PolyCE

Post-Consumer High-tech Recycled Polymers for a Circular Economy

Project Duration: **01/06/2017 - 31/05/2021**

Deliverable No.: **D8.2**

Deliverable Title: **Resource efficiency studies and Life Cycle Assessments**

Version Number: V0

Due Date for Deliverable: **30/09/2020**

Actual Submission date: 03/02/2021

Lead Beneficiary: UNU

Lead Author: Dr. Otmar Deubzer

Deliverable Type: R

- R = Document, report
- DEM = Demonstrator, pilot, prototype, plan designs
- DEC = Websites, patent filing, press & media actions, videos, etc.

Dissemination Level: PU

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730308

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Acronyms

AB	Avoided Burden
ABS	Acrylonitrile Butadiene Styrene
D	Dryer
DW	Dishwasher
C&F	Cooling and Freezing appliances
EEE	Electrical and Electronic Equipment
EI	Environmental Impact
EoL	End of Life
F&F	Fridges and Freezers
HDPE	High Density Polyethylene
HiPS	High Impact Polystyrene
KA	Kitchen Appliances
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHA	Large Household Appliances
LHA*	Large Household Appliances without cooling and freezing appliances
LDPE	Low Density Polyethylene
PA	Polyamide
PC	Polycarbonate
PoM	Put on Market
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinylchloride
PCR-plastics	Post-Consumer Recycled Plastics
RR	Recycling Rate
WEEE	Waste Electrical and Electronic Equipment
WM	Washing Machine

Definitions

- Closed-Loop-Recycling
  The new product is made up entirely from recycled plastic or a mixture with virgin plastic where the added virgin plastic ensures the product quality and improves the recyclability.[1]

- Open-Loop-Recycling
  The recycled plastic is not used for the same product again but for a different product with other requirements. This doesn't imply that the recycled plastic got a lower value but still the product properties are changing during the recycling process. [1]

- Primary plastics, virgin plastics
  Plastics produced from fossil raw materials, contrary to recycled plastics

- Secondary plastics, recycled plastics
  Plastics produced from used plastics, in the context of the PolyCE project relating to plastics produced from PCR-plastics from WEEE pre-treatment.

[1] Ragaert et al. 2017

1 Background, Objectives and Approaches of Tasks 8.3 and 8.4

PolyCE aspires paving the way for the use of PCR-plastics in new electrical and electronic equipment (EEE) addressing all actors of the various stages of the life cycle of electrical and electronic equipment and plastics. Tasks 8.3 and 8.4 of PolyCE Work Package 8 assess and evaluate:

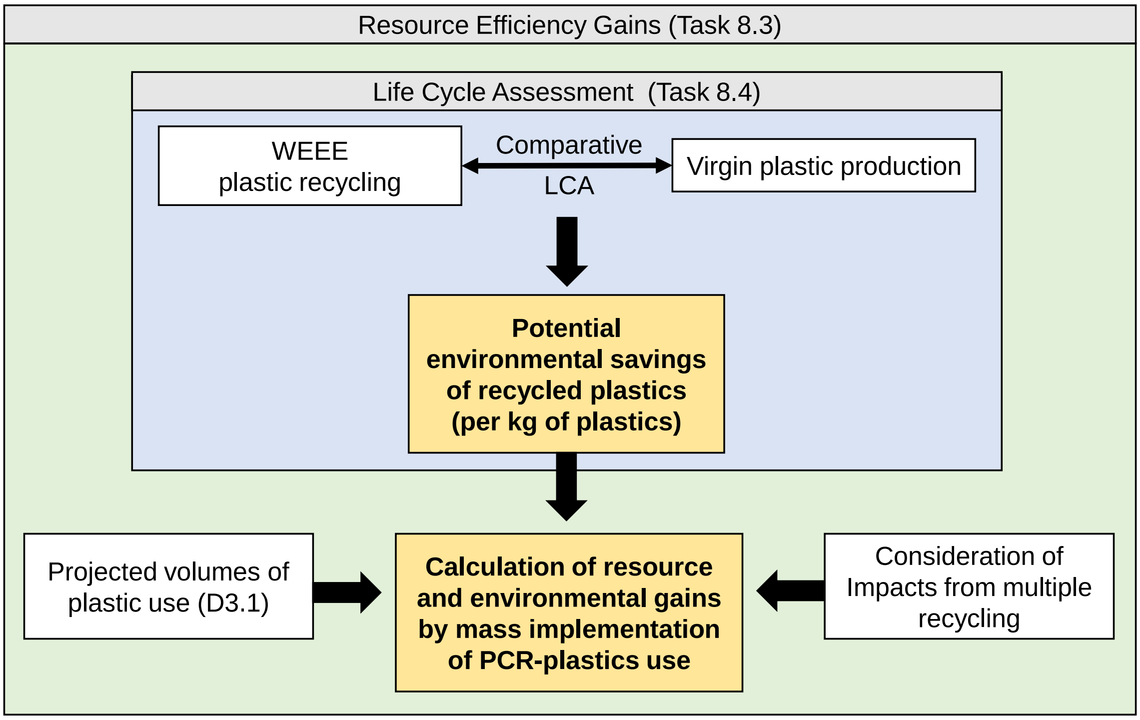
1) Whether and to which degree the production of PCR-plastics is environmentally beneficial compared to the production of primary plastics (Life Cycle Assessment of PCR and primary plastics production).

2) Which environmental and resource savings can be expected in a scenario where all PCR-plastics that can be produced from WEEE are used in new EEE (mass implementation of PCR-plastics use).

1.1 Approach Task 8.3

Differently from what the task numbering suggests, task 8.3 (Evaluation of resource efficiency gains across the value chain) builds on the results of task 8.4 (Environmental assessment in line with the European Platform on LCA) in that task 8.4 provides the basic data for the calculations of resource efficiency and environmental gains from PCR-plastics use in the mass implementation scenario.

Figure 1: Linkage of tasks 8.3 and 8.4



Task 8.4 will provide data enabling a comparison of energy and resource consumption as well as environmental impacts from the production of equal amounts (1 kg) of primary and PCR-plastics. This information will be used in task 8.3 to calculate the resource savings and avoided environmental impacts if all PCR-plastics recycled from the collected WEEE will be used in new EEE, i.e. a mass implementation of PCR-plastics use in production of new EEE.

The mass implementation scenario is defined by the following assumptions:

1) Until a time t = 0 only primary plastics are used in EEE. In each life cycle after the time t = 0, PCR-plastics will be produced from the EEE put on the market earlier and collected separately.

2) In each life cycle after the time t = 0, all plastics contained in the plastics fractions from the pre-treatment of separately collected waste electrical and electronic equipment (WEEE) in the European Economic Area, EEA) undergo a final processing to produce PCR-plastics from it.

3) All this PCR-plastics are used to produce new electrical and electronic equipment (EEE) which is put on the EEA market.

4) It is assumed that the life time of all EEE produced with the PCR-plastics is equally long so that these products come back as WEEE from the market at around the same time. This assumption eliminates the transition phase during which WEEE containing PCR-plastics from short-lived EEE and WEEE with primary plastics from longer-lived EEE come back from the market at the same time, which would be difficult to assess without adding much additional information.

This scenario implies that WEEE coming back from the market after the first life cycle already contains PCR-plastics, i.e. plastics which has already passed one recycling process before. These plastics will be recycled again at the end of this first life cycle to be used in a second life cycle. The result will be that with each additional life cycle, the PCR-plastics fraction produced from WEEE potentially contains shares of plastics which have passed several life cycles already and thus also several recycling processes. Since recycling of plastics is often related to downcycling processes, the quality of recycled plastics could decrease with each life cycle due to the multiple recycling of parts of the PCR-plastics produced.

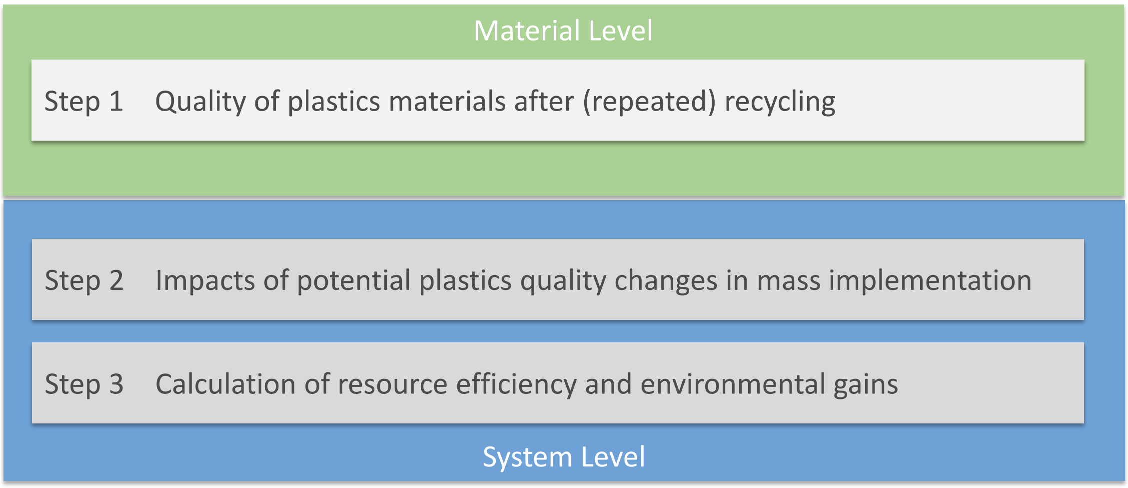
This raises questions

1) about the impacts of recycling on the quality of the recycled plastics, in particular for plastics which have passed several recycling processes (multiple recycling).

2) whether the increasing share of multiply recycled plastics coming back from the market for further recycling may either decrease the quality of recycled plastics – which the market with its defined quality requirements would not accept – or increase the efforts required to achieve the quality of PCR-plastics to suffice the demands, e.g. by adding more and more primary plastics, and/or applying other measures to improve the quality.

The quality impacts of (multiple) recycling on PCR-plastics and its usability will be investigated in the 3-step approach illustrated in Figure 2.

Figure 2: Approach to investigate role of quality impacts in mass implementation of PCR-plastics use



In step 1, potential quality impacts of recycling, in particular of multiple recycling, on plastics are investigated. In the second step, it is investigated whether and how far such quality impacts may affect the mass implementation of PCR-plastics use. This requires taking account of the system level to the material level. The “system” in this case is the production of primary plastics, its use in EEE, the separate collection of WEEE, its treatment and the related plastics mass flow in the EEA. Crucial aspects in this context are the WEEE collection rate, plastics losses in pre-treatment, and the separation losses of plastics coming from pre-treatment in final processing. Each of the previous steps results in losses of plastics which are assumed to be compensated with primary plastics. Whether and how far this may in the end compensate quality losses on material level from multiple recycling will be the objective of the second step.

In step 3, the resource efficiency gains will be calculated based on the data for primary and PCR-plastics production from task T8.4 assuming that all plastics used in for the production of new EEE are replaced by PCR-plastics. The volumes of PCR-plastics used in EEE are available from deliverable D3.1. In case quality losses assessed in step 1 - taking into account the findings of step 2 - require a compensation to ensure the adequate quality of PCR-plastics, the resource and environmental impacts of these compensating measures will be taken into consideration in step 3.

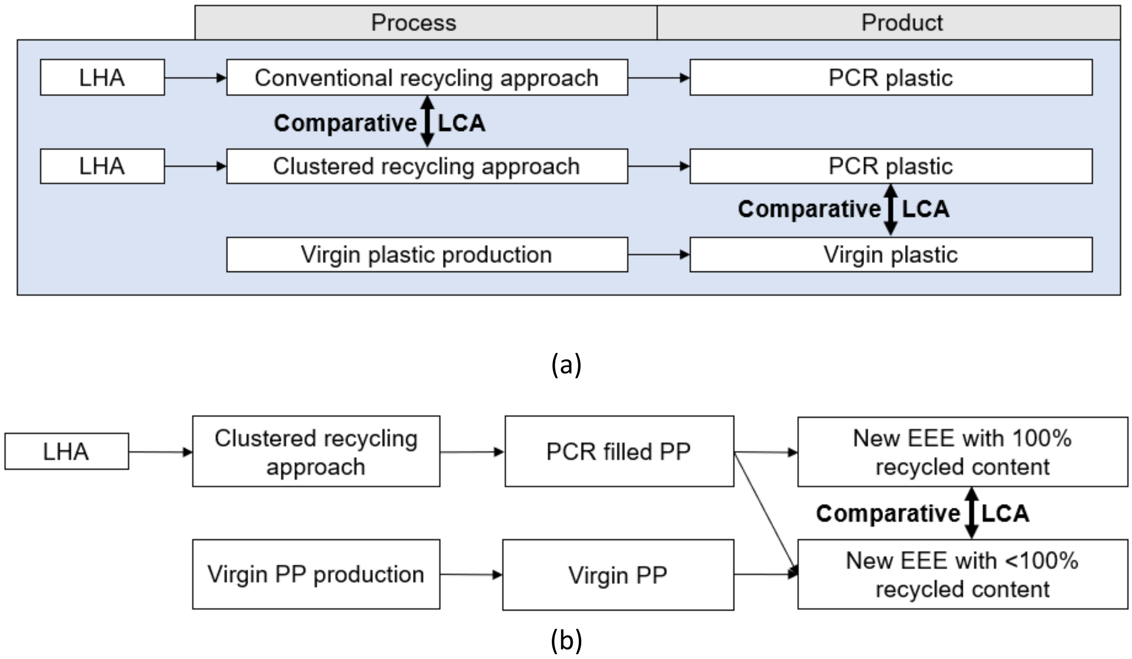
1.2 Approach Task 8.4

For task 8.4, the potential environmental benefits of research outcomes from the PolyCE project are investigated. Previous research conducted under Work Package 3 has shown the potential benefit of strategic pre-sorting of WEEE products in different product clusters.

Post-consumer recycling of plastics from WEEE is a complicated task due to, amongst other factors, the complex composition of the plastic fraction. WEEE contains a diverse mix of plastics with different types of additives, which can modify material properties such as mechanical properties, flame resistance and density (Martinho et al. 2012) and increase the difficulty of post-consumer plastic recycling (Wagner 2020). This results in a plastic recycling rate from WEEE of less than 25 % (Baxter and Nordisk Ministerråd 2015; Villanueva and Eder 2014) and the remaining fraction ending up in incinerators and landfills.

In task 2 of work package 3 it was concluded that by clustering product categories significant increases in plastic recycling rates can be expected, as clustering can avoid mixing of non-compatible plastics with overlapping densities, which are for this reason difficult to separate with commonly adopted density-based sorting technologies. Thus, the potential environmental burden reduction and increased plastic recycling rates of different clustering strategies are investigated (Figure 3 (a)). A focus is set on clusters for large household appliances (LHA) including cooling and freezing appliances (C&F).

Figure 3: Approach to investigate potential environmental benefits of (a) clustered LHA waste and (b) the resulting recycled plastic as part of a new EEE.



Additionally, the potential environmental impacts of the resulting post-consumer recycled (PCR) plastics are compared with the impacts of virgin plastic production (Figure 3 (a)). The methodological choice between different allocation procedures when dealing with multi-functionality in a recycling context may significantly impact the final results at individual product level and influence the decision making (Christiansen et al. 1995; Werner and Richter 2000; Nicholson et al. 2009). This is the case with this LCA, and thus the impact of using another allocation approach is evaluated in a sensitivity analysis.

The benefits of incorporating recycled plastics into a new electrical and electronic equipment (EEE) with different recycled content and considering more than one use cycle are also investigated (Figure 3 (b)). The effects of using different allocation procedures are considered for this LCA as well. Focus is set on a demonstrator, which is an EEE designed in Work Package 7 integrating the outcomes of other Work Packages.

Following the four phases of an LCA stated in the ISO norm 14040, the goal and scope of the LCAs are defined. As part of the scope, the modelling of the investigated systems is explained in detail in three different sections:

1) First, the composition of the generated LHA waste stream is characterized based on literature data complemented with chemical analyses of samples collected at recycling facilities in Europe.

2) Second, based on a detailed understanding of current state-of-the-art WEEE treatment, transfer-coefficients are proposed to model the destination / material flow of different plastic types in commonly adopted recycling process sequences.

3) Last, three different pre-sorting strategies are defined: (1) default situation without pre-clustering, (2) limited clustering; and (3) enhanced pre-sorting based on expected product composition and presence of targeted plastic types.

