CRM Raw Material Recovery Trials Evaluation Report (B1 &B2)

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1. Project Overview

Each year around 9.9 million tonnes of waste electricals and electronic equipment (WEEE) is generated in the EU. Only 30% of WEEE generated is reported as properly collected and recycled. Many modern electrical and electronic products contain metals which have been classified as Critical Raw Materials (CRMs) by the EC. CRMs are those where supply and their economic impact to the EU is at risk and higher than for other raw materials.

WEEE contains a high proportion of valuable resources, including precious metals such as gold, silver and platinum group metals which have been classified as Critical Raw Materials (CRMs). These CRMs are crucial to the production of many electrical products and the increasing pressure on their supply is a growing economic concern for businesses and governments. However, many CRMs appear in products in such low quantities, that their recovery is not commercially viable. As a result, most CRMs are virtually unrecovered from WEEE. The high losses of CRMs are attributed to the current collection and recycling arrangements. In the UK, WRAP undertook work to explore the viability of recovery of critical raw materials and precious metals from WEEE, by mapping product and material flows and looking at critical technologies and hotspots blocking progress. This work highlighted the need to find a solution which spreads much further than the UK.

The Critical Raw Material Closed Loop Recovery (CRM) project was therefore developed to take forward this work in partnership with experts and practitioners e.g. collectors and recyclers from across Europe.

1.1. Aims and Objectives

The primary aim of the CRM project is to demonstrate economically viable approaches to both the collection and recovery of CRMs that will increase the recovery of target CRMs by 5% by 2020, and that will continue to increase CRM recovery to 20% by 2030. Due to the commercial sensitivities detailed data pertaining to the cost of the trials have been omitted from this report.

The vehicle for this demonstration was delivery of several industry trials, which tested a range of collection and recovery mechanisms, together with detailed analysis of the material, economic and socio-economic outcomes from the trials, to ultimately develop policy and infrastructure recommendations for both the trial host countries and Europe aimed at increasing the collection of WEEE and the recovery of associated valuable CRMs.

Based on research conducted by the CRM project partners, which identified those CRMs and rare earth metals with both the highest value and concentration, and the products in which they are found in the greatest volumes, the following products and materials were the focus of the collection and recovery trials:

Target Product Categories:

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- Display, Consumer Electronics;
- Information and Communication Technologies (ICT); and
- Small Household Appliances

Target Materials:

- Graphite;
- Cobalt;
- Antimony;
- Tantalum
- Silver;
- Gold; and
- Platinum group metals (PGMs).

2. Introduction

This report provides a synthesis of outcomes from the 5 collection and recovery trials undertaken in Germany, Italy, Czech Republic, and UK, as part of the CRM Recovery project. Information gathered during the trials has informed findings in key project deliverables including those for work packages C1, C2 (monitoring and evaluation), B3 and B4 (policy and infrastructure plans). To avoid duplication of effort and content across these deliverables, the focus of this document is on the following project elements:

Stage 1 Collection Trials: To facilitate fulfilment of deliverable B1, a literature review and desktop study was conducted, to determine a range of potential collection mechanisms for inclusion in the trials (See Appendix 1). A subsequent matrix of collection methods was produced (see Table 1 below), which prioritised the following collection activities for inclusion in the trials:

Table 1 : Priority Collection Activities

Highest Priority	**Retailer Takeback; Incentivised Returns**
↓	Collection events; business collections; third sector donations; bulky waste collections
	Kerbside collections; recycling centre collections
Lowest Priority	Postal returns; house clearance

This work fulfilled the requirements for project deliverable B1, and made up part of the evidence for the collection activities as part of Progress Report 1 which was submitted on the 28th February 2016.

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The trials included a range of collection mechanisms and focused on recovery of CRMs in line with the waste hierarchy (e.g. prioritising product re-use, repair and remanufacturing activities over recycling and reprocessing). A key element of this work was the aggregation of CRM-rich and high value materials, to create commercially viable collection mechanisms. During the collection trials, communications were also tested and, where feasible, socio-economic impact data for subsequent work packages was collected.

