Recycling rates of materials and components in specific waste electric and electronic equipment in standard end-of-life treatments

Recycling rate assessments in Italy and Germany

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Report information

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DISCAIMER

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1 Definitions and acronyms

Black mass (from batteries)

It is a shiny, metallic mixture from batteries, and it contains all the valuable metals consisting of the battery anodes and cathodes;

Downstream operator

Any operator receiving materials or components of e-waste from for further treatment or disposal from a first treatment operator or a treatment operator further up in the flow chain of the e-waste after the first treatment operator.

DVD

Refers to Digital Video Disk player

Eddy current machine

A machine used to separate fractions based on their ratio of electrical conductivity to density through an electromagnetic induction;

EEA

European Economic Area (EU27 + Iceland, Liechtenstein and Norway);

EEE

Electrical and electronic equipment;

EU

European Union;

EPR

Extended Producer Responsibility, which is an environmental policy approach in which the responsibility of the producer for a product is extended along the whole product's life cycle, including the post - consumer stage (OECD, 2016);

Final treatment operator

The last and final stage of the treatment chain, e.g.; smelters producing recycled metals from the input they receive from upstream treatment operators;

Final processing

Treatment of materials or components of e-waste for recycling or disposal. Typical final processing plants are metal smelters (e.g. aluminum, copper, iron) or operations preparing materials received from upstream operators for disposal.

First treatment operator

The initial stage of the recycling chain including sorting of e-waste, removal of batteries, and possibly further treatment steps like shredding and mechanical separation are practiced;

FSPTO

Full-service pre-treatment operator, operator equipped and organized to conduct the full range of pre-pre-treatment operations from initial steps, e.g. sorting of e-waste and/or removal of batteries to output fractions that can directly be forwarded to final processing.

ICT

Information and communication technology

Internal cables

Cables placed internally in electronic devices;

LCD

Liquid crystal display (along the report, the voice LCD will refer only to the glass part of the display;

Magnetic separation

Industrial process aimed at separate fragments by using magnets to attract magnetic substances;

Metal mix

A fraction obtained and separated at the partially mechanical first treatment operator consisted of a mix of the following: aluminum, PCBs, materials that did not pass the sieve, copper, brass, plastics, non-ferrous materials;

N/A

Not applicable, not available, not assessed, or no answer

PCB(A)

Printed circuit board (assembly);

PTO

Pre-treatment operator, processors treating e-waste prior to its final processing. This may imply several operators practicing few steps of the pre-treatment such as the removal of batteries only, or a single treatment operator processing e-waste to the stage where it can be forwarded to final processing.

Recovery

Any operation, the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy (EU Directive 2008/98/EC on Waste).

Recycling

Any recovery operation by which waste materials are reprocessed into products materials or substances whether for original or other purposes (EU Directive 2008/98/EC on Waste).

Recyclable plastics

Plastics with a density of 1.08 g/cm^3 or less;

RR

Recycling rate, ratio of material/mass of component in input and output of a recycling process;

Second treatment operator

The second stage of the recycling chain where a further and more detailed separation and dismantling occurs;

Separation effectiveness

Describes to which degree the mechanical separation process directs materials into the dedicated fractions from which they can be recycled in subsequent processes.

SMS

Shredding and mechanical separation

Thermoplastics

Type of polymer that can be melted and recast continuously;

Thermosets

A polymer obtained by irreversibly hardening a solid or viscous liquid prepolymer;

TPEs/TPUs

Thermoplastic elastomer/thermoplastic polyurethane;

Treatment

Recovery or disposal operations, including preparation prior to recovery or disposal as well as recovery and disposal operations;

Waste Electrical and Electronic Equipment (WEEE) / E-waste

All types of EEE and its parts that have been discarded by the owner as waste without the intention of re-use. (StEP-Initiative, 2014)

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Background

2 Background

Due to the increasing global economic development, electrical and electronic equipment (EEE) has become widely present in current societies, resulting in a broad and intense production and usage (Forti et al., 2020). A direct and warning consequence of such a trend is the generation of higher amounts of waste streams that contain both hazardous and valuable materials. The specific waste stream is known globally as e-waste and in Europe as Waste Electrical and Electronic Equipment (WEEE). Estimations indicate that 57.4 Mt of e-waste were generated globally in 2021, an average of 7.3 kg per capita, mainly consisting of Small equipment (17.4 Mt), Large equipment (13.1 Mt) and Temperature exchange equipment (10.8 Mt). The increasing trend of e-waste generation is undoubtedly related to the higher consumption of EEE but is also due to short life-times, limited and insufficient repair and recycling options. Recycling options and technologies also varies depending on the type of e-waste, consisting in different recycling paths due to differences in materials, weights, dimensions and substances contained in the products.

Global e-waste recycling does not keep pace with the exponential growth of e-waste. In fact, in 2019, the reported collected and recycling was 9.3 Mt, which corresponds to 17.4 % of the e-waste generated. This is a growth of 1.8 Mt since 2014 while e-waste generated in the same period grew by 9.2 Mt.

Reacting to increasing consumption of resources and in view of the planetary boundaries, the EU enacted the Green Deal that, among others, includes efforts to circularize the economy. In the course of this policy, producers are moved to increase the resource efficiency of their products. One approach is the declaration of recyclability of products like EEE based on the standard EN 45555.

There is, however, no product level data concerning the recyclability of components and materials in standard e-waste treatment processes globally and in the European Economic Area (EEA). This study was therefore launched to obtain such data for most common recycling processes in selected countries to reflect regional differences.

2.1 EU normative framework

2.1.1 Directive 2012/19/EU (WEEE Directive 2012)

The EU WEEE Directive is the guiding legislation for the management of e-waste in the European Economic Area (EEA, i.e. EU27 + Iceland, Liechtenstein and Norway). The WEEE Directive is not the directly applicable legislation in the EEA member states. Member states are legally obliged to transpose the directive into their national legislation whereat they must implement the below core principles but are free in how exactly they want to achieve them. As a result, the national e-waste legislations differ between the member states of the EEA.

The WEEE Directive sets collection, recycling, reuse, and recovery targets for all six categories of e-waste. It provides the member states with measures to protect the environment and the human health through the prevention or the reduction potential impacts related to the generation and management of electrical and electronic equipment also in accordance with the Articles 1 and 4 of Directive 2008/98/EC contributing to sustainable development. More precisely, this regulation is in force in the European Economic Area (European Union plus Iceland, Liechtenstein and Norway).

The electrical and electronic equipment (EEE) in the scope of the WEEE Directive is classified in six categories

- Temperature exchange equipment;
- Screens and monitors, e.g., the scope products notebooks and tablets;
- Lamps;
- Large equipment, i.e., EEE with at least one outer dimension larger than 50 cm which does not fall into categories 1, 2 or 3;
- Small equipment, i.e., EEE with no outer dimension larger than 50 cm which does not fall into categories 1, 2, 3 or 6;
- Small IT and telecommunication equipment with no outer dimension of more than 50 cm, e.g., the scope products game consoles, mice and keyboards.

EEA member states have to take measures to ensure that minimum rates of separately collected e-waste are achieved and to prevent that e-waste or fractions thereof are disposed of untreated. The EEA members implemented technical infrastructure to enable compliance with the WEEE Directive. Most member states follow the shared responsibility approach where municipalities provide and operate collection points where citizens can hand in e-waste free of cost, and municipalities may also conduct curbside collections of e-waste. Additionally, consumers can give back e-waste in larger shops without cost.

The extended producer responsibility (EPR) requires producers to organize and finance the pickup of collected e-waste at municipal collection points, the transport to first treatment operators, and the sound treatment and disposal of the collected products. They must meet minimum material recovery and recycling targets in the treatment of the separately collected e-waste depending on the category of e-waste. The directive also requires removal and specific treatment of certain hazardous components and materials from e-waste. Member states report the volumes of separately collected and treated e-waste including the achieved recovery and recycling rates to the EU Commission in Brussels.

2.1.2 Standard EN 45555

The standard (EN 45555, 2019) "General methods for assessing the recyclability and recoverability of energy-related products" forms the basis for recyclability assessments in the EU calculated as:

$$R_{cyc} = \frac{\sum_{k=1}^{n}\left(m_k \cdot R_{cyc,k}\right)}{m_{tot}} \cdot 100\ \%$$

Equation 1: Calculation of the recyclability of products

Where:

R_{cyc} is the recyclability rate of the product;

$R_{cyc,k}$ is the recyclability of the specific material k;

n is the number of parts/materials;

m_k is the mass of material k in the product;

m_{tot} is the mass of the complete product;

The recyclability of the materials must be based on realistic and defined reference scenarios, taking into account specific design properties affecting the recyclability, e.g. the use of brominated flame retardants, the removability of components that have to be removed and treated separately for compliance with the WEEE Directive or other regulations, etc.

2.1.3 EN 50625 series of standards

EN 50625 is a set of harmonized EU standards and of Technical Specifications for collection, transport, treatment and reuse of e-waste.[1] The standards set requirements for collectors, logistic providers and e-waste treatment operators. The standards are voluntary, i.e., there is no legal obligation for operators to follow them. The compliance is verified by the WEEELABEX Organization[2] that also provides a list of certified operators.[3]

2.2 Infrastructural situation of e-waste treatment in the European Economic Area

Municipalities in EEA member states provide the collection infrastructure while logistics and treatment infrastructure are financed and operated by private, sometimes also civil society sector organizations. In most EEA member states, many first/pre-treatment operators are active that process e-waste financed by the producers. The range of their activities can be limited to manual depollution steps only such as the removal of batteries but include also further manual and mechanical dismantling steps. Components and fractions generated from such activities may be forwarded to other pre-treatment operators for further pre-processing or to final treatment operators if no further pre-treatment is required.

Large pre-treatment operators offer the full scale of pre-processing of almost all types of e-waste with mostly minimized manual and mainly mechanical means. The generated fractions are in most cases ready for final treatment. In smaller EEA member states such large scale operators may not be common, but waste or fractions thereof can in principle be transported for treatment to other member states.

The number of final treatment operators in the EEA is limited. The number of copper route smelters, for example, processing printed circuit board and copper fractions from e-waste treatment is limited to three larger ones in

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[1] C.f. CENELEC, https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Environment %20and %20Sustainability/Quicklinks %20General/Documentation %20and %20Materials/weee-brochure.pdf

[2] WEEELABEX Organisation, https://www.weeelabex.org/.

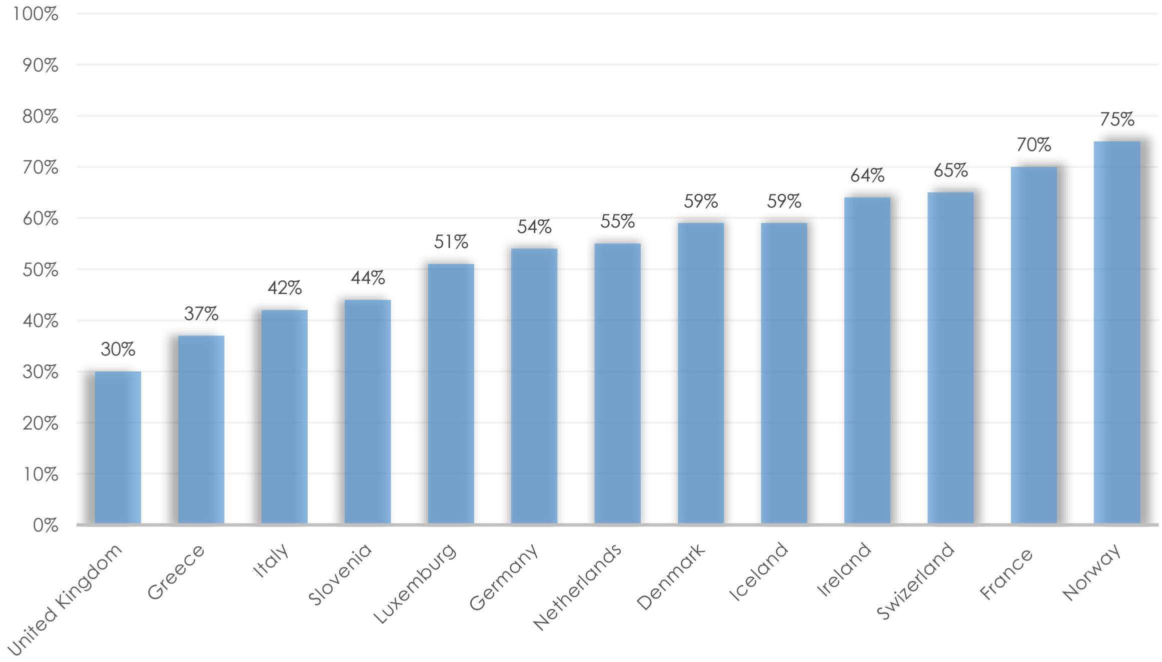
[3] List of certified operators, https://www.weeelabex.org/operators-list/

Belgium, Germany, and Sweden. The situation is similar for plastics recyclers while there are still few but more facilities for other fractions like iron. The end-of-life treatment chain is thus dependent on the transboundary movement of components and fractions at least within the EEA.

2.3 E-waste arising and collected in the European Economic Area

Figure 1 presents an overview of collection rates versus e-waste generation for the *EEA + Switzerland* and United Kingdom in 2021.

Figure 1 E-waste collection related to e–waste generated in 2021



Source: Baldé et al., 2022

Project definition and scope

3 Study scope, objectives, and approach

3.1 Objectives

This project shall contribute to enable the recyclability assessment of scope products (c.f. section 3.2) according to the EU standard EN 45555 (c.f. section 2.1.2). The assessment shall reflect e-waste treatments applied in the EU.

To this end, different EU member states were selected to collect data in the field from treatments practiced as standards in these member states for the products in scope.

3.2 Product and material scope

The products in scope of the recyclability assessment were:

- Laptops
- Tablets
- Game consoles
- Other Small IT (keyboards and mice)

As far as practicable, the output fractions reported in Table 1 were assessed, complemented, or replaced by other ones where the actual end-of-life treatments produced output components and fractions that deviated from the below list.

Table 1 Elements, components and material in scope

Components	Materials
LCDs (component or material level)	Neodymium Magnets
PCBs	TPEs/TPUs
Lithium-ion batteries	Rubber
Alkaline batteries	Plastics
Batteries	“Neat” thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)

	GF** thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)
	FR* thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)
	Thermosets
	Aluminum material
	Copper material
	Iron/steel material
	Magnesium

*FR = Flame Retardant

**GF = Glass Fiber

3.3 Geographical scope and collaboration with local partners

The project was carried out in the European Union (EU). The EU an important market for the scope products. While the EU WEEE Directive sets the framework for the e-waste management in the EU, the EU member states transpose and specify the WEEE Directive into their national regulations. While, as a result, the member states comply with the core requirements of the WEEE Directive, the national regulations and implementations define different ways how to achieve these targets. The recyclability assessment studies were therefore conducted in different member states of the EU which were selected according to the below criteria:

1. Level of development of the e-waste recycling infrastructure/technologies with the objective of capturing lower and higher maturity level treatments in EU member states

2. Volumes of e-waste collected and treated, i.e. focus on markets with larger volumes to enable results that are more representative for the overall recyclability of the scope products in the EU market;

3. Access to local partners with aspired data and insights, and with ambition to cooperate in the project.

3.4 Approach

Data required for assessing the recyclability of materials contained in the scope products were collected in collaboration with first treatment operators applying processes that can be considered as standard in the respective regions. Output components and fractions from first treatments are forwarded to downstream treatment operators. The downstream operators report the recovery and recycling rates they achieve with the forwarded components/materials to the first treatment operator, which can be used to calculate the recyclability of materials contained in the forwarded components and fractions. Where downstream treatment results were reported on component levels only, it was attempted to specify these data down to the material level by literature searches.

In their daily operations, first treatment operators process collection groups of e-waste unless treatments of individual products are legally required or economically beneficial. Where first treatment operators could not make available information on output components and fractions specifically for the scope products, pilot treatments were designed and conducted that best reflect the recyclability of the scope products in the respective first treatment standard processing.

3.5 Data quality assessment

The quality of data used for the study was evaluated following the data quality matrix displayed in Table 2. A quality assessment of the typical input streams was completed to assign the data quality score (c.f. section A.6 and A.9). It should be noted that the numeric thresholds represent a rule-of-thumb and are not rooted in technical evidence. The data were assigned a score a ranking from 1 (highest score) to 5 (lowest score) assigning the highest score to the data acquired on the field and the lowest to data aggregated and subject to estimations.

Table 2 Data quality matrix. Overview of indicator, sub-indicator and scoring rubric

Indicator and sub-indicator	(Highest score **Data quality score** (Lowest score)				
	1	2	3	4	5

Reliability of data	Material composition of the input batch	Gathered through primary data from the recycler used to calculate the input batch composition, verified through supporting documentation.	Gathered through primary data from the recycler used to sample and estimate the input batch composition, verified through supporting documentation.	Historical composition data for the relevant EEE stream in the batch being processed.	Gathered through a documented estimate based on factors verified through supporting documentation.	Gathered through and undocumented estimate or unknown source of documented secondary data.
	Batch being processed relevant to the product being assessed	>80% of the products the recycler processes fall into the same WEEE category as the product being assessed.	60-79% of the products the recycler processes fall into the same WEEE category as the product being assessed.	50-59% of the products the recycler processes fall into the same WEEE category as the product being assessed.	40-49% of the products the recycler processes fall into the same WEEE category as the product being assessed.	<40%of the products the recycler processes fall into the same WEEE category as the product being assessed.
	Yield rate across the whole reprocessing chain (T1 and downstream processes)	Primary yield rate data available across the whole reprocessing chain for all materials with distinct reference treatment scenarios.	Primary yield rate data available for T1 operator, and secondary yield rate data for all downstream processes.	Primary yield rate data available across the whole reprocessing chain for only selected materials.	Secondary yield rate data available for T1 and downstream processes.	Primary or secondary yield rate data only on T1 recycling process.

			Secondary yield rate data supplied by official regulations for the explicit purpose of supporting product recyclability assessments is accepted, as long as the geographic scope of the cited regulation and the recyclability assessment report are aligned.		Secondary yield rate data supplied by official regulations for the explicit purpose of supporting product recyclability assessments is accepted, as long as the geographic scope of the cited regulation and the recyclability assessment report are aligned.	Secondary yield rate data supplied by official regulations for the explicit purpose of supporting product recyclability assessments is accepted, as long as the geographic scope of the cited regulation and the recyclability assessment report are aligned.
Time	N/A	Literature or primary data source are less than 3 years old.	Literature or primary data source are less than 6 years old.	Literature or primary data source are less than 10 years old.	Literature or primary data source are less than 15 years old.	Literature or primary data source are less than 15 years old.
Completeness	N/A	Data have been captured for materials (with distinct reference treatment scenarios) that	Data have been captured for materials (with distinct reference treatment scenarios)	Data have been captured for materials (with distinct reference treatment scenarios) that together account for	Data have been captured for materials (with distinct reference treatment scenarios) that together	Data have been captured for materials (with distinct reference treatment scenarios) that together

		together account for >95 wt% of the product.	that together account for >90 wt% of the product.	80-89 wt% of the product.	account for 70-79 wt% of the product.	account for 60-69 wt% of the product.

Recyclability Assessment Italy

A Recycling rate assessment Italy

Being a member of the EU, Italy was selected for the first recyclability assessment of the scope products according to the selection criteria:

1. Level of development of the e-waste recycling infrastructure
   The legislative framework in Italy is well developed. Italy has a targeted Legislative Decree 49/2014 that arises from the transposition of the WEEE Directive 2012/19/EU which defines the measures and procedures for preventing and reducing environmental impacts associated to e-waste.

2. High volumes of e-waste generated, collected and treated, c.f. section 2.3.
   Italy contributes substantially to the e-waste generated in the EU. The country ranks 4th among EU member states with a total e-waste generation of 1.1 Mt (million tons) in 2021 (Figure 1). Italy is considered average in terms of e-waste collected and recycling performance. In fact, in 2021 the collection rate in Italy compared to e-waste generated was 42 % (Baldé et al., 2022);

3. Availability of a local partner that has access to and is willing to share required data and insights
   A cooperation with the local Producer Responsibility Organization (PRO) “Erion” could be established. Operational since 2008 as “Ecodom” and renamed into “Erion” after the merger with another Italian RPO in 2020, the PRO is experienced with all aspects of e-waste management including processing, data collection and management. In 2021, Erion managed around 53 % of the e-waste collected in Italy. With these high volumes of e-waste to be processed in the back, ERION has a strong market position and can reach out to treatment operators to participate in batch testing and data gathering required for the recyclability assessment of the scope products.

A.1 Summary Italy

A recyclability assessment was performed for materials and components in laptops, tablets, game consoles and small IT (scope products) based on standard treatment operations practiced in Italy in cooperation with the producer responsibility organization Erion and their treatment contractors. Two different treatments were assessed to reflect the situation in Italy. One treatment operator processed the scope products mainly mechanically, including shredding and mechanical separation (SMS) with a minimum share of manual labor. The other treatment operator dismantled the scope products to remove, as a minimum, the batteries and, depending on the products, further components and materials which were forwarded to an SMS processor.

For the study, batch tests simulating the actual treatments were designed since the volumes of scope products that could be collected for the study were too small for treatment in the large-scale standard processes.

The results for the recyclability of components and materials in the scope products confirm the high recyclability (≥ 80 %) of metals while for plastics and batteries still more than 50 % were found to be recyclable. In both treatment approaches, the separation of components and materials from the scope products prior to SMS increased the recycling rates, in particular in the manual treatment. Product designs supporting effective and efficient removal of components would therefore improve the commercial viability of such component separations and the recyclability.

Product designs enabling the use of plastic types that are recyclable, free of brominated flame retardants, and free of cavities in the plastic parts facilitate higher plastics recycling rates. Product designs supporting the separation of recyclable plastics without brominated and possibly other flame retardants, and a clear and reliable marking of respective plastic parts would further help the recyclability of the scope products.

The experiences made in the study show that the early stage understanding of actual and batch test processes are crucial for the access to data as well as their correct interpretation. Ensuring the same level of understanding among all partners for their respective approaches and intention related to e-waste treatment as well as the common understanding of the study objectives further help to achieve the study objectives effectively and efficiently.

A main data gap with influence on the recyclability results was the missing separation effectiveness for different components and materials in SMS which should be addressed in a follow-up project to consolidate the recyclability rates.

A.2 Background Italy

A.2.1 Transposition of the WEEE Directive in Italy

Italy transposed the WEEE Directive into the national Legislative Decree 49/2014. The decree foresees the below collection groups:

Table 3 Correspondence of Italian e-waste collection groups to EEE categories

ITA	EEE cat.	Category description according to categories in WEEE Directive
R1	1	Temperature exchange equipment
R2	4	Large equipment

R3	2	Screens and monitors
R4	5, 6	Small equipment, and small IT and telecommunication equipment
R5	3	Lamps

The decree thus groups the EEE of categories 5 and 6 of the WEEE directive into the collection group R4. Municipal collection points therefore provide 5 receptacles into which the e-waste is sorted before it is handed over to the producers or their legal representatives to take care of the transport and sound treatment and disposal of the collected e-waste as part of their extended producer responsibility.

The principle of 'Extended Producer Responsibility' is put into practice with the creation of Producer Responsibility Organizations (PROs), which guarantee:

- The pickup of e-waste collected at centers managed by municipalities;
- The transport of e-waste to appropriate pre-treatment facilities;
- Pre-treatment of the e-waste according to applicable environmental and safety criteria, achieving the minimum recovery and recycling targets and sound disposal of non-recoverable components and fractions thereof.

Compared to many other EU countries with a monopolistic approach or a limited number of operational PROs, Italy has 13 PROs in place, one of them being the largest Italian PRO Erion[4], the local cooperation partner for the recyclability assessment in Italy.

A.2.2 Cooperation with local partners

The local partner Erion selected and managed the collaboration with first treatment operators to carry out the field data collection and to obtain the respective downstream data that the downstream operators report to the first

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[4] Erion website: https://Erion.it/en/

treatment operators. Erion selected the two first treatment operators according to the below criteria:

- Considerable treatment capacity including for the products in scope of the study;
- Representation of processes and technologies that are commonly applied in Italy;
- Experienced in cooperation in EU and other research projects.

A.3 Adaptation of the specific approach to the data situation

A.3.1 Use of a mass balance approach

Section 3.4 describes the general approach that was followed for the recyclability assessment. Specifically, a mass balance approach was intended to be used for the calculation of the recycling rates from the batch test and downstream operator data. This specific approach had to be given up for different reasons:

- The recycling rates reported from downstream operators to the first treatment operator referred to masses of components or materials contained in the inputs to their processes. The masses of these inputs were not identical with the masses of the various output fractions obtained in the batch tests since these output fractions would have been too small to be processed individually by the downstream operators. The ratios of masses of the listed components, fractions and materials were not proportional to the masses of batch output fractions either. The output volumes of the batch tests would have been too small to be processed separately at the downstream operators. The reported downstream data referred to the components and fractions that were obtained from standard pre-treatments of large amounts of products, among others those in scope.
- The recovery and recycling rates reported by the downstream operators were reported in percentages as well, however, referring to the input into their processes as the 100 % base. The types of these inputs were not identical to the output fractions assessed during the batch tests. They referred to fractions that emerged from an additional shredding and mechanical separation (SMS) process during which some of the materials in the inputs to these SMS were lost to other fractions that were directed to recycling paths where they could not be recycled. These losses were not accounted for in the input fractions of the downstream

operators. No data was available on the percentages of materials in the output fractions that were separated into those fractions from which they could be recycled (separation effectiveness) to achieve the systematic parity of batch test outputs and the downstream processing inputs, i.e. an identical absolute masses for the respective relative 100 % bases.

- Full material compositions for the products in scope were not available at the treatment operators involved. The initial approach to fill this data gap was to use an internal UNITAR-SCYCLE database with component, material and element masses. This approach was later excluded in the development of the project as more recent data were necessary to calculate the recycling rate of the considered components and materials in the products in scope. The data from the database did not harmonize with those components and materials assessed for the scope products in the batch test.

As an alternative, the study team focused on assessing the percentages of recovery and recycling for the focus components, fractions and materials.

