

# WEEE treatment by vertical hammer mill – technological results, economic value and ecological implications

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## Abstract

Resource recovery gains more and more importance from an ecological point of view. Keeping resources in cycles includes the collection, transportation, proper environmental friendly pre-treatment and the delivery towards suitable recovery technologies. The recovery of resources of WEEE is often connected with the complete destruction of products and components in shredding machines, which leads to complex and inefficient post-treatment separation and sorting techniques. The hammer mill technology provides an adequate mean to separate fractions for easier post-treatment processes.

This paper will present the hammer mill technology applied in WEEE treatment, summarize results gained with the technology from a WEEE treatment plant, concludes its advantages. Additionally, economic results and advantages are presented. Finally, environmental implications during operation of WEEE in vertical mill are given.

## Keywords:

Hammer Mill; Recycling Technology; WEEE treatment

## 1 INTRODUCTION

Electric and electronic equipment more and more are found in all kinds of areas of life. The equipment is characterized by a constantly decreasing lifetime due to new product innovations and consumer behaviour. This involves an increasing amount of devices, which accumulate as waste after usage. An environmentally benign recovery of resources by means of recycling and the secure disposal of hazardous waste are goals to be prioritized.

The recycling industry is facing enormous challenges due to the complex composition of the devices and the diversity of the products. Nearly the overall range of elements is applied in electric and electronic equipment. Additionally, a high number of synthetic materials and organic compounds are used and those ingredients are constantly increasing. New concepts and technologies are therefore needed for e-waste recycling.

The production of valuable secondary raw material from e-waste is currently carried out by a combination of expensive manual or partly automated pre-treatment and mechanical recovery processes. New technical solutions are researched in order to raise the ratio of recyclable materials by increased mechanical treatment processes and less manual, expensive pre-treatment work. The vertical hammer mill is able to deal with these challenges.

To gain precise experiences, an on-site experiment was initiated, in which a bigger amount of not pre-treated e-waste was directly put into mechanical treatment processes. The on-site experiment was accompanied by emission and exposure measurements as well as by sampling and chemical analysis of solid assays to give evidence about the appearing pollution.

Goals of the on-site experiment were:

- the verification of prescriptive environmental limits from supervising authorities,
- the applicability of a vertical hammer mill for the mechanical treatment of not pre-treated e-waste and
- the improvement of the overall e-waste treatment processes in the facility.

In the focus of this paper, the overall treatment process for the on-site experiment and the applied hammer mill technology for the mechanical disassembly of e-waste is presented. The experiment is shown and economical and ecological results presented.

## 2 REFERENCE PROCESS AND HAMMER MILL

The company Solenthaler Recycling AG, St. Gallen, Switzerland, is providing their equipment and facility for these experiments – the applied treatment processes are shown in Fig. 1.

The e-waste is feed to the vertical hammer mill by means of a conveyor belt. The hammer mill is crushing the e-waste and causes the mechanical disassembly of the material compounds. The resulting mixture is freed from lighter materials in the zigzag wind sifter. It contains besides others plastics, glass, ceramic, wooden materials, rubber, paper, dust and small metallic parts. The air inlet to the zigzag wind sifter is also applied to clean the hammer mill from dusts and lighter materials. Both air streams go to a cyclone, where the dust is separated from materials with higher density and grain size.