Stage 2 Recovery Trials: To facilitate fulfilment of deliverable B2, EARN completed a desktop and literature study and process map into recovery mechanisms. These were used to agree on the recovery activities that would be completed as part of the trials. (See Appendix 2). Of the products collected, items suitable for re-use were separated out, and any remaining products were disassembled to target key components, and then prepared for component re-use or further reprocessing. The recovery trials, which included mechanical, microbial, and chemical technologies, were then conducted, to understand the impact on the CRM recovery techniques from changes made in the collections, pre-sorting, and concentrating activities, and approaches to target material recovery.

During the first CRM Recovery Project Stakeholders Group meeting (held on the 26th January 2016), WRAP consulted with the group on the proposed methodology for the collection and recovery trials. Feedback gained from stakeholders identified issues which would affect successful delivery of the trials, in particular relating to: the shipment of waste across borders; regulatory requirements; and associated and potentially prohibitive costs in relation to the trials budget. This feedback resulted in the decision to combine the collection and recovery trials, as agreed with Neemo during March/April 2016. This revised methodology required potential trial hosts to propose a supply chain approach that would be integral to their proposed trial, rather than the CRM project partners facilitating supply chain development and resulted in a much more efficient means to deliver the trials.

2.1. Trials Selection

An internal trials working group comprised of representatives from WRAP, EARN and Wuppertal Institute was convened, with the task of defining and agreeing the tender scope, assessment criteria, responding to tender enquiries, and evaluating tenders received. In addition, during the first Stakeholders Group meeting (on the 26th January 2016) consultation was undertaken regarding the proposed methodology for the collection and recovery trials. As a result of feedback gained from stakeholders, which identified issues that would affect delivery of the trials and increase costs of the trials relating to the shipment of waste, potentially across borders, and regulatory requirements, the decision was made to combine the collection and recovery trials. This methodology required potential trial hosts to propose a supply chain approach integral to the proposed trials, rather than the CRM project partners facilitating supply chain development, and this resulted in a much more efficient means to deliver the trials.

Collection and recovery trials were competitively tendered across 4 countries (Lots), between 11/02/16 and 07/04/16. Copies of each of the Invitation to Tenders (ITTs) received can be found in the relevant project folders. Forty eight organisations downloaded the ITTs

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(see Table 2 below), representing industry and consultancies across all four target host countries.

Table 2: Tender Downloads by Type of Organisation and Country

	Number of Downloads			
Organisation Type	UK	Italy	Germany	Turkey (changed to Czech Republic
Asset management	4			
Consultancy	14			4
Waste management	11	4	1	2
R and D	3	1	1	
Other	1	1		1
Totals	33	6	2	7

Five organisations submitted tenders to participate in Lot 1 (UK) and Lot 3 (Italy). Contracts were awarded to Axion and Re-Tek for Lot 1 and to Ecodom for Lot 3.

However, no tenders were received for Lots 2 and 4 (Germany and Turkey). Following review by the trials working group, it was agreed that additional supplier engagement was necessary for Lot 2 (Germany). Six organisations were identified and invited to participate in a selected tender procedure. This call opened in September and closed on 26/10/2016. Following independent assessment and panel assessment during a meeting held on 14/12/2016 and attended by ERP, KTN, WRAP, QSA Partners and EARN, the Recycling-Börse proposal was identified as the successful tender.

During development of the procurement strategy for the trial in Turkey, a coup was attempted, and a 3-month state of emergency was announced (21/07/16) for Turkey. As the personal safety of the project team was paramount, and the on-going political uncertainty created uncontrollable risks to the successful completion of the trials, a request was made to the EC to change the location of this trial to another country. Data on volumes of electronics manufacturing and WEEE arisings in other EU countries was analysed and the strengths of EARN, ERP and KTN's networks reviewed to identify a suitable alternative for the Turkish trial. The Czech Republic and Slovakia were identified as countries which scored favourably on each criterion. The proposal to change the trial site was submitted to the Commission (Appendix 3) on 10/10/16 and agreed (11/10/16).

The subsequent call for tenders was open between 21/11/16 and 16/01/17. WRAP, EARN, ERP and KTN communicated extensively with their networks to promote the call and engaged with 24 organisations and networks. Following assessment by panel, the decision was taken to award to tenderer ASEKOL a.s. on 07/03/17.