To enable this approach, the separation effectiveness was introduced to bridge the gap between the outputs identified in the batch tests and the downstream treatment data. In the absence of reliable data, it was assumed that treatment operators must comply with the minimum recovery and recycling targets set by the (WEEE Directive 2012). The separation effectiveness was therefore set as a default value that is high enough that these targets are met. This value was set to 85 % separation effectiveness which, according to Erion, is a conservative choice as some fractions are subject to an additional treatment step to remove materials that are in the wrong fraction and bring them to the appropriate recycling process before the remaining fraction is treated in downstream recycling processes. As an example, metals in plastics fractions may be separated for recycling before the plastics fraction is further processed.

The validity of the above approach of choosing a separation efficiency is backed by the fact that both first treatment operators involved in the project are compliant with the certification required by the national treatment agreement, prepared in accordance with the Italian Legislative Decree 49/2014, the transposition of the WEEE Directive. Certified operators have to prove annually their compliance with, among others, the minimum recycling targets set in the Italian regulation/WEEE Directive. In qualification it should be noted that compliance assessments focus on the recyclability of entire collection groups processed by certified treatment operators, not on specific products like the scope products, i.e. the treatment by certified operators does not guarantee that the minimum recyclability targets are met for individual products.

Further, the minimum recycling rates are not to be achieved for each individual material in the scope products. The separation efficiency could in principle be higher for some and lower for other materials. In the absence of data and indications as to whether and to which degrees such variations might occur, 85 % was used as a default setting for the separation effectiveness for all materials and components undergoing a mechanical separation in the study.

Recyclers established downstream routes that are characterized by many factors, and the recycling rate is just one of them. Other factors are commercial viability, logistic proximity, treatment capacity, long term agreements with downstream recyclers and frequency of deliveries. Instead of showing recycling results that strongly depend on a specific downstream route of the recyclers, it was considered more conservative and more representative to use mathematical averages that take into considerations the multitude of downstream solutions available on the market for e-waste recyclers.

A.3.2 Specific plastic recycling rate assessment on Small IT sample

In addition to the abovementioned batch tests, a deeper investigation on plastic recyclability was made. The separation process chosen was the densiometric separation by flotation, which is the most common for e-waste plastics in the EEA. The sample considered was the plastic fraction obtained from small IT, in particular from keyboards and mice. The analysis was conducted on a simplified small – scale separation because of the big dimensions of the production plant (more than 20 tons of plastic would have been needed to run a real case pilot).

In particular, the analysis involved: a separation of finest fraction from the rest of the sample, a separation of the metallic fraction from the plastic, a separation of plastic with additives and a separation of ABS+PS fragments from the PE+PP ones.

The results of the additional plastic investigation are reported in section A.5.1.6 on page 53.

A.4 Data collection

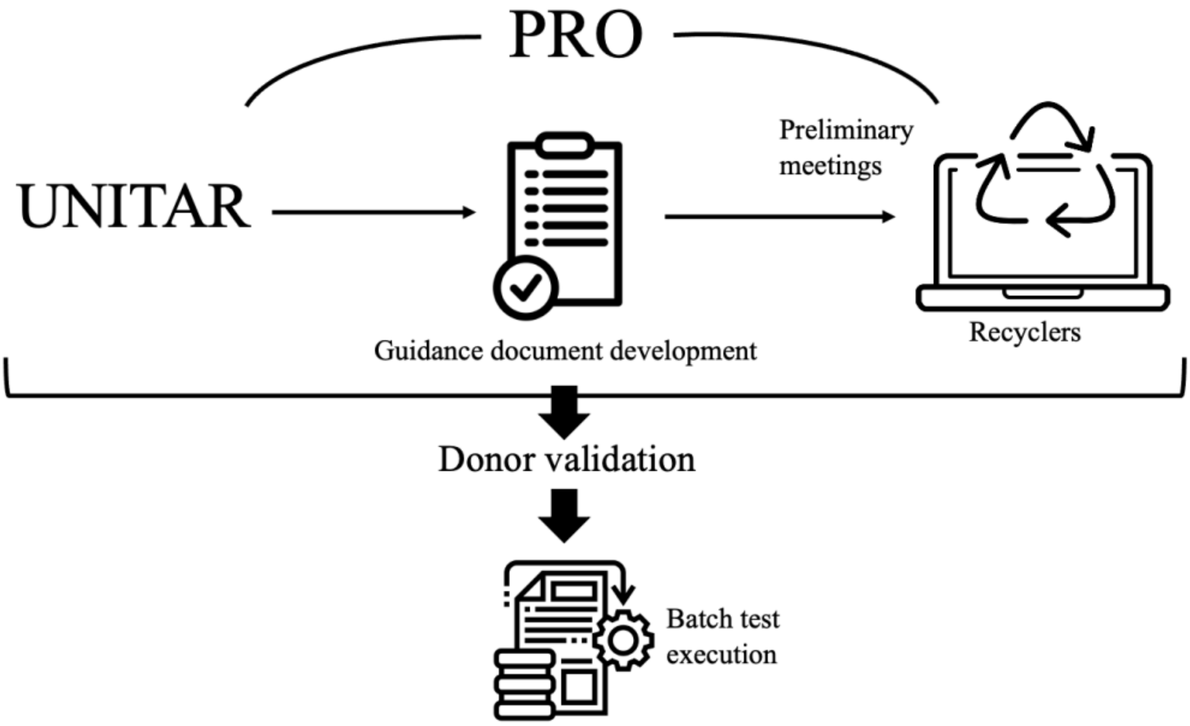
A.4.1 Designing and performing batch tests

Two different treatments were assessed to reflect the situation in Italy. One treatment operator processed the scope products mainly mechanical including shredding and mechanical separation (SMS) with a minimum share of manual labor. The other treatment operator dismantled the scope products to remove, as a minimum, the batteries and, depending on the products, further components and materials which were forwarded to an SMS processor. For the study, batch tests simulating the actual treatments were designed since the volumes of scope products that could be collected for the study were too small for treatment in the large-scale standard processes which would have required a minimum input of two tons.

The scope and timeline of the batch testing were determined beforehand, and, accordingly. The organization of the batch tests was discussed with the representatives of the treatment plants to ensure agreements on the treatment steps to perform and the data to be collected. A specific amount of e-waste products belonging to the categories in scope were stored and saved for the analysis by the plant operators. The mechanical treatment steps required certain minimum quantities of scope products to enable the treatment of the respective products. These products were sorted out from the incoming e-waste streams and stored separately for the batch testing.

Prior to the start of the batch test, a guidance document was developed to ensure that all relevant data were collected and recorded in the correct contexts, and to enable the calculation of the recyclability rates for the materials in the scope products. Figure 2 summarizes the steps undertaken to prepare and conduct the batch tests.

Figure 2 Steps undertaken to conduct the batch tests



Two UNITAR-SCYCLE team members attended the batch tests on the first treatment operators' sites to obtain detailed insights into the process and to collect the related data in the correct contexts.

A.4.2 PRO data for collection groups R3 and R4

The PRO collects data from its treatment operators reported via RepTool, a web-tool based on the WEEE Forum Key Figures database (WEEE forum, 2021) that is used for collecting and calculating the recycling rates of e-waste treated. The below tables show these data for the collection groups R3 "Screens and Monitors" and R4 "Small Equipment, Small Information and Communication Technology Equipment" (ICT). The PRO pointed out that the RepTool data are self-declared by the treatment operators, and that the data collected during the batch tests are more reliable.

Table 4 Screens and monitors – destination of fractions declared by first treatment operators in 2022

SCREENS AND MONITORS	**TOTAL VOLUME TREATED (ANNUALLY) TONNES**	**SHARE OF OUTPUT FRACTIONS BY THE PLANTS COMPARED TO THE TOTAL**			
	44,049.5804	100 %			
OUTPUT FRACTION		**RECYCLING (%)**	**ENERGY RECOVERY (%)**	**THERMAL DISPOSAL (%)**	**LANDFILL DISPOSAL (%)**
ALUMINIUM		100.00 %	0.00 %	0.00 %	0.00 %
COPPER		100.00 %	0.00 %	0.00 %	0.00 %
FERROUS METALS		100.00 %	0.00 %	0.00 %	0.00 %
OTHER METALS		99.97 %	0.00 %	0.00 %	0.03 %
PLASTICS		87.12 %	11.69 %	1.13 %	0.06 %
GLASS		99.92 %	0.00 %	0.00 %	0.08 %
CONE GLASS		97.69 %	0.00 %	0.30 %	2.00 %
Capacitors		0.13 %	0.24 %	31.50 %	68.14 %
WOOD		100.00 %	0.00 %	0.00 %	0.00 %
NON-HAZARDOUS WASTE		0.28 %	6.37 %	11.67 %	81.68 %

HAZARDOUS WASTE	0.32 %	2.75 %	3.88 %	93.04 %

For the interpretation of the above data and for comparisons with the batch test outcomes, it should be kept in mind that the above data refer to the entire collection group R3, not to individual or the group of the scope products "laptops" and "tablets". Table 4 reflects the large variety of the collection group that may affect the recyclability rates. The collection rate contains, for example, wood and cone glass from cathode ray tube TVs and monitors that still represent a considerable e-waste stream. Besides the four metal fractions on top of the list and glass and plastics, the other scope components and materials including the batteries are missing. Generally, the data are difficult to interpret in the absence of more details about the fractions forwarded to the downstream treatment operators, their compositions and their specific treatments.

As to the recycling rates for aluminum, copper and ferrous metals, it can be assumed that they refer to metal parts removed prior to SMS as the indicated 100 % recycling rates are even less realistic for shredding fractions which also contain shares of non-metal materials. Some other fractions were not plausible at first glimpse and required further clarification with the PRO.

The capacitors in the table probably stem from CRT-TVs and monitors. The WEEE Directive requires electrolyte capacitors containing substances of concern (height > 25 mm, diameter > 25 mm or proportionately similar volume) to be removed. Such large capacitors can be assumed not to be present in more recent technology EEE.

Even though of limited importance for the scope products, it seemed not quite plausible that "wood" – also from CRT-TVs -is sent to recycling according to the above table. The PRO explained that the wood is used to produce chipboards. Similarly, the cone glass from CRT-TVs was explained to be forwarded to the ceramics industry so that most of it is recycled.

Table shows the PRO data for the collection group R4.

Table 5 Small equipment and small ICT – destination of fractions declared by first treatment operators in 2022

SMALL IT AND TELECOMMUNICATION EQUIPMENT	TOTAL VOLUME TREATED (ANNUALLY) TONNES	SHARE OF OUTPUT FRACTIONS BY THE PLANTS COMPARED TO THE TOTAL
	18,959.4823	100 %

OUTPUT FRACTION	RECYCLING (%)	ENERGY RECOVERY (%)	THERMAL DISPOSAL (%)	LANDFILL DISPOSAL (%)
Batteries/accumulators	83.38 %	0.07 %	5.28 %	11.27 %
Aluminum	100.00 %	0.00 %	0.00 %	0.00 %
Copper	100.00 %	0.00 %	0.00 %	0.00 %
Ferrous Metals	100.00 %	0.00 %	0.00 %	0.00 %
Other metals	100.00 %	0.00 %	0.00 %	0.00 %
Plastics	93.92 %	5.61 %	0.27 %	0.20 %
Glass	100.00 %	0.00 %	0.00 %	0.00 %
Capacitors	0.74 %	0.01 %	26.81 %	72.43 %
Cartridges/Toners	96.31 %	0.00 %	3.69 %	0.00 %
Paper/Carton	100.00 %	0.00 %	0.00 %	0.00 %
Wood	100.00 %	0.00 %	0.00 %	0.00 %
Non-hazardous waste	12.22 %	35.60 %	2.38 %	49.81 %
Hazardous waste	9.81 %	3.38 %	1.09 %	85.72 %

Like in the above case, the table only includes a small portion of the scope components and materials. The most unexpected fraction, wood, in this case may be from EEE like speakers, and it is also use to produce chipboards. It is not clear from which EEE the capacitors come from that are mostly sent to landfill and “thermal disposal”.

The plastics recycling rate (around 94 %) is higher than for the sample of Small IT (keyboard and mice, 89 %) treated in a separate batch test (c.f. section A.5.1.6). It could have been expected that the recyclability rate of plastics would have been lower due to the larger variety of devices and the complexity of materials in the R4 collection group compared to the Small IT batch with keyboards and mice only.

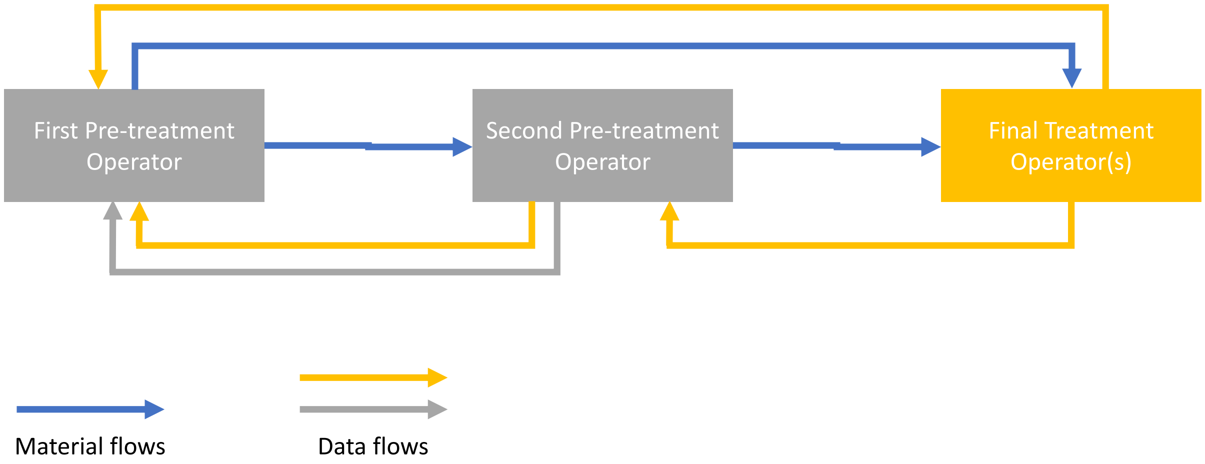
Overall, the PRO data do not provide crucial additional information as to the recyclability of components and materials in the scope products. They cover a small part of the scope components and materials only, and no background information is available concerning the processes and output fractions that were generated and treated. Adding to this, the PRO rates the reliability of the batch test data higher than that of the PRO data, which refer to entire collection groups, not to the treatment of the scope products like in the batch tests. These data were therefore not further taken into account in the assessment of the recyclability rates of the components and materials in the scope products.

A.5 Batch Tests

Recycling plants in Italy, as well as in other EU member states, usually have category-specific recycling lines, because the products falling into different categories have different characteristics in terms of material composition, average weight, presence of hazardous materials, etc., which justify the use of different recycling lines.

Two different batch tests were designed and conducted with pre-treatment operators to reflect common treatments in Italy, a partially mechanical and fully manual treatment of samples consisting of the scope products. The output fractions were forwarded to downstream recyclers for further treatment, and the data for the recyclability and disposal collected directly from the treatment operator and from downstream operators. Figure 3 depicts the material and data flows.

Figure 3 Mass and data flows



Downstream operators report the treatment data to the upstream operators from whom they had received the fractions they treated. Depending on the types of waste products, there may be only one pre-treatment operator. This applies in particular to scope products that do not contain batteries which may sometimes, like in the case of the partially mechanical treatment of laptops, have been removed by first treatment operators already.

A.5.1 Partially mechanical treatment

A.5.1.1 Characterization of the sample

Table 6 shows the four samples consisting of the scope products. Each sample was assigned a sample ID for reference during the batch testing.

Table 6 Sample for batch tests

Sample ID	**Sample descriptions**
1	Laptops
2	Tablets
3	Game Consoles
4	Small IT (mice and keyboards)

A minimum number of products needed to be accumulated to enable the batch testing. The small IT sample was intended to include routers, external drives, and accessories as well. These devices could, however, not be found in sufficient quantities to include them into the sample Table provides information on the number of devices in the samples and the sample masses.

Table 7 Numbers of devices and sample masses

Sample ID	**Products descriptions**	**Type of dismantling**	**Detailed description**	**Weight (kg)**	**Number (units)**	**Average mass per device (kg)**	**Brand**	**Age**
1	Laptops	Manual	Laptops mix – Notebook no batteries	66.20	25	2.65	Asus, Hp, Windows, Lenovo	Between 10 and 15 years
2	Tablets	Mechanical/manual	Tablets	110.00	250	0.44		
3	Game Consoles	Manual	Xbox and joystick	23.00	10	2.3		
4	Small IT	Mechanical/manual	Keyboards and mice	4.43	15	0.30		

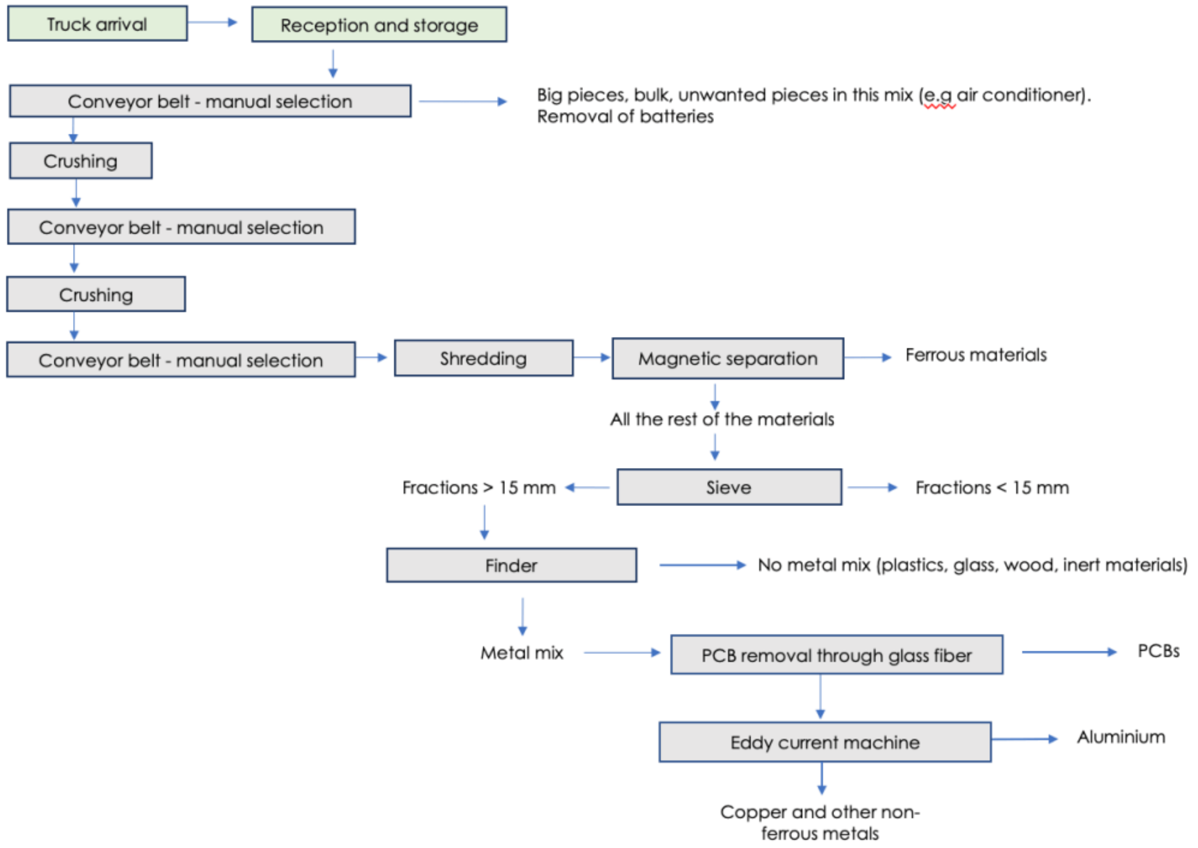
The first batch test series was performed in the facility of a first treatment operator processing the scope products manually and partially mechanically.

A.5.1.2 Description of the partially mechanical treatment process

The partially mechanical treatment combines the benefits of manual processing – precision of dismantling, cleaner output fraction, less material losses – with mechanical treatments enabling time and cost savings, less operators involved, and safety as workers are not directly exposed to hazardous substances and dusts.

E-waste arrives at the treatment plant in containers filled with waste devices of a certain collection group. For the scope products, these are collection groups R2 and R4 (c.f. Figure 4). The incoming e-waste is registered and stored for further processing. Figure 4 represents the treatment applied for laptops, game consoles and small IT.

Figure 4 Partially mechanical treatment - general treatment scenario for collection groups relevant for the scope products

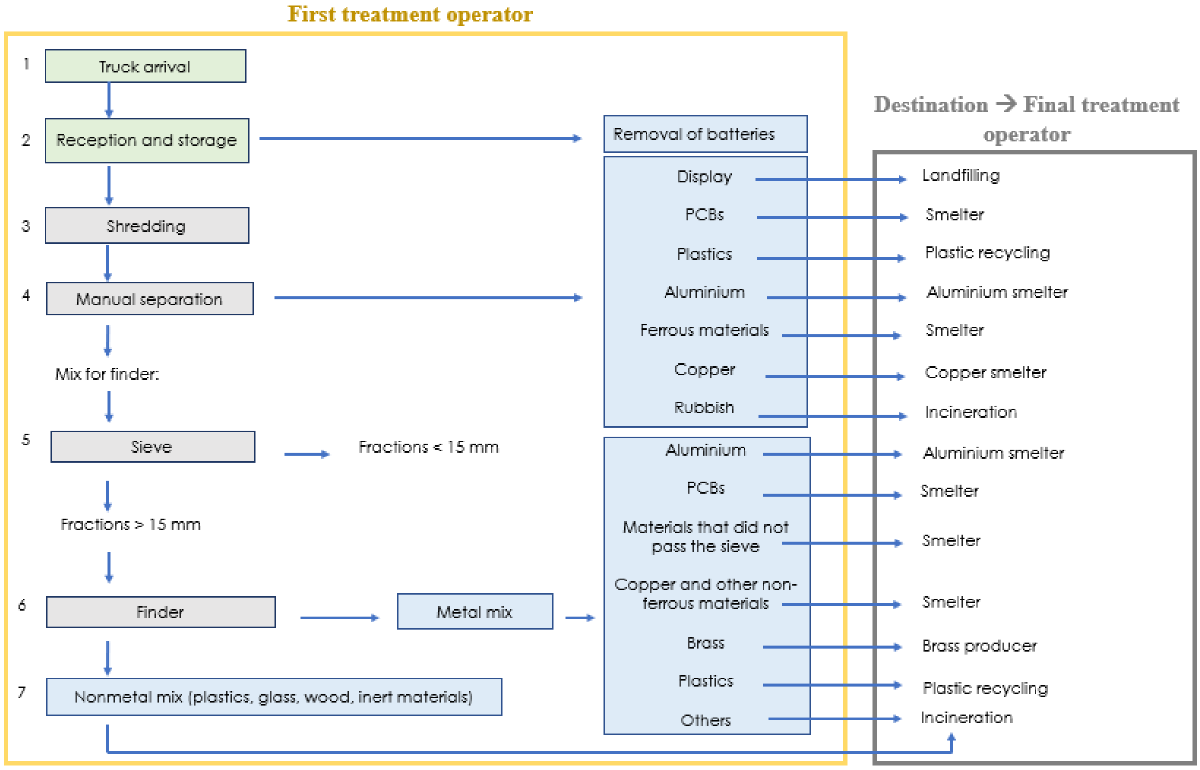


The waste devices are placed on a conveyor belt to remove devices that were collected in the wrong collection group or possibly are not e-waste and to remove batteries. An initial crushing cracks the devices. The output is placed again on a conveyor belt where further batteries that are accessible can be taken out and separated. Then, the material is crushed again to remove internal batteries that have now become accessible and separate interesting parts through a manual selection. This is followed by a shredding step and a magnet separation to remove ferrous materials from the shredding fraction. Subsequently, a sieve is used for gravity separation with a grid of about 15 mm so that particles smaller than 15 mm are removed because they are too small to be well processed in the following steps. The particles larger than 15 mm are processed in a "finder" that separates metals from non-metal materials such as plastics, glass, or wood. The metal mix is sent to a machine that removes the PCBs by detecting the glass fibers in them. Lastly, an Eddy current machine is used to separate aluminum (one output fraction) from copper and other non-ferrous metals (second output fraction). The aluminum, ferrous metals and the copper fraction with other non-ferrous metals are forwarded for recycling to the respective smelters.

A.5.1.3 Description of the batch test

Figure 5 depicts the batch test performed with the laptops.

Figure 5 Batch test - partially mechanical treatment for laptops



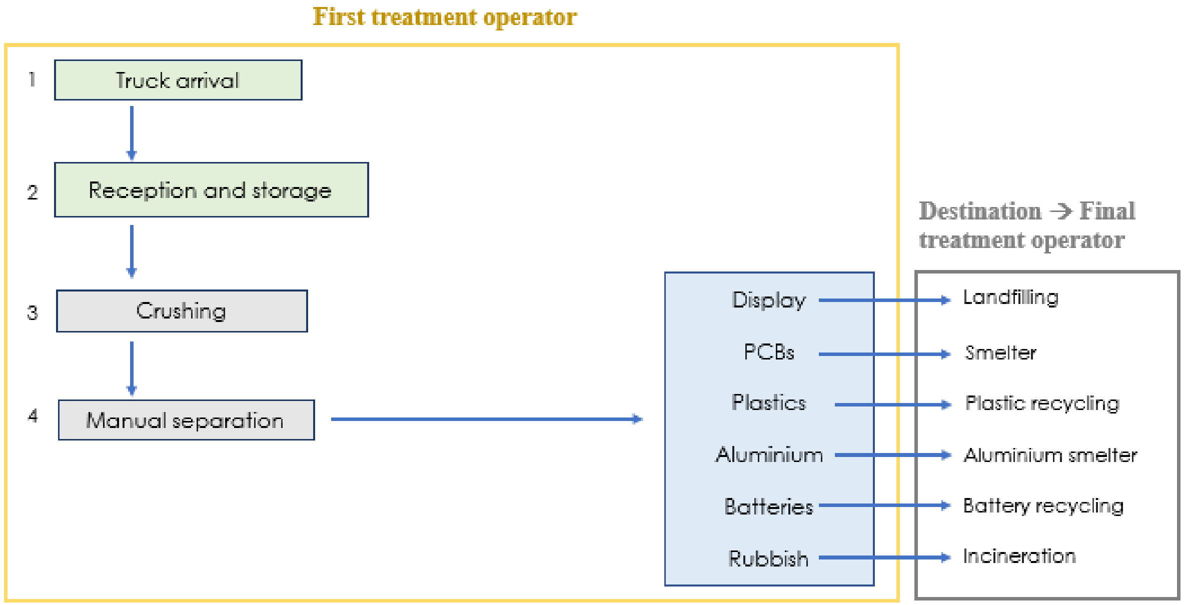
In the first step of the batch test process the batteries were removed and weighed manually by the plant operators. The sample consisted of 10 to 5 years old laptops so that access to the batteries was easier than with new laptops where batteries are integrated into the devices with often glued housings. This first removal was performed already when the laptops arrived at the treatment operator. Therefore, no batteries were considered in the recycling rate calculation.