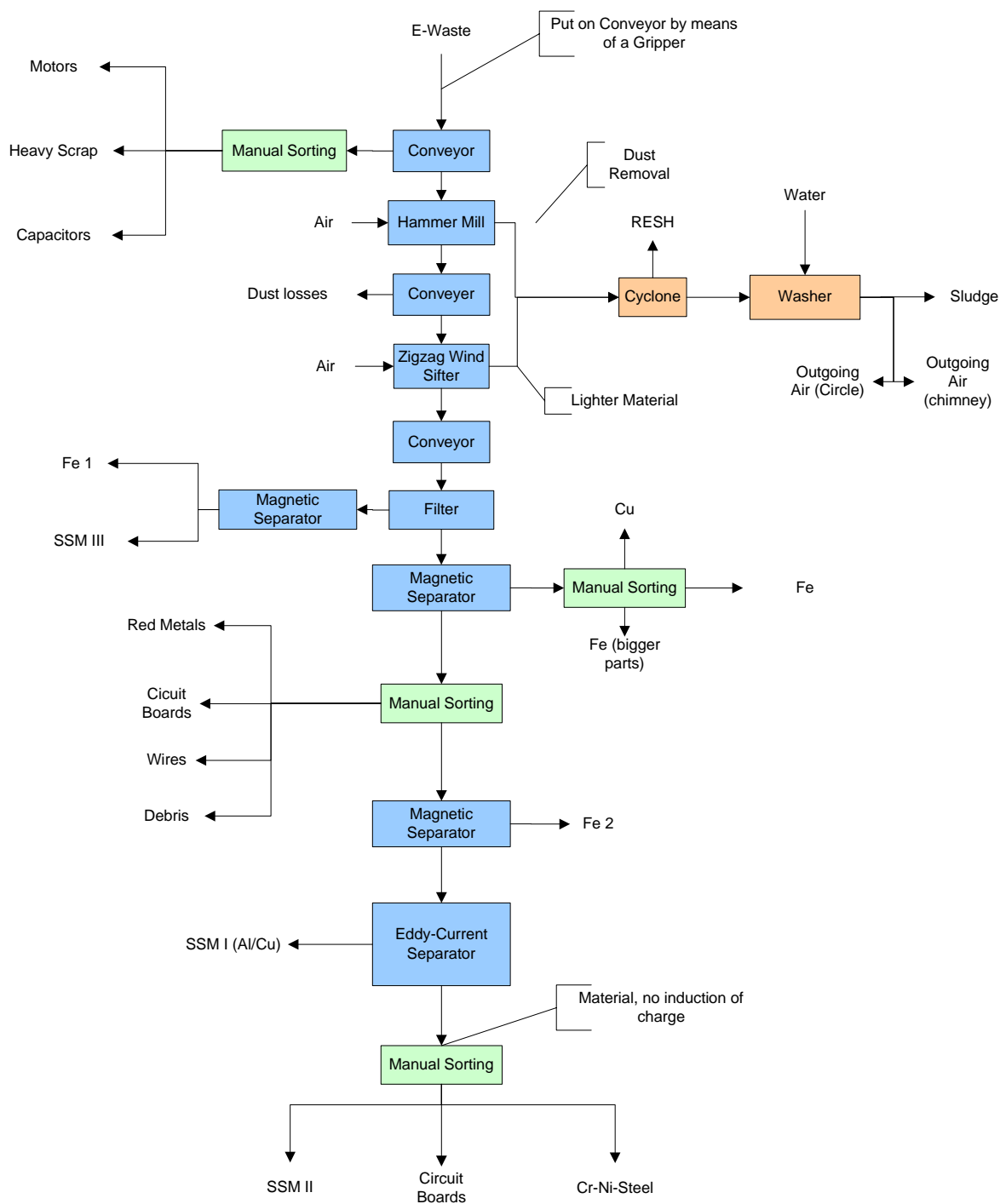


Figure 1: Reference Process Solenthaler Recycling AG, Switzerland

The other material from the wind sifter (heavier materials) falls on a conveyor belt, where in the next step a filter separates smaller and bigger particles. The smaller particles are further separated into ferrous and a non-ferrous materials by a magnetic separator.

The main material stream, consisting of parts with bigger grain sizes, is separated by a bigger magnetic separator into

a ferrous and into a non-ferrous production line. At both lines, a manual post sorting takes place. With 50%, the ferrous material is the biggest fraction that is generated out of the input.

At the non-ferrous line, a further separation of ferrous and non-ferrous materials is done by the application of further magnetic separator and an eddy-current separator . The

eddy-current separator collects activated non-ferrous metals e.g. copper, or aluminium. From the remaining fraction, the Cr-Ni steel is separated manually because it cannot be activated.

### 3 VERTICAL HAMMER MILL

For the crushing of the e-waste during the on-site experiment, a vertical hammer mill M 500-L from the company Henschel Recycling Technology (HRT) with a throughput of max. 15 mt/h was applied. An overview of the technology is provided in Fig. 2.



Figure 2: Hammer mill during maintenance activities.