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Trials activities began in May 2016 and were completed by March 2018. As the procurement took place over a series of time, and each trial had a different methodology, requiring differing time frames, the start and end dates of the trials were staggered. This benefited the project team, as a steady flow of activity took place which made the allocation of resources and task delivery easier to manage than if all the trials had started and completed simultaneously.

3. Collections Trials Summary

3.1. Description

The aims of the collection trials were to test mechanisms to maximise the collection of target WEEE (Display, Consumer electronics, ICT and small household appliances), i.e. those products with the highest concentrations of CRMs, and to collect data to facilitate evaluation of how the different approaches to collection impacted on the re-use and recovery of CRMs, and the socio-economic impact analysis of the trials (project action C2). This section summarises the collection trials, and details the 10 collection activities undertaken by the (5) trial hosts. The information below provides an overview of each collection trial. Detailed findings from the collections trials can be found in the individual trial reports, and summary reports.

3.2. UK Trials

Two trials were undertaken in the UK, led by Axion Ltd, a consultancy based in Manchester, and Re-Tek, an IT Asset Management company and AATF, located outside Glasgow.

3.2.1. Axion Collections Trial

Table 3: Axion Trial Summary

Trial Host	Axion – United Kingdom
Trial Partners	Dixons Carphone, British Heart Foundation, John Lewis
Target Products	ICT and consumer electronics – specifically targeting data bearing devices
Target CRMs	Cobalt, Antimony, Tantalum, Rare Earth Metals, Platinum Group Metals, Gold, Silver, (Tin and Copper – not CRMs)
Website Link	http://www.axionconsulting.co.uk
Collection Activity 1 *Charity Electricals Take-back at British Heart Foundation Stores and Online Platform* In-store collection of electricals for re-use and recycling. Electricals that were suitable for re-use were to be sold via the British Heart Foundation eBay site. Items not suitable for re-use were to be dismantled by E3 Recycling, and the printed circuit boards (PCBs) extracted for the recovery trial. The collections campaign was supported by	

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communications and surveying.	
Details	Nov 2016 – Apr 2017 Greater Manchester – Sale, Salford, Cheetham Hill, Harpurhey (UK)
Collection Activity 2 *Retail Electricals Take-back at Dixons Carphone Stores* In-store collection of unwanted electricals for re-use and recycling. Electricals were to be assessed for re-use by E3 recycling. Any items not suitable for re-use were to be dismantled and the PCBs extracted for the recovery trial. The collections campaign was supported by communications and surveying.	
Details	Feb 2017 – Jun 2017 Greater Manchester – Stockport, White City, Cheetham Hill, Bolton (UK)
Collection Activity 3 *Incentivised Electricals Take-back at John Lewis Stores* In-store collection of unwanted electricals for re-use and recycling. Customers were offered the incentive of free data wiping (usually £30). This trial partnered with the British Heart Foundation for the selling on of re-usable electricals. Any items not suitable for re-use were to be dismantled and the PCBs extracted for the recovery trial. The collections campaign was supported by communications and surveying.	
Details	Jun 2017 – Aug – 2017 York and Leeds (UK) and Leeds (UK)

The Axion collections trial focused on retailer take-back of data-bearing devices and worked with The British Heart Foundation, John Lewis and Dixons. Collections took place in Greater Manchester, York and Leeds. This trial was unique in that it tested and compared take-back through High Street retailers and the UKs largest charity retailer. The Axion trial also tested the use of incentives to increase product returns and collected data on the sales revenue earned from re-used products collected through the various collections methods, to facilitate return on investment (ROI) evaluation.

The collection phase was split into three separate trials to assess different means of engaging with and encouraging UK consumers to recycle their unwanted WEEE:

1. Retail take-back service with DixonsCarphone at five Currys PC World stores in Greater Manchester;
2. Charity donation trial with the British Heart Foundation at four furniture and electrical stores in Greater Manchester; and
3. Incentivised retailer take-back service at two John Lewis stores (Leeds and York).