The second phase of an LCA consists on the inventory data collected from recycling companies and consortium partners. Impact assessment is presented as the third phase and includes the sensitivity analysis conducted. The fourth and final phase is the interpretation, where conclusions are drawn and needs for further research are suggested.

2 Life Cycle Assessment (T8.4)

A Life Cycle Assessment (LCA) is a systematic tool to evaluate the environmental impact of products or processes within a pre-defined system boundary. The international series of standards ISO 14040 defines the method and requirements for conducting an LCA (ISO 2006, 14040). LCA studies quantify the potential environmental burdens associated with a particular product or service throughout the entire life cycle and the burdens associated with each stage are aggregated together and allocated to a particular functional unit. In this study, an LCA model is built using SimaPro 9.1 as software tool and the environmental impact assessment is performed using the ReCiPe method (Huijbregts et al. 2016).

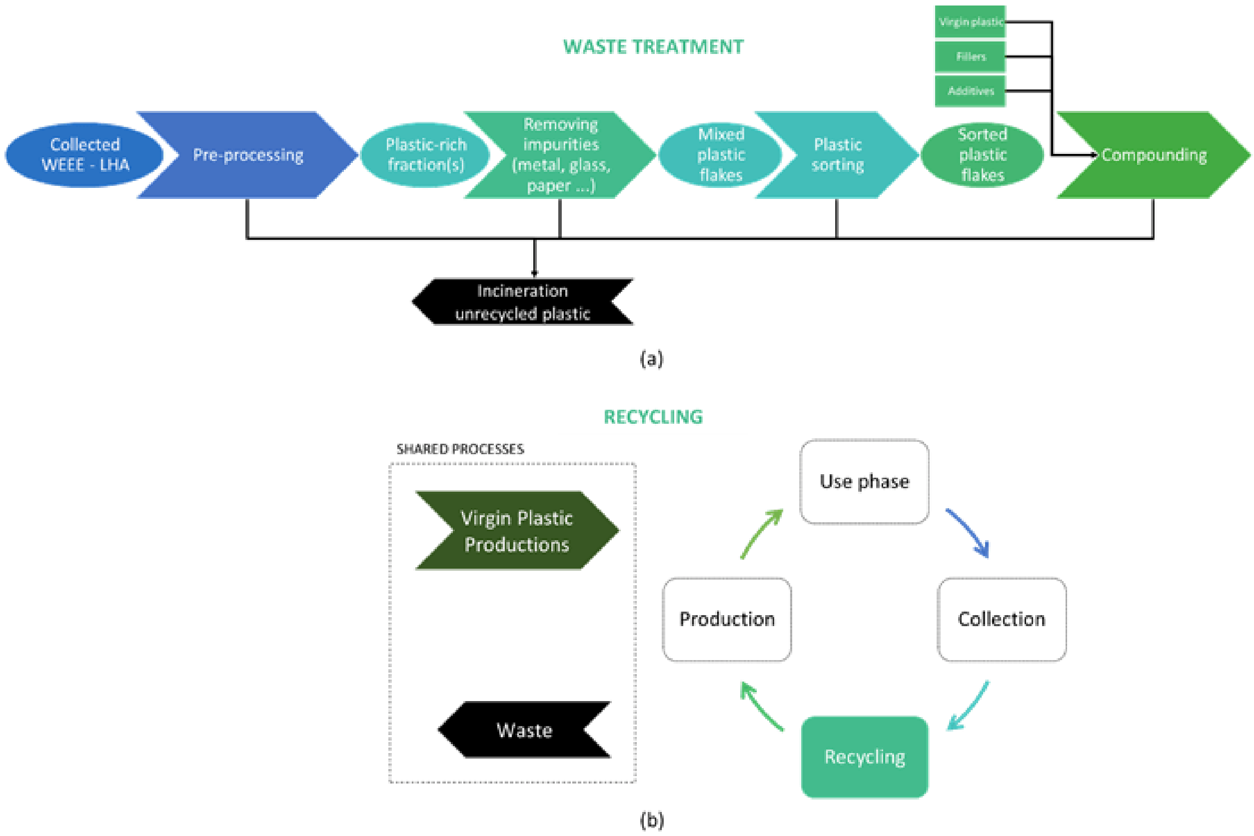
System expansion (without substitution) avoids the need for allocation procedures and is most in line with the holistic approach aimed at by LCA. For this reason, it is also the recommended solution for dealing with multi-functionality according to the ISO 14044 (2006) standards. As pointed out by Wäger and Hischier (2015), two different research questions can be investigated related to recycling systems which directly influences the choice of functional unit and related reference flow. When investigating the environmental performance of the waste management system, the functional unit is typically described as a service (treatment of waste) and the reference flow is determined by the input side of the process (amount of waste treated). When investigating the environmental performance of recycled material, the reference flow is determined by the output of the recycling process (amount of recycled material produced).

2.1 Goal and Scope

The overall goal of the study is to investigate the influence of different product clustering strategies on the environmental burden associated with both the waste treatment of plastic in WEEE and the production of recycled plastic. Although waste treatment and recycling activities are closely related, the considered perspective influences the considered system boundary and related functional unit (Wäger and Hischier 2015). Therefore, both approaches are covered in this deliverable.

When investigating the environmental performance of the waste management system, the functional unit is typically described as a service (treatment of waste) and the reference flow is determined by the input side of the process (amount of waste treated). The functional unit is described as the waste treatment of the plastic fraction contained in 1 ton of waste LHA. In this case, the focus is on documenting inventory data for the different processing steps shown in Figure 4 (a). Furthermore, the recycled feedstock recycled from plastic recycling and the energy and heat produced from plastic incineration are considered as by-products of the main function which remains waste treatment. System expansion (without substitution) avoids the need for allocation procedures and is most in line with the holistic approach targeted by LCA. For this reason, the generated co-products (recycled material and energy) are added to the defined functional unit by using a “basket of products”.

Figure 4: System boundary (a) for waste treatment of LHA and (b) for the production of recycled plastics



When investigating the environmental performance of recycled material, the reference flow is determined by the output of the recycling process (amount of recycled material produced). The functional unit is described as the use of 1 ton of recycled plastic. In this case, a broader perspective is taken as shown in Figure 4 (b). In a recycling system, both the material recoverability at end of life and reusability in similar products must be accounted for. In such a circular supply chain, where material quality is preserved, an appropriate allocation procedure is to partition the environmental burden equally over different use cycles. The virgin material and final waste disposal are then considered 'shared processes' that must be allocating across the different 'use' cycles of the material. If the potential application of the material is limited for the next use cycle due to quality degradation or properties changes, a correction factor can be applied.

2.1.1 Allocation procedures

In most cases, a product's composition drives its environmental profile because of the burden associated with extraction of raw materials and, in general, recycling is stimulated because it saves primary resources. Nonetheless, correctly assessing benefits and burdens associated with recycling activities is of increasing importance, as it can highly influence the end results and, thus, decision-making. In developed countries, waste management has evolved from landfilling towards more sophisticated recycling facilities. The main goal is no longer limited to efficient waste treatment, but focuses on generating added value with the production of secondary resources. The end of life (EoL) management of products has, therefore, become a multifunctional process and the distinction between the initially intended service (waste treatment) as primary function and the generation of recycled material as secondary function is not always clear. The importance of this recycling activity will depend on the amount and recyclability of valuable material, which is mostly determined by the product composition and product design.

Dealing with multi-functionality in a recycling context is a challenging issue and has been widely discussed in literature (Boguski, Hunt, and Franklin 1994; Ekvall and Tillman 1997; Ekvall 2000; Werner and Richter 2000; Atherton 2007; Christensen et al. 2007; Heijungs and Guinée 2007; Curran 2007; Nicholson et al. 2009; Dubreuil et al. 2010; Brander and Wylie 2011; Johnson, McMillan, and Keoleian 2013; Koffler and Florin 2013; Allacker et al. 2014; Santero and Hendry 2016). Most commonly applied allocation procedures have also been summarized and discussed by Schrijvers et al. (Schrijvers, Loubet, and Sonnemann 2016).

Although the allocation procedure applied in this study is not novel as such, this equal partitioning over the different use cycles is not often applied in existing literature. In many cases, either the cut-off approach or the avoided burden (AB) method is applied to solve the multi-functionality of recycling (Ekvall and Tillman 1997; Norgate 2004; Atherton 2007; Frischknecht 2010; Dubreuil et al. 2010; Laurent et al. 2014; Schrijvers, Loubet, and Sonnemann 2016). Nevertheless, the choice of the allocation approach may significantly affect the final results and influence the ranking of alternatives (Nicholson et al. 2009). Therefore, in this research, the importance of using different allocation procedures when integrating recycling into an LCA is investigated in a sensitivity analysis. The commonly applied allocation procedures are briefly explained in the next paragraphs and their potential influence on the LCA results is investigated in the sensitivity analysis.

The cut-off approach implies that the waste material is assumed to be “burden-free” and only impacts related to the recycling process are attributed to the next life cycle (Schrijvers, Loubet, and Sonnemann 2016). This means that the environmental burden associated with virgin material production is entirely allocated to the first material use cycle, which could be seen as “unfair” because the secondary material would not be available if the virgin material was never produced. In contrast, the final waste treatment is entirely allocated to the final use cycle, which could also be seen as “unfair” because this is a consequence of the virgin material production. In general, the cut-off rule tends to favour the use of recycled material because the burden associated with virgin production is usually much higher than final waste treatment.

The AB approach redistributes credits and burdens related to avoided processes. When considering the re-use of material, two main processes are avoided: the virgin material production and the final waste disposal. The credits can be awarded in different ways: (1) the EoL recycling approach method awards credits to the supplier of recycled material based on the avoided virgin material production, (2) the waste mining method awards credits to the user of recycled material based on avoided final waste disposal, and (3) the 50/50 approach combines both approaches.

2.1.2 System Modelling

In the following sub-chapters, the steps taken to model the system of recycling waste LHA plastics is presented. First, the plastic composition in this waste stream is characterized. Second, current state-of-the-art WEEE treatments, including issues concerning separability of plastics, are looked into to model the final destination of plastics. Last, using the material characterization and final destination of LHA plastics, three different product clusters are assumed using transfer-coefficients.

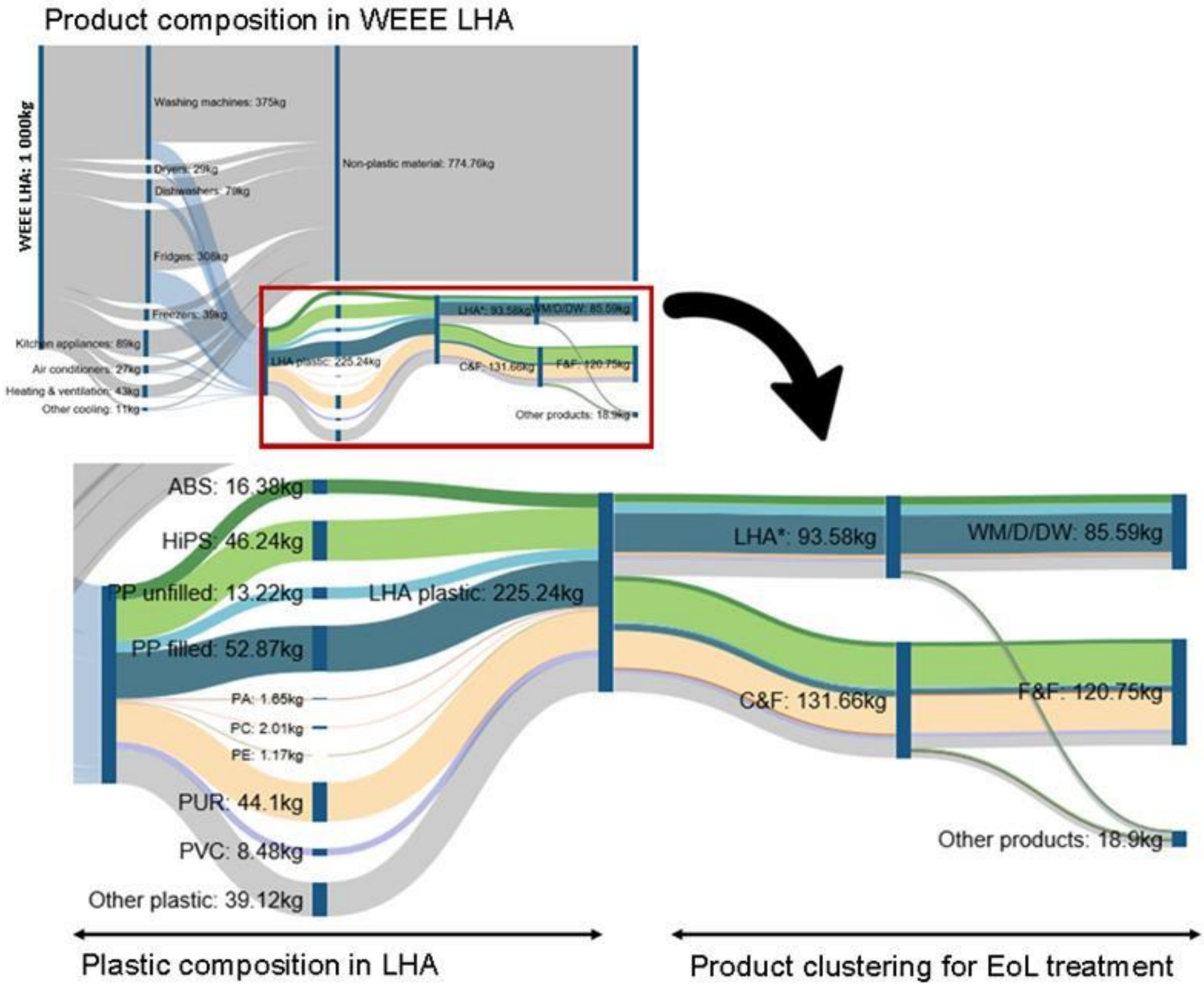
Plastic Composition in WEEE LHA

On average, the plastic fraction from WEEE amounts to 26 wt. % (Seyring et al. 2015) and contains a diverse range of plastic types that evolves over time. In 2012, high impact polystyrene (HIPS) and acrylonitrile butadiene styrene (ABS) constituted together more than half (51 %) of the mixed plastic WEEE stream, but, more recently, their contribution has been reduced to only 31 % (Slijkhuis 2020). This increasing complexity in composition is expected to reduce the recycling potential of valuable engineering plastics. In addition, the characterisation from the EERA revealed that the contamination of the mixed plastic stream from WEEE with metal, glass, mineral and wood parts has increased from 6 up to 13 % between 2012 and 2020 (Slijkhuis 2020).

The plastic composition varies widely depending on the WEEE category considered (Magalini et al. 2018). Large Household Appliances (LHA) is the largest WEEE category representing 56 w/w % of the total collected WEEE in Europe (European Commission 2019). The LHA stream is estimated to have a plastic fraction of 19.5 w/w %, resulting in around 700 kT of waste plastic generated each year in Europe alone (European Commission 2019; Balde et al. 2017).

Figure 5 shows the composition of the plastic contained in waste generated from LHA. The individual average product compositions are based on available literature (Magalini et al. 2018) and complemented with measurements on WEEE samples from recycling facilities in Europe (Duflou et al. 2020; Accili et al. 2019). The LHA plastic composition depends on the contribution of each product to the waste stream and the individual product composition. The contribution of each product type varies depending on which point of the value chain is considered for determining the composition. Data are available for EEE products put on market (PoM), WEEE generated and WEEE collected (European Union 2019; Balde et al. 2017). The difference between WEEE generated and WEEE collected results from low collection rates (<50 %). The product distribution from WEEE generated is used to estimate the plastic composition shown in Figure 5 and the importance of this assumption is later investigated in a sensitivity analysis.