The material is dropped into the mill on the top and falls down to the milling area. The milling area consists of a rotor and three different milling levels. Each milling level consists of two times six so-called ring hammers. The housing of the mill is coated with abrasive metal plates for easy exchange. The metal plates support the milling process by their specific form.

The material falls through the mill from the very top to the bottom and is beaten by the hammers against the housing of the mill. Due to the impact, the material is crushed into smaller pieces. Additionally, bigger metal parts are deformed into a more compact form. The distance between the hammer and the outer housing is getting less towards the bottom of the mill – a step-wise crushing is therefore supported. In the case of the experiment, the distance is set to 10 cm.

The dwell period of the input material is depending on its form: flat material like PCB's or housing plates might fall through the mill very fast without being crushed. Bigger parts are falling slower through the mill as they need to be crushed as long as they fit through the distance of the hammers and the mill housing.

Due to the impact, especially composite materials with different material characteristics are easy to separate in the vertical hammer mill.

### 4 ON-SITE EXPERIMENT

In the following, the on-site experiment will be presented. Goal of the examination and the laboratory supervision of the mechanical treatment of e-waste are the identification and discussion of

- the fulfilment of legislative and regulative authorities,
- the potential appearance of hazardous substrates in valuable fractions and residues,
- the relation of input materials containing hazardous respectively containing hazardous materials to the output material,
- forecast of future pre-treatment towards hazardous materials and components,
- the distribution of valuable materials in the output fractions.

The supervision and analysis were executed by a certified laboratory and the EMPA (Material Science and Technology) Foundation [1]. The EMPA is applying the legislative frame for the supervision coming from the SWICO system [2]. Additionally to the supervision of the hazardous substrates, an evaluation of the treatment, sorting and cleaning possibilities of the overall process and facility was in the focus of investigation. The results of the experiment give evidence for the ecologic impacts of the applied treatment processes.

#### 4.1 Experimental Set-up

The system boundaries for the on-site experiment are shown in Fig. 3. About 60 metric tons of not treated e-waste are used as input materials. Table 1 presents an overview of the products in the input stream.

Type of Device	Ratio (%)	Average Age (years)	Max. Age (years)
PC	47.6	7	10
Fax	3.2	4	6
Printer	23.8	5	7
Copier	15.9	5	7
other	9.5	2	10

Table 1: Overview of the input stream

#### 4.2 Sampling and Analytics

The framework for the sampling and the analytics are:

- Qualitative and quantitative determination of the fractions during the mechanical treatment,
- Determination of the fractions along the treatment and sorting processes,
- Determination of the hazardous substances in the fractions,
- Determination of the valuable materials in the fractions,
- Determination of the material and energy flux for the ecologic evaluation of the treatment process.

For the determination of the valuable and hazardous material contents, the on-site experiment was accompanied by a comprehensive measurement program. Solid samples were taken at three different reading points.

