10^{-02}$	$4.11\cdot10^{-03}$	$4.82\cdot10^{+00}$	$1.02\cdot10^{+01}$	$9.62\cdot10^{-02}$	$9.46\cdot10^{-02}$
Acidification	molc H+ eq	$1.21\cdot10^{-01}$	$1.53\cdot10^{-02}$	$3.24\cdot10^{+00}$	$6.80\cdot10^{+00}$	$1.79\cdot10^{-01}$	$9.65\cdot10^{-02}$
Terrestrial eutrophication	molc N eq	$1.83\cdot10^{-01}$	$1.31\cdot10^{-02}$	$1.36\cdot10^{+01}$	$2.88\cdot10^{+01}$	$3.14\cdot10^{-01}$	$3.74\cdot10^{-01}$
Freshwater eutrophication	kg P eq	$1.07\cdot10^{-02}$	$8.22\cdot10^{-04}$	$6.41\cdot10^{-04}$	$1.31\cdot10^{-03}$	$4.92\cdot10^{-04}$	$6.72\cdot10^{-04}$
Marine eutrophication	kg N eq	$1.62\cdot10^{-02}$	$1.13\cdot10^{-03}$	$1.24\cdot10^{+00}$	$2.63\cdot10^{+00}$	$6.88\cdot10^{-02}$	$3.49\cdot10^{-02}$
Freshwater ecotoxicity	CTUe	$4.02\cdot10^{+01}$	$2.26\cdot10^{+00}$	$7.79\cdot10^{+01}$	$1.61\cdot10^{+02}$	$1.32\cdot10^{+01}$	$3.15\cdot10^{+02}$

Land use	kg C deficit	$5.42\cdot10^{+00}$	$4.86\cdot10^{-01}$	$3.37\cdot10^{+00}$	$6.90\cdot10^{+00}$	$1.12\cdot10^{+01}$	$6.60\cdot10^{+00}$
Water resource depletion	m3 water eq	$6.03\cdot10^{-02}$	$-1.27\cdot10^{-03}$	$1.16\cdot10^{-01}$	$2.38\cdot10^{-01}$	$3.64\cdot10^{-02}$	$2.11\cdot10^{-02}$
Mineral, fossil & ren resource depletion	kg Sb eq	$7.56\cdot10^{-03}$	$2.61\cdot10^{-04}$	$1.06\cdot10^{-04}$	$2.17\cdot10^{-04}$	$5.72\cdot10^{-05}$	$3.76\cdot10^{-05}$

Table 43 - Impacts for Pre vs Post Pilot COLLECTION in Alba Iulia

Categoría de impacto	Unidad	Collection Resource Use and Infrastructure - Alba Iulia Pre	Collection Resource Use and Infrastructure - Post PlastiCircle ALBA iULIA
Climate change	kg CO2 eq	2,64E-02	1,38E+01
Ozone depletion	kg CFC-11 eq	3,02E-09	9,53E-07
Human toxicity, non-cancer effects	CTUh	8,99E-10	5,47E-06
Human toxicity, cancer effects	CTUh	3,96E-11	3,64E-07
Particulate matter	kg PM2.5 eq	9,01E-06	1,17E-02
Photochemical ozone formation	kg NMVOC eq	5,34E-05	6,72E-02
Acidification	molc H+ eq	1,37E-04	1,21E-01
Terrestrial eutrophication	molc N eq	1,86E-04	1,82E-01
Freshwater eutrophication	kg P eq	2,15E-06	1,07E-02
Marine eutrophication	kg N eq	1,73E-05	1,61E-02
Freshwater ecotoxicity	CTUe	3,81E-03	4,02E+01
Land use	kg C deficit	7,74E-03	5,41E+00
Water resource depletion	m3 water eq	2,09E-02	6,02E-02
Mineral, fossil & ren resource depletion	kg Sb eq	1,02E-07	7,56E-03