Figure 5: Product and plastic composition in-generated WEEE



Source: European Union 2019; Accili et al. 2019; Magalini et al. 2018; Balde et al. 2017

LHA (Large Household Appliances); C&F (Cooling and Freezing equipment); LHA* (Large Household Appliances without C&F); F&F (Fridge and Freezer); WM/D/DW (Washing Machines/Dryers/Dishwashers); KA (Kitchen Appliances)

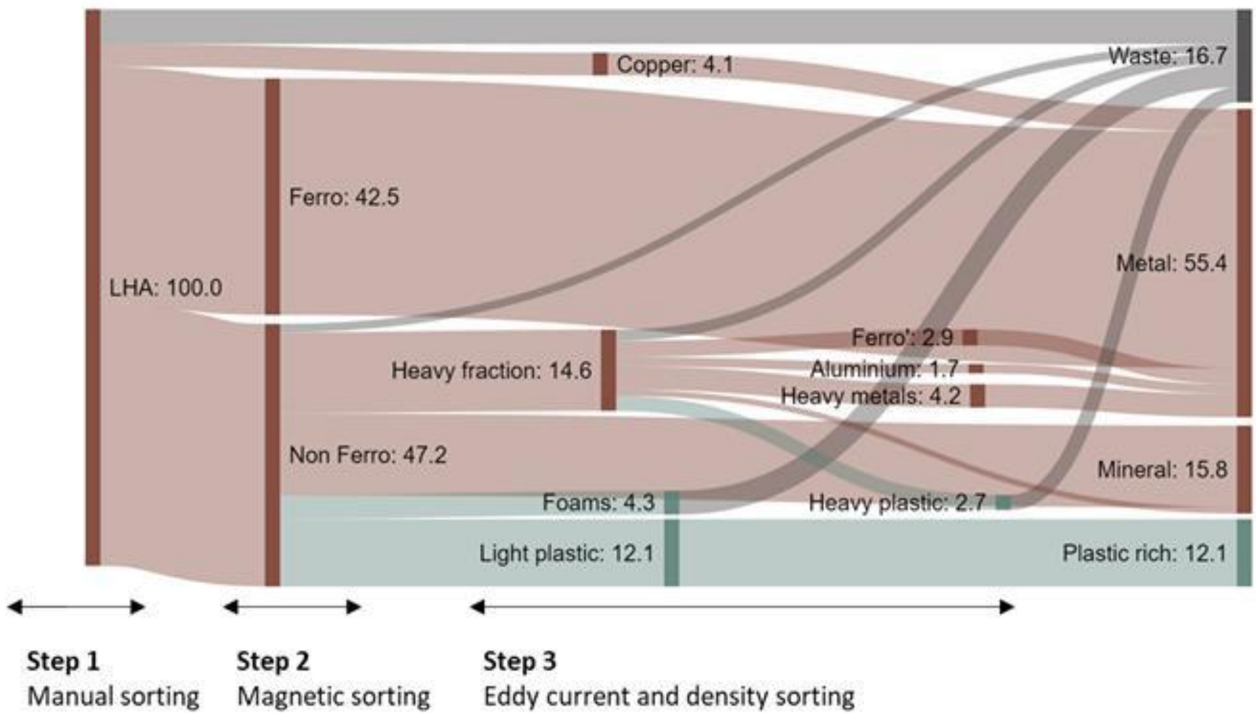
For the LCA, the focus is set on the recycling of four valuable plastics that represent about 57 % of plastic contained in the LHA stream: unfilled PP, ABS, (Hi)PS, and filled PP. Although considered to be valuable materials, the limited amount of polycarbonate (PC) and polyamide (PA) present in LHA (<1 %) is currently not targeted for recycling.

Recycling Operations for Plastics from WEEE LHA

The recycling operations required to close the loop for plastics from WEEE LHA can be summarized in five stages (Wagner 2020): (1) collection of EoL products; (2) pre-processing (3) plastic sorting (4) primary (and secondary) compounding; and (5) production of a plastic component. The state-of-the-art of different recycling operations is discussed in more detail below. Although increasing the collection rates is an important step toward achieving more circular supply chains, this is not considered, as this paper focusses on the material processing steps of plastic recycling.

After collection, WEEE is treated in pre-processing facilities for decontamination and material sorting. Figure 6 shows how materials are sorted at a state-of-the-art LHA pre-processing facility in Belgium based on a mass tracking experiment conducted in 2016. In this experiment, around 100 tons of LHA were treated including washing machines (WM), dryers (D), dishwashers (DW) and kitchen appliances (KA). Prior to mechanical treatment, a manual step is included to remove harmful substances (depollution) and the copper-rich fraction in the form of wires. After most metals and minerals are removed, about 19.1 % of the input material is sorted as plastic including foams (4.3 %), light plastics (12.1 %) and heavy plastics (2.7 %). However, only the light plastic fraction is further sorted for plastic recycling and most of the foams (PUR) and heavy plastics (PVC) are sent to incineration.

Figure 6: Material flow at state-of-the-art LHA pre-processing facility (based on measurements and data collected in 2016)



Unfortunately, not all recyclable plastic ends up in the plastic-rich fraction. Huisman et al. analysed the separability of main material fraction (ferrous and non-ferrous metals) from WEEE during pre-processing but, at the time, plastics were not targeted as recyclable material (Huisman 2003). Nevertheless, Huisman et al. estimated based on experimental data that around 12 % of the plastic would end up in the metal fraction by mistake, mostly in the copper fraction as cables are often coated with plastic.

The recycled plastic-rich fraction from pre-processing is further treated to sort different plastic types and remove impurities, such as stones, glass, metal and wood. A wide variety of plastic sorting techniques exist including density sorting, flotation, sensor-based sorting, magnetic sorting and electrostatic sorting. Additional processing steps such as dust removal, sieving, washing, drying, air classification and size reduction, are also commonly applied to achieve sufficiently pure plastic stream ready for further processing in compounding. Due to the complex plastic composition and overlapping material properties, a well-defined chain of separation processes is necessary to achieve homogeneous recycling fraction (Wagner 2020).

As shown in Figure 7, density separation will only allow to separate light polymers (PE and PP unfilled), medium-weight polymers (ABS and (HI)PS) and heavy polymers (PC, PA, PP-filled). Plastics in the density range between 1.08 and 1.15 kg/l are removed in order to minimize risks related to hazardous substances, such as brominated flame retardants. To achieve the desired purity (>90 %) for the targeted plastic fractions, the plastic flakes are either pre- or post-sorted with sensor-based technology or electrostatic sorting technologies. Previous research conducted by the PolyCE consortium has concluded that the efficiency of spectroscopic sorting varies depending on the colour and size of the plastic pieces that are sorted (Maisel et al. 2020). Nevertheless, an average efficiency of 87 % is assumed to be feasible (Bennett et al. 2009), which means that, on average, 87 % of the target plastic is successfully identified and removed from the material stream.

Figure 7: Overlapping density properties of polymers present in LHA

As a consequence of this complex separability and the combination of different sorting technologies, modelling the destination of plastics after recycling is not straightforward. Nonetheless, similar to the transfer coefficients determined based on the work of Huismans et al. for the metal fractions recycling (Hischier et al. 2007; Huisman 2003), coefficients for the different targeted polymer fractions are defined as presented in Table 1. These coefficients are derived based on optical sorting efficiencies and overlapping material densities, as shown in Figure 7. Although the liberation of material from EoL products will be influenced by the product design and density distributions might slightly vary depending on the material sources analysed, this is not considered in proposed transfer coefficients.

Table 1: Assumed transfer coefficient for plastic sorting

		Output fraction				
		ABS	(HI)PS	PP-filled	PP-unfilled	Non-target
Input fraction	ABS	**73 %**	11 %	0 %	0 %	16 %
	(HI)PS	1 %	**81 %**	8 %	0 %	10 %
	PA	0 %	0 %	11 %	0 %	89 %
	PC	0 %	0 %	3 %	0 %	97 %
	PE	0 %	0 %	0 %	13 %	87 %
	PP-filled	0 %	4 %	**88 %**	0 %	8 %
	PP-unfilled	0 %	0 %	0 %	**97 %**	3 %
	PUR	0 %	0 %	0 %	1 %	99 %
	PVC	0 %	0 %	2 %	0 %	98 %
	Others	5 %	24 %	24 %	0 %	47 %

Based on these transfer coefficients and the assumed material composition of the input stream (Figure 5), the recycling yield $M(Output)$ per target plastic can be calculated with the following equation:

$$\boldsymbol{M(Output)} = \sum T_{Input}^{output} \, M(input) \qquad (1)$$

The input mass *M(input)* of each polymer fraction is multiplied by the appropriate transfer coefficient *(T)* indicating the likelihood of a plastic type ending up in a specific output fraction *M(output)* for each of the targeted plastic.

After sorting, sorted plastic flakes with a purity above 90 % can be further processed into plastic granulates. During compounding, typically 5 % of additives are added to improve the properties of the granulates and about 3 % material loss occurs. The recycled-plastic granulates can be used for injection moulding of product parts and are typically mixed with virgin-plastic granulates to achieve the desired recycled-content.

Improved plastic recycling from LHA through product clustering

Previous research conducted for the PolyCE project has shown the potential benefit of strategic pre-sorting of WEEE products in different product clusters (Duflou et al. 2020). Duflou et al. concluded that by clustering product categories, significant increases in plastic recycling rates can be expected, as clustering can avoid mixing of non-compatible plastics with overlapping densities.

Nevertheless, after manual depollution, smaller recycling facilities often treat all LHA together to maximize their machine utility. In larger pre-processing facilities, limited product clustering occurs as cooling and freezing appliances (C&F) are often treated separately from the remainder

LHA stream (LHA*). Although measurement and statistic evidence are still lacking, according to the plastic recyclers this product clustering is known to have a positive influence on both the recycling operation and the achievable recycled plastic quality (Caris 2020).

The discarded product streams could be further clustered in order to reduce the number of target plastics per cluster while increasing their concentration at the same time. In the LHA* stream, washing machines (WM), dryers (D) and dishwashers (DW) have similar composition which is very different from kitchen appliances (KA) such as ovens and furnaces. In the C&F stream, fridges and freezers (F&F) have a similar composition that is different from other cooling equipment. Therefore, the potential benefits of treating WEEE LHA in three separate product clusters in term of environmental burden reduction and increased plastic recycling rates are further investigated. Table 2 provides an overview of the different clustering strategies that are assessed and compared.

Table 2: Different cluster strategies for LHA products

	1 cluster	**2 clusters**		**3 clusters**		
Products	**LHA**	**C&F**	**LHA***	**F&F**	**WM/D/DW**	**Others**
Air conditioner	X	X				X
Dishwasher	X		X		X	
Dryers	X		X		X	
Freezers	X	X		X		
Fridges	X	X		X		
Kitchen appliances	X		X			X
Heating & ventilation	X	X				
Washing machines	X		X		X	
Other cooling	X	X				X

2.2 Life Cycle Inventory (LCI)

A summary of the life cycle inventory data used to model the different waste treatment processes is given in

Table 3. The additives used for compounding are antioxidants that prevent plastic deterioration at high compounding temperature. Based on supplier data, they are modelled as a mixture of stearic acid, methyl acrylate, phosphorus trichloride and 2,4 di-tertbutylphenol. Background data from the ecoinvent 3.6 database are used to account for the waste treatment infrastructure and related process emissions. The (unrecycled) plastic waste is treated by municipal incineration with fly ash extraction (Waste plastic, consumer electronics | treatment of, municipal incineration with fly ash extraction | APOS, U). This study focusses on the treatment of the plastic fraction of WEEE LHA excluding other recoverable materials such as metals from the system boundaries.

Table 3: Summarize LCI for waste treatment processes of the collected plastic from LHA

Pre-processing		
Input		
Collected plastic LHA waste	*1*	*kg*
Electricity	0.08	kWh/kg collected plastic LHA waste
Infrastructure	8.0E-10	Mechanical treatment facility, waste electric and electronic equipment | market for | APOS, U
Output		
Plastic rich fraction recycled	0.88	kg/kg collected plastic LHA waste
Waste sent to incineration	0.12	kg/kg collected plastic LHA waste
Process emissions	-	Waste electric and electronic equipment | treatment of, shredding | APOS, U
Sorting and cleaning		
Input		
Plastic rich fraction recycled	*1*	*kg*
Electricity	0.3	kWh/kg mixed plastic rich fraction
Water	0.44	l/kg mixed plastic rich fraction
Salt (NaCl)	0.23	g/kg mixed plastic rich fraction
Output		
Sorting plastic flakes - yields depend on input composition and determined based on transfer coefficient in Table 1		
Compounding		
Input		
Sorted plastic flakes	*1*	*kg*
Electricity	0.5	kWh/kg sorted flakes
Water	0.66	l/kg sorted flakes
Additives	0.05	kg/kg sorted flakes
Output		
Material losses	0.03	kg/kg sorted flakes
Plastic granulates	1.02	kg/kg sorted flakes
Process emissions	-	Plastic granulate, unspecified, recycled | plastic granulate production, unspecified, recycled, formal sector | APOS, U

System expansion (ISO 14040:2006) is used to ensure comparability of different considered scenarios, specifically for the comparison of different clustering strategies. In this case, all systems must provide the same “basket of products” which is indicated in the rightmost column of Table 4. Primary production of plastics, electricity and heat is assumed to complement the basket of products in case the waste treatment scenario does not yield the considered output. A calorific value of 31 MJ/kg is assumed as an average for mixed plastic waste streams, which is known to vary between 27.9 and 38.4 MJ/kg (Tsjamis and Castaldi 2016). This embedded energy is valorized to produce power and heat at a gross efficiency, for which default values from ecoinvent have been used: 26 % and 13 % for heat generation and electricity generation respectively, hence yielding 4.0 MJ of electricity and 8.1 MJ of heat per kg of incinerated plastic (Wäger and Hischier 2015).

Table 4: Output generated by the different treatment strategies and definition of a common basket of products

	Default 1 cluster (LHA)	Limited clustering 2 clusters (LHA*/C&F)	Enhanced clustering 3 clusters (F&F/WM+/Others)	**Basket of products**
Primary function				
Amount of plastic treated [kg]	225	225	225	**225**
By-products				
recycled ABS [kg]	0	0	8	**8**
recycled HiPS [kg]	0	41	39	**41**
recycled PP unfilled [kg]	13	11	11	**13**
recycled PP-filled [kg]	0	42	41	**42**
Electricity production [MJ]	844	520	500	**844**
Heat production [MJ]	1699	1047	1006	**1699**

2.3 Life Cycle Impact Assessment

As mentioned in section 2.1, two different approaches were implemented to investigate the potential environmental impacts of recycling plastics from WEEE LHA, namely the impacts associated with the waste treatment of plastic and with the production of recycled plastic. In the following sub-sections, the LCA results of implementing different clusters for the waste treatment of WEEE LHA plastcs are presented. Furthermore, the LCA results of producing recycled plastic from WEEE LHA compared to the production of virgin plastics are presented, as well as the results of the use of recycled WEEE LHA plastic in a PolyCE demonstrator.

2.3.1 Environmental Impact of Different WEEE Treatment Strategies – Clusters

Table 5 shows the obtained purity of the different output streams estimated with the transfer coefficients presented in Table 1 using the input material composition presented in Figure 5. As expected and supported by experimental research in Work Package 3, the obtained purity notably improves with increasing number of clusters.