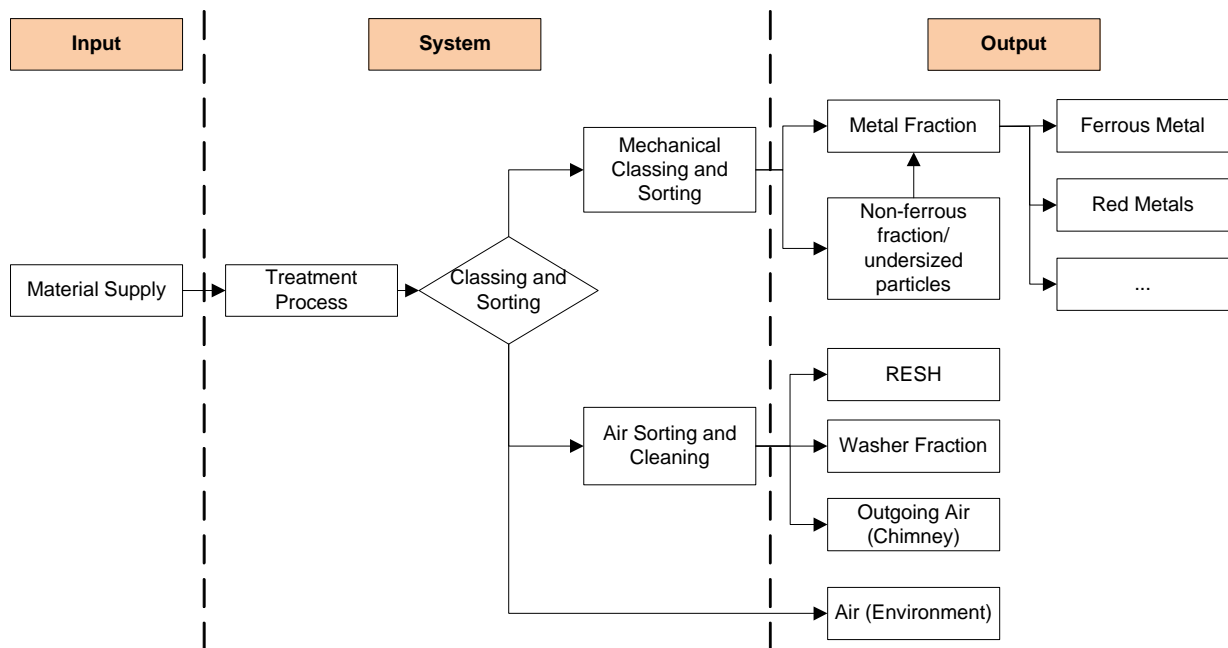


Figure 3: System Boundaries

Criteria for selection of these points were the assumed pollution with hazardous substances (based on plastics) and the feasibility for the sampling (grain size)

At the vent stack, measurements on hazardous emissions and nearby the manual workplaces, exposure measurements with focus on hazardous substances were executed. These measurements were planned together with the supervising laboratory. A summary of the sampling and analytics is given in Table 2.

### 4.3 Execution

The experiment was executed in one day beginning on 8 am and finishing at about 4 pm. In the beginning, all conveyor belts, boxes and treatment equipment was cleaned and freed from material rests. Shortly after the beginning, first samplings were taken from the respective measurement points according to the determined measurement plan, shown in table 2.

Altogether, the fractions RESH and non-ferrous undersized particle were sampled twelve times during the experiment. From each of these single samples, an experiment sample was created as a mixture of all single samples – ensuring that each single sample is represented with the same weight by a scale. The final samples were shredded into 1 to 2 mm grain size fractions for the chemical analysis in the laboratory.

In parallel to the solid samples, the emissions and exposure measurements were executed according to the plan in Table 2.

All fractions generated by the treatment process were collected in cleaned boxes and stored separately for weighting. The fractions are presented in Table 3:

<b>Metal fraction from mill</b>	<b>27.980 kg</b>
<b>Cu (wires and coils from manual sorting)</b>	<b>3.960 kg</b>
<b>Cr-Ni-Steel</b>	<b>420 kg</b>
<b>SSM I (Al/Cu)</b>	<b>3.840 kg</b>
<b>SSM II (non-ferrous undersized grain)</b>	<b>9.590 kg</b>
<b>SSM III</b>	<b>3.830 kg</b>
<b>Fe 1 (small ferrous parts)</b>	<b>510 kg</b>
<b>Fe 2 (ferrous bef. eddy-current separator)</b>	<b>1.570 kg</b>
<b>Circuit Boards 1 (manual sorting III)</b>	<b>590 kg</b>
<b>Circuit Boards 2 (manual sorting IV)</b>	<b>127 kg</b>
<b>Heavy scrap (before mill)</b>	<b>240 kg</b>
<b>E-motors (before mill)</b>	<b>590 kg</b>
<b>RESH</b>	<b>3.890 kg</b>
<b>Wires (manual sorting III)</b>	<b>360 kg</b>
<b>Coils, red metals (manual sorting III)</b>	<b>430 kg</b>
<b>Debris (manual sorting III)</b>	<b>147 kg</b>
<b>Capacitors (before mill)</b>	<b>15 kg</b>
<b>Large ferrous parts (manual sorting II)</b>	<b>420 kg</b>
<b>Sludge (approximated water content 50)</b>	<b>6 kg</b>
<b>Dusty losses (approximated)</b>	<b>20 kg</b>

Table 3: Produced Fractions.