After the size reduction through a shredding machine, a subsequent manual selection yielded the main output fractions displays, PCBs, plastics, aluminum, ferrous materials, copper, rubbish, and a mix of materials consisting of metals and other materials. The output fractions were weighed and stored in different boxes.

The mixed materials were treated in a finder machine which consists, first, in a sieving step where fractions larger and smaller than 15 mm are separated. The small particle fraction is sent for energy recovery. Second, the fractions bigger than 15 mm are magnetically separated between a metal mix (aluminum, PCBs, plastics, copper, brass, non-ferrous materials, the rest of the materials that previously did not pass the sieve and others) and the rest of the remaining materials called nonmetal mix which consists of plastics, glass, some wood and inert materials. The final treatment destinations for the fractions obtained from the finder are specified in Figure 5.

The tablets were sent to the crushing machine consisting of a hammer that breaks open the tablets (Figure 6).

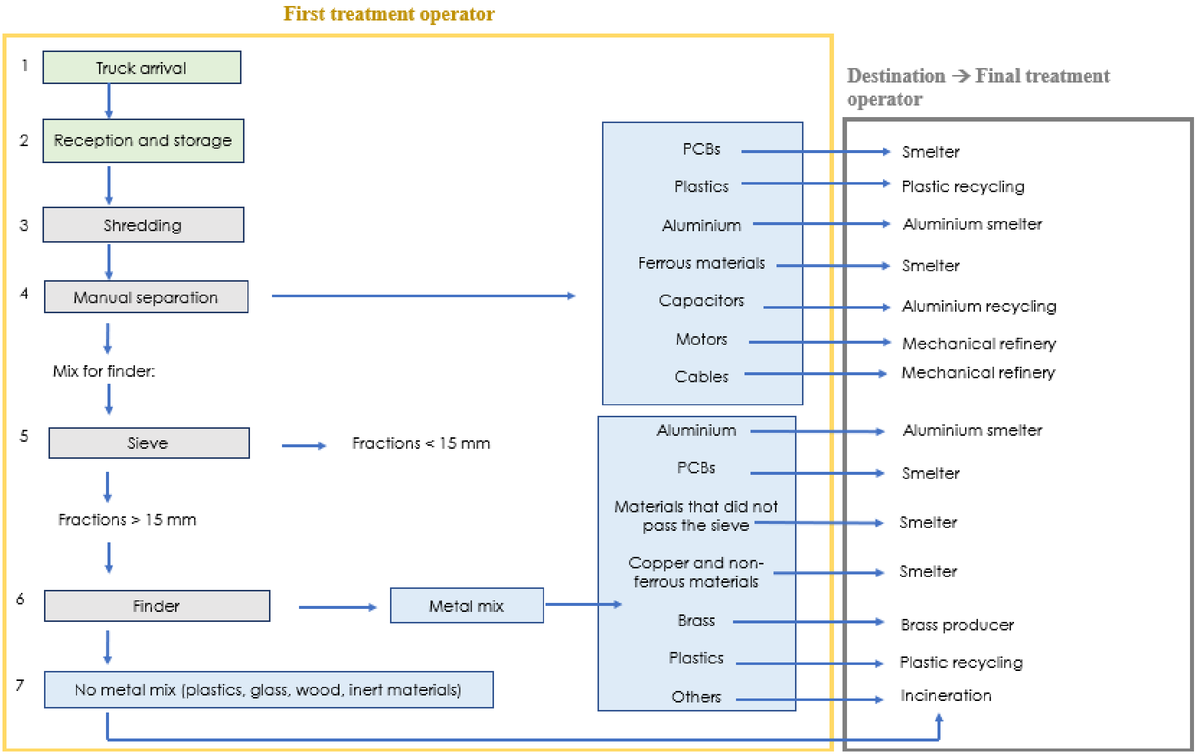
Figure 6 Batch test - partially mechanical treatment for tablet



Right below the crusher a conveyor belt was present, from which operators could pick different outcoming fractions and distribute them into specific boxes. From this step, five main output fractions were separated: displays, PCBs, plastics, aluminum, batteries and a remaining part of rubbish to be sent to energy recovery.

Figure 7 depicts the batch test for game consoles.

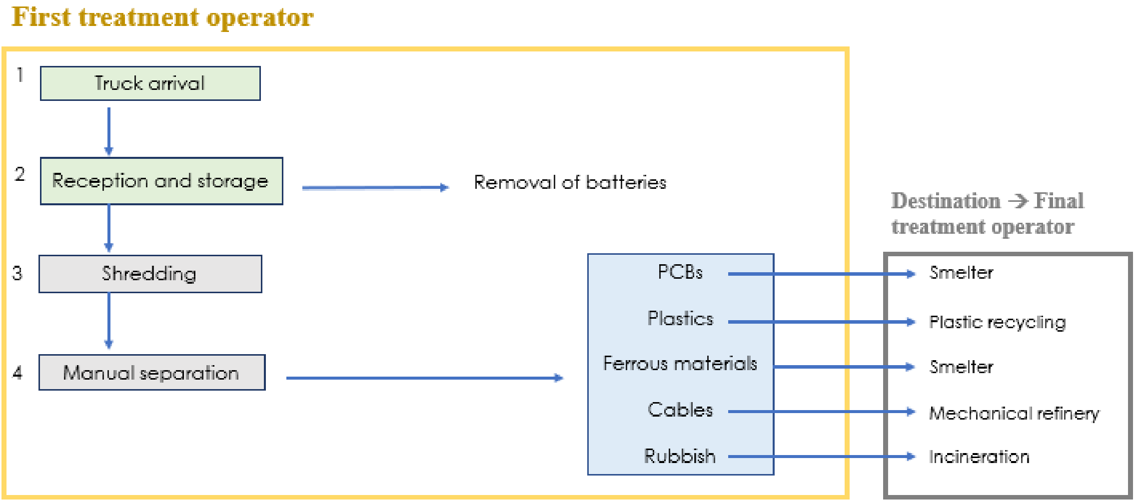
Figure 7 Batch test - partially mechanical treatment for game consoles



While the batch test process is the same as for the laptops, the output fractions from the manual separation differ: PCBs, plastics, aluminum, ferrous materials, capacitors, motors and cables, whose final destinations are listed in Figure 7 above.

Figure 8 illustrates the batch test performed with Small IT, i.e., mice and keyboards, including wireless ones that contain batteries.

Figure 8 Batch test - partially mechanical treatment for small IT



The first activity was the manual removal of batteries from wireless mice and keyboards. Afterwards, the sample was shredded in a dedicated machine, from which a manual separation of the main fractions was performed. The output fractions obtained were: PCBs that are subsequently sent to a smelter for the final treatment, plastics that are then sent to a plastic recycling facility, ferrous materials sent to an iron smelter, external cables destined for a copper refinery – possibly after the removal of the insulations - and last, a percentage of rubbish directly sent to energy recovery/incineration.

A.5.1.4 Description of the output fractions

The following figures show the mass percentages of the output fractions obtained from the batch tests of the scope products. The 100 % reference is the total mass of the product excluding, for the laptops, the mass of the batteries.

Figure 9 Output fractions from the laptop sample

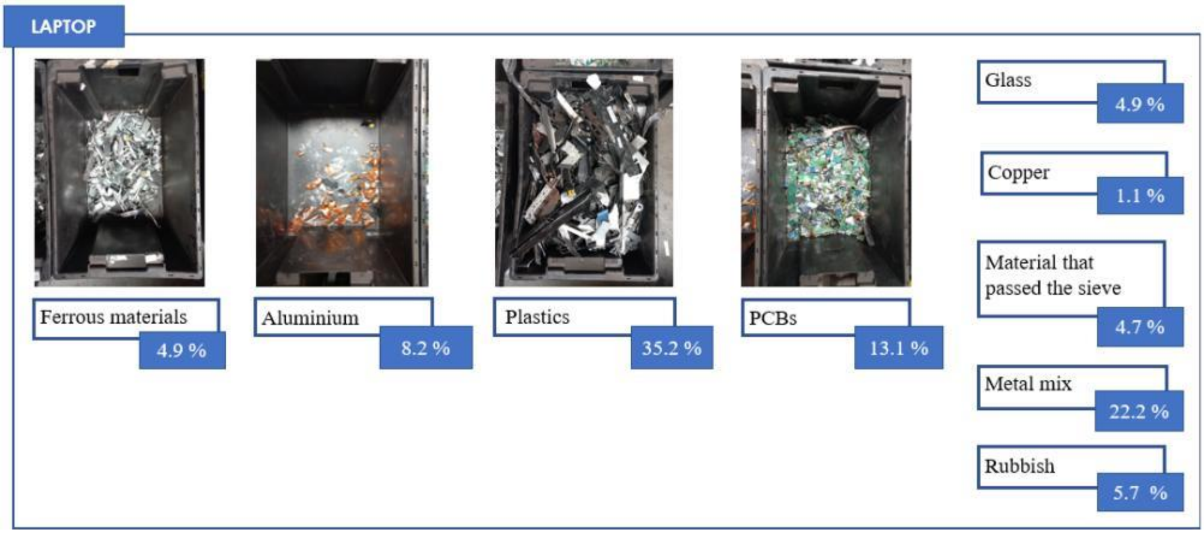


Figure 10 Output fractions from the tablet sample

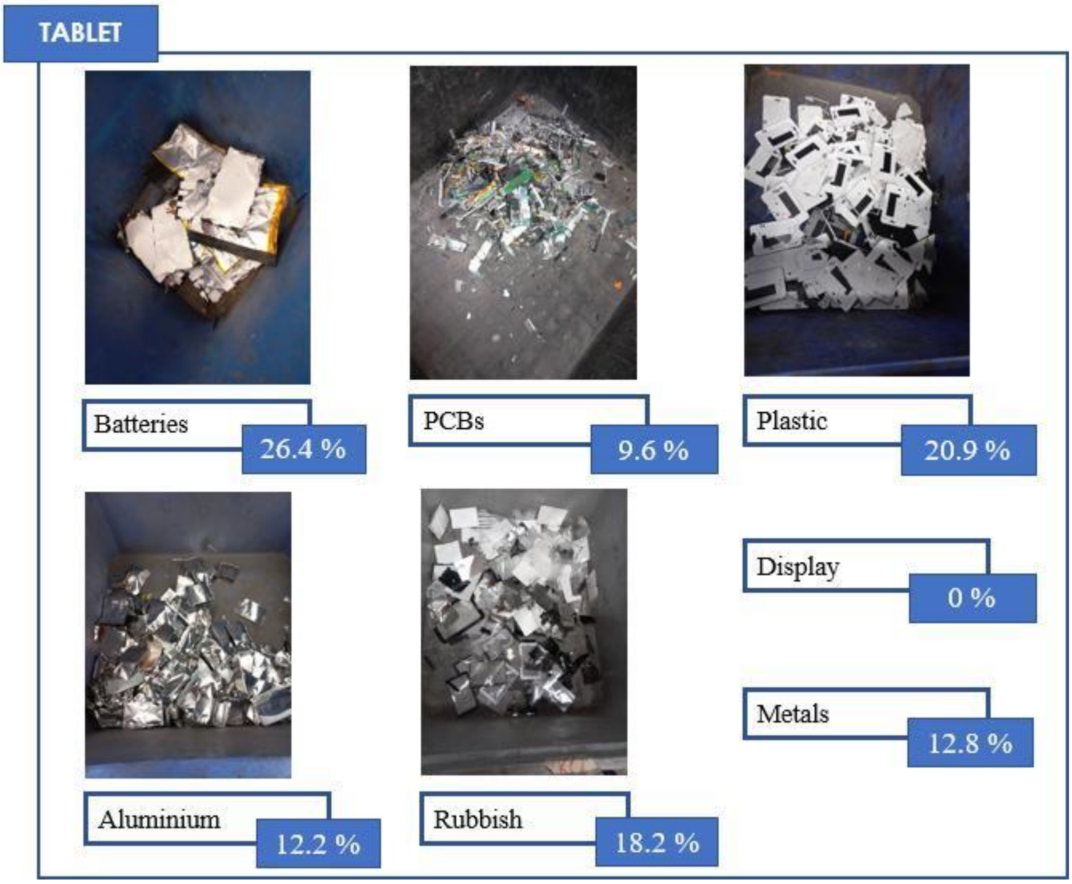


Figure 11 Output fractions from the game consoles sample

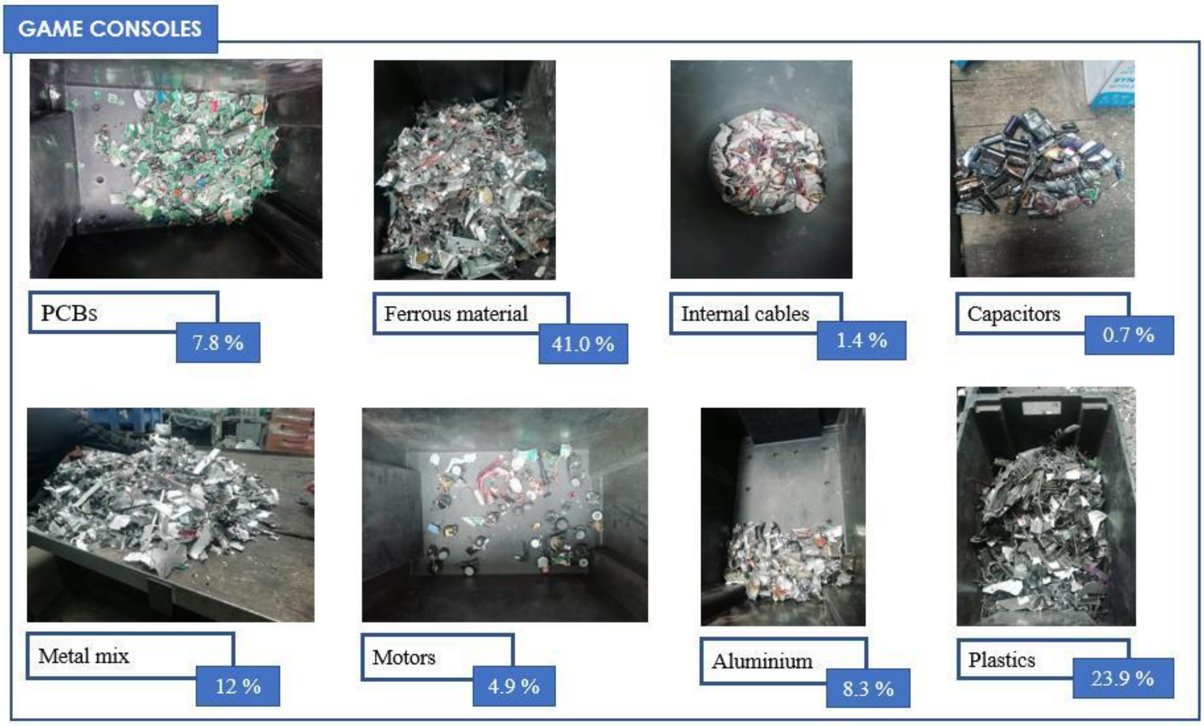
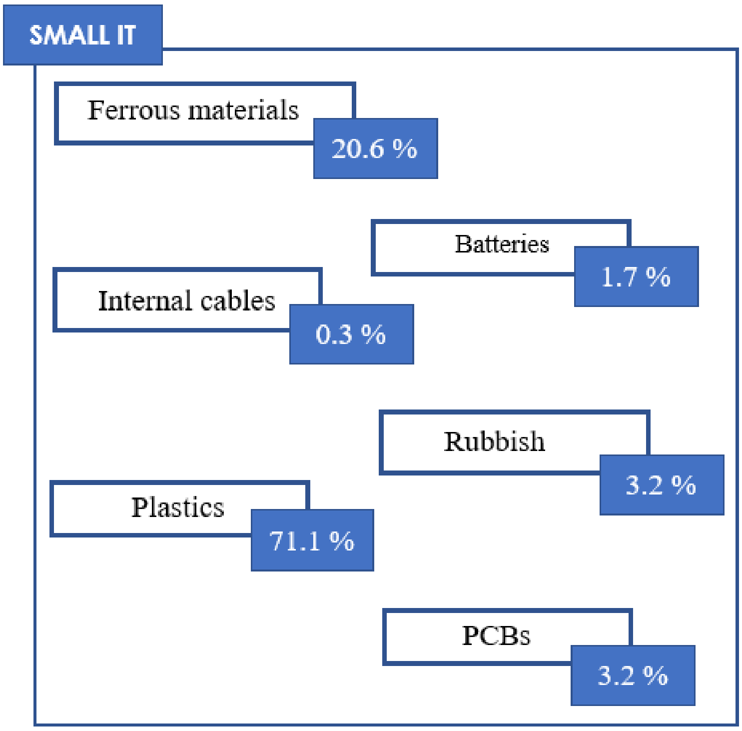


Figure 12 Output fractions from the Small IT sample



A.5.1.5 Recyclability assessment including final treatment of output fractions

The output fractions of the partially mechanical treatment reported in A.5.1.2 are forwarded to final treatment operators for recycling, energy recovery or disposal depending on their nature and quality. The downstream operators report the fate of the input fractions to their processes – the output fractions of the first treatment operator – to the first treatment operator. These figures are used by PROs to report the recovered, recycled and disposed volumes of e-waste to the authorities in Italy. Erion provided access to these data for the scope products and more details on the disposal routes for each output fraction obtained from the four samples are reported in Table 26 ANNEX II: Mass balance and destination routes Italy.

Subsequently, the recycling rates of the output fractions obtained at the first treatment operator were calculated following the approach presented in section 3.4. Table 8 lists the results for the output fractions generated during the batch tests.

Table 8 End of life treatment destinations of output fractions of the four-sampling analyses

Found in the pilot batch tests	Batch Test output fraction	Content in product (kg)	Separation effectiveness (%) - expert judging	Output in dedicated shredding fraction (kg)	Recycled (kg)	Fraction obtained from	Recycling rate
Laptops	Aluminum	9.9	85 %	8.39	7.9	In part removed in the manual separation after the shredding, in part after the finder	80 %
	Ferrous materials	3.82	85 %	3.25	3.18	Manual separation after shredding	83 %
	Brass	0.09	85 %	0.07	0.07	Finder	84 %
	Non-ferrous materials	5.5	85 %	4.67	2.66	Finder	48 %
	Copper	1.0	85 %	0.82	0.81	In part removed in the manual separation after the shredding, in part after the finder	84 %
	LCD-glass	3.8	85 %	3.3	1.04	Manual separation after shredding	27 %
	PCBs	11.6	85 %	9.86	2.86	In part removed in the manual separation after the shredding, in part after the finder	25 %

	Plastics	33.0	85 %	28.0	17.5	In part removed in the manual separation after the shredding, in part after the finder	53 %
	Material that passed the sieve	3.64	85 %	3.09	0.31	Manual separation after shredding	9 %
	Material that did not pass the sieve	1.17	85 %	1.00	0.10	Finder	9 %
	Rubbish	4.46	85 %	3.79	0.00	In part removed in the manual separation after the shredding, in part after the finder	0 %
Tablets	Aluminum	15.8	85 %	13.40	12.7	Manual separation after crushing	80 %
	Batteries	29.0	100%	29.0	16.8	Manual separation after crushing	58 %
	PCBs	12.5	85 %	10.61	3.1	Manual separation after crushing	25 %
	Plastics	27.0	85 %	22.96	14.3	Manual separation after crushing	53 %
	Metals	16.5	85 %	14.03	4.07	Manual separation after shredding	25 %
	Rubbish	23.5	85 %	20.00	0.00	Manual separation after shredding	0 %

Game consoles	Aluminum	2.9	85 %	2.46	2.3	In part removed in the manual separation after the shredding, in part after the finder	80 %
	Ferrous materials	11.04	85 %	9.38	9.19	Manual separation after shredding	83 %
	Brass	0.02	85 %	0.017	0.01	Finder	84 %
	Non-ferrous materials	1.03	85 %	0.87	0.50	Finder	48 %
	Copper	0.013	85 %	0.01	0.011	Finder	85 %
	PCBs	2.4	85 %	2.01	0.58	In part removed in the manual separation after the shredding, in part after the finder	25 %
	Plastics	7.5	85 %	6.36	4.0	In part removed in the manual separation after the shredding, in part after the finder	53 %
	Capacitors	0.17	100%	0,17	0.05	Manual separation after shredding	30 %
	Motors	1.32	85 %	1.13	0.92	Manual separation after shredding	70 %
	Internal cables	0.38	85 %	0.32	0.13	Manual separation after shredding	34 %

	Material that did not pass the sieve	0.22	85 %	0.19	0.02	Finder	9 %
Small IT	Batteries	0.08	100%	0.08	0.044	Removed prior to SMS	58 %
	PCBs	0.2	85 %	0.17	0.041	Manual separation after shredding	25 %
	Plastics	3.7	85 %	3.15	2.0	Manual separation after shredding	53 %
	Ferrous materials	1.07	85 %	0.91	0.89	Manual separation after shredding	83 %
	Internal cables	0.01	85 %	0.009	0.0048	Manual separation after shredding	34 %
	Rubbish	0.16	85 %	0.14	0.00	Manual separation after shredding	0 %

Table 9 below shows components and materials that are in the scope of the study but were not identified as output fractions in the batch tests. Some of them are partially included in the actual output fractions so that their fate can be constructed, others cannot be related to any output fractions. Literature sources were used to provide information as to what may happen to these materials in the assessed treatment process.

Table 9 Recycling rate of components and materials not identified in batch test output fractions

Component/ material	Recycling rate	Remarks
Magnesium	0 %	Not common in EEE; probably no recycling of Mg from copper, aluminum or iron smelters or from fractions coming from additional treatment of plastics fraction prior to recycling, also due to low concentration; probably ending up in slags (Cu smelter) and/or as contamination in metals (Al, Fe)

Neodymium Magnets (NdFeB)	60 %	Assumed to follow the iron/steel fraction (magnetic separation) with same recycling rate for iron while Nd and other REE as well as boron are normally not recycled. The mass share of iron in the magnetic being 72 % and the recyclability rate of iron 83 %, the recyclability rate of the NdFeB magnets is calculated as 83 % * 72 % = 60 %.
Alkaline Batteries	Unknown	If used in products, probably separated from e-waste like Li-ion batteries and sent for battery treatment
Rubber	0 %	Assumed to end up in plastics or fine fractions or as contamination in other fractions; no recycling, thermal decomposition with or without energy recovery most likely.
TPE/TPUs	0 %	Probably no recycling due to the share of rubber (see above); basic plastic like PU for itself would not be recycled from e-waste.
Thermosets	0 %	"A considerable amount of research has been done to investigate potential recycling techniques for thermoset composite materials. Despite this there is no commercially viable composites recycling activity, largely as a result of markets not being available at the right price for the recycled materials that are produced." (Source: https://doi.org/10.1016/j.compositesa.2005.05.030)
Foams	0 %	Probably following the plastics in the mechanical separation so that they end up in plastics and other fractions from which they ae not recycled; probably energy recovery.
"Neat" thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	< 85 %	Part of the plastics stream in mechanical separation subject to the separation effectiveness (see "plastics in Table 11); can be recycled from plastics fraction possibly with some additional losses during the plastics separation processes as part of the initial steps in the plastics recycling process.
FR* thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	0 %	Plastics with brominated flame retardants (BFR) follow the genera plastics stream in shredding and mechanical separation (c.f. plastics in Table 11); they are separated from the plastic waste stream in plastics recycling and sent to energy recovery, no recycling. No data for plastics with non-brominated FRs for the scope products.
GF** thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	0 %	Plastics with glass fibers (GF) are assumed not to be recycled from e-waste: "If we look back at the history of GRP recycling it could be seen to be a list of good intentions which came to nought, or very little" (Source: https://doi.org/10.1016/S0034-3617(13)70151-6); source is from 2013, but information was confirmed by German pre-treatment operator.

A.5.1.6 Recyclability of plastics from Small IT

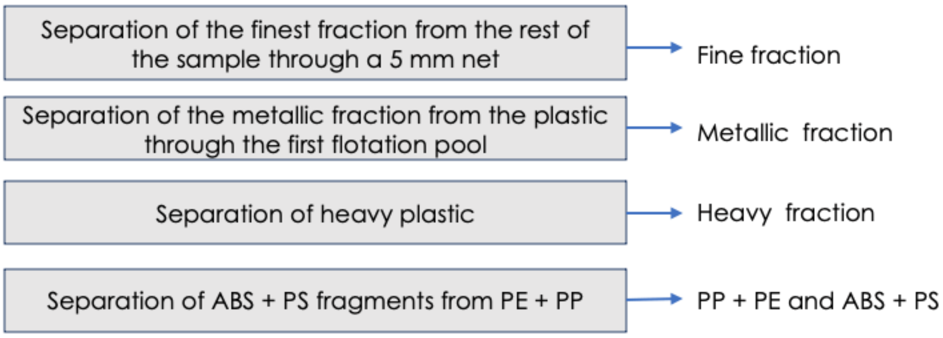
Since plastics dominate the composition of small IT (mice and keyboards), the recyclability of these plastics is crucial for the recyclability of these products. An additional recyclability analysis - different from the small IT sample considered in the first batch test reported in chapter A.5.1.4. - was therefore performed on a batch consisting of 5 keyboards and 10 mice with a total weight of 4.428 kg. The sample was subject to an SMS. Table 10 shows the output fractions and their fate.

Table 10: Output fractions from SMS of the small IT batch test sample (small deviations due to rounding)

Fractions	**Mass (g)**	**Share in total batch**	**Recycled**	**Energy recovery**	**Disposal**	**Recycled (mass, g)**	**Energy recovery (mass, g)**	**Disposal (mass, g)**	**Total (mass, g)**
Iron	910	21%	98%	2%		892	18	0	
Cables	12	0.30%	40%	60%		5	7	0	
Plastics	3,150	71%	80.80%	17.60%	1.60%	2545	554	51	3,150
PCBs	140	3%	29%	71%		41	99	0	
Waste	140	3%		100%		0	140	0	
Batteries	76	2%	36%	33%	31%	27	25	23	
Total	4,428	100%				3,509	845	74	4,428
						79%	19%	2%	100%

The 3.15 kg plastics fraction was forwarded to a plastics recycling facility for the further treatment illustrated in Figure 13.