Table 5: Purity of recycled plastic fraction depending on clustering of input stream

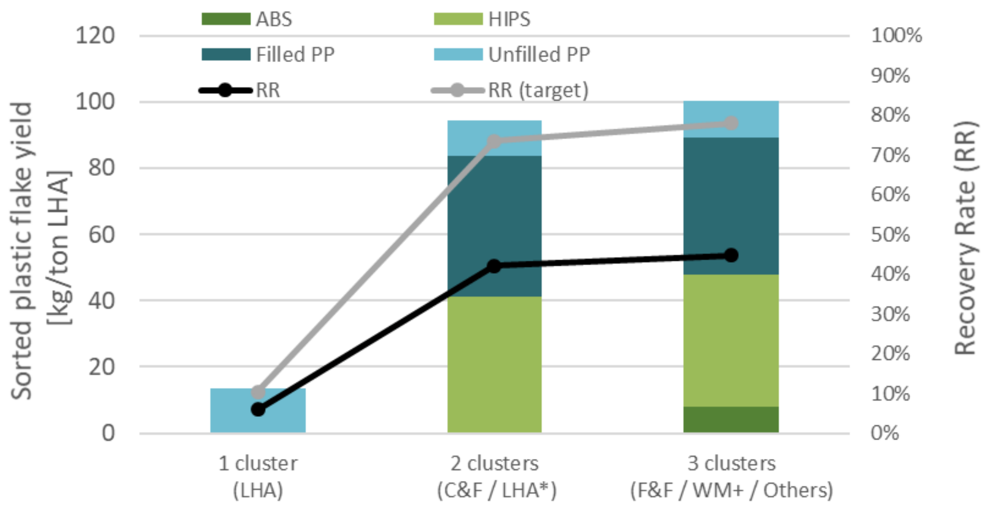
Purity levels
[80-90%[
≥ 90%

	1 cluster	2 clusters		3 clusters		
	LHA	C&F	LHA*	WM/D/DW	F&F	Others
ABS	83 %	75 %	89 %	91 %	77 %	58 %
HIPS	79 %	90 %	4 %	3 %	93 %	12 %
Filled PP	82 %	51 %	93 %	94 %	52 %	43 %

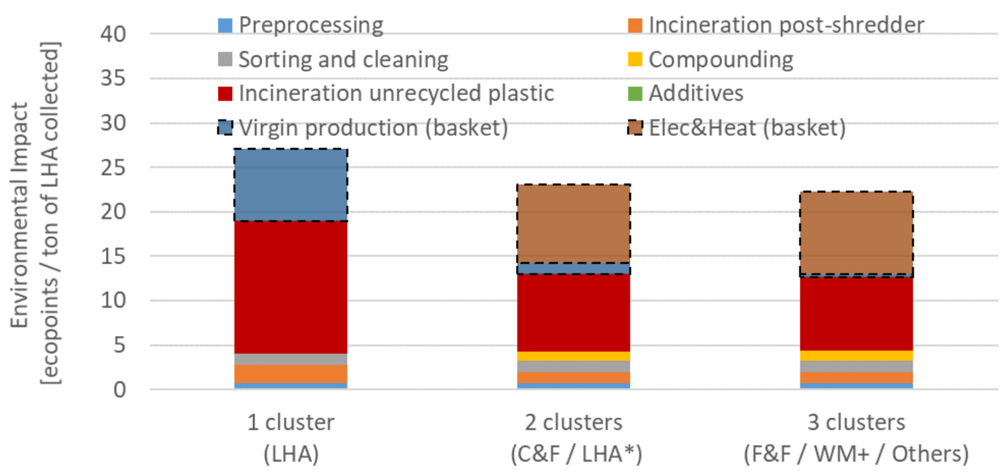
Figure 8 (a) shows the sorted plastic yields and recycling rates for the different clustering strategies. The maximum overall plastic recycling rate (RR) is 57 % as only part of the plastic present in the LHA are targeted while others plastics are present in small concentrations (PA, PC and PE) or considered as not recyclable (PUR) or lost during pre-processing (PVC). The achieved recycling rate for the target plastics (RR target) is also shown on Figure 8 (a) and only accounts for those plastics that have been identified as recyclable in this specific case. Although the improvement in terms of RR is rather limited for the three cluster scenario compared to the two cluster scenario, the enhanced clustering does allow to recover all four targeted plastics including the ABS material which is associated with a high cost and environmental burden in the production phase.

Figure 8 (b) shows the weighted LCA results for the different clustering scenarios using system expansion. As mentioned in the previous section (section 2.2), all systems must provide the same "basket of products".

Figure 8: Assessment results for different waste treatment strategies: (a) Yields and recycling rates (RR) for different clustering strategies (b) environmental impact (EI) using ReCiPe endpoint method



(a)



(b)

Climate change and particulate matter formation are the impact categories with the highest contribution for all considered waste treatment scenarios representing together between 74 and 76 % of the overall environmental burden. In addition, human toxicity also contributes between 20 and 22 % to the overall environmental burden while all other impact categories contribute less than 5 %.

Incineration of unrecycled plastic has the highest contribution to the environmental burden of waste treatment of plastic from LHA in all scenarios representing between 37-58 % of the environmental burden. In contrast, the contribution of recycling (pre-processing, sorting and cleaning, compounding and use of additives) to the overall environmental impact is limited. Even when recycling efforts are increased, it only represents 14 % of the total environmental burden in the enhanced clustering scenario. Obviously, generating virgin plastic and producing electricity (EU average) and heat to realize the same basket of goods have an important influence on the results. The system expansion represents between 30 and 44 % of the total environmental impact.

Overall, the results show that increasing the number of product clusters has a positive influence on the environmental burden associated with waste treatment of plastic in WEEE LHA. Avoiding the treatment of all LHA together and introducing two product clusters (C&F and LHA*), lowers the environmental burden by almost 20 %. Removing products with a different plastic composition such as kitchen appliances and air conditioners lowers the environmental burden further with an additional 3 %.

Sensitivity analysis

A sensitivity analysis was conducted to investigate the influence of uncertainties related to the assumed sorting efficiency and the assumed plastic composition of the input stream. Although the efficiency of the density separation cannot be directly improved, pre- or post-treatment with optic sorting will improve the overall plastic sorting efficiency. Figure 9 (a) and (b) show the change in plastic recycling rate (RR) and environmental impact (EI) as a function of the optic sorting efficiency. This sensitivity analysis shows that the one-cluster and three-clusters scenarios are not sensitive to the optic sorting efficiency. However, the scenario with two clusters is very sensitive to the assumed optic sorting efficiency: below 85 %, the RR is reduced by at least 40 %; and above 95 %, the RR is increased by 10 %.

Figure 9: Investigating the uncertainty of the results considering different sorting efficiencies (a+b) and considering different plastic distribution of the input material (c+d)

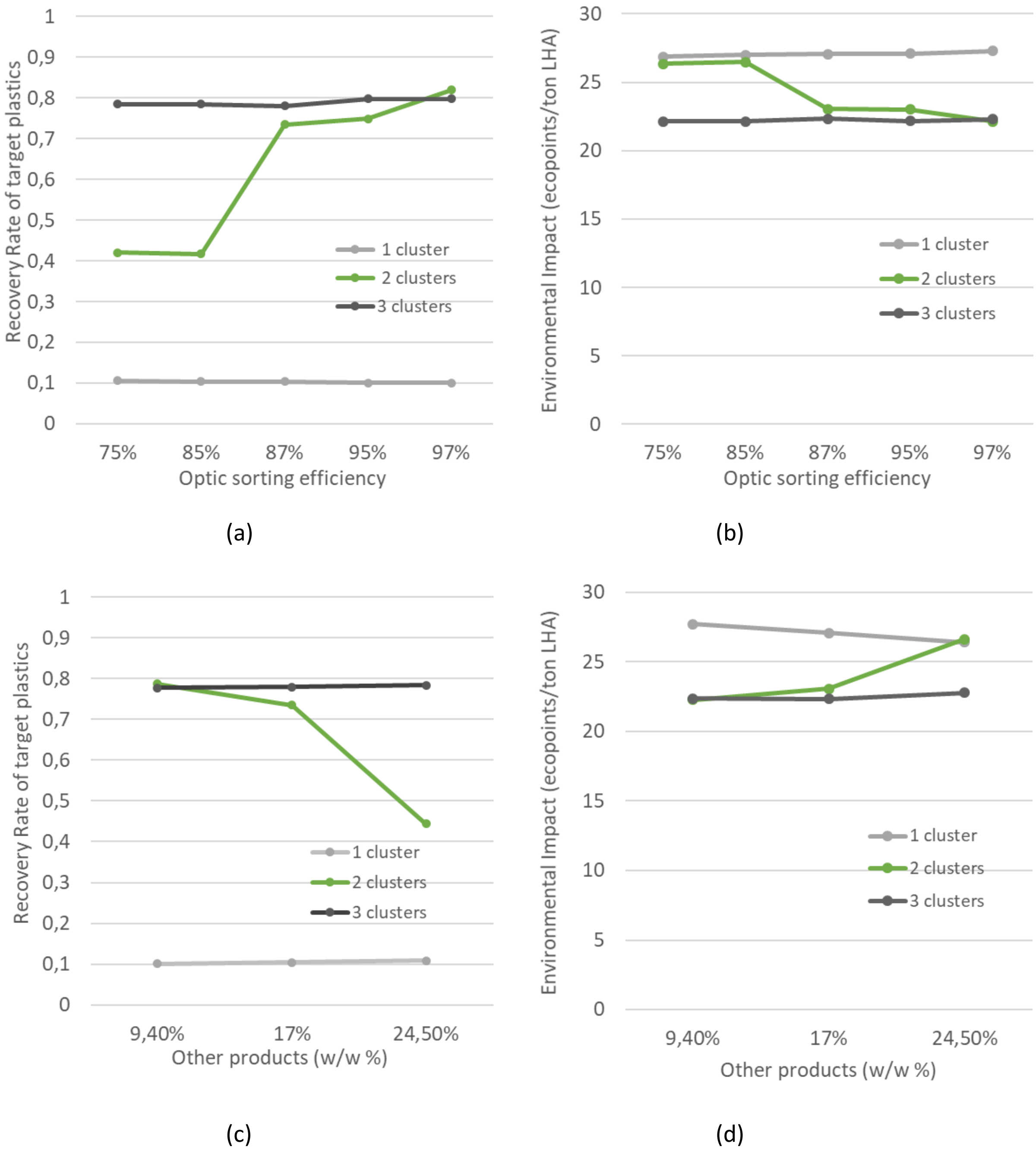
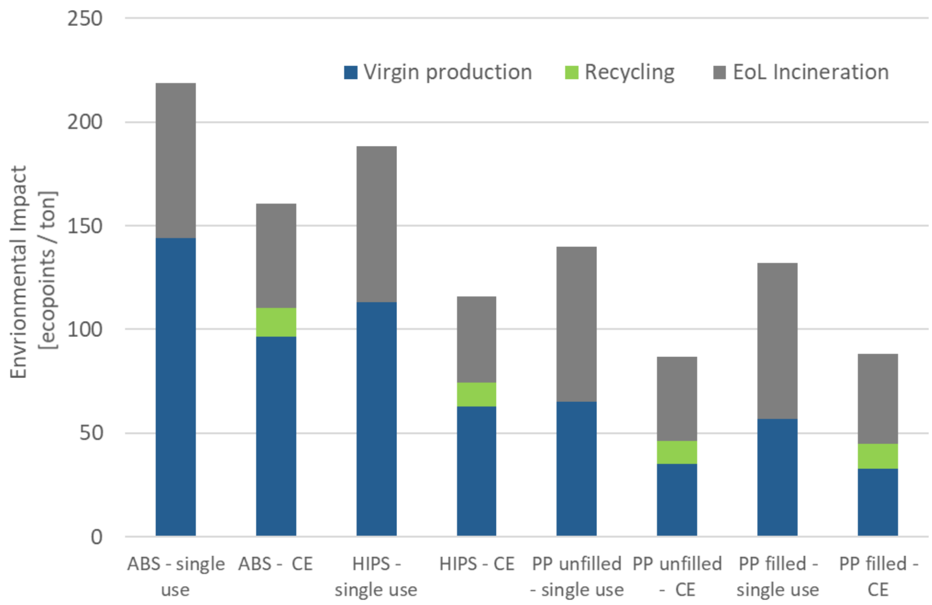


Figure 9 (c) and (d) show the influence of the input composition on the obtained results. Products belonging to the "other" product cluster (air conditioner, kitchen appliances, heating & ventilation and other cooling) contain many non-target plastics which make recycling target plastic more difficult. Therefore, the remaining product cluster ("others") has an important influence on the results. Based on WEEE sampling in pre-processing facilities in Europe, the contribution of "other" products to the LHA stream is currently expected to be less than 10 % (9.4 %). When considering the products put on the market (PoM), their contribution increases up to almost 25 % (24.5 %). Again, the sensitivity analysis revealed that the one and three cluster scenarios are not very sensitive to the input material composition. In contrast, the performance of the two cluster option is highly depended on the input material composition. When the contribution of "other" products is reduced from 17 to 9.4 %, the RR of target plastic increases with 7.1 % and the EI is reduced by 3.5 %. When the contribution of "other" products is increased to 24.5 %, the RR of target plastic reduces with 39.6 % and the EI is increased by 15.5 %.

2.3.2 Embedded Burdens of Recycled Plastic

Figure 10 compares the impact of using plastic in a system without recycling (single use of virgin plastic) with using plastic in a system where the plastic is recycled. In such a circular supply chain, material quality is preserved. As such, an appropriate allocation procedure is to partition the environmental burden equally over different use cycles. Virgin production and final waste treatment are then shared processes. However, in such a circular recycling system both the material recyclability at end of life and reusability in similar products must be accounted for. The amount of virgin plastic required to produce 1 kg of recycled plastic depends on the recycling efficiency which is different for each plastic type. For this analysis the enhanced clustering scenario is assumed resulting in the following recycling rates: 49 % for ABS; 84 % for HiPS; 83 % for PP unfilled; and 77 % for PP filled. Overall, the environmental impact of recycled plastic is reduced by 27 to 38 % compared to single use plastic.

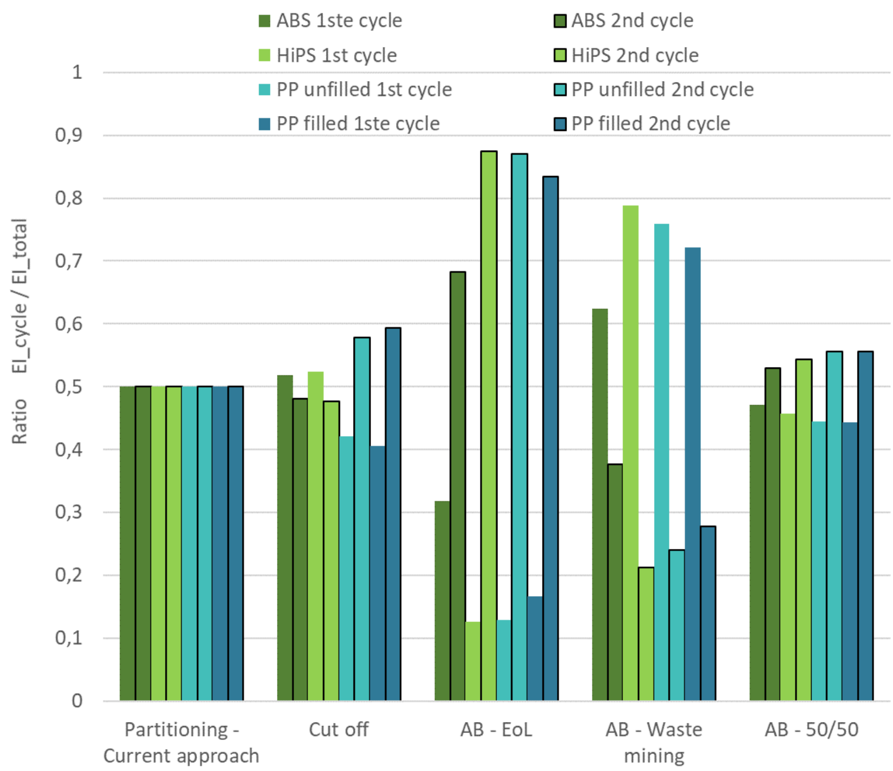
Figure 10: Comparing the environmental impact of single use virgin plastic and secondary use recycled plastic



Allocation Procedures

Although the overall environmental impact of a recycling system will not change, the allocation of the burden over the first and second cycled will depend on the approach taken by the LCA practitioner. Figure 11 shows the influence of the different allocation procedures on the results for the first and second use of plastic material compared to the current approach. The AB EoL and waste mining approach clearly differentiate between the first and second use cycle. The cut-off rule slightly favours the second cycle as long as the environmental burden of EoL treatment is lower than virgin production. However, this approach favours the first use cycle when the EI of exceeds the EI of virgin production. Although the AB 50/50 method favours the second use cycle, the difference between the impact attributed to the different use cycles remains limited.

Figure 11: Influence of allocation procedure on the allocation of the EI over first and second use cycle



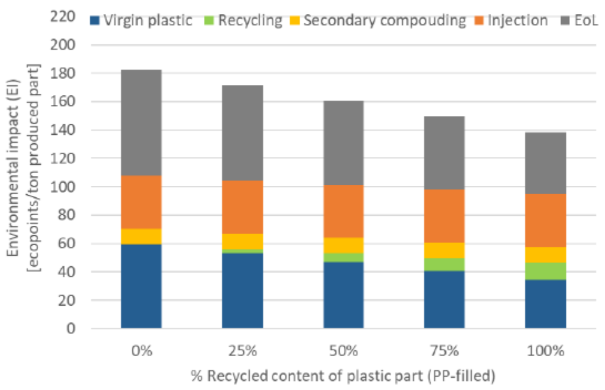
2.3.3 Environmental performance of plastic component with recycled content – PolyCE demonstrator

The demonstrator for the consortium partner *Whirlpool*, namely a washing machine component, was chosen to convey the environmental performance of incorporating a plastic part with recycled content into an EEE compared to a part made solely with virgin material. The material use for the demonstrator is mineral filled PP. For the purpose of clarity and scalability, the results in this sub-section are presented per tonne plastic part produced with injection moulding.