The energy consumption during the experiment was measured by means of the process control system. Based on power data of the system components, the ratio of the energy

use in comparison to the overall energy consumption could be determined.

Reading Point	Measurements
Non-Ferrous undersized particles, (solid sample)	<ul style="list-style-type: none"> <li>• Entry of qualities</li> <li>• Sampling and analytics: <ul style="list-style-type: none"> <li>• Half-hour sampling, firstly one hour after start</li> <li>• Generation of final sample based on single samples</li> </ul> </li> <li>• Analyzed: Au, Ag, Pt, Pd, Pb, Ni, Cd, Hg, Cr, Sn, Cu</li> </ul>
RESH (Shredder Residue) (solid sample)	<ul style="list-style-type: none"> <li>• (same as above)</li> <li>• Analyzed: Au, Ag, Pt, Pd, Pb, Ni, Cd, Hg, Cr, Sn, Cu, PCB</li> </ul>
Washer (sludge)	<ul style="list-style-type: none"> <li>• Entry of qualities</li> <li>• Sampling and analytics: <ul style="list-style-type: none"> <li>• One sampling at experiment end</li> <li>• Generation of final sample based on single samples</li> </ul> </li> <li>• Analyzed: Au, Ag, Pt, Pd, Pb, Ni, Cd, Hg, Cr, Sn, Cu, PCB, PCN, PBDE, Cl, Br, EOX</li> </ul>
Remaining fractions (solid samples)	<ul style="list-style-type: none"> <li>• Entry of qualities</li> <li>• Determination of material composition</li> </ul>
Outgoing air (chimney)	<ul style="list-style-type: none"> <li>• Emission measurements, 3 times: <ul style="list-style-type: none"> <li>• Late morning, early afternoon, afternoon</li> </ul> </li> <li>• Analyzed: dust, dust contents (Pb, Ni, Cd, Hg, Cr, Sn, Cu), Hg (gaseous), PCB, gaseous carbon</li> </ul>
Air (nearby manual workplace)	<ul style="list-style-type: none"> <li>• Exposure measurement, once over 5 to 6 hours,</li> <li>• Analyzed: dust, dust contents (Pb, Ni, Cd, Hg, Cr, Sn, Cu), PCB</li> </ul>

Table 2: Overview of the measurements

## 5 RESULTS

The existing facility was examined with respect to its applicability for the mechanical treatment of waste from electric and electronic equipment. Besides that, an assessment of the produced production quality was carried out.

The treatment and sorting process of the complete mechanical treatment (no manual pre-treatment) with support of the hammer mill has pointed out clear advantages and disadvantages.

Due to the minimization of the manual labour/manual disassembly, cost reduction potentials can be utilized. These costs can include labour, logistic, and storage costs and maybe also some operational costs (power, heating).

High throughput rates with e-waste can be utilized by means of the applied hammer mill. Disadvantageous remains the

fact, that not all products/components can be mechanically disassembled.

Essential seems to be the possibility to treat a very high amount of material in a very short time. The hammer mill is not fully utilized with e-waste during the experiment. Its production capacity allows bigger amounts to be treated. Also, the crushing power of the mill during the e-waste experiment exceeds all expectations from the operating company and the mill producer. Despite all critics, the expected fraction generation could be fulfilled.

Additionally, the outgoing air at the mill chimney is not polluted over the legislative limits – despite the fact that the installed applied air purification equipment is not the newest.

Inadequately seems to be the dust separation of the facility – the exceeding of MAK (“Maximale Arbeitsplatzkonzentrationen” – max. concentration at workplaces) values for dust and lead nearby the manual workplaces is requiring adaptations.

Bottlenecks in the facility during the on-site experiment with e-waste are the downstream classing and sorting operations, since they are currently designed for the treatment of ferrous mixtures at the Solenthaler facility.

The manual sorting effort rises due to the diversity of materials with the e-waste input. The sorting operations do not reach the known quality of the normally applied input from ferrous mixtures. The workers hardly could sort the materials at the workplaces due to the chosen high throughput during the experiment.

Basically, all fractions are recyclable materials and the hazardous contamination of the fraction within limits, potential carriers of hazardous substances (PCB parts, capacitors) are not crushed during the operation, but just simple dented or torn off the ground materials. They can easily be separated in further treatment steps.