Each trial focused on the following items:

- Games Consoles;
- Tablets;
- Cameras;

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- External hard drives;
- Laptops;
- Modems/ wireless routers;
- PCs;
- DVD/ Blu-ray players.

As part of the collections phase, customer surveys were carried out with consumers in each of the trial partners' stores at staggered intervals throughout the trial period. These surveys questioned respondents on their past handling of WEEE and their current preferences for disposing of EEE items. Results of the surveys found:

- Consumers are becoming more aware of data security and they are more likely to trust high street retail brands than charities to handle their data securely.
- Most of the customers stated that they would find using high street and charity retail take-back schemes very convenient to recycle their WEEE.
- Most respondents agreed that disposing of their WEEE through take-back schemes was good for the environment.
- Respondents said that they rarely disposed of WEEE and very few had disposed of more than two items in the previous 12 months.
- Consumers indicated that personal EEE items such as smartphones, tablets and laptops were often hoarded as they are easily stored out of sight and are therefore less of a priority for disposal.
- Respondents commented that data security was a factor in their decision to hoard these items.
- Personal EEE products were most likely to be re-used either through resale or passing on to family or friends.

The trials at John Lewis and DixonsCarphone stores accepted items in any condition. The British Heart Foundation trials only accepted items that were of good enough quality to be re-used. Almost 0.7 tonnes of WEEE was captured across the collections, of which 86% was ICT. The summary below provides detail of the number of items collected:

- 302 items were collected by the trial partners. Three quarters of all the items collected were six years old or more and around a third (110 items, 35%) of all the items collected were suitable for re-use.
- The proportion of WEEE items aged 6 years or more that were donated to the BHF and Dixons was much higher (81% and 72% respectively) than those donated to John Lewis, 48%.
- Almost two thirds (193 of 302) of all items collected by all collection partners were donated to the British Heart Foundation but only 19% of items were deemed suitable for re-use.
- Very few smartphones were donated to the trial. This may be because there are well established incentivised recycling schemes already in place which are more appealing than donating a device or returning it to a store for recycling.

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Of the two EEE categories (laptops and PCs) that were arising from both sources, John Lewis devices appeared to achieve greater resale value, this is likely due to these items being newer and therefore not experiencing as much depreciation. Overall, the average resale value of John Lewis items was higher than that of BHF items, again, likely due to the difference in age of items arising at each source. Lessons learned from Axion collection trials were as follows:

- Ensuring all staff were engaged proved difficult, staff attendance at training sessions was limited due to shift patterns.
- Having a "recycling champion" at each trial partner store to take responsibility for the day to day implementation of the scheme who encouraged members of staff to follow the trial procedures proved invaluable to trial. This also helped to maintain continuity between different shifts.
- Anecdotal evidence from consumers during surveys indicated that there was a general lack of awareness of the correct WEEE disposal routes for older devices. Respondents were more inclined to hoard these items, saving them as backups in case their newer devices stopped working.
- High street retailers and charities offer highly convenient and trusted locations for the general public to deposit WEEE.
- Retailers invariably have good logistical processes in place and therefore using these systems to backhaul captured EEE to a central processing facility may be an economically viable means of preventing CRMs from being lost to landfill or incineration through incorrect disposal routes.
- Selling secondhand EEE through the BHF eBay site was a very successful means of achieving value for older devices. eBay is traditionally seen by consumers as a place to get good deals on second hand items and many high street retailers already have a presence on the site.

3.2.2. Re-Tek Collections Trial

The collection models trialed by Re-Tek were developed to provide consumers with the opportunity to drop-off unwanted electrical and electronic appliances at a time and place that suited them, to reduce hoarding of potentially valuable resources. These hubs were also designed to minimise product damage and encourage drop-off. Communications used during the trial were also evaluated for effectiveness. The Re-Tek collections trial is summarised below.