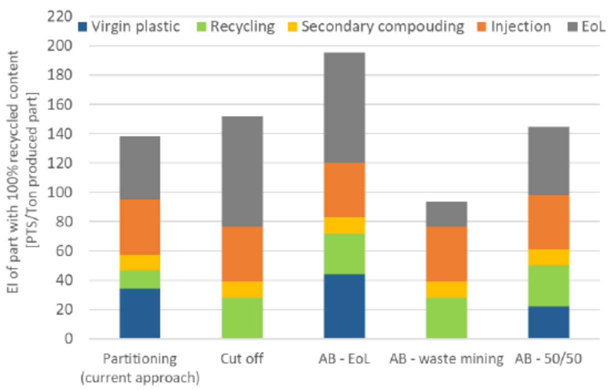
Figure 12 (a) shows the environmental impact of producing a plastic component with injection moulding in function of the recycled content for filled PP. The results show that the environmental impact of such a part can be reduced by up to 24 % when using only recycled feedstock. The results take a number of limitations into account related to the considered recycling system, such as the number of use cycles (two) and recycling rate (77 % for filled PP).

Although the contribution of virgin plastic and EoL significantly decreases when the amount of recycled content increases, it still represents 56 % of the environmental burden of a product with 100 % recycled content. In contrast, the additional burden from recycling activities (considered shared processes for all use cycles) remains limited (<10 %).

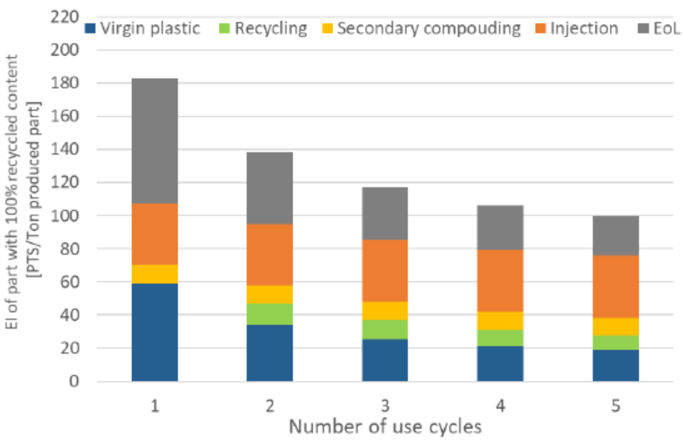
Figure 12: Environmental impact of producing a plastic component with injection moulding (a) in function of the recycled content for filled PP and (b) in function of different allocation procedure for a part with 100 % recycled content



(a)



(b)



(c)

Figure 12 (b) shows the influence of the allocation procedure on the LCA results for a product (or part) produced with 100 % recycled feedstock. For all allocation procedures, except partitioning, the environmental burden related to recycling activities is entirely allocated to the second use cycle. The avoided burden method, considering virgin production as an avoided process (AB – EoL), provides credits to the first use which results in an increase of the environmental burden associated with the second use cycle when the use of recycled feedstock is increased.

Figure 12 (c) shows the influence of the number of use cycles of the material on the environmental burden associated with a part manufacture from 100 % recycled content. The observed reduction is caused by the increased use of the plastic which can be calculated as follows for more than two use cycles:

$$U_n = \frac{1}{RR} + 1 + \sum_{i=3}^{n} RR^{(i-2)} \qquad (2)$$

The recycling rate (RR) of each target plastic not only determines the amount of virgin plastic required to produce 1 kg of recycled plastic after the first use ($\frac{1}{RR}$) but also how much material is recycled for reuse in the subsequent cycles. Although the environmental burden further decreases with each additional use cycle, most benefits are achieved moving from single to secondary use of plastic.

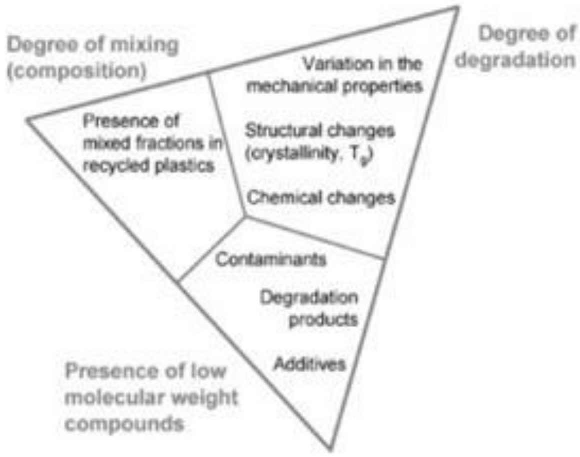
3 Effects of Multiple Recycling on Plastics Qualities and Environmental Gains from Mass Implementation of PCR Plastics Use (T8.3)

3.1 Impacts of (Multiple) Recycling on Secondary Plastics Material Quality on Material Level (Lab Scale)

Figure 13 gives an overview of the influences in the various life cycle stages that affect the quality of recycled plastics.

Figure 13: Influences on quality of PCR-plastics

INFLUENCES DURING USAGE PHASE
Oxidation (UV exposure)
Mechanical degradation
Chemical migration of other substances
PROCESSING INFLUENCES
Thermal degradation during: • Agglomeration • Melting
Mechanical degradation as a result of: • Forces on polymer • Shear forces
INFLUENCE OF MATERIAL USED
Purity/contamination of raw material
Additives/pigments/fillers added



Source: Partners for Innovation (2015)

Studies on multiple recycling of plastics are rare. Nevertheless, some experiments and statements could be identified related to multiple recycling.

3.1.1 Impacts of multiple recycling on material properties

(Vilaplana und Karlsson 2008) showed in an experiment which parts of the life cycle have the strongest impacts on the degradation of the recyclates. The processing and recycling is modelled by multiple processing, whereas the degradation is simulated by thermo-oxidative ageing in a forced ventilation oven. They conclude that different polymers are differently vulnerable:

➢ Thermo-oxidative degradation and therefore degradation during service life has a more severe effect on styrenic polymers (such as HIPS) than on other polymers. The ability for employing HIPS recyclates in second-market applications may consequently be influenced by the previous service life conditions.

➢ Thermo-mechanical degradation by multiple processing has a stronger impact on synthetic plastics such as polyolefins (HDP, PP) and PET than thermos-oxidative ageing. Therefore the focus should be on controlled processing conditions during mechanical recycling.

(Boldizar et al. 2003) made a similar experiment – an alternate combination of processing to simulate manufacturing of the product and accelerated ageing to simulate the usage phase in a cyclic procedure was applied to investigate the degradation profiles in HDPE, LDPE, ABS and PP. They conclude:

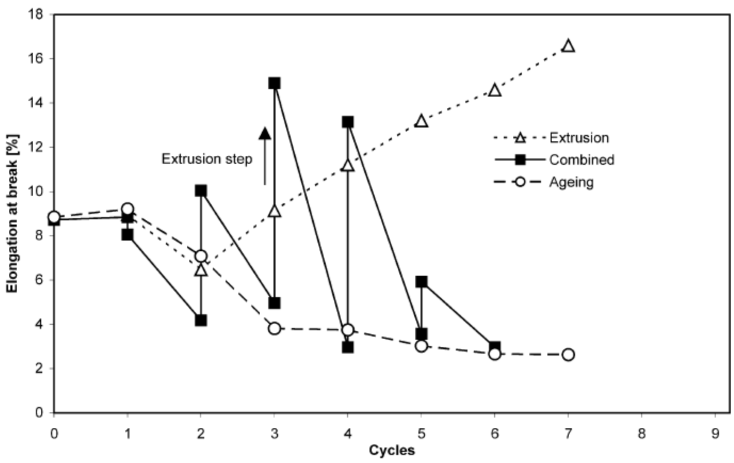
➢ The ageing steps are responsible for drastic deterioration.

➢ The reprocessing step almost restore the mechanical properties, which results in the "zigzag-shaped" behaviour illustrated in Figure 14.

➢ The combination of alternate processing and ageing cycles causes larger degradation than the same impacts performed separately.

Figure 14 presents the above-mentioned "zig-zag-shape" in the elongation behaviour for ABS.

Figure 14: The elongation at break for ABS vs. the number of cycles



(Boldizar et al. 2003) explain this observation by the homogenisation and dilution of the plastics material in the reprocessing steps, which almost restore the mechanical properties. After an increase in the first two circles the elongation properties decrease. An explanation could be that the brittle surface from the ageing phase is destroyed during the reprocessing step. The brittle particles from this surface now are homogeneously distributed in the ABS and these contaminations reduce the impact strength, i.e. propagation of cracks. But because of a limited "degree of saturation" the number of brittle particles do not affect the impact strength after a certain amount of cycles. The observed effect is an increase in elongation at break (Figure 14).

(Kuram et al. 2016) tested in an experiment the changes of properties for PC/ABS during five cycles of injection moulding followed by intermediate shredding. (Kuram et al. 2016) conclude that the chemical structure and melting temperatures of the blends did not significantly change with recycling. Comparisons of degradation and thermal behavior of the blends did not show significant differences between the recycled and virgin specimen. In general, the recycling processes did not significantly alter the flexural properties and tensile strength of PC/ABS. For PC/ABS, the elastic modulus increased, while MFI and impact strength decreased with recycling. On the other hand, increasing recycling process led to a continuous decrease in the elastic modulus and tensile strength of PA6/PC/ABS, while MFI, flexural properties, and impact strength of the ternary blends were increased gradually. As a conclusion, the incorporation of PA6 into PC/ABS improves the impact strength, flexural properties, and strain of PC/ABS, while the elastic modulus and tensile strength values dropped.

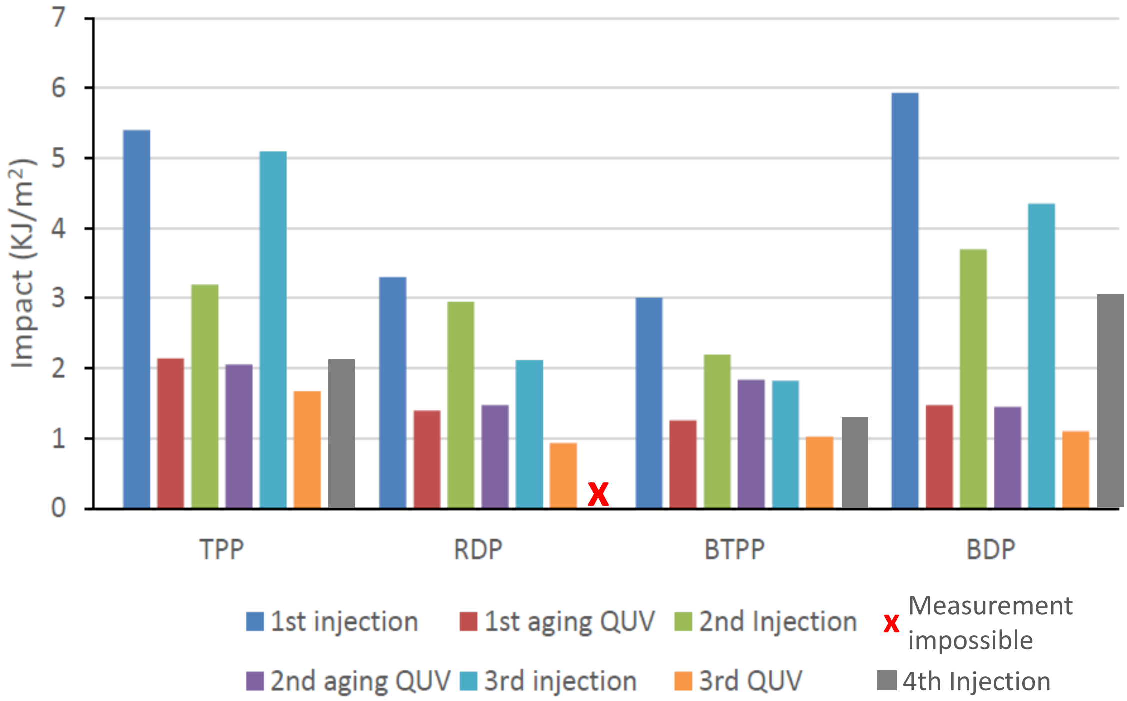
Generally, the quality of PCR-plastics seems to decrease in multiple recycling processes, with the strongest degradations occurring after the first recycling and thereafter an asymptotic approximation to a quality level after which subsequent recycling does not further affect the material properties.[1]

Villanueva et al. (2021) tested the material properties of PC/ABS samples produced from primary plastics with different flame retardants in four cycles of injection, aging with ultraviolet light (UV) with a QUV model device, and reinjection. The reinjections represent the multiple recycling. [2]The material strength was tested after (re-) injection and after aging respectively. Figure 15 presents the results.

[1] Personal communication with Florian Wagner, KU Leuven

[2] For details of the experiment and the results see PolyCE deliverable D5.5 of Villanueva et al. 2021.

Figure 15: Impact properties of PC/ABS plastics samples with different flame retardants after (re-) injections and aging



Source: Villanueva et al. (2021), modified

TPP: triphenyl phosphate

RDP: Resorcinol bis (diphenyl phosphate)

BTTP: Butylated tri phenyl phosphate

BDP: Bis phenol-A-bis (diphenyl phosphate

The results show that the impact strength has decreased after the fourth compared to the first injection in all four samples. The PC/ABS sample with RDP was too brittle by then to measure the impact strength. While the samples with BTTP and in particular with RDP decrease continuously with each reinjections, the other samples recover part of their impact strength in the third injection, but arrive at their smallest impact resistance after the fourth reinjection.

In an experimental setting similar to the one described above, (Fiorio et al. 2020) studied the effects of different systems of stabilizers in ABS in multiple rounds of UVA aging of ABS parts followed by mechanical recycling and injection molding. They found a severe degradation of the irradiated surface caused by embrittlement and physical aging deteriorating the mechanical properties of the ABS. The major fraction of the polymer, the core, did not present noteworthy degradation. The accelerated aging and recycling steps substantially reduced the toughness of the ABS. The mechanical recycling of the samples after accelerated aging exhibited a considerable increase in the strain at break and unnotched impact strength, in addition to a slight decrease in the tensile modulus, due to disruption of the brittle surface and elimination of the thermal aging. Therefore, (Fiorio et al. 2020) concluded, recycled ABS can be used for the manufacturing of new plastic parts in which high impact strength, toughness, and clear colors are not a stringent requirement.

(Fiorio et al. 2020) also showed that adding mixtures of stabilizers with sufficient endurance increases the thermal-oxidative resistance of ABS for several aging and mechanical recycling steps. Thus, if the correct stabilization system is added before the manufacture of ABS plastic parts, the thermal-oxidative resistance can remain adequate during service life and various recycling steps, contributing to the maintenance of the properties of the polymers in (multiple) recycling and to the circular economy. More test results on reprocessing and ageing are available for ABS in section 6.2 on page 60 of the Annex.

The above experiments show principal impacts of multiple recycling on material quality, but also that additives such as flame retardants as well as antioxidants affect the material properties. Conversely, additives to primary plastics should be selected taking into account whether and how far they are appropriate to support multiple life cycles.

3.1.2 Influence of Additives and Impurities

An experiment of (Kühnel et al. 2019) shows the influence of label impurities in recycling on the mechanical properties of PC/ABS materials. The different labels consist of paper or two different types of polymers with a mass share of 0.17 % to 1.03 %. (Kühnel et al. 2019) proved that the contamination and the type of contamination strongly influence the mechanical properties. The influence of the PP label was much lower than that from paper. The paper contamination causes crack initiation points due to the cellulose particles of the paper resulting in early breakage and low toughness of the recycled material. Certain contaminations are hard or even impossible to remove from the waste stream. Labels from TV screens for example can even withstand size reduction sorting processes which are used during mechanical recycling.

According to (Buekens und Yang 2014), most resins and some additives are mutually incompatible. Figure 16 shows the miscibility of different types of plastics which are commonly used in in LCD TVs in recycled plastics. (Peeters et al. 2014) conclude from this that the compatibility of different plastics is different. PET for example can only be mixed with the same material, not with other plastics like ABS or HIPS.