Figure 13 Densiometric flotation separation of plastics

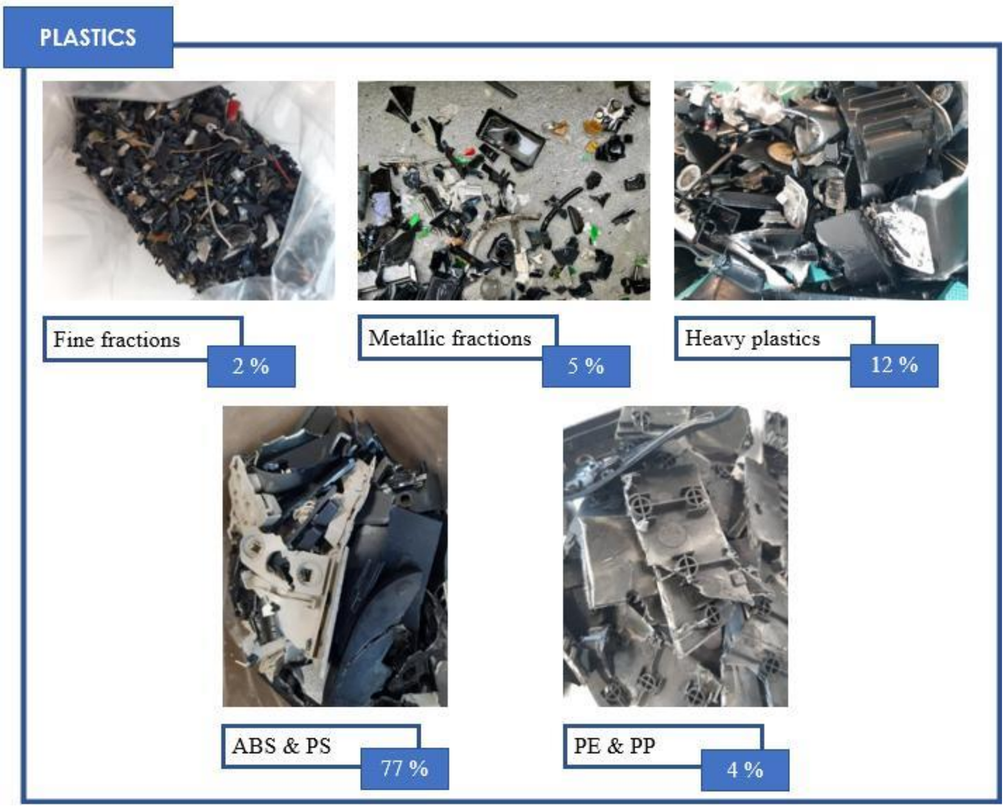


The plastics fraction was initially screened through a 5 mm net in order to separate the finest fraction (2 % of the total mass) that otherwise would not get separated and could potentially contaminate the other fractions in the next steps. Subsequently, the coarsest fraction is immerged into the first flotation pool, filled with a saline solution of a density equal to 1.23 kg/L to remove metallic residuals (5 % of the whole mass). The heavy metallic fraction sinks and remains at the bottom of the pool while the plastic fractions float. Where plastics are attached to metallic parts, they may sink or float depending on the shares of the different materials in the compound.

The fraction floating in the tank is skimmed with a net and transferred in a second tank filled with a liquid of 1.08 kg/L density. Heavier plastics, and plastics containing brominated or possibly other flame retardants and/or other additive materials precipitate (12 % of the total weight of the plastic sample). Plastics with brominated flame retardants are, among others for legal reasons, not recycled to avoid concentrations exceeding 0.1 % (mass) of polybrominated biphenyl ethers (PBDE) or polybrominated biphenyls (PBB), whose use is restricted in electrical and electronic equipment according to Directive 2011/65/EU (RoHS Directive).

The floating fraction is placed into a third tank filled with a liquid of 1.00 kg/L density to separate lighter plastics. Polyethylene (PE) and Polypropylene (PP) (4 % of the total weight) float on top and are thus separated from heavier polymers Acrylonitrile Butadiene Styrene (ABS) and Polystyrene (PS) polymers (77 % of the total weight). Figure 14 details the mass shares of the different fractions in the total output of the densiometric separation process.

Figure 14 Output fractions from the densiometric separation of the plastics fraction



Only ABS and PS, and PE and PP can be recycled. The recyclability assessment was therefore focused on these four types of plastics (“focus plastics” in the above output fractions. 81 % (4 % + 77 %) of the plastics fraction were identified as these types of plastics. It is plausible that the fine fraction and the metallic fraction each contain 80 % of plastics corresponding to the energy recovery of 80 % of material from each of these fractions. It is assumed that the shares of the focus plastics (4 % and 77 %) are equivalent to their shares in the plastics fractions that were identified as ABS/PS and PE/PP.

Furthermore, these plastics can be expected to be contained also in other SMS output fractions listed in Table 10 due to the separation effectiveness of less than 100 % in the SMS processing. Each of the output fractions listed in the Table 10 contains a share of organic material that is energetically recovered. Analogously to the above assumptions for the fine and metallic fractions, it can be assumed for some of these sub-fractions that they consist of 4 % + 77 % focus plastics.

This assumption is applicable to the iron fraction and to the waste fraction while it is not plausible for the other fractions. Cables in most cases do not contain any of the focus plastics. Their insulation is rather produced from PVC or other plastics. Batteries are removed prior to SMS and are forwarded to final treatment operators. There is no data as to their contents of focus plastics and their possible recycling. PCBs contain large shares of resins, mostly epoxy resins. It cannot be excluded that smaller amounts of any of the focus plastics may be used in components, but their volume can be assumed to be negligible compared to the focus plastics present in other fractions.

Based on the above considerations, Table 11 details the overall contents in the various fractions and the recyclability of the focus plastics.

Table 11 SMS and downstream treatment of fractions including densiometric separation of the plastics fraction

	Mass of fractions (g)	Output fractions	Share (%)	Mass (g)	Shares/masses (g) of PP, PE	Shares/masses (g) of ABS, PS	Energy recovery (%)	Landfill disposal (%)	Recycled (%)	Recycled plastics (g)
Treatment of SMS plastics fraction and densiometric separation of plastics	3,150	Fine fraction	2%	63	3%	62%	80%	0%	20%	0
					2.0	39				
		Metallic fraction	5%	158	3%	62%	80%	0%	20%	0
					5	97				
		Heavy plastics	12%	378	0	0	100%	0%	0%	0
		PP + PE	4%	126	126	-	0%	2%	98%	123
		ABS, PS	77%	2,426	-	2426	0%	2%	98%	2,377
SMS output fractions with ABS/PS and PP/PE	910	Ferrous Fraction		910	0.1%	1.5%	2%		98%	0
					1	14				
	140	Waste		140	4%	77%	100%			0
					6	108				
		Total:		4,200	139	2,683				
Recyclability rates:					89%	89%				

Separation effectiveness into plastics fraction (focus plastics):	95%	95%

The above analysis shows that 89 % of the PP, PE, ABS, and PS are recyclable from the small IT sample provided they do not contain additives that push their density over the 1.08 g/cm^3 threshold. Above this threshold, they become part of the heavy plastics fraction which is sent for energy recovery. Such additives are brominated flame retardants, possibly also other flame retardants and glass fibers. The above batch test facilitates the assessment of the separation effectiveness for the focus plastics. It was calculated with 95 %, i.e. 95 % of the focus plastics content in the small IT sample were directed into the plastics fraction which is sent for plastics recycling.

A.5.2 Fully manual treatment

While the above partially mechanical treatment operator worked with limited manual labor, the second operator who participated in the batch testing of the scope products applied manual labor only to prepare the e-waste for the mechanical treatment. After this preparation, the output components and materials are forwarded to a mechanical treatment operator.

In Italy, around 13 % of the treatment plants perform a manual dismantling for the category small IT (mice and keyboards) and game consoles. No such data is available for the category screens and monitors (laptops and tablets).

A.5.2.1 Characterization of the sample

Laptops, tablets and game consoles were analyzed while mice and keyboards were not treated manually in the plant. Details on the input samples are reported in Table 12.

Table 12 Input sample – weights and qualitative characteristics

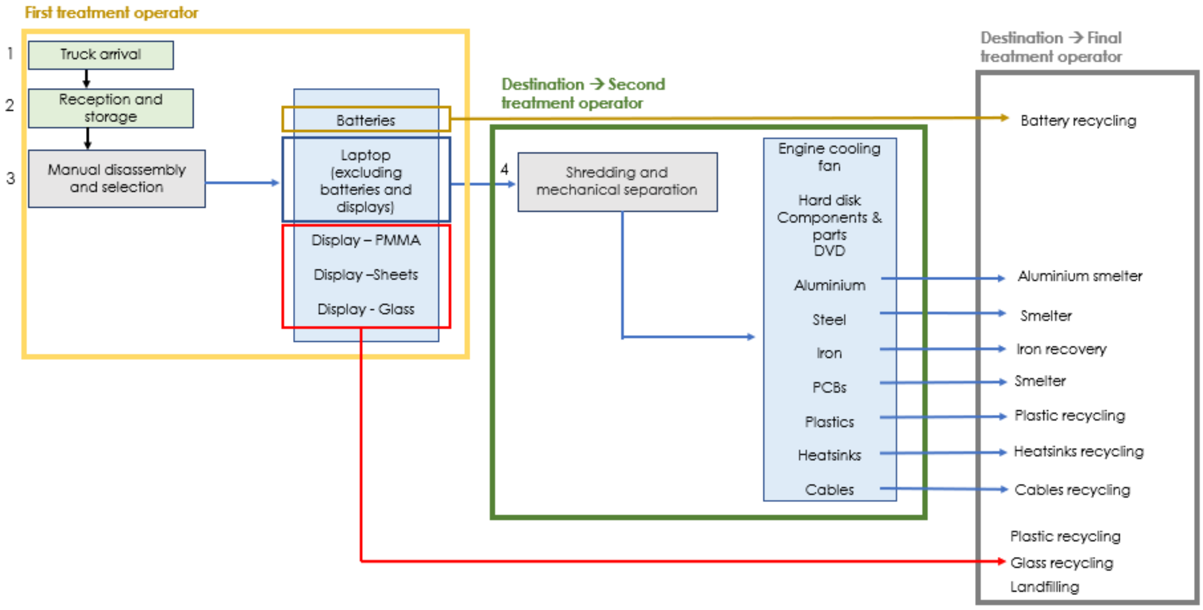
Sample ID	**Products descriptions**	**Type of dismantling**	**Detailed description**	**Weight (kg)**	**Number (units)**	**Average weight (kg)**	**Production year**
1	Laptops	Manual	Laptops - with batteries	75.00	20	3.75	Between 10 and 15 years
2	Tablets	Manual	Tablets	40.00	91	0.44	
3	Game Consoles	Manual	Game consoles	73.00	15	4.87	

Unlike the sample for the partially mechanical treatment, the 20 laptops still contained batteries. Their weight was included in the total weight of the sample.

A.5.2.2 Description of the pre-treatment processes and batch tests

Different from the partially mechanical treatment (A.5.1.2 and A.5.1.3), the real manual pre-treatment and the batch tests were almost identical. The study team had asked to perform an additional step in the batch tests to dismantle and further characterize in more detail the samples and the output fractions. Figure 15 reports the treatment steps and output fractions for laptops.

Figure 15 Laptop treatment – manual disassembly and separation



The laptops are disassembled using simple tools like hammers and electric screwdrivers. After opening the main case of the laptop, three main output fractions are separated: the batteries, the displays parts (PMMA, sheets and glass) and the remaining part of the laptop (more information on the output fraction in A.5.2.3). Components/fractions requiring further (mechanical) pre-treatment are forwarded to a mechanical treatment operator. Other components/fractions are sent to final processing. Other components/fractions are sent to final processing. Figure 16 shows the process steps and their output fractions for the tablets.

Figure 16 Tablet treatment – manual disassembly and separation

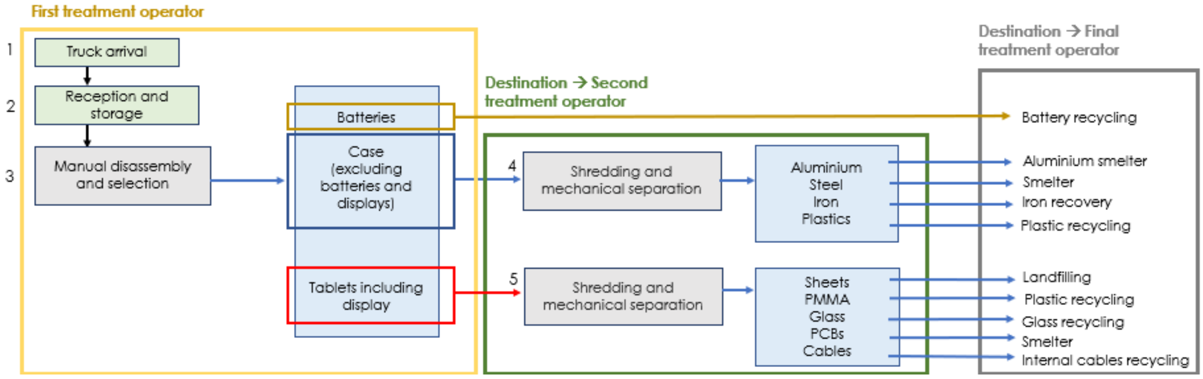
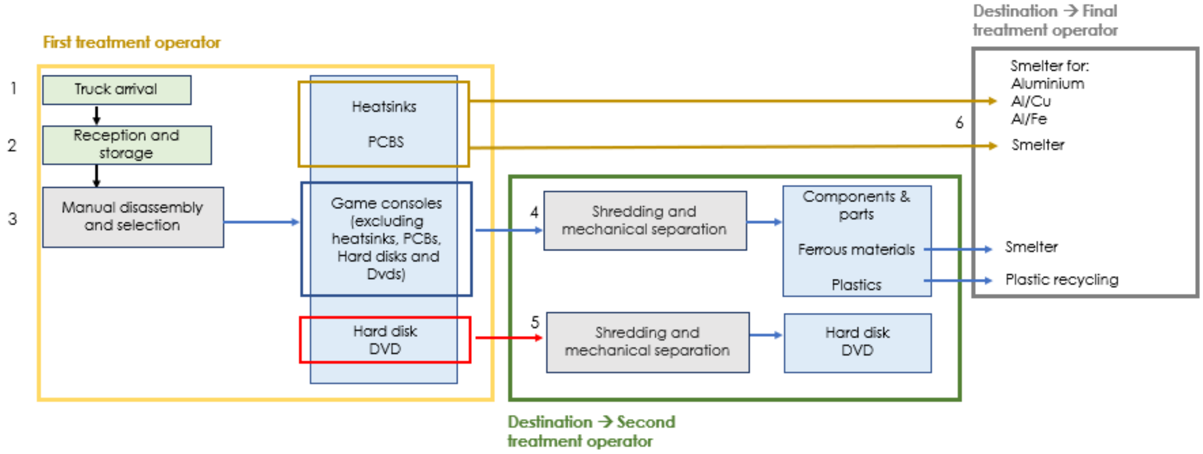


Figure 17 displays the output fractions obtained from game consoles. They were found to be more difficult to break and open.

Figure 17 Game consoles treatment – manual disassembly and separation"



A.5.2.3 Description of the output fractions

The below figures describe the shares of the various output fractions in the mass of the total products.

Figure 18 Output fractions from the laptop (75 kg) and tablet (73 kg) samples

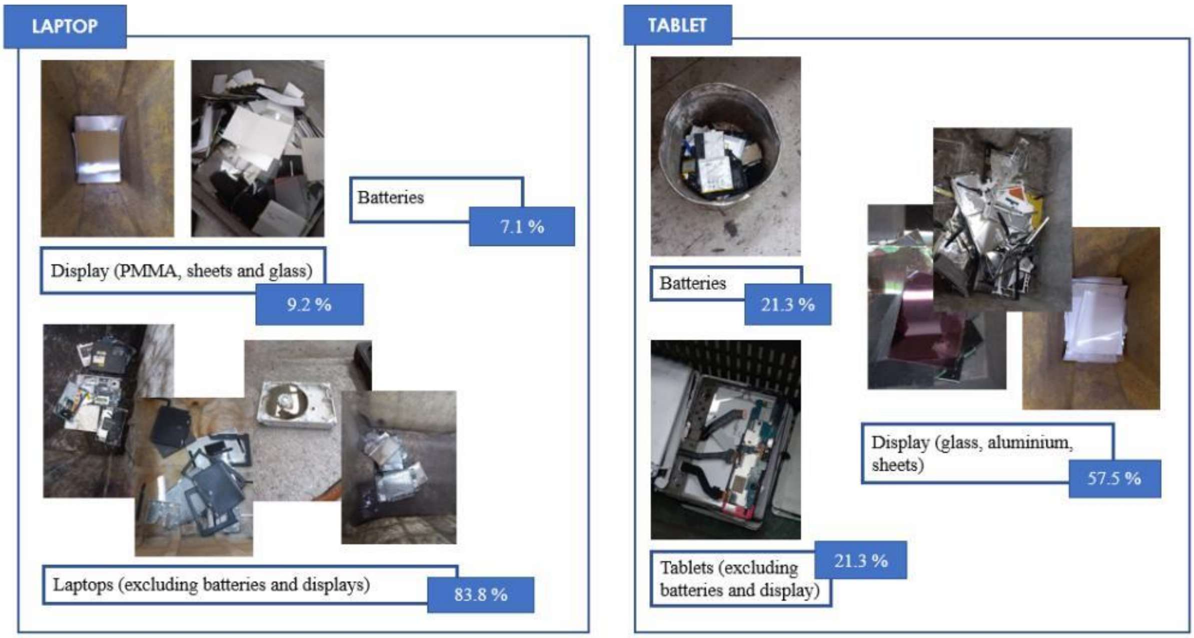
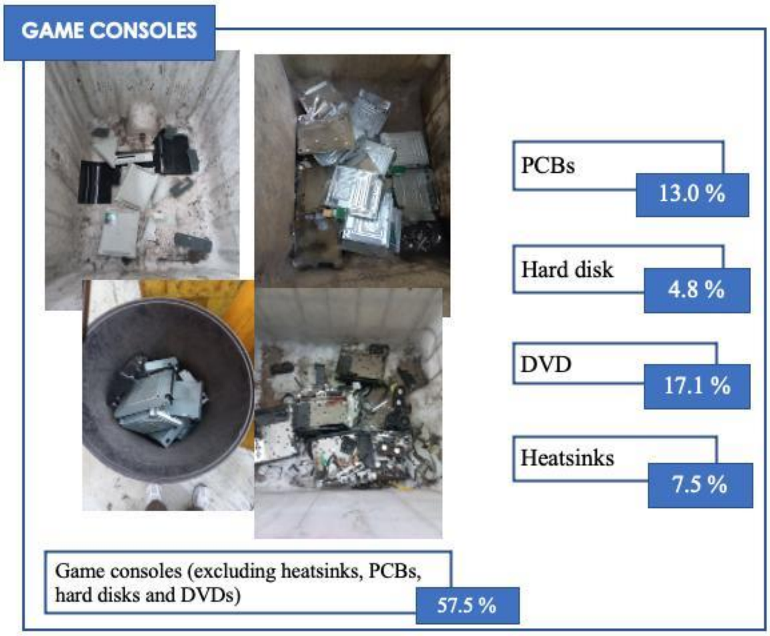


Figure 19 Output fractions from the game consoles sample (73 kg)



A.5.2.4 Recyclability assessment including final treatment of output fractions

A further breakdown of the various output fractions that are forwarded to downstream operators for further pre-treatment or final treatment is reported in Table 26 ANNEXES

ANNEX II: Mass balance and destination routes. The downstream operations are performed in Italy or in other EU member states.

Like in the case of the partially mechanical treatment, the separation effectiveness was introduced to link the above output fractions to the recycling rates reported by the downstream to the upstream recyclers. For components that were separated manually and could be forwarded directly to final treatment operators – e.g., PMMA sheets, aluminum parts, batteries – the separation effectiveness was set at 100 % while 85 % default effectiveness were assumed for output fractions that were subject to downstream SMS processes. shows the recyclability of the output fractions and materials obtained from the manual pre-treatment process.

Table 13 Recycling rates of the manual treatment output fractions

Second treatment operator							**Final treatment operator**	
Found in the batch tests	Batch test output fraction (kg)	Content in product (kg)	Separation effectiveness (%) - default setting*	Output in dedicated shredding fraction (kg)	Recycling rate final treatment (%)	Recycled (kg)	Where fractions are obtained	Overall recycling rate
Laptops	Aluminum	9.48	85%	8.06	95%	7.6	Removed by the second treatment operator	80%
	Al/Cu	4.08	85%	3.47	99%	3.4	Removed at second treatment operator through a shredding	84%
	Iron	4.32	85%	3.67	99%	3.6	Removed at second treatment operator through a shredding	84%
	LCD – glass	6.87	100%	6.87	35%	2.4	Manually removed at the first treatment operator	35%
	Batteries	5.32	100%	5.32	58%	3.1	Manually disassembled in the first treatment operator	58%

	PCBs	6.3	85%	5.35	29.0 %	1.6	Removed in the second treatment operator through a shredding	25%
	Plastics	13.26	85%	11.27	62.3 %	7.0	Removed in the second treatment operator through a shredding	53%
	Hard disk	5.48	85%	4.66	99%	4.6	Removed at second treatment operator through a shredding	84%
	Components and parts	13.50	85%	11.48	80%	9.2	Removed at second treatment operator through a shredding	68%
	DVD	5.45	85%	4.63	75%	3.5	Removed at second treatment operator through a shredding	64%
	Heatsinks	0.56	85%	0.48	99%	0.5	Removed at second treatment operator through a shredding	84%
	Internal cables	0.35	85%	0.30	60%	0.2	Removed at second treatment operator through a shredding	51%
	Sheets	0.17	100%	0.17	0%	0.0	Manually disassembled in the first treatment operator	0%

	PMMA	1.45	100%	1.45	49%	0.7	Manually disassembled in the first treatment operator	49%
Tablets	Aluminum	2.26	85%	1.92	95%	1.824	Removed in the second treatment operator through a shredding	81%
	Steel	1.40	85%	1.19	99.0 %	1.2	Removed in the second treatment operator through a shredding	84%
	Iron	0.97	85%	0.82	99%	0.8	Removed at second treatment operator through a shredding	84%
	LCD – glass	15.40	85%	13.09	32.0 %	4.2	Removed in the second treatment operator through a shredding	27%
	Batteries	8.5	100%	8.5	58%	4.9	Manually disassembled in the first treatment operator	58%
	PCB	3.70	85%	3.15	29.0 %	0.9	Removed in the second treatment operator through a shredding	25%
	Plastics	3.87	85%	3.29	62.3 %	2.1	Removed in the second treatment operator through a shredding	53%

	Internal cables	0.19	85%	0.17	60%	0.1	Removed at second treatment operator through a shredding	51%
	Sheets	1.56	85%	1.33	0%	0.0	Removed at second treatment operator through a shredding	0%
	PMMA	2.14	85%	1.82	49%	0.9	Removed at second treatment operator through a shredding	41%
Game consoles	Aluminum (heatsinks)	1.50	100%	1.5	95%	1.425	Removed by first treatment operator and sent to final treatment	95%
	Al/Fe (heatsinks)	2.0	100%	2.0	99%	1.98	Removed at second treatment operator prior to SMS	99%
	Al/Cu (heatsinks)	2.0	100%	2.0	99%	1.98	Removed at second treatment operator prior to SMS	99%
	Ferrous material	15.5	85%	13.18	99%	13.0	Removed at second treatment operator through a shredding	84%
	PCB	9.50	100%	9.50	29%	2.8	Removed at first treatment operator, prior to SMS	29%

	Plastics	14.00	85%	11.90	62.3 %	7.4	Removed at final treatment operator, through a shredding	53%
	Components and parts	12.5	85%	10.63	80%	8.5	Removed at second treatment operator through a shredding	68%
	Hard disk	3.5	100%	3.50	99%	3.5	Manually disassembled at the first treatment operator	99%
	DVD	12,5	100%	12,5	75%	9,4	Manually disassembled at the first treatment operator	75%

Like in the partially mechanical treatment, some components and materials in the scope of the study could not be identified in the manual treatment process and batch tests. Table 14 below provides information on the recyclability of those components and materials that may deviate from the fate of these components and materials in the partially mechanical treatment (c.f Table) due to the higher share of manual processing.

Table 14 Recycling rate of components and materials not identified in batch test output fractions

Component/ material	**Recycling rate**	**Remarks**
Magnesium	0 %	Not common in EEE; probably no recycling of Mg from copper, aluminum or iron fractions or from fractions coming from additional treatment of plastics fraction prior to recycling, also due to low concentration; probably ending up in slags (Cu smelter) and/or as contamination in metals (Al, Fe); If magnesium parts are accessible and removable manually and are forwarded to dedicated smelter, magnesium could be recycled with high rates.

Neodymium Magnets (NdFeB)	60 %	Assumed to follow the iron/steel fraction (magnetic separation) with same recycling rate for iron while Nd and other REE as well as boron are normally not recycled. The mass share of iron in the magnetic being 72 % and the recyclability rate of iron 83 %, the recyclability rate of the NdFeB magnets is calculated as 83 % * 72 % = 60 %. If accessible and removable prior to crushing or SMS – requiring additional, also manual treatment steps – magnet materials could be reused for new NdFeB magnets (Magnet to Magnet (MtM) production), or for recycling of Nd and other elements. For details see CEWASTE project, https://cewaste.wpenginepowered.com/wp-content/uploads/2020/03/CEWASTE_Deliverable-D1.1_191001_FINAL-Rev.200305.pdf)
Alkaline Batteries	Unknown	If used in scope products, probably separated from e-waste and sent for battery treatment
Rubber	0 %	Assumed to end up in plastics or fine fractions or as contamination in other fractions; no recycling, thermal decomposition with or without energy recovery most likely.
TPE/TPUs	0 %	Probably no recycling due to the share of rubber (see above); basic plastic like PU for itself would not be recycled from e-waste.
Thermosets	0 %	"A considerable amount of research has been done to investigate potential recycling techniques for thermoset composite materials. Despite this there is no commercially viable composites recycling activity, largely as a result of markets not being available at the right price for the recycled materials that are produced." (Source: https://doi.org/10.1016/j.compositesa.2005.05.030)
Foams	0 %	Probably following the plastics in the mechanical separation so that they end up in plastics and other fractions from which they ae not recycled; probably energy recovery.
"Neat" thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	< 85 %	Part of the plastics stream in mechanical separation subject to the separation effectiveness (see "plastics in Table 11); can be recycled from plastics fraction possibly with some additional losses during the plastics separation processes as part of the initial steps in the plastics recycling process. In manual pre-treatment, these plastics could in principle be separated and sent directly to plastics recycling, which would largely avoid separation losses. In practice, clear identification of plastics types during manual dismantling may be too challenging as markings of plastics parts are not sufficiently reliable.
FR* thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	0 %	Plastics with brominated flame retardants (BFR) follow the genera plastics stream in shredding and mechanical separation (c.f. plastics in Table 11); they are separated from the plastic waste stream in plastics recycling and sent to energy recovery, no recycling. No data for plastics with non-brominated FRs for the scope products.