Table 44 - Impacts for Pre vs Post Pilot TRANSPORT in Alba Iulia

Categoría de impacto	Unidad		
Climate change	kg CO2 eq	2,02E+02	2,00E+02
Ozone depletion	kg CFC-11 eq	4,71E-05	4,63E-05
Human toxicity, non-cancer effects	CTUh	9,93E-06	9,80E-06
Human toxicity, cancer effects	CTUh	6,25E-08	6,15E-08
Particulate matter	kg PM2.5 eq	3,62E-01	3,57E-01
Photochemical ozone formation	kg NMVOC eq	1,94E+00	1,92E+00
Acidification	molc H+ eq	1,33E+00	1,31E+00
Terrestrial eutrophication	molc N eq	5,49E+00	5,42E+00
Freshwater eutrophication	kg P eq	2,78E-04	2,74E-04
Marine eutrophication	kg N eq	5,00E-01	4,94E-01
Freshwater ecotoxicity	CTUe	3,29E+01	3,24E+01
Land use	kg C deficit	1,46E+00	1,44E+00
Water resource depletion	m3 water eq	5,04E-02	4,96E-02
Mineral, fossil & ren resource depletion	kg Sb eq	4,61E-05	4,53E-05

7.6 Annex 6 – Washing Conditions

PET Bottles/Trays Washing		Mass Losses	30-35%		
STAGES --> 1 - Wet Grinder; 2- friction Washer; 3 - Compact Washing Line; 4 - Friction Washer; 5 - Separation; 6 - FrictionWasher; 7 -Mechanical dryer; 8 - Blower					
Capacity of the process	2	ton/h	Herbold (Germany)		
Pre-Washing	Power of machines (kW)	Energy consumed(kWh/ton)			
NIR sorter	0	0			
Washing	Power of machines (kW)	Energy consumed (kWh/ton)	Source	Benchmark	
Elec. Energy	390	136,5	AXION Internal DataBase		Electricity, medium voltage {RER}| electricity voltage transformation from high to medium voltage | Alloc Def, U
Wet Grinder	75	26,25	AXION Internal DataBase		
Friction Washer 1	18,5	6,475	AXION Internal DataBase		
Compact washing line*		0	AXION Internal DataBase		
Pump	22	7,7	AXION Internal DataBase		
Thermal heater	70	24,5	AXION Internal DataBase		
Friction Washer 2	18,5	6,475	AXION Internal DataBase		
Pump	30	10,5	AXION Internal DataBase		
Hydrocyclone	70	24,5	AXION Internal DataBase		
Friction Washer 3		0	AXION Internal DataBase		
Mechanical Dryer	75	26,25	AXION Internal DataBase		
Blower	11	3,85	AXION Internal DataBase		
Extrusion Line					
Extruder	-				
Water Use*	Units				
Fresh water (m3)	m3	2	Herbold Wash on PET Tray/Bottle Mix	3–5m3 (Khaled M. Bataineh, 2020)	
Purge water (m3)	m3	2		1 to 2 m³ fresh water per tonne (Herlbold, 2015)	
Additives*	Units				
Sodium hydroxide (50% w/w)	l/tonne	10	AXION Internal DataBase	*Khaled M. Bataineh, 2020*	Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, membrane cell | Alloc Def, U
Washing agent	l/tonne	6		24,5 kg NaOH	Detergent (internal Database)
Antifoam	l/tonne	4		0,79 kg Defoamer	Ethylene glycol {RER}| production | Alloc Def, U
Acid (85% w/w)	l/tonne	8,6		2,46 Wetting Agent	Hydrochloric acid, without water, in 30% solution state {RER}| hydrochloric acid production, from the reaction of hydrogen with chlorine | Alloc Def, U
Flocculant	l/tonne	1,9		0,98 kg Surfactant	Aluminium sulfate, without water, in 4.33% aluminium solution state {RoW}| production | Alloc Def, U

PE Films					
		Mass Losses	22-26%		
Capacity of the process	1	ton/h			
Pre-Washing	Power of machines (kW)	Energy consume (kWh/ton)			
NIR sorter					
Washing	Power of machines (kW)	Energy consumer (kWh/ton)	Source	Benchmark	Ecoinvent
Elec. Energy	350	245	Mixed sources	0,8-1 kW per kg (incl extrusion)	Electricity, medium voltage {RER}| electricity voltage transformation from high to medium voltage | Alloc Def, U
PlastiC shredder Machine			ASG Machinery		
Wet Plastic Granulator			ASG Machinery		
Friction Washer			ASG Machinery		
Sink Float Separation			ASG Machinery		
Centrifugal dewatering machine			ASG Machinery		
Screw Press dewateriung Machine			ASG Machinery		
Thermal Dryer			ASG Machinery		
Cyclone Separator			ASG Machinery		
Product Silo			ASG Machinery		
Extrusion Line					
Extruder		400 kWh/ton			
Water Use*	Units				
Fresh water (m3)	m3	3	Herbold Wash on PE Films	1 to 2 m³ fresh water per tonne (Herlbold, 2015)	
Purge water (m3)	m3	3			
Additives*	Units				
Sodium hydroxide (50% w/w)	l/tonne	15	AXION Internal DataBase		Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, membrane cell | Alloc Def, U
Washing agent	l/tonne	9			Detergent (internal Database)
Antifoam	l/tonne	6			Ethylene glycol {RER}| production | Alloc Def, U
Acid (85% w/w)	l/tonne	12,9			Hydrochloric acid, without water, in 30% solution state {RER}| hydrochloric acid production, from the reaction of hydrogen with chlorine | Alloc Def, U
Flocculant	l/tonne	2,9			Aluminium sulfate, without water, in 4.33% aluminium solution state {RoW}| production | Alloc Def, U