Figure 16: Miscibility preference scheme for some plastics commonly used in LCD TVs

	ABS	ABS BFR	HIPS	HIPS BFR	PET	PC	PMMA	PC/ABS PFR	HIPS/PPE PFR
ABS	G								
ABS BFR	G	G							
HIPS	Y	Y	G						
HIPS BFR	Y	Y	G	G					
PET	O	O	O	O	G				
PC	G	G	O	O	G	G			
PMMA	O	O	O	O	Y	O	G		
PC/ABS PFR	G	R	O	R	R	G	O	G	
HIPS/PPE PFR	O	O	G	G	R	O	O	Y	G

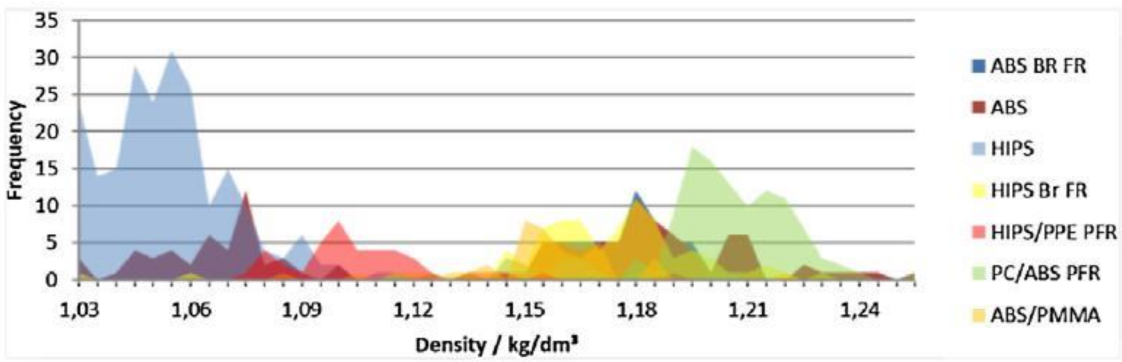
G	Good miscibility (contamination>5%, properties>80%)
Y	Reasonable miscibility (contamination=2-5%, properties>80%)
O	Limited miscibility (contamination=0.1-2%, properties>80%)
R	Bad miscibility (contamination<0.1%, properties<80%)

Source: (Peeters et al. 2014)

This shows that in a multiple recycling scenario, the clean separation of different types of plastics is of importance, in particular for those plastics whose miscibility is limited. Chapter 6.1 on page 56 shows how properties of ABS and HIPS are affected if they are blended with each other and with PC.

The usage of additives is complicating the mechanical recycling process, including the separation of different plastics types via the standard density-based separation processes. The high variety of flame retardants and other additives influences the densities of the material and results in overlapping densities of otherwise different materials. Figure 17 illustrates this situation for different plastics and their densities.

Figure 17: Density distribution and overlaps of different plastic types for housings of LCD TVs



Source: (Dewulf et al. 2019)

Br FR: brominated flame retardants *PFR: phosphorous flame retardants*

Due to overlapping densities, the separation process for different plastic types can produce fractions consisting of a mix of different, possibly incompatible plastic types and plastics legally restricted substances like PBB and PBDE flame retardants, which are banned in the European directive 2011/65/EU (RoHS Directive). These fractions may have to be disposed of since their recycling would result in low quality plastics and/or plastics with contents of restricted substances above legal thresholds.

3.1.3 Mitigation Techniques

To minimize the degradation of mechanically recycled plastic different additives, fillers or primary material are added to improve the properties of the material.

Restabilization and rebuilding describe a procedure in which stabilizers and rebuilding agents are added to protect the thermomechanical degradation during processing and enhance the long term stability of the recycled products. Modification in the chemical and molecular structure are needed to achieve greater upgrades in the properties of the recycled product.

(Vilaplana und Karlsson 2008) describe rebuilding with certain additives such as radical generators or compounds with reactive functional groups. They can be effective in inducing branching or crosslinking reactions in the degraded polymeric chains from waste materials during meld reprocessing knowns as “reactive extrusion”. Rebuilding increases the molecular weight of the molecule chains and improves rheological and mechanical properties.

Compatibilizers are additives facilitating the mechanical recycling process for mixed waste polymers. The function is based on physical or chemical effects. Non-reactive compatibilizers (physical) improve the interfacial adhesion due to good miscibility with both polymers of the blend. Reactive compatibilizers (chemical) create effective links among the components of the blend through reactive extrusion. They are usually graft or block copolymers in which the blocks are chemically similar or identical to the blend components. For many polymer couples, suitable compatibilizers can be found. (Ignatyev et al. 2014)

3.2 Impacts of (Multiple) Recycling on plastics for PCR recycling on System Level

The previous chapter showed on a material level that the use and (multiple) recycling of plastics affects the quality of the PCR plastics, even though to different degrees depending on the types of plastics, exposition to ultraviolet light and other damaging impacts in the use phase, the pre-treatment of waste electrical and electronic equipment (WEEE), and the subsequent separation and recycling process.

Whether and how far these quality changes may affect the overall quality and practicability of PCR-plastics in a scenario of a mass-implemented PCR-plastics use in EEE can only be answered taking into account the mass flows of EEE and fractions thereof in the European Economic Area (EEA).

Specific conditions to be taken into account are:

1. The collection rate of WEEE

EU Directive 2012/19/EU (WEEE Directive) foresees a minimum collection rate of 65 % of WEEE in an EU member state calculated as average of EEE put on the market in the three preceding years respectively in this member state, or of 85 % of WEEE arising in a year in this member state. In 2017, this collection rate was 47 % of EEE put on the market in the European Union on average of the three preceding years according to EUROSTAT (2020), and it can be assumed that this rates has not yet increased considerably since then.

2. Losses in pre-treatment

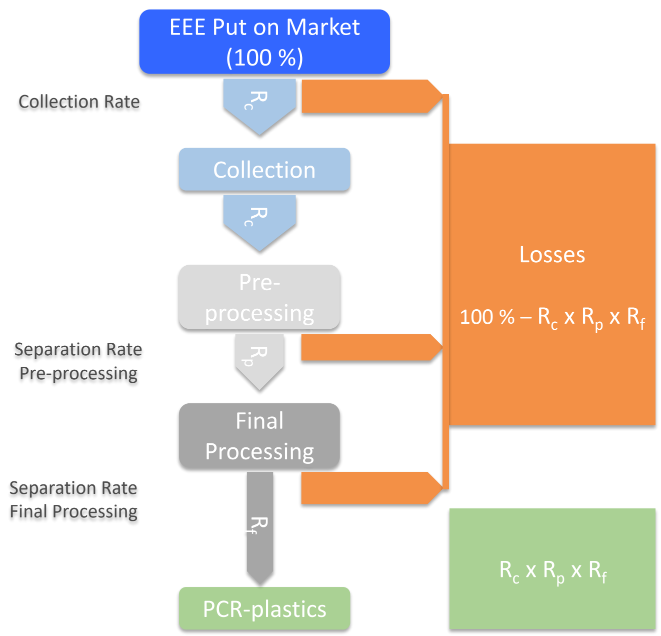
   In shredding and mechanical separation, not all plastics in WEEE can be directed and collected in the plastics fraction which is then available for PCR plastics production. Part of the plastics are ending up in other fractions, i.e. the iron, aluminium and copper fractions. This rate is assumed with 12 % like in the LCA.

3. Losses in sorting and cleaning in PCR plastics production

   Around 50 % of the plastics originating from pre-treatment[1] have to be sorted out because they contain brominated flame retardants, or because they cannot be separated from other types of plastics to a degree that enables producing recycled plastics with the aspired quality.

Figure 18 illustrates the situation.

Figure 18: Losses of used plastics from collection to final processing



[1] Personal information Günther Höggerl, MGG Polymers

Assuming the above figures, only the share P of plastics contained in EEE put on the market will become available as PCR-plastics for use in new EEE:

$$P = 47\ \% \times 88\ \% \times 50\ \% = 21\ \%$$

This means that in each life cycle, on average 79 % of primary plastics have to be added to compensate the losses in the mass balance assuming a stable market with no growth and the same rates of collection and material losses in final processing. For a collection rate of 65 %, the mass of primary plastics to be added to compensate losses still would be 67.5 %.

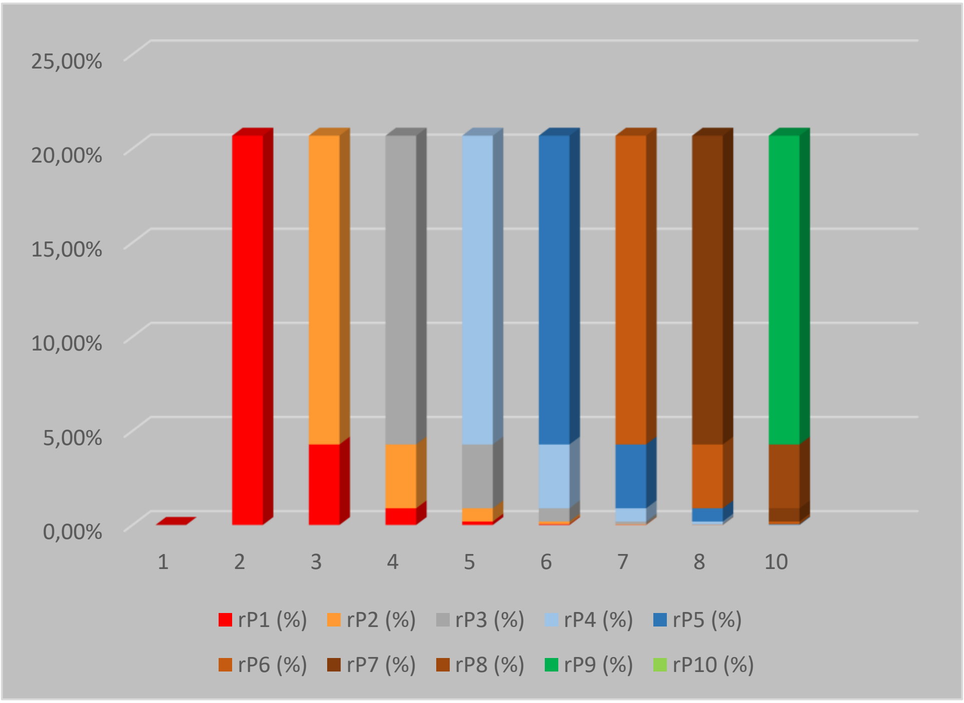
The below tables and figures present the share of multiply recycled plastics in the total volumes of plastics after different rounds of life cycles for the above collection rate and separation loss.

Table 6: Share of recycled plastics in PCR plastics in n life cycles at 47 % collection rate, 12 % losses in pre-treatment and 50 % separation losses

n (Number of Life Cycles)	rP1 (%)	rP2 (%)	rP3 (%)	rP4 (%)	rP5 (%)	rP6 (%)	rP7 (%)	rP8 (%)	rP9 (%)	rP10 (%)
1	0,00%									
2	20,6800%									
3	4,2766%	16,4034%								
4	0,8844%	3,3922%	16,4034%							
5	0,1829%	0,7015%	3,3922%	16,4034%						
6	0,0378%	0,1451%	0,7015%	3,3922%	16,4034%					
7	0,0078%	0,0300%	0,1451%	0,7015%	3,3922%	16,4034%				
8	0,0016%	0,0062%	0,0300%	0,1451%	0,7015%	3,3922%	16,4034%			
9	0,0003%	0,0013%	0,0062%	0,0300%	0,1451%	0,7015%	3,3922%	16,4034%		
10	0,0001%	0,0003%	0,0013%	0,0062%	0,0300%	0,1451%	0,7015%	3,3922%	16,4034%	

rPx *share of recycled plastic of generation x after n life cycles*

Figure 19: Share of recycled plastics in n life cycles at 47 % collection rate, 12 % losses in pre-treatment and 50 % separation losses



rPx share of recycled plastic of generation x after n life cycles

Table 6 shows that in the second life cycle, 21 % of plastics can be produced as PCR plastics and can be used in new EEE. Only 4.3 % of plastics from the first life cycle will be contained in PCR plastics used in the third life cycle.

From the sixth life cycle on, this plastics has practically disappeared from the PCR plastics fractions due to the losses in collection and PCR production with a share of only 0.04 % remaining. The total share of plastics with more than one life cycle in the produced PCR plastics stabilizes at around 4.3 %, while the produced PCR plastics contain a stable share of 79 % primary plastics.

Assuming that the quality of the plastics coming from collected WEEE and used for PCR plastics actually decreases, it can be assumed that in practice the quality of this input material for PCR production stabilizes latest after the fifth life cycle since the plastics from earlier life cycle stages practically have disappeared.

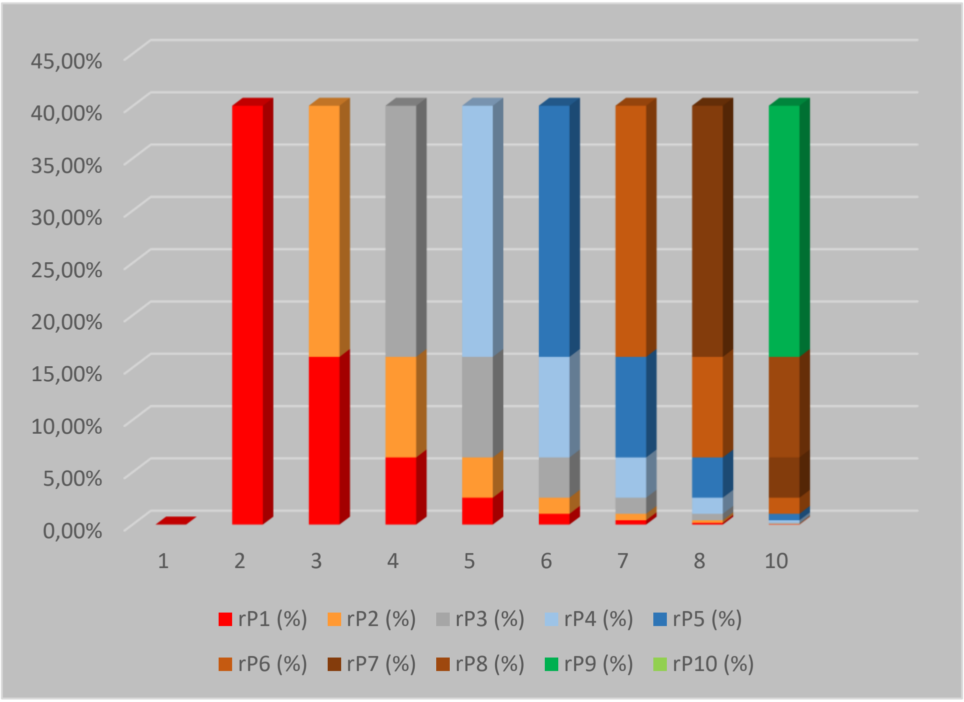
Table 7 and Figure 20 illustrate the situation for a 65 % WEEE collection rate as stipulated as minimum collection rate in the WEEE Directive and a separation loss of only 30 %, e.g. due to a reduced use of flame retardants so that less plastics have to be disposed of and remain available for recycling.

Table 7: Share of recycled plastics in plastics of n life cycles at 65 % collection rate and 30 % separation losses

n (Number of Life Cycles)	rP1 (%)	rP2 (%)	rP3 (%)	rP4 (%)	rP5 (%)	rP6 (%)	rP7 (%)	rP8 (%)	rP9 (%)
1	0,00%								
2	40,0400%								
3	16,0320%	24,0080%							
4	6,4192%	9,6128%	24,0080%						
5	2,5703%	3,8490%	9,6128%	24,0080%					
6	1,0291%	1,5411%	3,8490%	9,6128%	24,0080%				
7	0,4121%	0,6171%	1,5411%	3,8490%	9,6128%	24,0080%			
8	0,1650%	0,2471%	0,6171%	1,5411%	3,8490%	9,6128%	24,0080%		
9	0,0661%	0,0989%	0,2471%	0,6171%	1,5411%	3,8490%	9,6128%	24,0080%	
10	0,0265%	0,0396%	0,0989%	0,2471%	0,6171%	1,5411%	3,8490%	9,6128%	24,0080%

rPx share of recycled plastic of generation x after n life cycles

Figure 20: Share of recycled plastics after x life cycles at 65 % collection rate and 25 % separation losses



rPx share of recycled plastic of generation x after n life cycles

The share of recycled plastics in PCR plastics amounts to 40 % so that 60 % of primary plastics are required to compensate the material losses in collection and processing. Around 16 % of the first generation plastics will remain in the third life cycle. From the tenth life cycle on, the first generation plastics has practically disappeared from the PCR plastics fractions with only 0.03 % remaining. The total share of plastics with more than one life cycle in the produced PCR plastics stabilizes at around 16 % while the produced PCR plastics on average would have to contain 60 % of primary plastics on average.