Table 4: Re-Tek Collections Trial Summary

Trial Host	**Re-Tek – United Kingdom**
Trial Partners	Enscape
Target Products	Display equipment, ICT, consumer electronics
Target CRMs	Cobalt, Gold and Silver
Website Link	http://www.enscape.eu/what-we-do/criticalrawmaterials/

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Collection Activity 1 *Employee Amnesty* Amnesty periods where employees could bring household unwanted electricals to be collected via the business WEEE collections. This scheme operated across 2 private companies, 2 not-for-profit organisations, 1 local authority and 3 social enterprises. Items that were suitable for re-use were sorted by Re-Tek and had the data wiped. Items not suitable for re-use had the printed circuit boards removed for the recovery trial and the remaining product was recycled.	
Details	Sep 2016 – Jan 2017 Various locations across Scotland
Collection Activity 2 *Household Waste and Recycling Centres* Containers for housing re-usable WEEE were placed next to the existing containers for standard WEEE collections (which focus on recycling and disposal rather than re-use). Residents and site staff were then able to keep potentially re-usable electricals separate to help preserve quality. These items were then assessed for re-use by Re-Tek.	
Details	Sep 2016 – Jan 2017 Cumnock and Kilmarnock (UK)
Collection Activity 3 *School Collection Hubs* Schools were invited to become safe donation points, enabling parents to securely donate unwanted equipment into schools. These items were then assessed for re-use by Re-Tek.	
Details	Sep 2016 – Jan 2017 Cumnock and Kilmarnock (UK)
Collection Activity 4 *Unite Halls of Residence* The concierge at the Unite Halls of Residence acted as a collection point for any waste electricals from students at the end of the winter term and the start of the spring term. Leaflets were distributed across all students in the Halls. Re-Tek collected the containers and assessed electricals for re-use.	
Details	Dec 2016 – Jan 2017 Unite Halls of Residence – Durham, Newcastle, Edinburgh, Glasgow (UK)

The Re-Tek trial included the following collections mechanisms:

- Re-use containers at two Household Waste Recycling Centres (HWRCs)
- Employee amnesty collections at six businesses
- Two collection hubs at schools
- Six collection hubs at University Halls of Residences
- Linking with two Social Enterprise organisations, as collection partners.

The type of equipment sought was functional ICT as listed below:

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• Laptops • Desktop/Inkjet Printers • Compact Digital Cameras • Computer Components • Networking Items • Digital Set Top Boxes • Gaming Devices	• Misc. Audio/Video Devices • Personal computers • Tablets • Flat Screen Monitors • Flat screen Televisions • Mobile Phones • New Printer Cartridges

Key findings from the Re-Tek collections trials are as follows:

- ICT collected from Schools had the highest re-use level, at 25.4%, followed by Social Enterprise collections (23.4%), B2B (15.7%) and finally Household Waste Recycling Centres (HWRCs) (11.5%).
- Although school collections had the highest levels of re-use, the largest numbers of units collected were from HWRCs.
- The type of collection system appeared to influence the types of equipment deposited e.g. high percentages of printers were deposited at HWRCs and higher levels of data-bearing equipment at schools e.g. laptops. This indicated that it may be of benefit to set up collection schemes in a range of locations to give individuals a choice.
- Across all collection points, the equipment donated was generally within the 3 to 6-year age range.
- Setting up collection schemes to enable re-use was a labour intensive exercise, discussions took place over months, rather than weeks as was anticipated at the outset of the project.
- Informal feedback from the public and participating organisations was very positive.
- Feedback, in terms of why items were typically being hoarded, related to a lack of knowledge concerning what should be done with functional, but unwanted, technology; there were felt to be limited options. This was coupled with fears about data security, which meant that with the small-size of items it was a straightforward decision to hoard items.

A range of communications and marketing materials were produced to encourage donations. The following provides a summary of the key communications activities:

- Re-use container at East Ayrshire HWRCs (2 locations): The re-use containers were sited adjacent to the WEEE recycling container, making it easy for the residents to place items in the correct container. Posters were produced for HWRC users, and staff were provided with a check-list of items that were accepted.
- Employee amnesty scheme (5 companies): Staff were able to donate personal targeted equipment through their employers. Posters and emails advertising the scheme were provided to participating companies. One company further supported the scheme by offering a charitable donation for each item donated.
- Schools as collection hubs (2 schools): The schools received parent letters and posters to publicise the collection scheme. Pupils at Strathdon Primary School

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(Aberdeenshire) also received a workshop, which introduced the collection scheme and discussed the importance of disposing of unwanted electrical equipment securely and in an environmentally responsible way. The workshops provided a “hands-on” opportunity for P4 – P7 pupils to process ICT equipment for re-use, and younger children “repaired” lego phones (an age-appropriate way of engaging them in the topic).