8 Annex: Injection-Moulding Consumption

Energy consumption: As explained in Hischier,R (2007), EcoInvent LCI dataset for the injection-moulding process is created by calculating the average of three processes—injection-moulding of poly(vinyl chloride) (PVC), polypropylene (PP), and polyethylene terephthalate (PET)—and considering an average electricity consumption (1.47 kWh/kg) [27]as well as an average consumption of water, lubricating oils, chemicals, fillers, solvents, packaging materials, natural gas for the factory, generated waste, etc. Among the process on the industries studied, there are injection moulding steps for different polymers (PP, PET or PA) with different properties even with same material (flexible or rigid, different MFI) and different type of machinery and installation power (different industrial scales). To provide accurate consumption references and inputs, direct information from the industries on the process and if not possible, consistent studies from literature have been. For instance, this issue had already been faced up by Elduque A. et al. (2018), which provides a model representation comparing Ecoinvent databases with real data and empirical models as depicted on **Figure 17** [28-29].

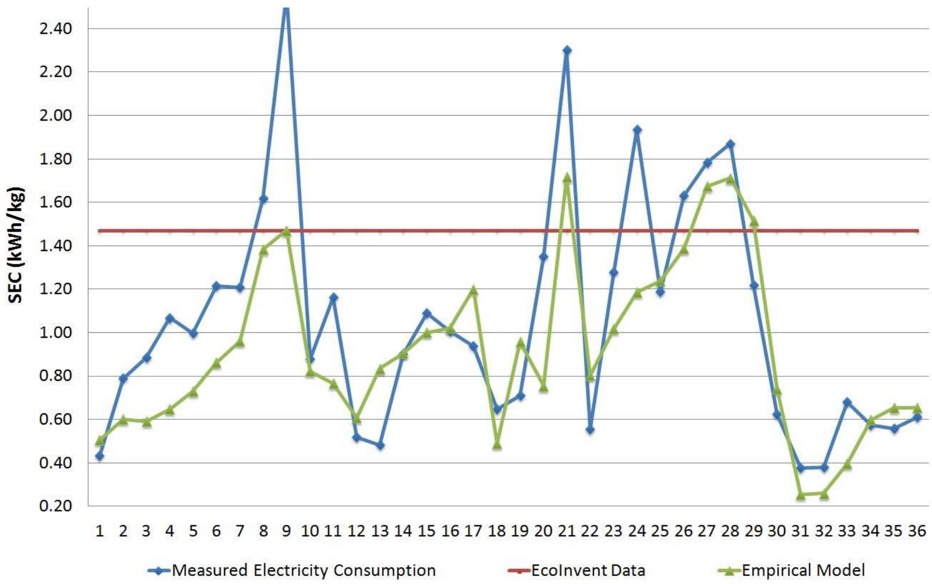


Figure 17 - Energy consumption (kWh/kg) differences from Ecoinvent model to real and empirical calculations. Extracted from Elduque et al. (2019)

In case of not being able to assess the power consumption via primary data, either with a proper model, theoretical calculation can be an option to avoid using directly fixed values from Ecoinvent inventory. As described on [30], a thermodynamic-empirical model can be applied considering not only hydraulic motors and barrel heater but also idling and water cooling, as expression on Eq. below. For this calculation main characteristics on the piece injected and the machinery specifications must be known.

$$Econsumed = \frac{m_{injected} * Cp * \Delta T + \lambda * m * Hf + \bar{p} * Vmold}{\varepsilon} + tcooling * (P_{idle} + P_{cooling\_system}) \quad [4]$$

For this specific report, CRF/Proplast and Hahn plastic injection processes were modelled applying the considerations described during this Annex.

PlastiCircle
TOO VALUABLE TO WASTE

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