While the previous chapter showed that multiple recycling affects the quality of plastics, the high share of primary plastics required to simply balance the losses of plastics in collection and treatment will already contribute to improve and stabilize the quality. It cannot be excluded that additional efforts might be required to produce the PCR quality which the market demands, in particular at higher collection rates and reduced losses in processing, these effects are not certain to occur and cannot be quantified based on the accessible knowledge and the current industrial experiences. The calculation of environmental gains in the next section will therefore not introduce a correction factor to reflect higher efforts stemming from multiply recycled plastics coming from WEEE as base for PCR plastics production.

3.3 Resource and Environmental Gains from Mass Implementation of PCR-plastics Use in the EU

Following the approach illustrated in Figure 1 on page 9, the environmental gains from mass implementation of PCR plastic use instead of primary plastics are calculated based on the plastics content of WEEE generated in Table 8. The table shows the volumes of different types of recyclable plastics, their total volume, and the amounts of other plastics which currently cannot be recycled.

Table 8: Plastics contained in WEEE generated in the EEA

WEEE plastics	ABS	PS	PA	PC	PE	PP	Others	Total	Total (recyclable)
Total (tonnes)	542.400	317.100	7.200	60.200	16.600	461.700	604.800	**2.010.000**	**1.405.224**

Source: Accili et al. (2019), PolyCE deliverable D3.1, page 43, modified

To calculate the resource efficiency and environmental gains, the cumulated energy demand (CED), the greenhouse gas (GHG) emissions and the environmental impacts (expressed in Ecopoints) assessed in the LCA per tonne of plastics are multiplied with the volumes of plastics generated for PCR recycling after collection and pre-treatment of the WEEE. Additionally, the heat and electricity generated in the incineration of plastics are taken into account as avoided CED, avoided GHG emissions and avoided environmental impacts.

From the total of around 2 million tonnes contained in WEEE arising in the EU, only a certain share will be available for recycling due to the losses in collection, pre-treatment and in the recycling process as illustrated in section 3.2 on page 39. Table 9 shows the different collection and loss rates assumed along the EoL chain in different scenarios

Table 9: Percentages of plastics available for production of PCR-plastics

Scenarios	A	B	C
Collection rate	47%	65%	**65%**
Losses in pre-treatment	12%	12%	**12%**
Losses in final processing	50%	50%	**30%**
Remaining for PCR-plastics production	**21%**	**29%**	**43%**

Column A reflects the current status (baseline scenario). The green fields in scenarios B and C indicate improvements compared to the baseline in scenario A. In scenario B, it is assumed that the EU member states on average achieve the 65 % minimum collection rate in compliance with the WEEE Directive. Scenario C implies technical improvements in the sorting and cleaning step in final processing of the plastics fractions coming from pre-treatment to reduce the high losses of 50 % plastics in this stage to only 30 %.

Table 10 displays the environmental gains of the above scenarios, i.e. how they reduce the cumulated energy demand (CED), the greenhouse gas (GHG) emissions and the overall environmental impact (Ecopoints) if the recyclable plastics are recycled and used as PCR plastics instead of using the same volumes of primary plastics. It is assumed that the primary plastic is incinerated after its use. Since data for energy consumption of PCR plastics production were only available for PP, it was further assumed that all recyclable plastics is PP.

Table 10: Reduction of environmental burdens and environmental impacts by mass implementation of PCR-plastics use compared to primary plastics use (in absolute and relative reductions)

Scenarios	A	B	C	A	B	C
CED (PJ)	-15	-21	-31	-70%	-70%	-75%
GHG emissions (kilotonnes CO2eq)	-1.420	-1.970	-2.850	-84%	-84%	-87%
Ecopoints (million Pt)	-7	-9,9	-18,5	-36%	-36%	-48%

The above environmental gains show that the mass implementation of PCR plastics use considerably reduces the CED, the GHG emissions and the overall environmental impacts compared to primary plastics use in EEE.

Table 11 shows the environmental gains of scenario B and C compared to the baseline scenario A.

Table 11: Reductions of environmental burdens and impacts of scenarios B and C compared to scenario A

Scenarios	A	B	C
CED	0%	-38%	-108%
GHG emissions	0%	-38%	-100%
Ecopoints	0%	-38%	-158%

The increase of the WEEE collection rate from the current 47 % reflected in scenario A to the 65 % minimum target stipulated in the WEEE Directive in scenario B results in a 38 % reduction of the CED, GHG emissions and the environmental impacts. If the losses in final processing of the plastics fractions from pre-treatment could be reduced from the current 50 % to around 30 % (scenario C), the savings compared to baseline scenario A strongly increase. In particular the overall environmental impact decreases due to the fact that 20 % less plastics that had been treated and had thus caused environmental burdens and impacts had to be sorted out prior to compounding and was incinerated while it remains available for PCR plastics production in scenario C. The avoided incineration in particular drives the reduction of the overall environmental impacts. The environmental gains may, however, be overestimated since the additional efforts required to reduce the waste plastics from 50 % to 30 % in sorting and cleaning are unknown and could not be taken into account.

To put the reductions of CED and GHG emissions by mass implementation of PCR plastics use compared to primary plastics into perspective, Table 12 illustrates how they are related to 2018 CED and GHG emissions of Luxemburg, one of the smallest EU member states, and the EU27.

Table 12: Reductions from PCR use scenarios related to the 2018 CED and GHG emissions of Luxemburg and the EU 27

	Scenario A		Scenario B		Scenario C	
	Luxemburg	EU27	Luxemburg	EU27	Luxemburg	EU27
CED (PJ)	8%	0,03%	11%	0,04%	17%	0,06%
GHG emissions (million tonnes CO2eq)	11%	0,04%	16%	0,05%	23%	0,07%

Sources for CED and GHG emissions 2018: Eurostat, https://ec.europa.eu/eurostat/databrowser/view/t2020_33/default/table?lang=en, 2018, and https://ec.europa.eu/eurostat/statistics-explained/images/e/e3/Total_greenhouse_gas_emissions_by_countries%2C_1990-2018_%28Million_tonnes_of_CO2_equivalents%29.png

Table 12 indicates that the mass implementation of PCR plastics use may decrease the CED and GHG emissions of the EU27 in the three scenarios in the range 0.03 % and 0.06 % for the CED, and between 0.04 % and 0.07 % for the GHG emissions. Compared to the CED and GHG emissions of Luxemburg the reductions are equivalent to 8 % to 17 % of CED and 11 to 23 % of GHG emissions.

3.4 Uncertainties and Remarks

- The resource efficiency and environmental gains were calculated based on the assumption that all plastics used in EEE was PP since data for PCR production were only available for this type of plastics. The energy consumption for the production of other types of plastics are different. They are higher for HIPS and ABS, for which such data are available. It can be assumed that the energy consumption for production of PCR plastics from these plastics would be higher as well, but the data situation and accessible information does not allow concluding on quantitative correlations. As a consequence, the results for the environmental and resource efficiency gains should be understood as reflecting magnitudes and trends related to the discussed scenarios rather than the exact impacts of PCR plastics mass implementation.
- While the LCA applied a clustering scenario, such a scenario is not reflected in the calculations of the resource and environmental gains. The clustering effects assessed in the LCA are related to large household appliances, while the mass implementation scenario is based on plastics used in all EEE put on the market in the EU. The clustering effects can therefore not be applied to the mass implementation scenario. The general insight that clustering may increase the share of plastics from collection and pre-treatment available for PCR plastics production is however reflected in scenario C in the assumption that the waste rate in PCR production decreases from 50 % to only 20 %. The respective results therefore illustrate the impacts of clustering and improvements in the PCR production.

- The effects of multiple recycling on system level are based on a simple static calculation, i.e. they do not take into account that the various types of plastics are used in different EEE with different life times. The calculations in this chapter therefore neither reflect nor aspire to reflect the real composition of plastics fraction from pre-treatment used for PCR production. The intention of these calculations was to show for how many life cycles the different generations of plastics remain in the plastics recycling loop to gain insights into how multiply recycled plastics could actually affect the quality of plastics available for PCR plastics production in a mass-implementation of PCR plastics use.

4 Conclusions and Recommendations

4.1 Life Cycle Assessment (T8.4)

The presented results of the LCAs conducted demonstrate that the environmental impact of plastic in a circular supply chain is reduced by 27 to 38 % compared to single use plastic depending on the plastic type. In addition, the results of the LCA show that the potential environmental impact of a plastic component produced by injection moulding with recycled feedstock is reduced by 24 % compared to single use plastic.

Increasing the number of product clusters has a positive influence on the environmental burden associated with waste treatment of plastic in waste LHA. The treatment of processing the waste in two product clusters (C&F and LHA*) lowers the environmental burden by almost 20 % compared to one single cluster (LHA). Removing products with a different plastic composition from both clusters, such as kitchen appliances and air conditioners, lowers the environmental burden by an additional 3 %. The sensitivity analysis revealed that this enhanced clustering scenario is highly sensitive to both the optic sorting efficiency during recycling and the input material composition.

Furthermore, different allocation procedures for the first and second use of plastic materials is compared to the current approach. In this study, from a circular economy perspective that envisions quality preservation, the burden is evenly distributed between the first and second use. However, commonly used allocation procedures redistribute the environmental burden based on the relative difference between virgin production and final waste treatment. Considering shared processes and evenly distributing the burden is a more appropriate approach as long as the material quality is preserved. If the quality of the material deteriorates during recycling, a material quality correction factor that reflects the potential limitations for the next use is more appropriate to adequately distribute the burden over the different lifecycles.

In conclusion, the LCA findings demonstrate the potential environmental benefits of using recycled plastics compared to single use plastics and of implementing clusters during LHA plastic recycling. Nonetheless, some limitations have to be considered in conjunction with these findings, namely the limitation of recycling systems to reduce the overall burden associated with products and the relevance of different allocation procedures when integrating recycling into an LCA.

4.2 Quality Impacts of Multiple Recycling in Mass Implementation of PCR-plastics Use (T8.3)

Material degradations from the use phase, impurities from shares of other plastics types than the aspired one and sometimes non-plastics materials, such as paper labels, and chain scissions during the recycling process may affect the quality of PCR-plastics. These effects can at least in part be mitigated by the PCR production process and by specific additives. The experiments with multiple recycling assumed a loop with a single plastics material which is aged and recycled several times. However, in the market the plastics fractions originating from WEEE pre-treatment are mixed plastics with many different additives and impurities. Additionally to the effects observed in the ageing and multiple recycling tests, blending of different plastics types and the varieties of additives and their potential interactions may result in stronger alterations of material PCR plastics properties than assessed in the reviewed experiments. These tests already show that on a material level, adverse quality impacts accumulate over multiple life cycles, which may require increased efforts, e.g. adding more primary plastics, to produce the market-demanded quality from the used plastics coming back from the market.

On a system level, a high share of primary plastics is, however, required anyway to compensate the losses of plastics materials due to non-collected WEEE, separation of plastics in other than the plastics fraction in mechanical separation step in WEEE-pre-treatment, and separation of plastics with brominated flame retardants and other unwanted substances/impurities in the final processing. Currently, around 79 % of the plastics material put on the market in new EEE are lost in the end-of-life phase for production of PCR plastics and need to be compensated by the addition of primary plastics assuming a stable market for the production of new EEE and their plastics share, i.e. no market growth and no changes in the composition of new EEE. In the baseline scenario reflecting the current situation only 4.3 % of plastics from the first life cycle will be contained in the PCR plastics used in the third life cycle, which will have been eliminated almost completely from the sixth life cycle on. The total share of plastics with more than one life cycle in the produced PCR plastics stabilizes at around 4.3 %, while the produced PCR plastics contains a stable share of 79 % primary plastics across all life cycles.

In this setting, the high volumes of added primary plastics in conjunction with the currently practiced mitigation techniques may be sufficient to compensate potential or actual quality losses of the multiply recycled plastics coming back from the market to be reapplied and used as PCR plastics in the next life cycle. In this case, no additional efforts would be needed compared to the current situation to achieve the PCR plastics quality sufficing the market requirements.

Increasing collection rates and reducing the losses in end-processing as reflected in scenario C (65 % collection and only 30 % losses in PCR plastics) increases the shares of multiply recycled materials coming back from the market for PCR production. Still 60 % of primary plastics are required to compensate the material losses in collection and processing. Around 16 % of the first generation plastics will remain in the third life cycle, and will practically have disappeared from the plastics coming back from the market after the ninth life cycle. The total share of plastics with more than one life cycle in the produced PCR plastics stabilizes at around 16 %. It cannot be excluded that this may have an impact on the quality of plastics coming back from the market for PCR-plastics production resulting in increased efforts in PCR plastics production to compensate such effects in order to achieve marketable qualities. In the absence of clear experimental data and practical industrial scale experiences, it cannot be excluded that such effects do not occur, even though the high addition of 60 % of primary plastics to compensate the mass balance could reasonably be assumed to be sufficient to achieve the required PCR plastics quality without additional efforts compared to the current situation of PCR plastics production.

Since WEEE collection rates will always remain below 100 % and plastics losses in pre-treatment and PCR plastics production cannot go down to zero, the production of PCR plastics on average will always need inputs of primary plastics to compensate the losses, and each generation of plastics will thus disappear from the waste plastics from pre-treatment used for PCR production. Adverse effects on the quality of these plastics through multiple recycling will therefore always be limited, and the quality of the plastics for PCR production will stabilize on a certain level.

4.3 Resource Efficiency and Environmental Gains from Mass Implementation of PCR-plastics Use (T8.3)

With the current collection rate of 47 % on average in the EU, and the current treatment technologies, recycling of plastics in collected WEEE and use of PCR plastics could save 21 % of primary plastics production for plastics in

WEEE. Additionally, it avoids incineration of plastics, or other routes of waste plastics disposal which might also still be practiced such as landfill. Increased collection and potential future improvements can further increase resource efficiency by keeping 29 % and up to 40 % of plastics in the loop.

Mass implementation of PCR plastics use yields considerable environmental gains, reducing the CED, GHG emissions and the overall environmental impacts. This effect would already occur if PCR plastics was produced and used from the plastics contained in the currently 47 % of collected WEEE in the EU.[1] Increasing the collection rate to 65 % as required in the WEEE Directive would further increase the environmental gains for 38 % compared to the baseline scenario. Additionally, reducing the waste rate in the sorting and cleaning step in final processing would yield remarkable environmental gains. The example of scenario C shows that reducing the waste rate from the current 50 % to 30 % combined with the 65 % collection rate would more than double the environmental gains compared to the baseline scenario.[2] Increasing collection rates and upgrading sorting techniques in final processing thus have a considerable potential to reduce environmental burdens and impacts from plastics used in EEE in a mass implementation of PCR plastics use. This would however imply that the additional efforts required to improve the sorting and cleaning processes are energy and resource efficient and limited to avoid that the environmental gains are partially or fully outweighed by the environmental impacts caused by these processes.

While the resource efficiency gains and the avoided CED and GHG emissions from PCR plastics use are massive, they reduce the overall CED and GHG emissions of the EU27 by around 0.03 % in the baseline scenario A, and for 0.06 % in scenario C. For the CED, the reductions would be 0.04 % to 0.07 % respectively. These reductions are probably at least in proportion to the share of plastics for EEE in the overall production and other activities which cause CED and GHG emissions in the EU27, but does not have crucial influence on the overall CED and GHG emissions, i.e. that it is a contribution but not a replacement for other additional measures to reach the EU climate and other environmental targets.

4.4 Recommendations

Recycling of plastics from WEEE and PCR plastics use in EEE produce remarkable environmental and resource efficiency gains compared to primary plastics use. The results underpin that the circular economy approach (CE) should be further followed, and the gains can be further increased:

- Producers should start and/or further increase their respective efforts towards PCR plastics use in EEE. Targets for PCR plastics use in the EcoDesign Directive may be a way to move all producers into this direction.
- The production of PCR plastics from plastics in collected WEEE should be further promoted to make sure these plastics are actually used to produce PCR plastics.
- If the EU member states would reach at least the 65 % collection target, the environmental gains from PCR plastics use would strongly increase provided the waste plastics is used to produce PCR plastics.