GF** thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	0 %	Plastics with glass fibers (GF) are assumed not to be recycled from e-waste: "If we look back at the history of GRP recycling it could be seen to be a list of good intentions which came to nought, or very little." (Source: https://doi.org/10.1016/S0034-3617(13)70151-6); source is from 2013, but information was confirmed by German pre-treatment operator.

A.6 Data quality assessment

The results of the data quality assessment are reported in Table 15. The data quality matrix was built by dividing the data in three main groups based on their origin: data obtained from the PRO, data obtained from partially mechanical treatment operator analyzed in the first batch tests and, last, data obtained from the fully manual treatment operator analyzed in the second batch tests. The data quality was evaluated in terms of reliability, time and completeness. The data were rated against a scale from 1 (best quality) to 5.

For the reliability assessment, the rationale for the approach was that data direct from a source are more reliable than data originating from further downstream that are handed up the treatment chain and are possibly aggregated.

Both partially mechanical and fully manual treatments received a score equal to 4 for the first indicator, considering that the input compositions were obtained considering data reported from first treatment operator and adjusted with the separation effectiveness assumption.

In the case of the indicator referring to the batch processed, the partially mechanical and the fully manual treatment scored equal to 2 as more than 60 % of the products the recycler processes fall into the same WEEE category as the product being assessed.

Last, the yield rate indicator was scored equal to 3 in both treatments as primary yield rate data available across the whole reprocessing chain were available for only selected materials.

Table 15 Data quality matrix. Results of indicator, sub-indicator and scoring rubric

Indicators	Sub indicators	Data quality score						
		(Highest score = 1)						
				1	2	3	4	5
Reliability of data	Material composition	Partially mechanical treatment	First treatment operator				X	

	of the input batch	Fully manual treatment	First treatment operator				X	
	Batch being processed relevant to the product being assessed	Partially mechanical treatment	First treatment operator		X			
		Fully manual treatment	First treatment operator		X			
	Yield rate across the whole reprocessing chain (T1 and downstream processes)	Partially mechanical treatment	First and second treatment operator			X		
		Fully manual treatment	First, second and final treatment operator			X		
Time		Partially and mechanical treatment		X				
Completeness		Partially mechanical treatment						
		Fully manual treatment						

In the time rating both treatments scored with the maximum result = 1 as 2023 data have been used for the batch test and so for the recyclability calculation.

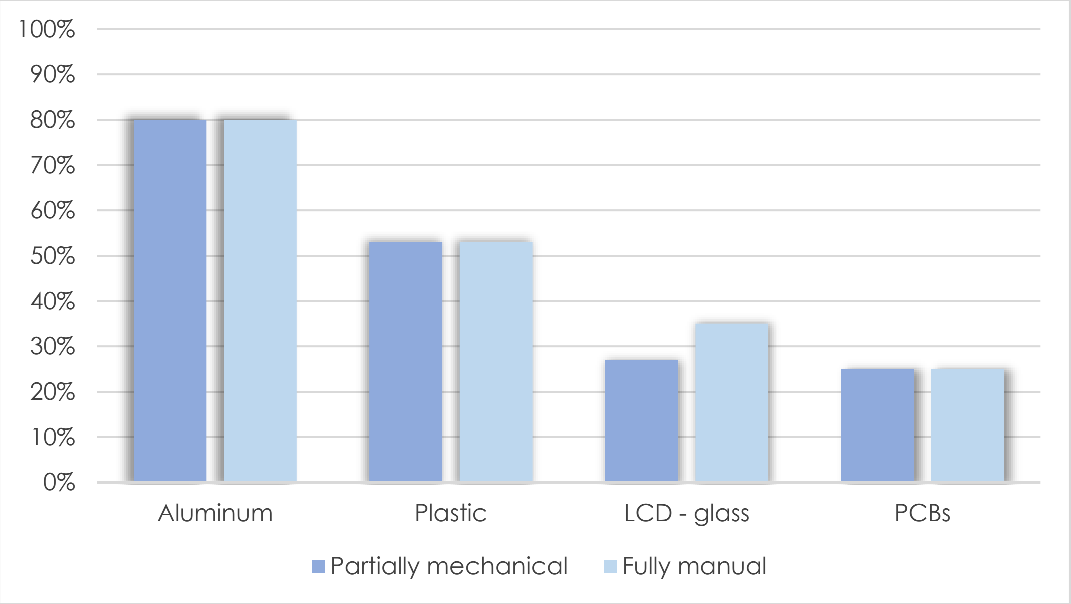
The completeness check cannot be completed fully as a reference product is missing. Therefore, the approach was to collect all the materials and components for which a recycling rate was calculated in all of the different products in scope. More details can be accessed in Annex III: Completeness check Italy. Details of data quality matrix.

A.7 Comparison of recyclability of core outputs in manual and mechanical treatment

The below figures illustrate the recyclability of output fractions obtained in the partially mechanical and the fully manual treatment scenario from laptops, tablets and game consoles. Since no manual treatment of Small IT was performed in the fully manual treatment, this group of scope products could not be included in the comparison.

Figure 20 shows that for laptops the LCD-glass recycling benefits from the manual treatment compared to the partially mechanical one. The removal and treatment of the display from the laptops prior to SMS reduces the material losses.

Figure 20 Comparative recycling rate analysis of laptops



For tablets (Figure 21), the recycling rate of LCD glass differs strongly between the manual and the mechanical treatment, where LCD glass is not recycled.

Figure 21 Comparative recycling rate analysis of tablets

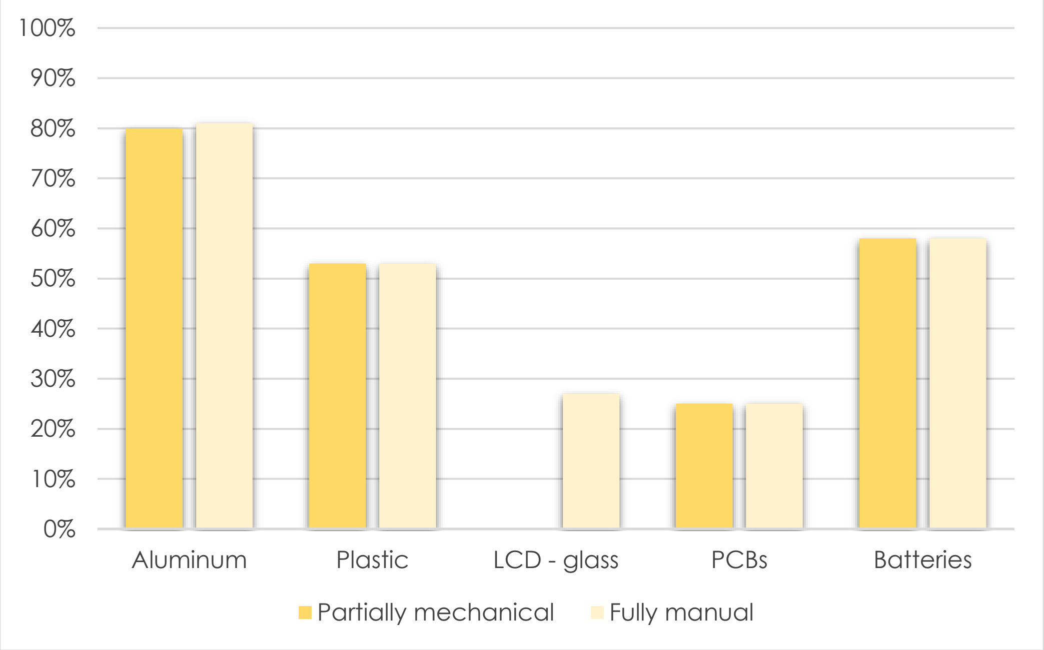
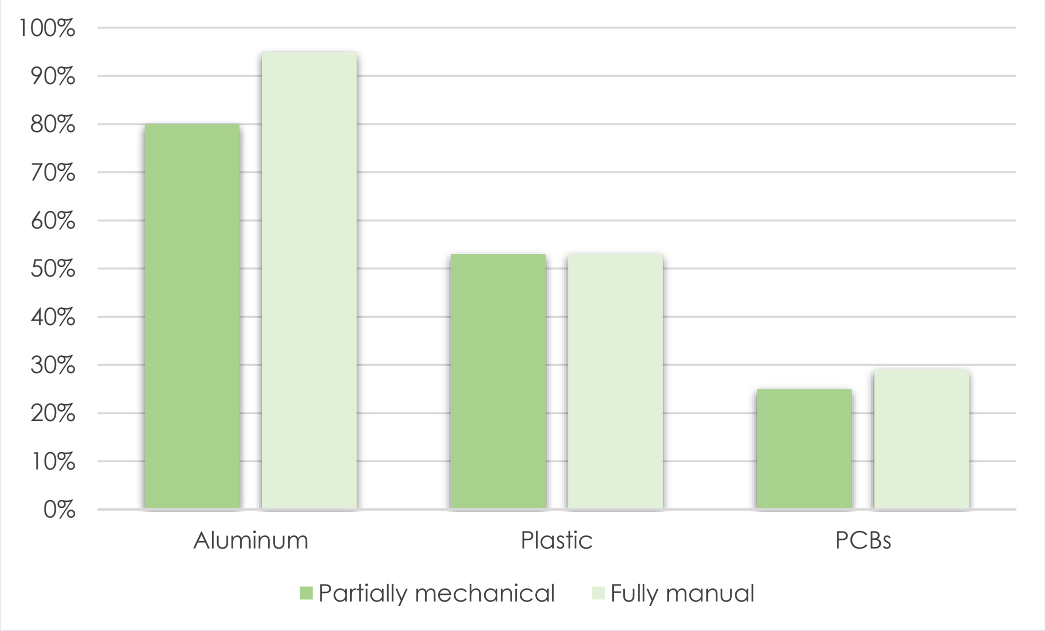


Figure 22 illustrates for game consoles that the recycling rate for aluminum in the fully manual treatment is higher than in the partially mechanical treatment. The aluminum was recycled from heatsinks that were manually separated from the game consoles in the fully mechanical treatment prior to SMS. The heatsinks were directly sent to the final treatment so that the losses during SMS were avoided.

Figure 22 Comparative recycling rate analysis of game consoles



The recycling rate of PCBs are lower in the partially mechanical treatment. This reflects the situation that PCBs are partially separated from the game consoles prior to SMS in the fully manual treatment, which, like for the aluminum heatsinks, avoids the losses occurring during the mechanical separation.

A.8 Conclusions and recommendations

The results for the recyclability of components and materials in the scope products confirm the high recyclability of metals like iron, aluminum and copper in the applied manual and partially manual/mechanical pre-treatment and subsequent downstream processes. The highest recycling rates were observed for aluminum (≥ 80 % in both treatments). Copper in the partially mechanical, and steel in the fully manual treatment achieved a recycling rate equal to 84 %. Plastics and batteries were more than 50 % recyclable. The recycling rates of printed circuit boards generally remain below 30 %, which refers to the mass of the entire PCB including e.g., the organic substrate with glass fibers. The recyclability of the various metals on the PCB was not reported by downstream operators.

The results of the manual and mechanical treatments reveal better recyclability of those components and materials that were separated prior to SMS and could be sent directly to final treatment. These components and materials were not subject to losses in SMS which increased their overall recyclability. Their less complex compositions compared to SMS output fractions additionally may ease the recycling in the final treatment. This applied to batteries in all scope products. Their removal prior to SMS is stipulated in the WEEE Directive, and mechanical treatment operators remove them in their own interest as at least Li-ion batteries may cause damage of the equipment during SMS. Furthermore, PCBs were removed prior to SMS at least partially in the mechanical treatment scenario, and fully in the manual one. Heatsinks were removed from game consoles in the fully manual treatment.

Generally, the separation of these parts can be performed manually prior to any mechanical treatment, or after crushing processes that crack open the devices and make the components accessible for removal. The manual removal generally achieves the best results. In the end, the ratio of labor cost and expected additional revenues from the sales of fractions limits the invested additional labor time for further dismantling.

For products with batteries, the product design should enable easy access and removability of the batteries but also of other components. Once the devices are opened to remove the batteries as legally required, other components like PCBs and heatsinks could be separated as well. An appropriate design would thus reduce the related labor cost on the one hand. On the other hand, higher recycling rates and possibly better qualities could be achieved for the removed materials and components which could be sold at higher prices increase the revenues from their sales. For PCBs, such product design efforts could be limited to products contained in information and communication technology devices – laptops and tablets – and other devices like game consoles. They contain PCBs with high shares of precious metals and copper and low contents of iron, aluminum and plastics (high-grade PCBs)

For other devices like mice and keyboards, a design optimized for SMS would be more beneficial. The PCBs contained are not high-grade PCBs. They benefit from SMS as the larger shares of plastics would be reduced, and other metals like iron and aluminum could be allocated to their dedicated output fractions from where they can be recycled rather than being treated in copper smelter where they would end up in slag.

The recycling rates of plastics largely depend on the use of plastics with recycling potential[5] which do not contain brominated flame retardants, or other additions like for example glass fibers. Product designs enabling the use of such plastics would facilitate higher plastics recycling rates. The influence of flame retardants other than brominated ones could not be assessed in this study but it can be assumed that they disturb the recycling of plastics if their addition increases the density to more than 1.08 g/cm³.

Feedback from plastics recyclers was that cavities in plastics should be avoided. They disturb the plastics recyclers' density separation processes. Further increases of plastics recyclability rates could be achieved if plastics without brominated flame retardants could be dismantled prior to SMS. This would avoid the losses in the mechanical separation as well as in the density separation processes and increase the recyclers' revenues from the plastics. Sorting of these plastics parts according to plastic types by the pre-treatment operators could further improve the recyclability and the prices plastics recyclers pay for these cleaner fractions. Plastics recyclers could produce high-quality post-consumer recycling plastics with less effort. This would, however, require a clear and reliable marking of such plastics parts and that these parts can be easily and quickly dismantled from the products. Additionally, at least a large majority of EEE producers would have to join this design and marking initiative since it can be assumed that pre-treatment operators would otherwise not apply a prior dismantling and even sorting of plastics as a standard pre-treatment step. A cost-benefit assessment of such initiatives for producers and pre-treatment operators might be useful for decision making as to such an initiative. As an alternative for individual producers, an individual

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[5] Examples of well recyclable plastics are PP, PS, PE and other thermoplastics while thermosets like PU or epoxy resins are difficult to recycle.

takeback scheme could in principle be considered that processes only own brand products, whose commercial viability could, however, be critical even for producers of large volumes of EEE.

Lessons learned from the study in Italy can be helpful for recyclability assessments in other countries. The early stage understanding of the actual pre-treatment processes and the derived batch tests in all details could save time and support the correct interpretation of data and other information. The experience from this study will help to ask the right questions and to raise the critical points in the beginning.

This is of particular importance since treatment operators as well as PROs look at the treatments and their results from a different point of view. They do not focus on recyclability of individual products and their materials/components but rather consider volumes and treatment results of entire collection groups, at PRO level even at collection group results across different recyclers. The treatment operators' and PRO's data are organized accordingly and were therefore not always appropriate in this recyclability assessment study. It is therefore crucial to ensure that treatment operators as well as PROs and the study teams each are aware and understand the others' approaches and intentions.

The recyclability results of the study are based on individual batch tests for each scope product simulating the actual treatment processes and treatment results since EEE producers need to calculate the recyclability of their products for individual products according to EN 45555. In daily standard operations, the scope products are not treated separately, but mostly with other products of the same or maybe even other collection groups which would only allow calculating the recyclability of the entire input into the treatment processes. The higher complexity of the actual input fractions may reduce the separation effectiveness and thus the recyclability results of the scope products as parts of such input fractions. The recyclability of these products in the daily operation practices may therefore be different – probably in tendency lower – than assessed in the study.

In the data reported from downstream to the first upstream treatment operator, data related to the separation efficiency in SMS were not accessible, and the separation effectiveness had to be estimated. The next study should therefore be designed to shed light on this aspect of the scope products' recyclability. This should include insights into potential additional treatments of shredding fractions by (final) treatment operators, e.g. processing of aluminum fractions to separate and forward to recycling other metals prior to treating the fraction in the aluminum smelter.

Recyclability Assessment Germany

B Recycling rate assessment Germany

B.1 Summary Germany

A recycling rate (RR) assessment was conducted for the scope materials and components of the scope products: keyboards, mice, tablets, and laptops, mirroring with batch tests the standard treatment operations commonly practiced in Germany. The assessment was carried out in collaboration with a pre-treatment operator that processes e-waste from the initial stages to output fractions which are forwarded to final processing.

The approach adopted for the RR assessment involved having analyzed in a laboratory the concentrations of scope materials in all output fractions of the shredding and mechanical separation (SMS) process that were forwarded to downstream treatment. The results facilitated assessing the separation effectiveness of the SMS process, or vice versa, the losses of scope materials during the SMS process, except for the recyclable plastics. Additionally, to calculate the overall RR, literature data were used for the recycling rates of the scope materials in the output fractions. The separation effectiveness for recyclable plastics had to be assessed indirectly with worst case assumptions based on the content of recyclable plastics in the total volume of organic matter, i.e. including non-recyclable plastics, in the plastics output fraction. The recycling rates for focus components could be calculated indirectly using the key materials data and/or data from additionally analyzed indicator metals. The applied approach facilitated calculating the separation effectiveness of SMS. Unlike in the Italy study, The calculation of the overall RR thus did not depend on estimated separation effectiveness and general, collection-group specific data from downstream operators but could be calculated specifically for each scope material in each of the scope products.

Prior to SMS, batteries were removed manually from tablets and laptops during which some materials/components were taken out as well if they were in the way to the batteries. Cables of keyboards and mice were cut off. The manually removed materials and the batteries were 100% forwarded to the downstream treatment, i.e. without any losses like they occur in SMS. The overall RR could be calculated with the above-mentioned RR in the final processing, except for the batteries where downstream data had to be used indicating the overall RR of 36 % for the entire lithium-ion batteries.

Ferrous metals, aluminum and copper achieve high recycling rates in final processing. More than 90 % of these scope metals contained in the designated output fractions from pre-treatments can be recycled, and more than 50 % of the zinc. Around 85 % of recyclable plastics (densities of ≤ 1.08 g/cm^3) contained in plastics fractions are recycled as well. These numbers represent the overall recycling rates for the respective materials contained in materials and components that are removed from the focus products prior to SMS since these materials and components are forwarded for 100 % to downstream treatment/final processing.

Overall, including the separation effectiveness of each of the scope materials in the scope products, high recycling rates of 90 % and more can be achieved for iron/steel in keyboards and laptops, and for copper in mice, tablets and laptops. Keyboards and mice achieve around 80 % RR for recyclable plastics. From tablets and laptops, around 80 % of aluminum and brass can be recycled, and more than 40 % of Zn and neodymium-magnets (assessed only for laptops). For mice and tablets, the recycling rate of iron/steel is around 40 %, while only around 30 % are achieved for recyclable plastics in laptops and around 10 % in tablets. Recycling rates, specifically for LCD displays in tablets and laptops could not be assessed.

During SMS, more than 90 % of the mass of printed circuit board assemblies (PCBAs) in mice, tablets and laptops are separated into the copper fraction from which copper and zinc can be recycled with the RRs described above for final processing. For keyboards, the shares of PCBAs in the copper fraction are around 35 % only.

Plastics like thermosets, TPE/TPU, plastics with densities of around 1.1 g/cm³ and higher, as well as neodymium in magnets, and magnesium cannot be recycled and should not be used in the focus products.

Overall, the assessment of the recyclability rate for materials and components within the scope products was successful. It is recommended to use the approach developed for the recycling rate assessment in Germany as the standard procedure for future evaluations, while adapting it to specific conditions and treatments and exploring possibilities for further enhancements.

B.2 Background Germany

B.2.1 Transposition of the WEEE Directive (waste management)

E-waste management in Germany operates under the Electrical and Electronic Equipment Act (ElektroG), within the framework of the European Directive on Waste Electrical and Electronic Equipment (Directive 2012/19/EU, WEEE Directive). According to the ElektroG, key stakeholders in the German e-waste management system include the public waste management authorities (PuWaMA), electrical and electronic equipment producers, and the clearing house, known as the "Elektro-Altgeräteregister" (EAR).

ElektroG 2022 mandates PuWaMA to collect e-waste across six collection groups, which partly correspond to the six categories of electrical and electronic equipment outlined in ElektroG 2022 and the WEEE Directive, as illustrated in Table 16.

Table 16 Correspondence of German e-waste collection groups to EEE categories

WEEE Directive		ElektroG	
	EEE Categories	**EEE Categories**	**E-waste collection groups**
1	Temperature exchange equipment	Temperature exchange equipment	Temperature exchange equipment
2	Screens and monitors	Screens and monitors	Screens and monitors 2(a): with batteries
3	Lamps	Lamps	Lamps
4	Large equipment	Large equipment	Large equipment
5	Small equipment	Small equipment	Small equipment & Small IT and telecommunication (EEE cat. 4 and 5) 5(a): with batteries
6	Small IT and telecommunication equipment	Small IT and telecommunication equipment	Photovoltaic panels

B.2.2 Cooperation with local partners

The local partner selected for the project is a full-service pre-treatment operator (FSPTO), i.e. the partner is equipped and organized to conduct the full range of pre-treatment operations. Other criteria for selection included the substantial treatment capacity, experience and strong market position, capability to process the categories and types of electrical and electronic equipment in the project scope, proficiency in data collection and analysis, collaborative research background, and representation of German processes and technologies.

B.3 Data Collection

The data collected for the recyclability assessment included: mass fractions from batch test outputs, analytical data obtained according to the guidance document from the analysis of the output fractions, downstream fate information from PTO, data from literature regarding downstream processes (such as recycling rates of materials in final processing), and input data provided by the producer for calculating recycling rates of certain materials (e.g., composition of focus components, metals, etc.).

B.3.1 Representativeness

Representativeness has been ensured at two levels: firstly, the local partner, a major player in the sector both nationally and beyond, provides a robust representation of the German market with a significant market share. Secondly, the treatment processes conducted during batch testing closely mirror real-case scenarios, albeit with a smaller volume of input material. The treatment approach with a minimum share of manual labor and maximized mechanization reflects the socioeconomic conditions in Germany with high cost of manual labor (minimum statutory wage of around 12.41 €/h, status 2024) and good access to, and expertise for using state of the art and advanced technologies.

B.3.2 Scope materials and components

Differently from the Italian case, the products in scope of the recyclability assessment were keyboards, mice, tablets and laptops. Whereas the materials in scope assessed are reported in Table 17.

Table 17 Materials and components in scope

Scope Components	Scope Materials
Printed circuit boards	Steel / ferrous material
Batteries (split by lithium-ion vs. alkaline if possible)	Aluminum
LCDs (component or material level)	Copper
Rare earth magnets	Zinc
	Magnesium
	Brass (if distinguishable from copper)
	Plastics (split by type: Ex. ABS, HI(PS), PC, PC/ABS, etc.) (with or without glass fiber or flame retardants)

	*Very important to at least differentiate between recyclable and unrecyclable plastics
	Thermosets
	TPEs/TPUs

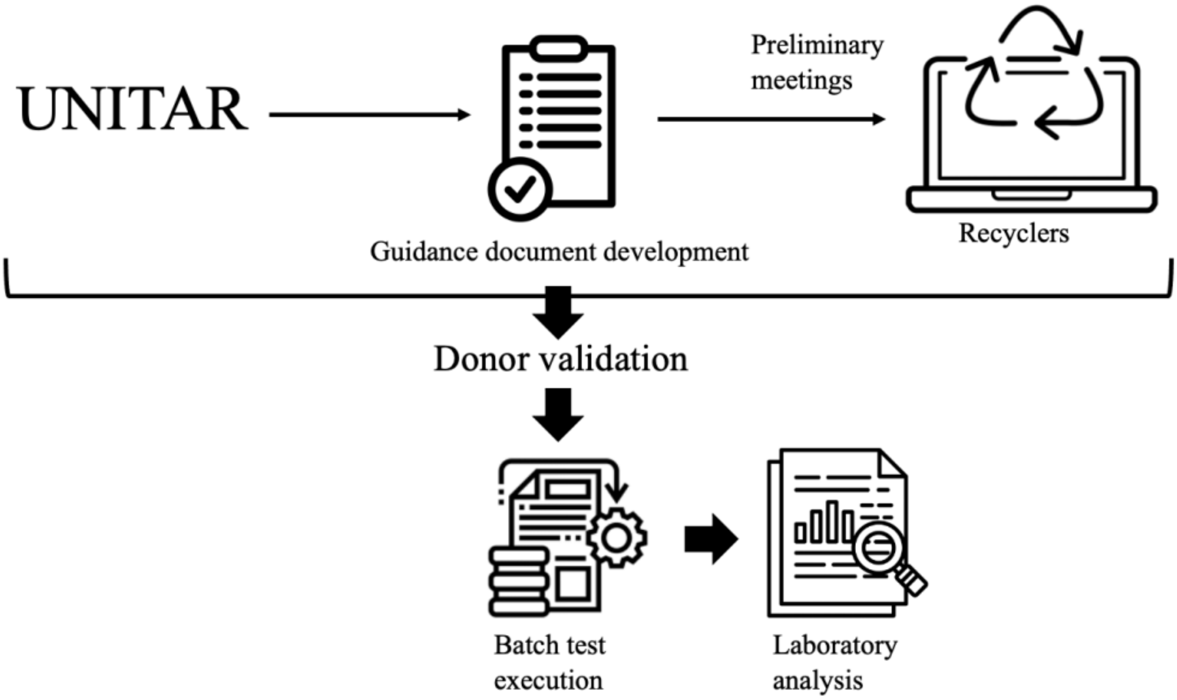
B.3.3 Designing and performing batch tests

The batch test treatment was designed to mirror the standard procedure for e - waste for each focus products. The treatment operator primarily employed mechanical processes for handling scope products, such as shredding and mechanical separation (SMS), with minimal manual labor involved at the initial stages.