- Re-use containers at student halls of residence (10 halls of residence in Glasgow, Edinburgh and Newcastle): Every student received a postcard-sized leaflet providing information on what could be donated through the scheme within their “welcome” pack. Posters (paper and electronic) were provided for the collection container and for monitors within the reception area.
- Social Enterprises (2 organisations): CFINE (Aberdeen-based) utilised their list of contacts to send round an email to several partner organisations in Aberdeen about the scheme, with one deciding to participate after this.
- Glasgow Science Fair: The project aims were communicated as part of a wider science festival, through interactive activities including an opportunity to “urban mine” phones and a microscopic view of the microbes being trialed.

More than 800 (829) items were collected during the Re-Tek trial. A total of 6.5 tonnes of WEEE was collected through the trial with 71% being ICT.

The Re-Tek trial identified that developing collection models to the point where a financial return would be realised requires the following:

- A significant improvement in recycling value earned in the market-place.
- Improved marketing, screening of equipment to ensure that higher value ICT is collected.
- Market development to secure the highest possible level of functioning ICT as early as possible after it becomes redundant/surplus – thereby increasing resale income.

Although re-use is a fundamentally sustainable approach for keeping CRMs in circulation in the economy for as long as possible, re-use collection schemes are challenging to sustain due to low levels of items donated. This is compounded by the age profiles of those that are donated (which have no or limited re-use markets). It is therefore likely that increasingly innovative collection schemes should be accompanied by significant awareness raising campaigns, possibly at a national level.

3.3. Italian Trials

Trial host ECODOM is the largest compliance scheme in Italy. Working together with trial partners, the Ecodom collections trials were designed around the following key objectives:

- Increase collection of target products (such as Display, Consumer electronics, Information Communications Technology and Small household appliances) by launching a dedicated collection activity on a large scale in Milan;

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- Improve collection of target materials (as graphite, cobalt, gold, silver, platinum group metals) and sorting the products in 6 streams:
    - high CRM stream: Small Household Appliances with High CRM containing WEEE for material recovery;
    - other stream: Small Household Appliances with low CRM content; and
    - display and monitors.
- Additional criterion for sorting was identified, to explore the possibility of re-using WEEE items, so each stream above was divided into a further two categories:
    - Judged as suitable for re-use by the citizen disposing it;
    - Judged as not suitable for re-use by the citizen disposing it.

A summary of the Ecodom collections trial is shown in Table 5 below.

Table 5: Ecodom Collections Trial Summary

<table>
<tr><th>Trial Host</th><th>Ecodom - Italy</th></tr>
<tr><td>Trial Partners</td><td>AMSA, STENA, ENEA, SEVAL, Institut für Materialprüfung Glörfeld GmbH</td></tr>
<tr><td>Target Products</td><td>display equipment, ICT, consumer electronics, small household appliances</td></tr>
<tr><td>Target CRMs</td><td>Graphite, cobalt, platinum group metals, gold, silver</td></tr>
<tr><td>Website Link</td><td>http://www.ecodom-consorzio.it/it/iniziativa/crm-recovery</td></tr>
<tr><td colspan="2">Collection Activity 1
Collections in Public Squares
A large blue collection container was sited in a series of public squares across Milan on 4 consecutive Sundays in each square (21 Sundays in total). The containers were manned and extensive communication campaigns were carried out in the local area before the events. Wider communications were carried out via social media, local radio and local television.</td></tr>
<tr><td>Details</td><td>Sep 2016 – Dec 2016
May 2017-Jun 2017
5 public squares across Milan (Italy)</td></tr>
<tr><td colspan="2">Collection Activity 2
School and Community Collection Day
Two collection days were run in Comano School. The first was just for students of the school and followed engagement sessions with students. The second day was open to the local community to donate electricals too.</td></tr>
<tr><td>Details</td><td>Feb 2017
Comano School, Milan (Italy)</td></tr>
<tr><td colspan="2">Collection Activity 3
Collection in two COOP Grocery Stores
Ecodom had developed the design for the new WEEE bring banks, 2 of which units were placed indoors, in 2 Coop Grocery Stores. They were collected every 1 or 2 weeks. Communication activities had been organised in order to increase collection activities.</td></tr>
</table>