[1] C.f. Table 10 on page 43

[2] C.f. Table 11 on page 43

- Reducing the waste rate of currently around 50 % in the PCR plastics recycling would strongly decrease environmental burdens in particular from incineration, which is the current standard disposal route for inappropriate plastics sorted out in the sorting and cleaning of the plastics after the pre-treatment of WEEE. This would require changes and technical upgrades, possibly with new technologies, in the plastics recycling plants. Efforts from PCR plastics producers, and support for research of ways to turn more plastics waste into PCR plastics will be needed. Member states and the EU should support such research efforts in their national and EU research programmes.
- Clustering of WEEE can potentially yield higher recycling rates of PCR plastics and thus lower the potential environmental burden of processing WEEE plastics as shown in the LCA. However, this scenario will only be possible with additional sorting efforts prior to shredding and mechanical separation of WEEE, which may require more technical and manual labor and thus increase cost. The sorting of WEEE into such clusters could alternatively take place as early as in the collection phase. The current collection groups in the WEEE Directive were introduced with, among others, view to promoting the recycling of valuable resources and avoid releases of toxic substances into the environment. In the next review of the WEEE Directive, the specific requirements of PCR plastics production could be taken into account additionally and the collection groups be adapted accordingly. Complementarily, the WEEE Directive could stipulate further clustering at the pre-treatment stage considering that such efforts need to be financed – in case of the mentioned amendment under the producers' extended producer responsibility – and be enforced to maintain a level playing field for producers and WEEE processors.
- The above measures need to be aligned and developed step by step, i.e. that in particular the demand and offer have to be further developed in parallel to achieve a situation of mutual push and pull towards mass implementation of PCR plastics production and use.
- The mass implementation of PCR plastics would lead to multiple recycling of plastics as described section 3 on page 33 et sqq. The potential impacts of multiple recycling on plastics qualities, or the efforts to produce PCR plastics from WEEE plastics that meet the market demand, have been assessed in in some experiments, but mainly with one or two different types of plastics. Such effects should be further researched in multiple aging and recycling experiments for mixes of different types of plastics with manifold additives and impurities as they are already found nowadays in WEEE plastics shredding fractions from pre-treatment. While PCR plastics producers are experienced to process such shredding fractions to PCR plastics, the multiply recycled plastics contained in these shredding fractions in a mass-implementation of PCR plastics use would add to the challenges to overcome in order to meet the market demands for plastics in new EEE.
- An allocation which considers shared processes ("basket of products") and evenly distributes the burdens of virgin production and recycling of WEEE plastics between all lifecycles is recommended in LCAs including more than one lifecycle if material quality preservation is assumed. If the quality of the material deteriorates during recycling, a material quality correction factor that reflects the potential limitations for the next use is more appropriate to adequately distribute the burden over the different lifecycles.

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6 Annex: Properties of ABS, HIPS and PC and Blends thereof over Several Life Cycles and for Different Blends

6.1 Properties of ABS, HIPS and PC Blends

Virgin ABS with Post-Consumer ABS blend

Quelle: [6] R. Scaffaro, "Physical properties of virgin-recycled ABS blends: Effect of post-consumer content and of reprocessing"

MUT		**Twin-screw extruder:**	**Injection moulding:**
ABS	Pc_ABS	OMC, Italy	Sandretto,Italy, model m
SD-0150	Ground phones	mperature profil [°C]: 190-2	injection pressure = 95 MPa, holding pressure = 50 MPa
MFI = 3.3	MFI = 3.6	D= 19, L/D = 35	nperature profil [°C]: 200-235
Density = 1.04	Density = 1.04	rpm = 200	

Main characteristics of the polymers used in the frame of the present work.

Material	Density (g/cm^3)	MFI* (g/10 min)	HDT (°C)
Virgin ABS	1.04	3.3	76.5
Post-consumer ABS	1.03	3.6	74.7

* Load: 2.16 kg; temperature: 235 °C.

	Process Cycle			**Conclusion**
Blend ABS/PC (w/w)	**first**	**sec**	**third**	
	Tensile Strength [Mpa]			Tensile properties of ABS/pc-ABS blends decreased during the first reprocessing, even by adding the smallest amount of pc-ABS. Further increase of pc-ABS amount or further reprocessing did not cause significant changes.
0/100	37	34	33,5	
20/80	36,5	33,5	33	
50/50	35.5	33	32	
80/20	34,2	32,8	31,5	
100/0	33.5	32.2	31	
	Tensile Modulus [Mpa]			
0/100	1530	1370	1350	
20/80	1470	1380	1340	
50/50	1420	1375	1330	
80/20	1380	1350	1325	
100/0	1370	1340	1320	
	Elogation at Break [%]			On the contrary, flexural properties were almost unaffected by pc-ABS amount and only slightly influenced by the recycling operations.
0/100	11,5	6,5	4,8	
20/80	10,2	5,5	4,5	
50/50	9	5	4,2	
80/20	7	4,75	4	
100/0	6	4,5	4	
	Imapct Stength [J/m]			The impact resistance of the blends significantly decreased both by adding pc-ABS and by increasing the number of reprocessing steps.
0/100	255	225	195	
20/80	250	210	185	
50/50	235	195	185	
80/20	225	195	182	
100/0	215	185	180	
	Melt Flow Index [g/10min]			The rheological measurements showed that the viscosity of ABS blends was not substantially different by virgin ABS up to two reprocessing steps.
0/100	3,3	3,45	3,7	
20/80	3,4	3,5	3,75	
50/50	3,5	3,55	3,9	
80/20	3,5	3,65	3,95	
100/0	3,58	3,82	4	

Virgin HIP with Post-Consumer HIP blend				
Quelle: Guojun Xu et. Al.:"INSIGHTS INTO REUSE OF ELECTRONICS EQUIPMENT HOUSINGS HIGH				
MUT	**Twin-screw extruder:**	**Injection moulding:**		
ground pieces of printer and monitor housings		Sumitomo injection molding machme		
		Temperatur profil: 380°F to 440°F		
Blend HIP/PcHIP (w/w)	**Tensile Strength [Mpa]**	**Conclusions**		
0/100	21,8	The tensile modulus, tensile strength, flexural modulus and flexural strength increase slightly with the increase of the weight percentage of PCR. **It is found that the physical properties of blends having recycled resin are better than the properties of virgin resin.**		
25/75	21,5			
50/50	20,4			
75/25	19,1			
100/0	18,9			
	Tensile Modulus [Mpa]			
0/100	1960			
25/75	1900			
50/50	1876			
75/25	1784			
100/0	1777			
	Flexual strenght [MPa]			
0/100	37,6			
25/75	36,4			
50/50	35			
75/25	33			
100/0	30,9			
	Flexual Modulus [MPa]			
0/100	1979			
25/75	1939			
50/50	1889			
75/25	1852			
100/0	1802			
	Impact strenght [J/m]			
0/100	104	The impact strength increases with the increase of weight percentage of PCR when the percentage is small and finally the strength reaches a stable value		
25/75	104			
50/50	107			
75/25	95			
100/0	90			

Virgin ABS with polycarbonates (PC) blend			
Quelle: P.A. Tarantili: "Processing and properties of engineering plastics recycled from waste			
MUT		**twin-screw extruder: Haake PTW 16**	**Injection moulding: ARBURG 221K ALLROUNDER**
ABS	PC	Temperatur: 220-280 °C	
Terluran GP-22	Makrolon, Bayer, Germany	D= 16, L/D = 25	screw of 25 mm diameter and clamping unit force of 350 kN.
	melt volume rate: 9.5 cm3/10min	rpm = 36	
Blend ABS/PC (w/w)			
	Tensile Strength [Mpa]	it can be observed that the incorporation of ABS into PC is accompanied by a **decrease** in both, tensile strength and ductility of the blend in comparison with pure PC. In fact, the tensile strength **decreases as the concentration of ABS increases** in the polymer blend, as expected by the law of mixtures	
0/100	69 +- 0.2		
20/80	64 +- 0.7		
50/50	62 +- 1		
80/20	58 +- 1		
100/0	51 +- 5		
	Modulus of elasticity [MPa]	However, the modulus of elasticity shows **some improvement** in both cases, due to the improvement of stiffness of the corresponding blends	
0/100	1960 +- 24		
20/80	2075 +- 111		
50/50	2040 +- 140		
80/20	2180 +- 84		
100/0	1920 +- 82		
	Elogation at break [%]	typical stressestrain curves for PC, ABS and their blends. PC exhibits the highest yield strength and ductile behaviour, whereas ABS breaks at lower load essentially showing elastic deformation, i.e. without significant yield.	
0/100	57 +- 5		
20/80	37 +-5		
50/50	28 +-3		
80/20	10 +- 4		
100/0	4.4 +- 2		
		ABS seems to act as plasticizer when incorporated into PC at concentrations of about 20%, probably due to the dispersion of the polybutadiene phase within the thermoplastic matrix of the blend. This effect was also clear during the determination of rheological characteristics of the PC/ABS blend via MFI measurements. Here again, the sample with composition 80/20 shows **increased flowrate** which suggests easier processing.	
0/100			
20/80			
50/50			
80/20			
100/0			
	Melt flow index [g/10min]		
0/100	2.6 +- 0.14		
20/80	4.6 +- 0.27		
50/50	2.0 +-0.28		
80/20	2.0 +- 0.09		
100/0	0.23 +- 0.01		

Virgin ABS with high-impact polystyrene (HIP) blend			
Quelle: P.A. Tarantili: "Processing and properties of engineering plastics recycled from waste			
material		**twin-screw extruder: Haake PTW 16**	**Injection moulding: ARBURG 221K ALLROUNDER**
ABS	HIP	Temperatur: 220-280 °C	
Terluran GP-22	Styron A-TECH 1200 (Dow Hellas, Greece)	D= 16, L/D = 25	screw of 25 mm diameter and clamping unit force of 350 kN.
		rpm = 36	
Tensile Strength [Mpa]	the tensile strength **decreases** as the concentration of ABS increases in the polymer blend, as expected by the law of mixtures. The same trend can be seen for ABS/HIPS systems but a synergistic effect can also be observed in the modulus of elasticity of ABS/HIPS blends, which is more significant at the composition of ABS/HIPS: 80/20		
32 +- 1.3			
35 +- 0.65			
41 +- 0.5			
47 +- 0.4			
51 +- 5			
Modulus of elasticity [MPa]	However, the modulus of elasticity shows **some improvement** in both cases, due to the improvement of stiffness of the corresponding blends		
1320 +- 42			
1410 +- 14			
1975 +- 57			
2045 +-60			
1920 +- 80			
Elogation at break [%]	A **decrease** in mechanical properties, in terms of tensile strength and elongation, was recorded for both types of mixtures i.e. PC/ABS and ABS/HIPS, with respect to the properties of pure polymers.		
40 +- 3			
40 +-5			
23 +- 6			
21 +- 6			
4.4 +-2			
	On the other hand, the mixtures of HIPS and ABS seem to consist in **fully miscible** blends and, furthermore, the determined changes of blend properties are mostly in **good agreement** with values calculated from the law of mixtures.		
Melt flow index [g/10min]			
5.7 +- 0.3			
6.0 +- 0.19			
4.2 +- 0.23			
2.3 +-0.09			
1.8 +-0.13			

6.2 Influence of Reprocessing and Ageing on ABS polymers

Reprocessing ABS

Quelle: 2007_Bai, Xiaojuan_Reprocessing Acrylonitrile–Butadiene–Styrene

MUT			Measuring
ABS 1	ABS 2	ABS 3	The notched Izod impact tests were performed (on ABS1 and ABS3) at room temperature using a Ray Ran Universal Pendulum Impact System. Tensile testing was carried out on a Hounsfield H25K-S Benchtop Testing Machine at room temperature.
impact and tensile properties respectively with different temperatures and rotational speed		multiple reprocessing.	
Preperation			
Granulated particles of each individual housing were introduced into a torque rheometer controlled at a specific temperature The solid material was granulated again and made into samples for mechanical testing using a Ray Ran Injection Molder.		the granulated particles were processed in the torque rheometer cooled, granulated, and injection molded	

Tensile Strength [Mpa]

Reprocessing Step		**Conclusion**
Zero	<36	tensile strength increased slightly. These small increases in strength may again be related to loss of the small molecules (including lubricant molecules) and degradation (including cross-linking) of the rubber phase [5].
First	<36	
Second	>36	
Third	>36	
Fourth	>36	

Tensile Modulus [Mpa]

Zero	1,4	did not change significantly with increasing number of reprocessing cycles
First	1,4	
Second	1,4	
Third	1,3	
Fourth	1,3	

Imapct Strength [J/m]

Zero	10	impact strength reduced significantly... The greatest reduction was during the first reprocessing cycle, impact strength dropping by about 44%....With subsequent reprocessing cycles, the impact strength diminished more slowly could be explained by the major loss in volatile molecules found during the first cycle since a loss in impact strength has been associated with loss of these small molecules
First	5	
Second	4	
Third	3	
Fourth	1,5	

Tensile Strength [Mpa]

rpm↓ Temperatur →	190°C	230°C	270°C	
20	<36	<36	>36	both the tensile modulus and strength were slightly higher after reprocessing
60	<36	<36	>36	
100	<36	<36	>36	

Tensile Modulus [Mpa]

rpm↓ Temperatur →	190°C	230°C	270°C	
20	>1.6	>1.6	>1.8	impact strength reduced with increasing reprocessing temperature....reduction in entanglements stabilized by rubber particles, chain scission of the graft between the SAN matrix and the rubber phase...at the same reprocessing temperature, the impact strength is slightly reduced with increasing rotational speed. Oxidation of the polymer, particularly the rubber component, might have been factor since higher rotational speeds provide oxygen to diffuses into the polymer
60	>1.6	>1.6	>1.8	
100	>1.6	>1.6	>1.8	

Imapct Stength [J/m]

rpm↓ Temperatur →	190°C	230°C	270°C
20	n/a	>12	8
60	>14	>12	6
100	>14	>10	>6

Accelerated ageing

Quelle: Boldizara,A:"Degradation of ABS during repeated processing and accelerated ageing	
MUT	**Measuring**
commercial general-purpose grade, denoted Terluran 967 K and produced by BASF, commonly used for automotive plastic parts.	Tensile measurements were performed according to ISO 527-5A, with a conventional testing machine, Frank Universalpru¨ fmaschine 81803.The tensile measurements in the study of physical ageing were performed with a Zwick 1455 apparatus The melt volume-flow rate (MVR) was determined at 220 C in accordance with ISO 1133 with a Gottfert MPS-E tester.The thermal properties were investigated with a Mettler 30 TA4000 differential scanning calorimeter
Preperation	
aged in air at 90 C for 235 h, then milled, dried and extruded again. After the second extrusion, samples were subjected to parallel ageing in air and in a nitrogen atmosphere at 90 C for 96 h. extrusions were performed with a Brabender Plasti-Corder PLE 651 Extrusiograph	

Elogation at break [%]

Cycles	Extrusion	Combined	Ageing
0	8,2	8,2	8,2
1	8,2	8 → 8,2	8,5
2	6,5	4 → 10	7
3	8,2	5 → 15	3,8
4	11,5	3 → 13	3,8
5	13	3,8 → 6	3
6	14,5	3	2,8
7	16,5	n/a	2,8

Conclusion

The value increased in the extrusion series and **decreased in the ageing series.** In the combined extrusion and ageing series, remained fairly constant during the first cycle. In the second cycle, decreased markedly during the ageing step, whereas in the third to the sixth cycles, increased during each extrusion step and decreased during each ageing step.

Melt Volume Flow rate [cm³/10min]

Cycles	Extrusion	Combined	Ageing
0	15,5	15,5	15,5
1	15	16	16
2	15	14 → 15	15
3	15	14 → 15,5	14
4	16	14,5 → 16	12,5
5	15	15 → 17	14
6	14	20 → 22,5	14
7	16	27,5	12,5

Conclusion

The MVR remained almost constant in the extrusion as well as in the ageing series, see Fig. 2. Also in the combined series, the MVR values remained fairly constant up to the fourth cycle. However, after the fourth cycle there was a significant increase in MVR values. One possible explanation for the increase of MVR in the combined series may be that antioxidant stabilisers are consumed during the extrusion, resulting in a less protected ABS during the following thermo-oxidative ageing process. The oxidation of the grafted polybutadiene can lead to a degrafting of SAN, which would be in line with the observed increase of MVR (i.e. a decrease of viscosity). A viscosity change due to reduction of the molar mass of the SANmatr ix can be ruled out by the SEC experiment below. A slight reduction in MVR was seen in the ageing series. The changes in MVR in the extrusion series were within the estimated maximum error range of 10% of the given values. **MVR-results imply that recycling of the ABS should be limited to about four cycles, due to the increasing change in the flow properties.**