Although the batch test involved smaller volumes than usual, it closely simulated the standard treatment scenario. The scope and timeline of the batch testing were predetermined, and discussions were held with treatment plant representatives to ensure consensus on the treatment steps and data collection procedures. A specific quantity of e-waste products falling within the scope categories was reserved for analysis by plant operators. These products, necessary for the mechanical treatment steps, were segregated from incoming e-waste streams and stored separately for batch testing purposes. Prior to commencing the batch test, the guidance document developed for the Italian case was adapted to reflect the new approach agreed upon for the German case study.

Figure 23 summarizes the steps undertaken to prepare and conduct the batch tests.

Figure 23 Steps undertaken to conduct the batch tests



Two members of the UNITAR-SCYCLE team participated in the batch tests conducted at the facilities of the initial treatment operators. Their aim was to comprehensively understand the processes, collect relevant data within the appropriate contexts, and engage in discussions with the plant operators and managers regarding further steps involving the analysis of the upcoming output fractions.

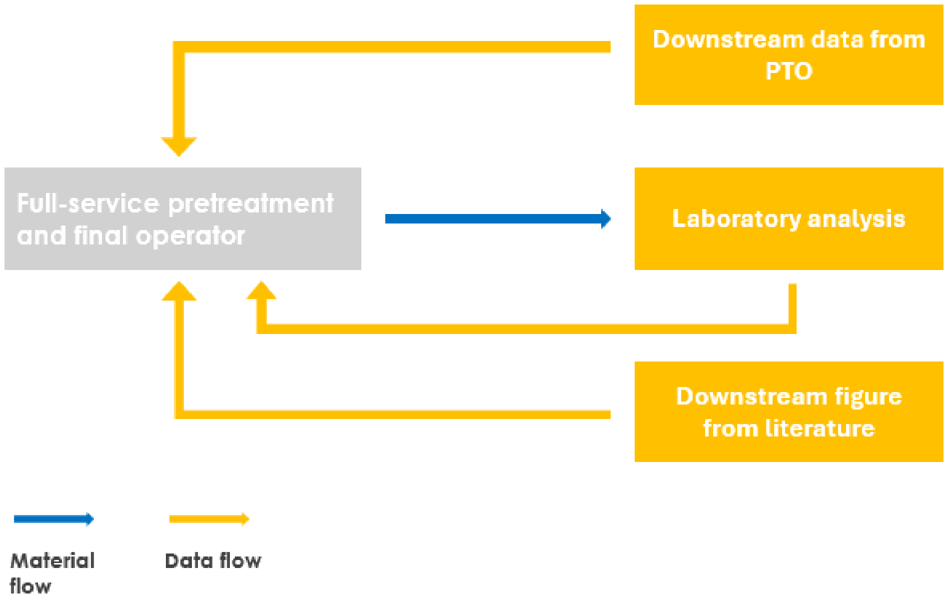
B.4 Batch test

As seen in the former Italian case and in other EU countries, recycling facilities in Germany utilize category-specific recycling lines, as products belonging to distinct categories exhibit diverse traits regarding material composition, average weight, and the presence of hazardous materials. These differences necessitate the implementation of tailored recycling lines.

A single batch test was designed and developed with the pre – treatment operator to reflect common treatments in Germany.

The output fractions obtained from the batch test underwent further analysis in specific laboratory procedures aimed at understanding the content of specific metals and plastics within the output fractions. Additionally, for the calculation of the overall recycling rate, downstream data from literature and downstream fate reported by the PTO were taken into consideration. Figure 24 illustrates the material and data flows.

Figure 24 Mass and data flows



Within the scope of the batch test, the output fraction materials obtained at the PTO were forwarded for laboratory analysis, adhering to the analytical plan displayed in section "Laboratory analyses on page 93".

The PTO engaged in the project serves as first, second, and, in most cases, final treatment operators. Consequently, the output fractions obtained from the PTO, in a real treatment scenario, are either directly routed to recycling or incineration without any intermediate treatments.

An exception applies to batteries, which, once separated from the rest of the product, are directly dispatched to battery processors.

B.4.1 Characterization of the sample

Table 18 characterizes the four scope product samples that were processed in the batch tests. The small IT sample consisted of keyboards and mice. Game consoles were not found in the e-waste which the PTO has received for treatment during the preparation phase of the project. Game consoles can be assumed to follow the same treatment route like laptops since they are, besides the battery and screen that are removed from the laptops, similar in terms of valuable electronics contained. Controllers and headsets for game consoles may contain batteries. If they are wireless, the batteries would be removed, and they would be treated together with other devices containing batteries, e.g. tablets and laptops. Controllers and mice with cables are assumed to contain no batteries. They would be processed with keyboards and mice.

Table 18 Samples for batch tests

Collection group (ElektroG)		**Type of product**	**Treatment**	**Weight (kg)**	**Number (units)**	**Average mass per device (kg)**	**Brand**	**Age**
5	Small equipment and small IT	Keyboards	Mechanical, partially manual	211.2	N/A	N/A	N/A	N/A
5	Small equipment and small IT	Mice	Mechanical, partially manual	232.2	N/A	N/A	N/A	N/A
2(a)	Screens and monitors with batteries	Tablets	Mechanical, partially manual	1115.0	N/A	N/A	N/A	N/A
2(a)	Screens and monitors with batteries	Laptops	Mechanical, partially manual	14903.0	N/A	N/A	N/A	N/A

The batch test was performed in a single facility processing the scope products mechanically.

B.4.2 Description of the processes

B.4.2.1 General process description

The PTO only processes e-waste of collection groups 2 (screens and monitors), 4 (large equipment) and 5 (small equipment and small IT), for which the full range of pre-treatment processes down to output fractions are performed that can be forwarded to final processing. The share of manual labor is generally reduced to avoid high labor cost and minimize the cost of the treatment.

- The very first stage of the process is the arrival of e-waste and its registration, reception, weighing, unloading and/or storage.
- Additional classification could be done manually if specific products collected within the same stream need to be treated separately, e.g., cathode ray tube (CRT) TVs and monitors, or devices containing batteries. Even though the ElektroG stipulates the separate collection of the latter, this is, according to the PTO, often disregarded or not supervised closely enough on collection sites to ensure proper enforcement.

- The initial pre-treatment steps are the manual removal of cables from keyboards and mice, and of batteries from tablets and notebooks as well as from keyboards and mice if they are wireless. The removal of cables and in particular of the batteries are in the PTO's core interest to avoid negative impacts on the subsequent treatment processes, and for safety reasons since lithium-ion batteries may cause fires.
  During these initial steps, some materials/components may already be removed manually if necessary to access the battery which is a standard situation in tablets. The removed components are collected separately and are forwarded to downstream operators for further treatment/final processing.

- The remaining parts of the waste EEE is subjected to shredding and mechanical separation (SMS). Pretreatment operators may perform an "input design", i.e. combining certain types of devices in the input, to enable better quality treatment. It is crucial for the quality of this step to ensure that as much of the materials and components in the treated waste EEE are directed to those output fractions from which they can be recycled in subsequent final processing. Materials and components separated into the wrong fractions, e.g. copper and aluminum in the ferrous metal fraction, cannot be recycled and may even contaminate the recycled iron.

- The SMS output fractions are forwarded to final processing or to incineration/energy recovery or disposal.

Even though e-waste treatment operators like the PTO have developed routine treatments over the years for the various types of e-waste, there is no standardized process in the sense that the input is fed into a shredder on the start side of a process line with different machines being connected in a certain order, and the output appears on the other end. Rather, the facility is equipped with a range of machines whose interim outputs are captured in receptacles, are quickly inspected, e.g., for optical appearance or for density grasping a handful of the material by experienced staff. This staff then decide on the next treatment step, to which the receptacle is transported for further processing. This can imply repeating processing steps with or without modifications, or applying an additional, different, intermittent process step before the fraction is forwarded to the next routine process step. Thus, while the same machines are utilized, the sequence and frequency of their usage can vary.

Process flow diagrams therefore are only an abstraction of the actual processing. They normally display process steps based on the principle that subsequent (groups of) process steps operate best with inputs of certain qualities which must be achieved in the previous (groups of) process steps. Process flow diagrams do not reveal how the (groups of) process steps are operated exactly to achieve these qualities to protect the knowhow of pre-treatment operators.

Regular maintenance of the machinery is essential, including the replacement of hammers in shredders every three to four weeks to ensure optimal performance. As the hammers wear down over time, cutting efficacy diminishes, prompting the need for additional steps in the subsequent process steps and increasingly affecting the quality of the outputs.

B.4.2.2 Downstream treatment of output fractions

The output fractions from the treatment of various types of e-waste on the PTO's premises are forwarded to downstream treatment/final processing:

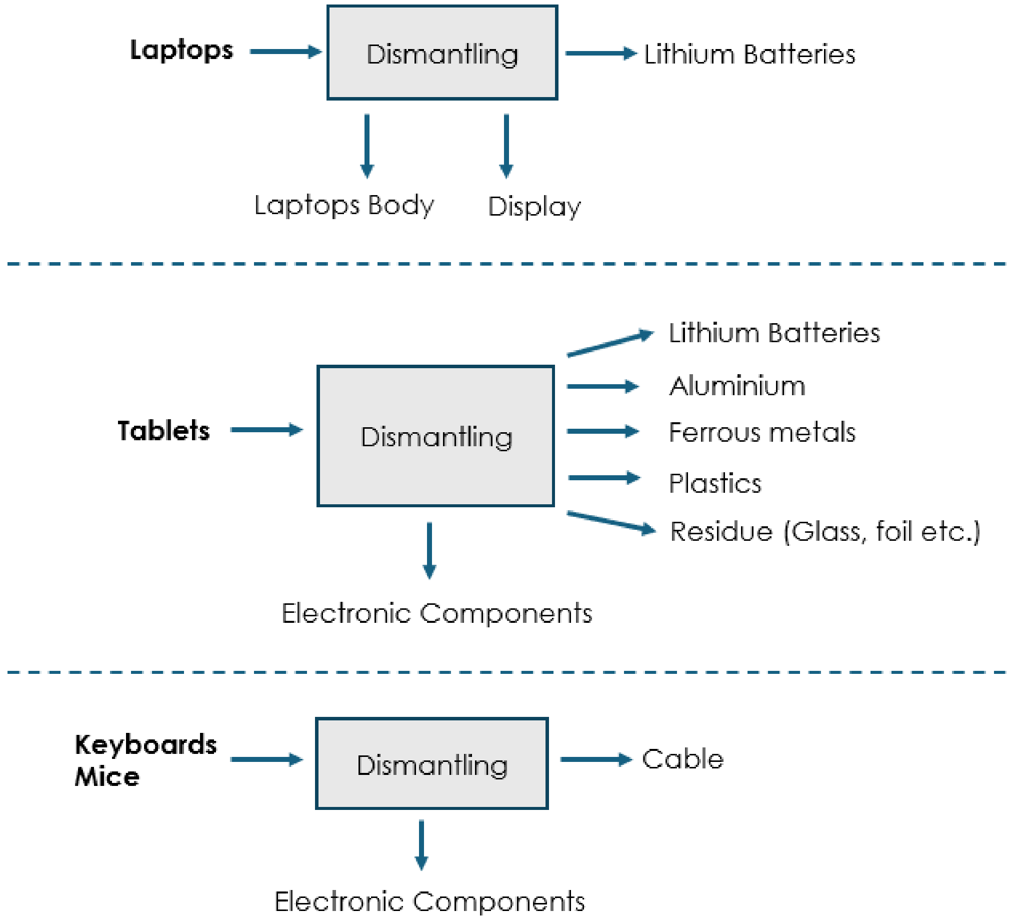
- Ferrous and aluminum fractions to the respective smelters
- Copper fractions to primary or secondary smelters, or to smelters that are specialized in the treatment of copper fractions that are rich in precious metals (high grade copper fractions), e.g. UMICORE in Belgium. The high-grade fractions can be treated in all types of smelters while the latter only accept high grade or also medium grade copper fractions.
- Plastics to the plastics recyclers where recyclable and non-recyclable/plastics with brominated flame retardants are separated, mostly via a density separation in swim-sink-analyses (SSA). Prior to this separation process, plastics recyclers performed a pre-treatment, for example via Eddy Current, to remove rests of PCB(A)s from the plastics fraction. This step increases the purity of the plastics fraction and generates a profitable copper fraction which is sold to copper smelters.

B.4.2.3 Batch test process descriptions

The batch tests for the scope products were conducted following the processing principles described above, with captures and inspections of interim outputs. The batch test flow sheets are an abstraction of the actual processes, i.e. they do not reveal the PTO's proprietary processing knowledge.

Figure 25 illustrates the initial manual dismantling steps. External cables are cut off from keyboards and mice. If batteries are present, they are manually removed from the devices, which involves the physical opening or breaking open of the device to access the battery. In the case of tablets this necessitates the removal of materials and components that bar the access to the batteries. The exact types of materials and components to be removed besides the batteries on the one hand depend on the design of the tablets, and on the other hand on the individual workers who decide whether they access the batteries through from the backside or through the screen.

Figure 25 Initial dismantling steps in batch testing

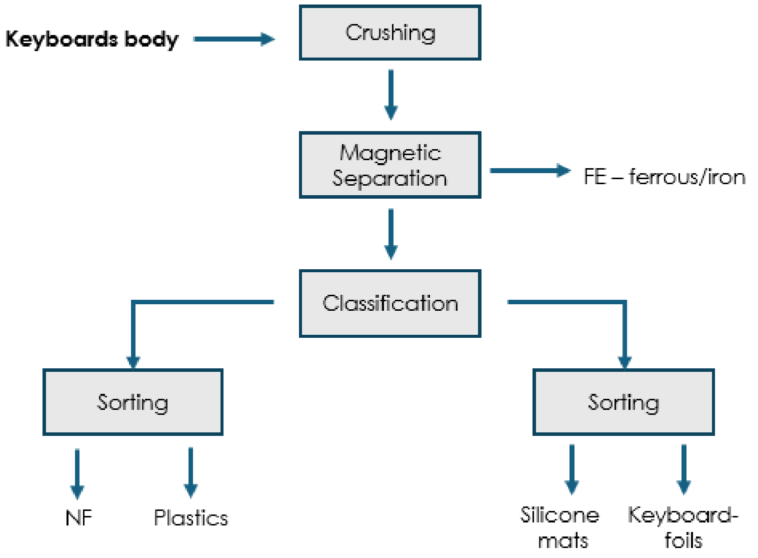


Iron parts typically consist of screws or battery covers. Residues encompass items that are neither metal nor recyclable plastic and lack attachment to electronics or PCBs, such as foils, rubber, or glass.

Disassembly must be executed swiftly. Some housings are glued with adhesives, while others are fastened with screws or clips. They are opened by hammering, bending, or unscrewing where feasible. In certain instances, devices are opened by cutting or breaking off the upper or lower edge. Battery extraction may involve removing the display, back panel, or both, plastics, glass or foils as outputs of the manual dismantling. Manually removed materials and components are collected and forwarded to downstream processing/final processing or disposal.

The devices remaining after the dismantling step are subjected to an SMS process reflected in Figure 26 for keyboards. An initial crushing is followed by magnetic separation, resulting in a ferrous/iron fraction. Finally, the materials are classified into fractions: NF (non-ferrous), plastics, silicone mats, and keyboard foils. Aluminum was not contained in the keyboards but would otherwise become part of the NF-fraction.

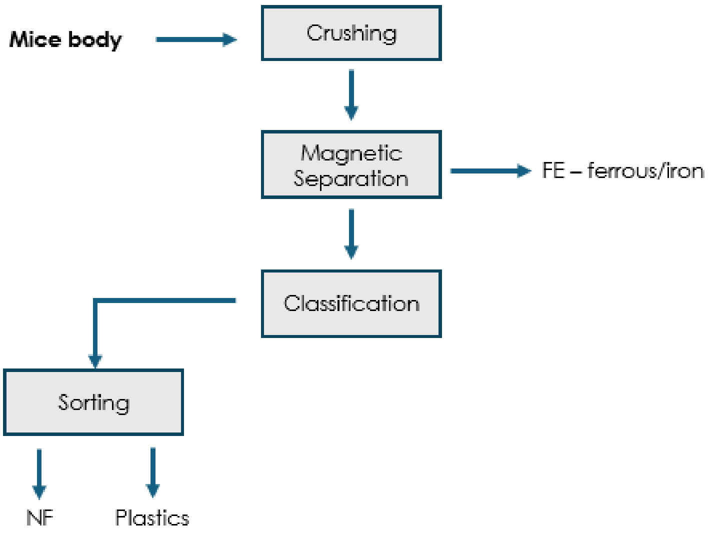
Figure 26 Batch test mechanical treatment for keyboards



NF = Non - ferrous metals
(Cu, Zn, PCB ..)

Figure 27 illustrates the SMS processes for mice where only two fractions, NF and plastics, are obtained from the final stage of classification.

Figure 27 Batch test mechanical treatment for mice



NF = Non - ferrous metals
(Cu, Zn, PCB ..)

While keyboards and mice are typically treated together, they were processed separately during the batch test.

The SMS process for tablets is shown in Figure 28. Following the removal of batteries and other potential materials, the tablet body undergoes crushing, and the ferrous/iron fraction is magnetically separated. Subsequently, a further separation process is implemented, splitting the output stream into aluminum, other non-ferrous metals (NF), and plastics fractions which are forwarded to final processing.

Figure 28 Batch test mechanical treatment for tablets

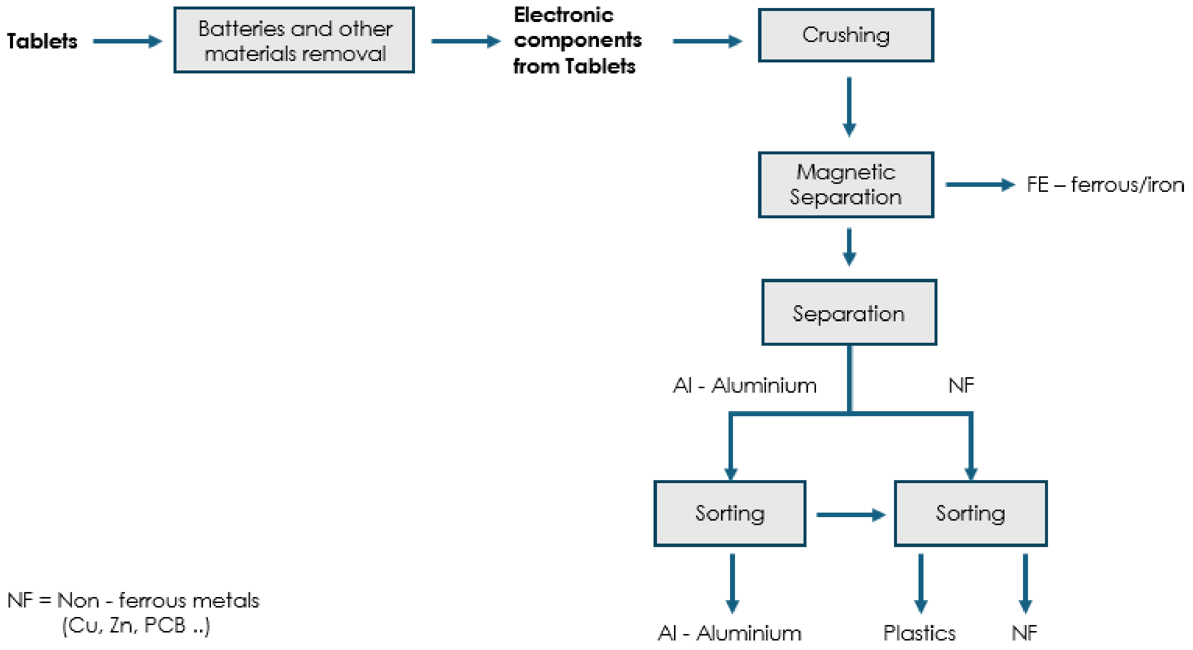
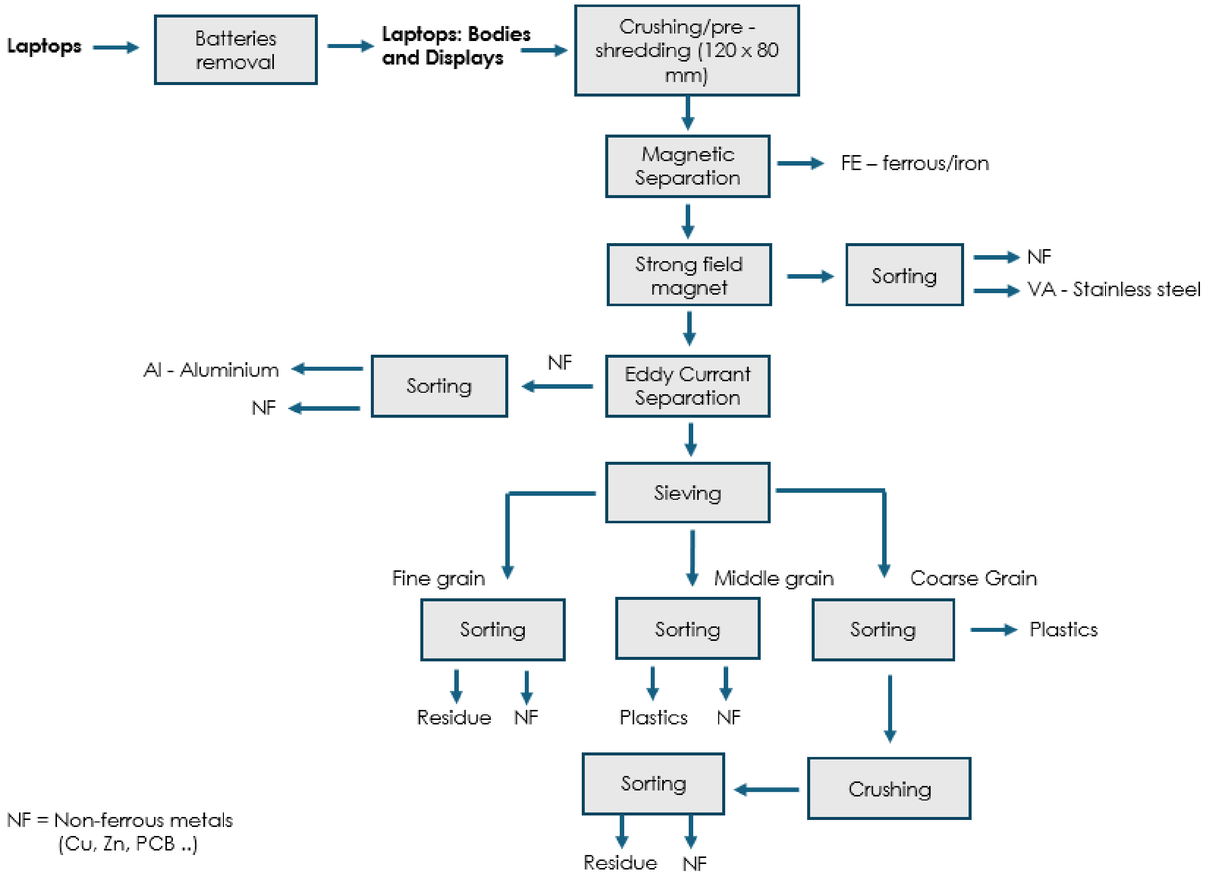


Figure 29 depicts the SMS process performed with the laptops.

Figure 29 Batch test mechanical treatment for laptop



Laptop bodies and displays are reported to have been treated together. After an initial size reduction step via crushing or shredding, followed by two magnetic separation steps to bring out the ferrous/iron fraction, an Eddy Current separation segregates aluminum and the NF fraction (copper fractions) from the rest. The remaining material stream is sieved into three grain size categories based on granulometric dimensions (fine, middle, and coarse grain), allowing for the separation of residues, plastics, and three further NF metal fractions.

B.5 Batch test results

B.5.1 Description of the output fractions

The following figures show photos of the output fractions generated in the batch testing of the scope products, including their shares (weight) in the total output fractions of each scope product, i.e. 100 % are the total mass of output fractions of each scope product.