### 5.1 Ecologic results

The results of the supervising laboratory are given in Table 3. The numbers include the emissions at the outgoing air chimney. The detailed analysis and the inspection certificates are available, but cannot be presented in this paper.

The laboratory results are compared to the given limits by legislative authorities (air pollution prevention).

All substances that are listed in the prevention act are below the given limits during the treatment of e-waste in the Solenthaler process. No limits are given for Polychlorinated Biphenyls (PCB) from the legislative frame, since its use in new product is already prohibited by the local material regulation.

For dust, which is emitted to the environment, hazardous limits are given by the SWICO for cadmium (1 mg/kg) and PCB (50 mg/kg). In addition, the pollution of mercury in the dust emission should be determined during the experiment. In relation to the dust content of the air of average 19,7 mg/m<sup>3</sup>, a pollution of less than 0,51 g/kg for Cadmium and mercury and 45,3 mg/kg for PCB result from the measurements.

In summarization, both limit values given from the SWICO system can easily be fulfilled during operation with untreated e-waste.

Substance	Measurement, averaged [mg/m <sup>3</sup> ]	Measurement, averaged [g/h]	Limit (Air Pollution Legislation) [mg/m <sup>3</sup> ]	At a mass flow of [g/h]
Dust/solid materials	19,7	390	50	≥ 500
Pb, Lead and its compounds	0,42	9,66	5	≥ 25
Cu, Copper and its compounds	0,013	0,31	5	≥ 25
Cr, Chromium and its compounds	< 0,01	< 0,2	5	≥ 25
Sn, tin and its compounds	< 0,01	< 0,2	5	≥ 25
Gaseous, organic materials (carbon)	5-11		50	
Ni, Nickel and its compounds	< 0,01	< 0,2	1	≥ 5
Cd, Cadmium and its compounds	< 0,01	< 0,2	0,1	≥ 0,5
Hg, Mercury and its compounds	< 0,01	< 0,2	0,2	≥ 1
Polychlorinated Biphenyl (PCBs)	0,00089	0,02	prohibited	-

Table 3: Comparison of the emission test results with air pollution legislation as an example for ecologic results

SWICO also implies a limit of 0,05 mg/m<sup>3</sup> for the pollution with mercury in the ambient air. Within the exposure measurements, no mercury could be identified in the ambient air during the whole experiment (detection limit: 0,01 mg/m<sup>3</sup>). The requirements of SWICO towards the mechanical treatment can be fulfilled in this point.

Further details on the environmental friendliness cannot be provided in this short summary, but are available upon request.

## 5.2 Economic results

Simply said, it is worth to substitute manual disassembly operations by mechanical treatment processes by means of a hammer mill. However, the quality of the resulting fractions can be improved if single manual disassembly operation are carried out at specific product groups.

The manual disassembly should focus on the extraction of high valuable printed circuit boards mostly coming from PC's. They contain the most valuable materials but also a very high amount of hazardous wastes. If they are manually disassembled, the resulting contamination of fractions, dusts and sludge with hazardous substances can be reduced. The manual disassembly of the other products e.g. brown and white goods, does not seem to be reasonable. The reduced manual disassembly effort will lower the costs significantly.

Some of the produced fractions are requiring further treatment (SSM I, II, III), in order to gain the most maximum value out of it. RESH can be easily disposed for normal costs. In the case of mechanical treatment of e-waste in the hammer mill, no additionally fees are expected due to possible exceedance of contaminant loads.

## 6 SUMMARY

For gaining experiences in the mechanical treatment of e-waste without prior disassembly, an on-site experiment with the help of Solenthaler Recycling AG, Gossau (SG), Switzerland, was initiated. During the experiment, about 60 metric tons of untreated waste from electrical and electronic components were treated in the existing facility.

During the experiment, several monitoring activities for the determination of hazardous materials in the air (emission, exposure measurements) in the solid fractions as well as the determination of the valuable content in the produced solid fractions took place.

As a result, the mechanical treatment of e-waste without any pre-treatment seems to be reasonable with the vertical hammer mill technology.

## 7 REFERENCES

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