Figure 30 Output fractions from the keyboards sample

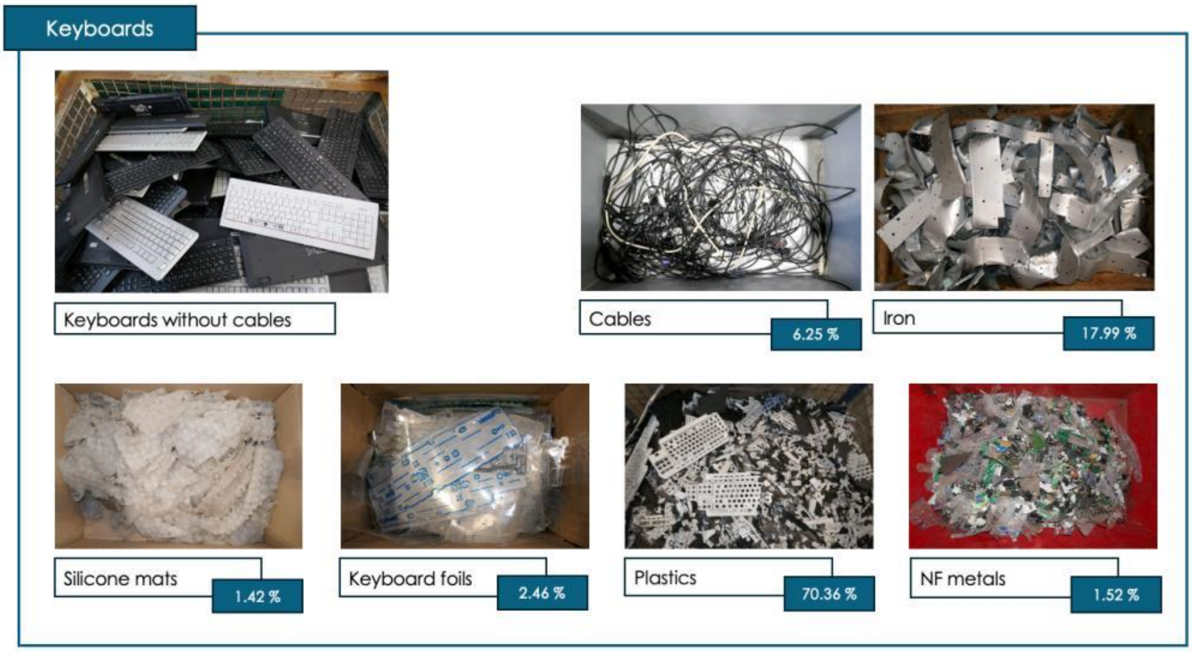


Figure 31 Output fractions from the mice sample

Figure 32 Bodies of tablets going into SMS after initial manual dismantling to remove batteries

Figure 33 Output fractions from the tablet sample

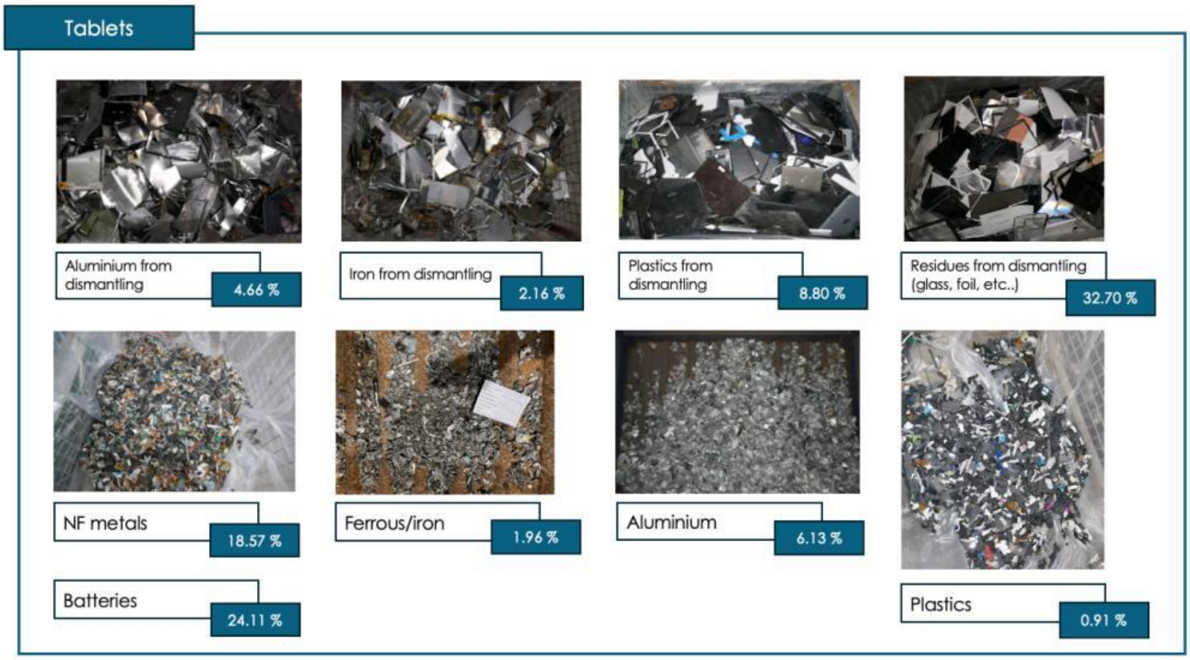
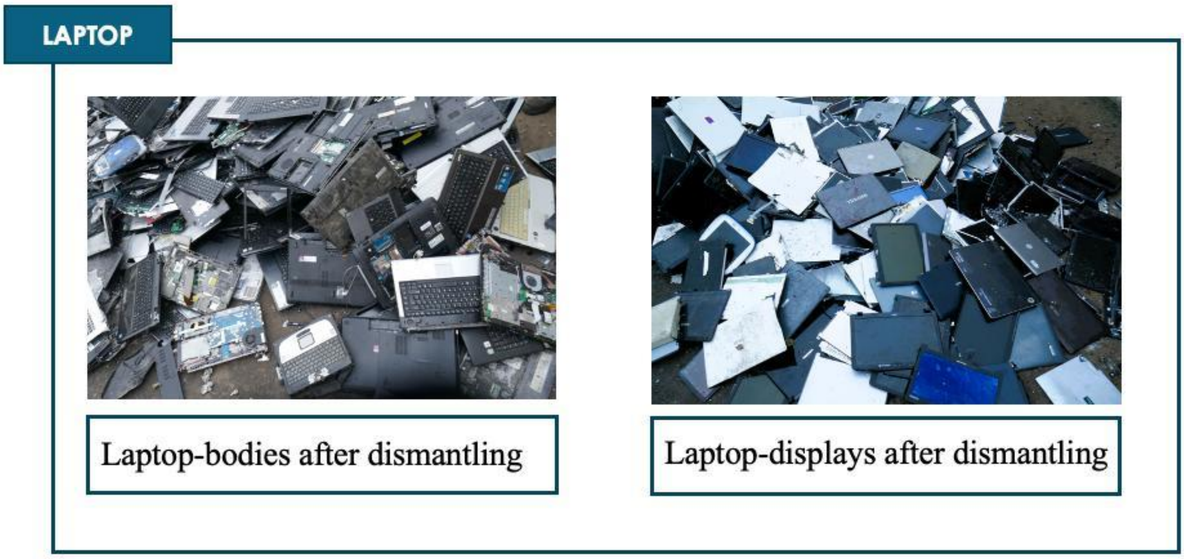
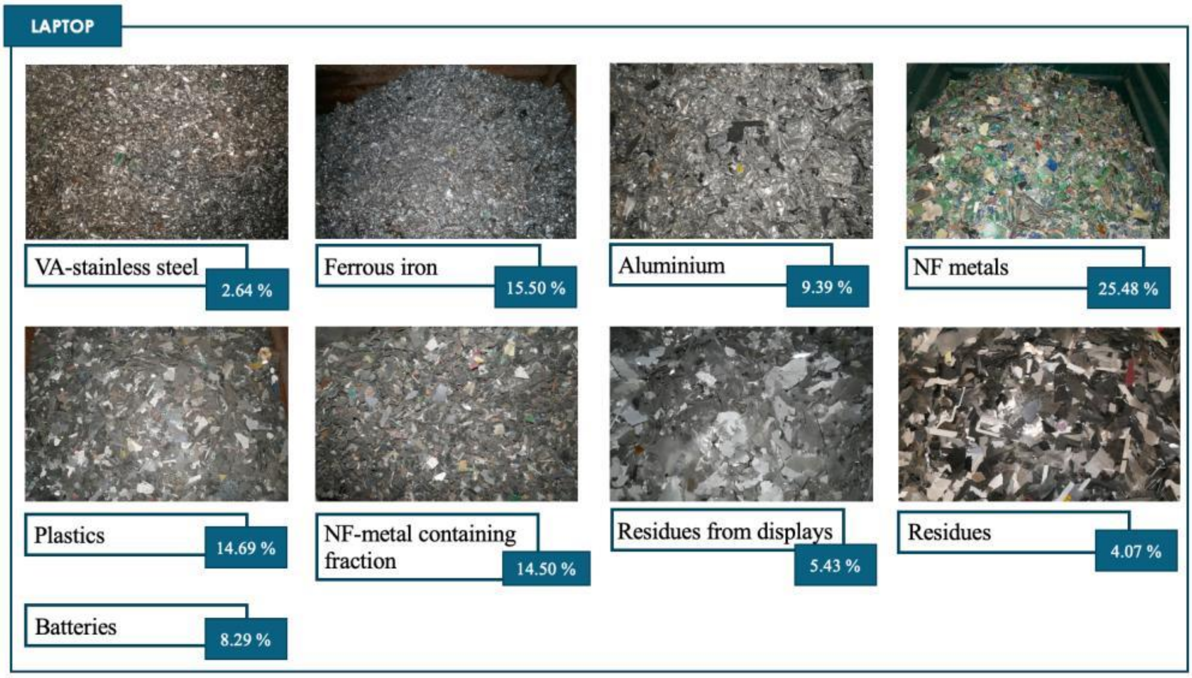


Figure 34 Laptop bodies and displays after initial manual dismantling of laptops before SMS



The displays were removed manually from the laptops to be shredded separately from the laptop bodies. According to the PTO, the results showed that a separate treatment is not necessary so that the displays can remain at the laptops and can be shredded together with the laptop bodies. The SMS output fractions depicted in the below figures include those from the laptop bodies and the displays.

Figure 35 Output fractions from e laptops and displays



B.5.2 Laboratory analyses of scope materials in SMS output fractions

Each scope material shall be analyzed in each output fraction to obtain insights into their distribution over the output fractions and, in the end, assess the share of each scope material in the correct fraction, i.e. the output fraction from which it can be recycled.

Deviating from this approach, the concentrations of the metals in “their own” output fractions was not analyzed, i.e. no analyses of iron in ferrous and no analysis of aluminum in aluminum fractions. These fractions consist mainly of these metals, and the analyzed contents of other materials in these fractions can be used to calculate the Fe-/Al-content more exactly. Further on, output fractions were not analyzed for scope materials which appeared not to present in significant amounts based on optical inspection (cf. the output fraction photos in the previous section) and the share of the output fraction in the total outputs. Very small concentrations of a scope material in a small output fraction are, for example, not sufficiently relevant for the overall result to justify the expenses for the analysis. Magnesium was not analyzed with view to the available budget because it is unlikely to be present in the processed focus products and cannot be recycled in from the output fractions in the downstream processes/final processing.

The share of recyclable plastics could only be identified in the plastics fraction via a swim-sink analysis (SSA) conducted by a plastics recycler. To determine the proportion of recyclable plastics, the samples were placed in a liquid with a density of 1.1 g/cm³, and the mass of floating particles was determined. The floating particles are recyclable plastics such as PP, PE, ABS or PS. The share of organic matter was assessed in a laboratory via ignition loss (IgL) assessment in all output fractions except for the iron fraction (VA – stainless steel and ferrous metals/iron) which where optically identified not to contain relevant shares of plastics.

The SMS mass flows originating from the scope components rare earth element magnets and PCBAs could not be followed directly in SMS. Indicator metals were therefore defined for these scope components that are most likely to occur exclusively in these scope components: Tin (Sn) and gold (Au) for the PCBAs, and neodymium (Nd) for neodymium-iron-boron (Nd-) magnets. Other rare earth element magnets, for example those based on samarium, are not likely to be used in the scope products. No indicator materials could be defined for the LCD-displays and brass. This approach ensured that the necessary analysis could be conducted within the available budget.

The manually dismantled output fractions were not analyzed. They were not subjected to SMS and thus 100 % forwarded to downstream treatment (final processing) where the scope materials are recycled according to the recycling rates of the applied recycling processes.

Table 19 reports the analytical plan developed with the PTO and agreed with the producer for the analyses in a laboratory which the PTO has been contracting in the past years already for analyses of SMS output fractions.

Further details on the calculation of the RR starting from the results of the laboratory analysis and eventual assumptions are reported in the following sections B.5.4 and B.5.5.

Table 19 Analytical plan for the laboratory analysis of scope and indicator materials in the focus products

Keyboards												
Fractions	%	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	SSA	IgL
Fe-fraction	18						1		1			
Keyboard foil	2.5							1		1		
Plastics	70.4						1	1	1		1	1
Cu-fraction	1.5						1	1	1		1	1
Sum	100	0	0	0	0	0	3	3	3	1		2
Mice												
Fractions	%	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	SSA	IgL
Fe-fraction	1.5											
Cu-fraction	9.7	1					1	1	1		1	1
Plastics	57						1	1	1		1	1
Sum	100	1	0	0	0	0	2	2	2	0		2
Tablets												
Fractions	%	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	SSA	IgL
Cu-fraction	18.6	1	1		1		1	1	1		1	1
Fe-fraction	2		1		1		1	1	1		1	1
Aluminum	6.1	1			1		1	1	1		1	1
Plastics	0.9	1	1		1		1	1	1		1	1

Sum	100	3	3	0	4	0	4	4	4	0		4
Laptops												
Fractions	%	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	SSA	IgL
VA - Stainless Steel	2.6		1		1	1	1	1	1			1
Fe-fraction	15.5		1		1	1	1	1	1			1
Al-fraction	9.4	1			1	1	1	1	1		1	1
Cu-fraction NF 1	25.5	1	1		1	1	1	1	1		1	1
Plastics (mix)	14.7	1	1		1	1	1	1	1		1	1
Cu-fraction NF 2	14.5	1	1		1	1	1	1	1		1	1
Residue from displays (foils, films)	5.4	1	1		1	1	1	1	1		1	1
Residue	4.1	1	1		1	1	1	1	1		1	1
Additional sample from mixed NF fine grain												
Sum	100	6	7	0	8	8	8	8	8	0		8

Notes: 1 = analyzed IgL: ignition loss SSA: swim-sink analysis

Regarding keyboards, Cu and Ag were analyzed in the foil fractions as these foils contain conductor tracks and therefore Cu and Ag were likely to be present.

In keyboards and mice, Al, Zn and Nd-magnets, according to the PTO and the producer, were not supposed to be present. No particles of iron were to be expected, either, in the plastics fractions based on visual inspection by the PTO. No analyses were therefore commissioned for these cases.

As for the case of tablets, Zn and Nd were not analyzed in agreement with the producer. All other scope materials were analyzed according to the analytical approach described above.

B.5.3 Separation effectiveness of SMS

The distribution of the scope materials in the SMS processing was calculated based on the analytical results[6], i.e. their concentration in the various output fractions, and the mass of the individual output fractions. The percentages of scope materials and components in those fractions from which they can be recycled indicates the separation effectiveness of the SMS process. The separation effectiveness for scope materials and component is indicated in the green fields in the below table. Neodymium (Nd), tin (Sn) and gold (Au) are no focus materials but indicator metals for the presence of Nd-magnets (Nd), and PCBAs (Sn and Au, cf. B.5.2 at page 93). Nd itself cannot be recycled from any output fraction but the iron contained in the Nd-magnets is recycled from the Fe-fraction. The Fe-fraction is therefore considered as the target fraction for Nd.

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[6] Cf. Annex IV: Results of the analysis of scope materials in the output fractions (Germany)on page 124

Table 20 Distribution of focus materials and components over SMS output fractions (percentages) and separation effectiveness

Keyboards											
Output Fractions	**Fe**	**Al**	**Zn**	**Nd**	**Sn**	**Cu**	**Au**	**Brass**	**Organic Matter**	**Recycl plastics**	**PCBA**
	%	%	%	%	%	%	%	%	%	%	%
Fe	100	0	0	0	0	0	0	0	0	0	0
Cu	0	0	0	0	25	31	13	31	1	1	19
Plastics	0	0	0	0	75	69	87	69	99	99	81
Mice											
Fe	44	0	0	0	0	0	0	0	0	0	0
Cu	56	0	0	0	95	94	76	94	8	6	86
Plastics	0	0	0	0	5	6	24	6	92	94	14
Tablets											
Fe	40	3	4	0	0	2	1	2	0	0	0
Al	0	84	32	0	1	1	1	1	3	3	1
Cu	59	14	64	0	99	98	99	98	85	82	99
Plastics	0	0	0.03	0	0	0	0	0	12	14	0
Laptops											
Stainless Steel	13	1	1	3	2	2	1	2	0	0	1
Fe	84	1	8	79	3	2	2	2	0	0	2
Al	0	81	5	3	3	1	1	1	0	0	2
Cu NF1	1	10	76	7	73	83	62	83	26	25	68
Cu NF2	1	3	9	4	18	10	30	10	24	24	24
Plastics	0	1	0	4	1	1	1	1	34	34	1.24
Residue displays	1	2	0.05	0	0	1.03	2.88	1	8	8	1
Residue	0	1	0.04	0	0	0.19	0.25	0	8	8	0

🟧 The pretreatment operator had indicated this value to be too high, also compared to shares of Al in Fe-fractions of other scope products. In the absence of another value, it was used, nevertheless. If it is actually too high, it reduces the separation effectiveness of Al.

🟨 The laboratory had indicated these values as "smaller than" so that they are lower than indicated. They were used as maxima which decreases the separation effectiveness of Zn and Nd.

The distribution of recyclable plastics over the output fractions could only be calculated indirectly as data for the contents of recyclable plastics were available merely for the plastics fractions, while the share of organic matter was known in all output fractions. For the baseline scenario, it was assumed that the ratio of recyclable plastic and organic matter in the plastics output fractions are equal in all output fractions, which represents a worst-case scenario.

In a further step, the separation effectiveness of recyclable plastics in the above table was improved by accounting for the contents of nonrecyclable plastics contained in PCBAs which indirectly increased the share of recyclable plastics in the plastics fraction, even though to a different degree for each focus product. For details of the calculations see section B.5.5.4 on page 103. The shares of recyclable plastics in the plastics fractions are therefore higher in the above table than the share of organic matter. This produces a visible difference, however, only for mice and tablets. The magnitude of the effect depends on the share of non-recyclable organic matter contained in the PCBAs of the scope products.

B.5.4 Recycling rates of focus materials and components

The recycling rates of the scope materials that were subjected to SMS are based on the separation effectiveness in Table 20 above, and the recycling rate of each scope material in downstream processing of each output fraction.

The manually removed parts (greenish fields) were not treated in SMS so that no losses occurred. The removed focus materials and components were assumed to be 100 % forwarded to downstream treatment operators where they were recycled according to the recycling rates of the contained materials in these processes. The RR displayed in the green fields for the manually removed scope materials and components indicate the overall recycling rates which only depend on the recycling rate of these materials in the downstream processes.

To make most efficient use of the budget for analyses, magnesium was not analyzed as it was likely not to be contained in the treated waste focus products. Further on, magnesium is not recycled from any output fractions in the current downstream/final processing of the output fractions (status 2024).

Table 21: Recycling rates of focus materials in focus products

Keyboards	**Fe**	**Al**	**Mg**	**Zn**	**Nd**	**Cu**
Cables (manually removed)	0 %					97 %
Silicone mats (manually removed)						
Keyboard foil (removed manually after pre-treatment where it was not destroyed)						98 %
Overall RR from SMS output fractions	**94 %**	**n. an.**	**0 %**	**n. an.**	**0 %**	**30 %**
Mice	**Fe**	**Al**	**Mg**	**Zn**	**Nd**	**Cu**
Cable (manually removed)	0 %					97 %
Overall RR from SMS output fractions	**42 %**	**n. an.**	**n. an.**	**n. an.**	**0 %**	**92 %**
Tablets	**Fe**	**Al**	**Mg**	**Zn**	**Nd**	**Cu**
Batteries						
Aluminium from manual disassembly		94 %				
Steel from manual dismantling	94 %					
Mixed plastic from manual disassembly	0 %	0 %	0 %	0 %	0 %	0 %
Waste from manual dismantling (glass, foil, etc.)	0 %	0 %	0 %	0 %	0 %	0 %
Overall RR from SMS output fractions	**38 %**	**79 %**	**0 %**	**41 %**	**0 %**	**96 %**
Laptops	**Fe**	**Al**	**Mg**	**Zn**	**Nd**	**Cu**
Batteries						
Overall RR from SMS output fractions	**91 %**	**76 %**	**0 %**	**55 %**	**0 %**	**90 %**

n. an.: not analyzed Recycl.: recyclable

The above table displays two different recycling rates of recyclable plastics contained in the focus products reflecting two different settings. While the first value indicates the worst-case approach, the second value takes into account the non-recyclable organic matter in the PCBAs for the focus products keyboards (40 %), mice (30 %), tablets (20 %) and notebooks (10 %). For details refer to the below section B.5.5.4 “Zn in keyboards and mice

The recycling rates of Zn in Table 24 from PCBAs were calculated based on the shares of PCBAs in the Cu-fraction generated during SMS. The Zn contained in these PCBAs would be recycled with the recycling rate of Zn in Cu-smelters. This recycling rate would also apply to the Zn of PCBAs that are removed from keyboards and mice prior to SMS.

Zn contained in brass can be assumed to follow the copper during SMS so that the share of Cu in the Cu-fraction is applied to brass. Zn contained in the copper fraction stemming from brass would therefore be recycled with the RR of Zn in Cu-smelters.

Zn related to ferrous metals, e.g., applied as corrosion protectant, would be recycled from the share of ferrous metals in the Cu-fraction with the recycling rate of Zn in Cu-smelters. The Fe-shares in the copper fractions were, however, not analyzed because their concentrations in these fractions could be assumed to be negligibly small. The RR for Zn is thus 0 %.

Recyclable plastics”B.5.5.4. These values are based on bills of materials for two PCBs. The PCB with the lower share of organic material (10 %) was allocated to the keyboard, the one with the highest share (40 %) to the laptops. The PCBs of the other focus products were assumed to contain organic matters in between. It is recommended to apply actual values for current PCBAs in focus products if available. If the share of nonrecyclable organic matter in PCBAs is higher, the differences can be larger than the current maximum of around 2 %.

Thermoset and TPU plastics cannot be recycled, their overall RR is “zero.” They are properly directed to the residues and to other fractions where they are incinerated/energetically recovered. The same applies to magnesium. It is not recycled in the currently practiced standard downstream processing/final processing of the output fractions.

Table 22 displays the recycling rates of brass (scope material) and scope components which could not be directly assessed but were calculated indirectly, cf. section B.5.5 Calculation of recycling rates of scope components and separation effectiveness for PCBAs).

Table 22: Recycling rates of brass and scope components in scope products

	Keyboards	**Mice**	**Tablets**	**Laptops**
Brass	26 %	80 %	84 %	79 %
Nd-magnets	Not relevant		48 %	49 %
Li-ion batteries	36 %			
LCD displays	No data available			

It should be noted that the recycling rates of the materials contained in brass and the above scope components are already included in the recycling rates in Table 21, except for the batteries which are removed manually prior to SMS and sent for downstream treatment. The RR for the batteries is adopted from the downstream data received from battery recyclers.

The below table shows the shares of PCBAs in the Cu-fraction, which is forwarded to Cu-smelters where the scope metals Cu and Zn are recycled. Other metals in the Cu-fraction like precious metals, tin, lead, bismuth, nickel, antimony, etc., are recycled as well but are not scope metals, and are not relevant for a purely mass-based recyclability assessment due to their small shares in the total weight of a PCBA. Organic contents are not recycled.

Table 23: Shares of PCBAs in the copper fraction after SMS

PCBAs	A: Share of PCBAs in Cu-fraction after SMS	B: Share of PCBAs in Cu-fraction including additional separation by plastics recycler
Keyboards	19%	35%
Mice	86%	98%
Tablets	99%	99%
Laptops	92%	93%

Certain portions of PCBA pieces are directed into the plastics fraction. Since PCBAs can be of considerable economic value – in particular those from tablets and laptops – plastics recyclers apply an additional process step to separate these rests of PCBAs from the plastics fraction. The removed PCBAs are forwarded to Cu-smelters as well for recycling. This additional volumes of PCBAs were added to the shares of PCBAs in the Cu-fraction after the first separation step at the PTO.

Such a post-treatment can be applied to Al-fractions as well. The separated Cu-containing material is sold to Cu-smelters. According to the PTO, the output fractions that are generated in their treatment are processed directly by Al-smelters due to their high purity. Such a post-treatment was not taken into account considering also the copper content of less than 1 % in the aluminum fractions which would thus not add substantially to the shares of copper, brass and PCBAs in the Cu-fraction.

In the batch test performed, Zn was not analyzed in the output fractions generated from keyboards and mice according to the reasoning expressed in B.5.2. The recycling rates for Zn were therefore calculated yielding the RR displayed in Table 24.

Table 24 RR of Zn used in keyboards and mice

	Zn on PCBAs (SMS, A*)	**Zn on PCBAs (SMS, B*)**	**Zn on PCBAs (manually removed)**	**Zn/ Steel**	**Zn/ Brass**
Keyboards	13%	23%	65%	0%	20%
Mice	56%	64%	65%	0%	60%

Aluminium was not contained in the keyboard and mouse test batches so that no aluminum fractions were generated, and no aluminium recycling rates could be assessed in the batch tests. It can be assumed that aluminium contained in keyboards and mice would be separated in SMS into aluminium fractions so that the recycling rate is higher than 0 %. Since aluminum is a main output fraction itself, the recycling rate could not be derived from other metals in other outputs or from other products.

B.5.5 Calculation of recycling rates of scope components and separation effectiveness for PCBAs

B.5.5.1 Nd-magnets

The RR of NdFeB-magnets reflects the recycling of iron (Fe) from the Nd-magnets in the ferrous metal output fraction. Neither neodymium nor any other metals are recycled from these magnets in the iron fraction. The RR for Nd-magnets in Table 22 only applies to Nd-magnets with 64 % content of iron. Nd-magnets cannot be followed through an SMS to the final output. The concentrations of Nd were therefore analyzed as an indicator metal for Nd-magnets in all output fractions from laptops since Nd was assumed to occur in larger quantities in magnets of these products in the batch test. The Nd-magnets largely follow the ferrous metal stream (around 82 % in the laptop case), and Fe is recycled from these magnets.

Since neodymium magnets may be used in tablets, the recycling rate of Nd-magnets was derived from the laptops. In their treatment, 82 % of Nd – and thus of the magnets – are found in the two ferrous metal output fractions: 3 % in the VA-stainless steel fraction, and 79 % in the other ferrous metal fraction. The SMS of the tablets generates no VA-stainless steel fraction, only a ferrous metal fraction. It is assumed that this fraction, like in the case of laptops, would contain 79 % of the Nd-magnets if they were used in tablets. Multiplying these 79 % with the Fe-content of the magnets and the recycling rate of Fe contained in ferrous metal output fractions in Fe-smelters results in the recycling rate of Nd-magnets in tablets indicated in Table 22.

B.5.5.2 Brass

The flow of brass during SMS could not be differentiated from the Cu- and Zn-flows so that the RR of brass had to be calculated indirectly. The metals in brass – mainly Cu and Zn – can only be recycled from the Cu-fraction. It was assumed that brass follows the Cu in SMS so that the distribution of brass over the output fractions is identical to that of Cu. The RR of brass is then calculated from the share of brass in the Cu-fraction as recycling rates of Cu, Zn and Sn in Cu-smelters. The RR indicated in Table applies to brass with a composition of 69 % Cu, 30 % of Zn and 1 % of Sn and should be recalculated for the specific types brass used in specific types of focus products.

B.5.5.3 PCBAs in the Cu-fraction

The flow of PCBAs cannot be followed through the SMS process to the output fractions because the PCBAs are destroyed in the shredder and the pieces directed to different output fractions in the subsequent separation process. Tin (Sn) and gold (Au) were therefore analyzed in the output fractions as indicator metals for PCBAs. These metals were identified as those most likely to be found exclusively in PCBAs of the focus products. The share of PCBAs in the output fractions was calculated as an arithmetic average of the distribution of Sn and Au over the output fractions.

The share of PCBAs removed from the plastics in the second separation step processed by the plastics recycler was calculated applying the same effectiveness for the separation of PCBA pieces into the copper fraction like in the first separation process practiced by the PTO. For each focus product, the separation effectiveness was calculated as ratio of the percentage of PCBAs contained in the Cu-fraction(s), and the sum of the percentages of PCBAs contained in the SMS output fractions without the PCBAs contained in the Fe-output-fraction. The percentage of PCBAs in the Fe-fraction was not considered because the ferrous metals, and with them the percentages of PCBAs in the Fe-fraction – are removed prior to the process step separating the Cu-fraction with PCBAs from aluminum and plastics. The shares of PCBAs in the ferrous fraction are thus irrelevant for the separation effectiveness of this separation process.

B.5.5.4 Zn in keyboards and mice

The recycling rates of Zn in Table 24 from PCBAs were calculated based on the shares of PCBAs in the Cu-fraction generated during SMS. The Zn contained in these PCBAs would be recycled with the recycling rate of Zn in Cu-smelters. This recycling rate would also apply to the Zn of PCBAs that are removed from keyboards and mice prior to SMS.

Zn contained in brass can be assumed to follow the copper during SMS so that the share of Cu in the Cu-fraction is applied to brass. Zn contained in the copper fraction stemming from brass would therefore be recycled with the RR of Zn in Cu-smelters.

Zn related to ferrous metals, e.g., applied as corrosion protectant, would be recycled from the share of ferrous metals in the Cu-fraction with the recycling rate of Zn in Cu-smelters. The Fe-shares in the copper fractions were, however, not analyzed because their concentrations in these fractions could be assumed to be negligibly small. The RR for Zn is thus 0 %.

B.5.5.5 Recyclable plastics

The only information available specifically for recyclable plastics is their share in the plastics output fraction. This information was provided by a plastics recycler as the result of a swim-sink analysis of the plastics output fraction generated from each focus product. The density of the liquid used for the SSA was 1.1 k/cm^3, which separates the recyclable from the non-recyclable plastics but does not allow a specification of the various types of recyclable plastics.

The laboratory analyses yielded the share of organic matter in each SMS output fraction from each focus product assessed via an ignition loss test. The laboratory did not specify the share of recyclable plastics in these output fractions. The available data, however, enabled calculating the ratio of recyclable plastics and organic matter in the plastics output fractions.

For the assessment of the shares of recyclable plastics in the other output fractions, it was assumed that the ratio of recyclable plastics and organic matter is identical in each output fraction. This approach represents a worst-case approach since it can be reasonably assumed that the ratio of recyclable plastics and organic matter is highest in the plastics fraction. The objective of the plastics separation into the plastics fraction is not only to remove organic pollution from the metal output fractions but also to generate a fraction that can be sold to plastics recyclers. Plastics fractions with higher concentrations of recyclable plastics would thus achieve higher prices.

In a further step, the above worst-case approach was improved taking account of the organic matter in PCBAs. The share of PCBAs in each plastics output fraction was calculated indirectly. PCBAs are assumed to largely contain types of plastics that cannot be recycled, e.g. epoxy resins, or possibly also plastics that are in principle recyclable but contain brominated flame retardants, which disqualifies them for recycling. The share of organic matter in PCBAs in each of the output fractions other than the plastics fraction was therefore subtracted from the share of organic matter in these output fractions. For the remaining organic matter in these output fractions, the worst-case approach was applied, i.e. it was assumed that the share of recyclable plastics in these remaining output fractions is identical to the share of recyclable plastics in the plastics fractions of each focus product.

As a result, the calculated share of recyclable plastics in the output fractions other than the plastics fractions mathematically decreases. The share of recyclable plastics in the plastics output fraction, however, remains constant since this value was not calculated but assessed by the plastics recycler. In consequence, the share of recyclable plastics in the plastics output fraction increased so that the RR of plastics in the focus products also increased.

A.9 Data quality assessment

The results of the data quality matrix are reported in Table 25. The data quality matrix was built considering the data gathered from various sources as outlined in B.3: data from batch test outputs, data from laboratory analysis, data from literature regarding downstream processes and input data provided by the producer.

The data quality was evaluated in terms of reliability, time and completeness and rated from 1 (best quality) to 5.

Specifically, details on the reliability and completeness rankings are provided individually for the focus materials in Annex V: Details of data quality matrix for Germany. on page 122.

The reliability indicator was assessed following the rationale that data from a source are more reliable than data originated from further downstream and possibly aggregated.

In particular, the first reliability indicator "*material composition of the input batch*" scored 2 as the input batch was represented through the assessment of the output batch we analyzed.

Regarding the second reliability indicators, "*batch being processed relevant to the product being assessed*", a general ranking of 1 was assigned as more than 80 % of the products recycler processes fall into the same WEEE category as the product being assessed. Most of the materials scored 1, as they were obtained as output fractions or part of the output fractions of the batch test.

The only exceptions were reported in the case of PCBs, as they were not found as entire materials/components in output fractions but rather calculated through indicator metals. Brass was not found in the output fractions analyzed either but rather calculated through assumption and interpretation.

Lastly, for the indicator yield rate across the whole reprocessing chain (T1 and downstream processes), some downstream data were gathered from literature, while the rest were primary data directly reported from the batch test and the laboratory analysis. In this case also, single ranking of the individual scope materials was specifically assessed in Annex V: Details of data quality matrix for Germany. Most of the scope materials received score 1. Few exceptions apply for PCBs which was scored 2 as the analysis was conducted based on indicator metals and yield rate were calculated based on assumptions, batteries which scored 3 as downstream data from the Italian project were used and brass scored 2 as it was not analyzed directly but it was calculated. The plastics rate was broken down into two scenarios analyzed: a worst-case scenario and an improved scenario, details of which are reported in B.5.5.4. In both scenarios, a correctness check scored 3 while a "*safe to use*" check scored 1. The worst case was adopted to reflect a safer position without knowing detailed data of recyclable plastics in the rest of the non – analyzed output fractions.

In the time rating, the treatment scored 1 as 2024 data have been used for the batch test, the laboratory analysis and therefore for the recyclability calculation.

Regarding the completeness, the approach was to collect all the materials and components for which a recycling rate was calculated in all the different products in scope. More details can be accessed in Annex V: Details of data quality matrix for Germany.

Table 25 Data quality matrix. Results of indicator, sub-indicator and scoring rubric

Indicators	Sub indicators	Data quality score						
		(Highest score = 1)						
				1	2	3	4	5
Reliability of data	Material composition of the input batch	Partially mechanical treatment	First, second and final treatment operator		X			
	Batch being processed relevant to the product being assessed	Partially mechanical treatment	First treatment operator	X				
	Yield rate across the whole reprocessing chain (T1 and downstream processes)	Partially mechanical treatment	First, second and final treatment operator		X			
Time	Partially mechanical treatment			X				

Completeness	Partially mechanical treatment	X				

B.6 Conclusions and recommendations

Assessing the recycling rates of scope materials and components requires larger volumes of scope products in proportion to pre-treatment operators' treatment capacities to enable an adequate treatment that reflects the results of standard treatments. The processed volumes of focus products also need to generate volumes of output fractions that allow preparing samples including backup samples for the subsequent analysis of the output fractions. Collecting and stockpiling adequate volumes of scope products proved to be a time-critical step that can require several months and can hardly be shortened. The adequate volumes to be collected and the time required for collecting them should therefore be discussed with pre-treatment operators as early as possible and be reflected in the time-planning for batch testing projects.

Components that are manually removed from the focus products prior to SMS are fully (100 %) forwarded to downstream treatment. Losses in the mechanical separation process are thus avoided. Understanding which materials and components are removed manually and according to which treatment rules is therefore crucial for the assessment of recycling rates of scope materials and components. Attending the manual processing steps and talking to workers is highly recommended to grasp the actual practices applied to the scope products. This would avoid situations as experienced with the tablets where the materials and components that were indicated to be manually removed did not match the earlier communicated rules of how workers proceed until it turned out that it is at the workers' discretion how they perform the task.

The onsite visit on the PTO's premises for the batch testing – and the daily treatment of e-waste – revealed that the exact order of the various steps in SMS processing is output-controlled rather than following a fixed order. Interim output fractions are inspected, and the next process steps are decided based on the quality of these interim fractions. "Representativeness" of processes thus comprises the equipment used for processing as one aspect. The other aspect is that the PTO uses the experience and expertise to optimize the treatment result. In this case, it can be assumed that good results are achieved for the focus products in batch testing like in the daily processing of collection groups including the focus products. This adds, however, complexity to "representativeness" since the expertise of a PTO cannot be assessed like the technologies used in the process. The selection of experienced PTOs with a longer history of e-waste treatment is therefore important to ensure good results under the respective technical, legal and socio-economic conditions in all RR assessment projects.

Plastics and aluminum output fractions can be subject to post-treatments. Plastics recyclers conduct an additional separation step to remove rests of copper/PCBAs from the SMS Al-fractions, whose mass was added to the Cu-fractions from SMS for the RR calculation. Aluminum smelters may apply such an additional process step as well depending on the composition of the Al-fractions. This was not relevant for the output fractions generated in the batch tests but it should be kept in mind for next batch testing projects that such post-treatments have to be considered if they significantly affect the recycling rates.

The internal competences and organization of PTO companies can give rise to misunderstandings. The persons communicating to the outside are not necessarily involved into the practicalities and decisions concerning the daily technical operations, which may cause misunderstandings as to the intentions and the implementation of the batch testing exercises. The technical staff working on the ground should therefore be involved as far and as soon as practicable in the discussions and decision-making on how to implement the batch tests.

The selected approach of performing analyzes of all output fractions for all focus materials proved to be practicable and expedient except for recyclable plastics. The share of recyclable plastics in output fractions other than the plastics fraction could not be analyzed for technical reasons. The separation effectiveness of SMS processing could thus not be assessed directly and without additional assumptions for this scope material like for the other scope materials. Determining the content of recyclable plastics in non-plastics output fractions is beyond the spectrum of standard tasks for laboratories and plastics recyclers. Additional restrictions may arise from the small size of plastics particles in such output fractions that can impede standard identification methods of recyclable plastics like swim-sink analyses. These aspects should be discussed with treatment operators and laboratories at the beginning of next projects to overcome this shortcoming. For all other output fractions, the separation effectiveness of the SMS processing could be assessed directly for all scope materials and indirectly, even though with additional assumptions, for the scope components.

The determination of the separation effectiveness lifts the dependency on the recyclability rates reported from downstream operators for the forwarded output fractions. These data are related to collection groups, so not to individual products or specific groups thereof, and they only report summary recycling rates without any specifications of the materials in the treated fractions and their recycling rates. Instead, however, the applied approach requires data for the recycling rates of the focus materials in the downstream treatments/final processing. Such data are available from literature and were used in the recycling rate assessments, but they are afflicted with uncertainties. It can be assumed that more and possibly better data will become available in the coming months and years if more producers of EEE conduct recyclability assessments according to EN 45555 and publish the underlying data. Regular screenings of publications to improve and broaden the data base are therefore recommended.

Bulk metals like iron/steel, aluminum and copper (and precious metals) achieve high recycling rates in final processing, and good values of separation effectiveness in pe-treatment operations including SMS. PTOs prioritize achieving high separation effectiveness for these metals in output fractions for commercial reasons. The same applies to precious metals which are, however, irrelevant for a purely mass-based recyclability assessment of the scope products.

Other metals like tin or zinc are commercially irrelevant for PTOs but are recycled in final processing of copper-fractions even though with far lower recycling rates than copper and precious metals. Magnesium and rare earth elements like Nd in magnets are not recycled in the current downstream/final processing of SMS output fractions. If Nd-magnets were removed from the focus products and be collected, there would be technical possibilities to recycle/reuse them, e.g. in magnet-to-magnet manufacturing of new Nd-magnets.[7] This is, however, commercially impracticable and therefore not practiced in the treatment of e-waste like the scope products. Recycling of magnesium would be technically feasible provided the respective parts are manually or otherwise separated prior to SMS and sent to a specific treatment. This may be commercially practicable – to be tested - for larger parts that are easily removable from the focus products. In the current downstream processing of SMS output fractions, magnesium cannot be recycled. If magnesium is used in alloys, the recycling of magnesium would imply the loss of the other metals contained in the alloy. Overall, applying magnesium in the scope products is not recommended unless technical necessities urge its use.

The removal of batteries from tablets and laptops with integrated batteries is a tedious task and implies the risk that batteries are damaged during the removal operation and may cause fires and health implications for workers. A product design enabling the quick and easy removal of batteries is highly

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[7] Cf. CEWASTE project Deliverable 1.1, https://cewaste.wpenginepowered.com/wp-content/uploads/2020/03/CEWASTE_Deliverable-D1.1_191001_FINAL-Rev.200305.pdf

recommended to minimize risks and save labor time – and thus reduce the cost – for the pre-treatment.

Plastics used in EEE should be monomaterial recyclable plastics without any coatings or lacquers, they should not be glued because glues contaminate the plastics fraction. Plastics with brominated flame retardants are not recycled for legal reasons (RoHS-Directive). Flame retardants should generally be avoided, as well as plastics with densities of around 1.1 g/cm³ or less.[8] Such plastics are separated partially or completely into the fraction of non-recyclable plastics which are going to incineration/energy recovery. Cavities in plastics parts disturb the separation processes (SSA) and increase the risk of contamination in the separated recyclable plastics by non-recyclable ones.

Overall, the recyclability rate assessment for scope materials and components in the scope products can be considered a success. It is recommended to apply the approach elaborated for the recycling rate assessments in Germany as the basic procedure for further assessments, with adaptations to the specific conditions and treatments of the scope products.

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[8] The plastics recyclers in the Italian study identified densities of around 1.08 g/m³ to already affect the separation of recyclable from non-recyclable plastics.

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Annexes

5 ANNEXES

5.1 ANNEX II: Mass balance and destination routes Italy

Table 26 Partially mechanical treatment – mass balance and destination routes

Input sample	**Sample weight**	**Output fraction first treatment operator**	**Total output fraction (kg)**	**Output fraction first treatment operator**	**Total output fraction (kg)**	**Energy recovery (%)**	**Landfill disposal (%)**	**Recycled (%)**
Laptop	66.21	Glass	3.25			0 %	68 %	32 %
		PCBs	8.65			36 %	0 %	64 %
		Plastics	23.33			36 %	2 %	62 %
		Aluminum	5.41			6 %		95 %
		Ferrous materials	3.25			2 %	0 %	99 %
		Copper	0.76			1 %		99 %
		Material that passed the sieve	3.09			80 %	10 %	10 %
		Metal mix	14.68	Aluminum	2.98	6 %		95 %
				PCBs	1.20	36 %	0 %	64 %
				Material that did not pass the sieve	1.00	80 %	10 %	10 %
				Copper	0.06	1 %		99 %
				Brass	0.07	1 %		99 %
				Plastics	4.71	36 %	2 %	62 %
				Non-ferrous materials	4.67	37 %	6 %	57 %
		Rubbish	3.79			50 %	50 %	
Tablet	110.00	Aluminum	13.40			6 %		95 %
		Plastics	22.96			36 %	2 %	62 %
		Display	0.00					

		PCBs	10.61			36 %	0 %	64 %
		Metals	14.03			5 %		95 %
		Batteries	29.00	Black Mass	19.09	17 %	25 %	58 %
				Al foil + aluminum	2.57			
				Cu foil	3.30			
				Elettrolits	2.20			
				Rubbish	1.84			
		Rubbish	20.00			100 %		
Game consoles	22.90	Plastics	5.48			36 %	2 %	62 %
		Aluminum	1.90			6 %		95 %
		Ferrous materials	9.38			2 %	0 %	99 %
		PCBs	1.78			36 %	0 %	64 %
		Capacitors	0.17			70 %	0 %	30 %
		Motors	1.13			18 %	0 %	82 %
		Cables	0.32			36 %	4 %	60 %
		Metal mix	2.75	Aluminum	0.56	6 %		95 %
				PCBs	0.23	36 %	0 %	64 %
				Material that did not pass the sieve	0.19	80 %	10 %	10 %
				Copper	0.01	1 %		99 %
				Brass	0.01	1 %		99 %
				Plastics	0.88	36 %	2 %	62 %
				Non-ferrous materials	0.87	37 %	6 %	57 %
Small IT	4.43	Ferrous materials	0.91			2 %	0 %	99 %

		Internal cables	0.01			36 %	4 %	60 %
		Plastics	3.15			36 %	2 %	62 %
		PCBs	0.14			36 %	0 %	64 %
		Batteries	0.08			17 %	25 %	58 %
		Rubbish	0.14			50 %	50 %	

Table 27 Fully manual – mass balance and destination routes

	Weight of the sample (kg)	Output fraction first treatment operator	Total output fraction (kg)	Components/materials	Total output fraction (kg)	Energy recovery (%)	Landfill disposal (%)	Recycled (%)
Laptops	74.94	Batteries	5.32			16.7 %	25.3 %	57.9 %
		Laptops (excluding batteries and displays)	62.77	Hard disk	5.48	1.0 %	0.0 %	99.0 %
				Components and parts	13.50	12.0 %	8.0 %	80.0 %
				DVD	5.45	24.0 %	1.0 %	75.0 %
				Aluminum	9.5	5 %		95 %
				Al/Cu	4.08	1.0 %	0.0 %	99.0 %
				Iron	4.3	1.0 %	0.0 %	99.0 %
				PCBs	6.3	36.0 %	0.0 %	64.0 %
				Plastics	13.3	35.8 %	1.9 %	62.4 %
				Heatsinks	0.6	1.5 %	0.0 %	98.5 %
				Internal cables	0.4	35.9 %	3.8 %	60.4 %
		PMMA	1.5			50.0 %	1.5 %	48.5 %
		Sheets	0.2			50.0 %	50.0 %	0.0 %
		Glass	5.3			0.0 %	68.0 %	32.0 %
Tablets	40.00	Tablets (excluding batteries and displays)	8.50	Aluminum	2.26	5 %	0.0 %	95 %
				Steel	1.40	1.0 %	0.0 %	99.0 %
				Iron	0.97	1.0 %	0.0 %	99.0 %

				Plastics	3.87	35.8 %	1.9 %	62.4 %
		Tablet Displays	23.00	Sheets	1.56	50.0 %	50.0 %	0.0 %
				PMMA	2.14	50.0 %	1.5 %	48.5 %
				Glass	15.40	0.0 %	68.0 %	32.0 %
				PCB	3.70	36.0 %	0.0 %	64.0 %
				Internal cables	0.19	35.9 %	3.8 %	60.4 %
		Batteries	8.50			16.7 %	25.3 %	57.9 %
Game consoles	73.00	Game consoles (excluding heatsinks, PCBs, Hard disks and DVDs)	42.00	Components and parts	12.50	12.0 %	8.0 %	80.0 %
				Ferrous material	15.5	1.5 %	0.0 %	98.5 %
				Plastics	14.0	35.8 %	1.9 %	62.4 %
		Heatsinks	5.50	Aluminum	1.5	5 %		95 %
				Al/Fe	2.0	1.0 %	0.0 %	99.0 %
				Al/Cu	2.0	1.0 %	0.0 %	99.0 %
		PCB	9.50			36.0 %	0.0 %	64.0 %
		Hard disk	3.50			0.6 %	1.6 %	97.8 %
		DVD	12.50			0.6 %	1.6 %	97.8 %

5.2 Annex III: Completeness check Italy. Details of data quality matrix

Table 28 Completeness checks in partially mechanical treatment

PARTIALLY MECHANICAL		
Product in scope	Scope materials and components	Completeness check
Laptops, tablets, game consoles, small IT	LCDs (component or material level)	Covered for laptops, not for tablets
	PCBs	Covered
	Lithium-ion batteries	Covered, c.f. batteries
	Alkaline batteries	Not covered
	Batteries	Covered
	Neodymium Magnets	Not covered
	TPEs/TPUs	Not covered
	Rubber	Not covered
	Plastics	Covered
	"Neat" thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	Only ABS covered in the specific Small IT sample
	GF** thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	Not covered
	FR* thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	May be (partially) covered by heavy plastics fraction in densiometric plastics separation
	Thermosets	Not covered
	Aluminum material	Covered
	Copper material	Covered
	Iron/steel material	Covered
	Magnesium	Not covered

Table 29 Completeness checks fully manual treatment

FULLY MANUAL		
Product in scope	Scope materials and components	Completeness check
Laptops, tablets and game consoles	LCDs (component or material level)	Covered for laptop and tablets, not for game consoles
	PCBs	Covered
	Lithium-ion batteries	Covered, c.f. batteries
	Alkaline batteries	Not covered
	Batteries	Covered for laptop and tablets, not for game consoles
	Neodymium Magnets	Not covered
	TPEs/TPUs	Not covered
	Rubber	Not covered
	Plastics	Covered
	"Neat" thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	Not covered
	GF** thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	Not covered

	FR* thermoplastics (ABS, HIPS, PC, PC-ABS, PET, PC-PET)	Not covered
	Thermosets	Not covered
	Aluminum material	Covered
	Copper material	Covered for laptop and game consoles, not for tablet
	Iron/steel material	Covered
	Magnesium	Not covered

5.3 Annex IV: Results of the analysis of scope materials in the output fractions (Germany)

Table 30 Results of the analysis of scope materials in the output fractions (Germany)

Keyboards													
			Concentrations										
			%	%	%	%	%	%	%	g/t	g/t	%	%
Fractions	%	kg	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	IgL	Recyclable plastics
Cables	6.3	13.2											
Ferrous/iron	18	3											
Silicone mats	1.4	5.2											
Keyboard foil	2.5	38							0.18		3446		
Plastics	70.4	3.2						0.04	0.33	1.9		94.84	91.6
Cu-fraction	1.5	148.6						0.63	6.83	13.6		55.49	
Total	100	211.2											
Mice													
Fractions	%	kg	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	IgL	Recyclable plastics
Cables	31.8	74.2											
Ferrous/iron	1.5	3.6											
Cu-fraction	9.7	22.6	19.96					2.05	7.75	19		49.3	
Plastics	57	132.8						0.019	0.09	1		98.52	91
Total	100	233.2											
Tablets													
Fractions	%	kg	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	IgL	Recyclable plastics
Batteries	24.1	268.8											
Aluminium from manual disassembly	4.7	52											
Steel from manual dismantling	2.2	24.1											
Mixed plastic from manual disassembly	8.8	98.1											
Waste from manual dismantling (glass, foil, etc.)	32.7	364.6											
Fe-fraction	2	21.9		9.19		0.32			2.25	8.4		0.7	
Al-fraction	6.1	68.3	0.28			0.79		0.037	0.28	2.0		2.83	
Cu-fraction	18.6	207.1	13.53	5.09		0.52		0.84	14.48	112		30.43	
Plastics	0.9	10.1	0.38	0.81		<0.005			0.05	3		87.25	41.3
Total	100	1115.00											
Laptops													
Fractions	%	kg	Fe	Al	Mg	Zn	Nd	Sn	Cu	Au	Ag	IgL	Recyclable plastics
Batteries	8.3	1235											
Fe-fraction VAU/Stainless Steel	2.6	394		5.48		0.19	0.018	0.22	4.28	6.9		0.1	
Fe-fraction	15.5	2310		0.74		0.28	0.09	0.05	0.88	2.9		0.85	
Al-fraction	9.4	1400	0.7			0.29	< 0.005	0.09	0.84	3		1.47	
NF 1 Cu-fraction	25.5	3798	0.55	4.42		1.54	< 0.005	0.86	20.4	67.2		38.04	
NF 2 Cu-fraction	14.5	2161	0.83	2.16		0.33	< 0.005	0.37	4.25	57.5		61.07	0.83
Plastics (mix)	14.7	2189	0.5	0.69		0.01	< 0.005	0.03	0.55	1.9		84.59	59.7

Residue from displays (foils, films)	5.4	809	1.83	4.45		<0.005			1.19	14.6		54.1	
Residue	4.1	607	0.55	1.68		<0.005			0.29	1.7		70.26	
Total	100	14903											

5.4 Annex V: Details of data quality matrix for Germany.

Table 31 Details on reliability and completeness check of the data quality matrix

PARTIALLY MECHANICAL							
Product in scope	**Scope materials and components**	**Reliability check**					**Completeness check**
		Material composition of the input batch	Batch being processed relevant to the product being assessed	Yield rate across the whole reprocessing chain (T1 and downstream processes)		Total reliability	
Laptops, tablets, keyboards and mice	Printed circuit boards	-	Not directly found	2 (calculated based on assumption)		2	Covered
	Batteries (split by lithium-ion vs. alkaline if possible)	-	1 Separated from manual dismantling	3 (downstream data + literature data)		3	Covered
	LCDs (component or material level)	-	Not directly analyzed	1 (not recycled)		1	Covered only glass
	Rare earth magnets	-	1 found in output fractions	1 (calculated on analysis results)		1	Covered
	Steel / ferrous material	-	1 found in output fractions	1 (calculated on analysis results)		1	Covered
	Aluminum	-	1 found in output fractions	1 (calculated on analysis results)		1	Covered
	Copper	-	1 found in output fractions	1 (calculated on analysis results)		1	Covered
	Zinc	-	1 found in output fractions	1 (calculated on analysis results)		1	Covered
	Magnesium	--	-	1 (not recycled in current final processing)		1	Covered
	Brass (if distinguishable from copper)	-	2 (calculated, no analyzed)	2 (calculated, no analyzed)		2	Covered
	Plastics that are not recyclable (with or without glass fiber or brominate flame retardants), including thermosets and TPE/TPU	-	1 Plastics mix found in output fractions	No calculated		-	Not covered
	Plastics that are recyclable (with or without glass fiber or brominate flame retardants)	-	1 Plastics mix found in output fractions	Worst case scenario	3 (correctness check)	3	Covered
					1 (safe to use)	1	Covered
				Improved Scenario	3 (correctness check)	3	Covered
					1 (safe to use)	1	Covered