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Details	Jun 2017- Dec 2017 2 Grocery Stores located in Via Gozzoli and Via Palmanova, Milan (Italy)

The collection trials in Italy involved three primary routes to collection. First, from September to December 2016 and from May to June 2017, in a series of public squares across Milan on consecutive Sundays in each square, a large blue collection container was placed to collect the citizen's WEEE. During the collection activities, the WEEE was sorted into 6 categories: flat screens (reusable/not reusable), high content of critical raw material (reusable/not reusable), and low content of CRMs (reusable/not reusable). Two tonnes of WEEE were collected via this route.

Two days of collections and awareness-raising about the issues surrounding CRMs were carried out in the Comano (Milan) High School. Almost one tonne of WEEE was collected during this element of the collection trials.

Second, from June to December 2017, two WEEE bring banks were placed permanently indoors, in 2 Coop Grocery Stores in Milan. The design of the container was developed by ECODOM, specifically for the collection of small WEEE. Overall more than 2.5 tonnes of WEEE was collected.

During the collection trials, more than 5.5 tons of WEEE were collected (2 tonnes during the collection events in squares, almost 1 tonne during the event in school and more than 2.5 tons through the collection in grocery shops) (See Table 6 below).

Table 6: Quantitative Results of the Ecodom Collection Trials

		Collected Quantities (kg)			Declared Reusable (%)		
Location	Participants	High CRM	Low CRM	Screens	High CRM	Low CRM	Screens
Public square	375	539	1,121	348	28.6	19.6	15.6
Grocery stores	nd	2,615		-	nd		-
School	149	540.4	393.5	9.1	7.7	3.3	-

The collection mechanisms trials addressed the problems caused by cherry-picking valuable components (particularly relevant for those rich in CRM), and reduced damage of the products collected and maintained their re-use potential. Items disposed were those not usually found in municipal collection points and included: ICT equipment and mobile phones which are not present at all in traditional collection points (due to hoarding).

Table 7: Qualitative Results of the Ecodom Collection Phase

Products Collected	% Collected as a Proportion of

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	the Total Number Collected
Televisions and Monitors	2%
Body care appliances	6%
Kitchen appliances	6%
Other small household appliances	11%
PC and accessories	11%
Video devices	6%
Audio devices	9%
Mobile phones	16%
Other consumer electronics	10%
Other (ICT)	12%
Total	**100%**

Surveys conducted with members of the public dropping off WEEE identified that most people (94% of respondents) would agree that their WEEE should be re-used instead of treated for material recovery purposes, when possible. Interestingly, 68% of respondents declared they were sufficiently confident about the proper management of personal data contained in their disposed devices, therefore this was not reported as a deterrent to collections.

The Ecodom trials found that by facilitating a convenient and trusted route for the disposal of WEEE to members of the public, it is possible to increase the quantity and the quality of the WEEE collected. The communication effort was extremely important to reach the achieved result. Dissemination and educational activities in schools, is an important starting point to increase social awareness about CRM issues. However, the cost of having one-off collections was prohibitive, despite the amount of materials collected. Collection events would need to be conducted regularly, a higher volume of materials needs to be collected, and transport payloads should be maximised to make collections cost effective.

3.4. German Collections Trial

The German collections trial was undertaken by Recycling-Börse, a well-known re-use organisation in Germany. The trials focused on trialing new collection methods as well as the testing/ preparing devices collected for re-use. Initially, four collection methods were taken into consideration: Re-use Olympics at schools; Re-Bag; Re-Box; and Re-Envelope. The first three methods, detailed below, were successful and broad experiences were gained during the trial period:

1. “Re-use Collection Olympic” for schools and kindergartens. Schools acted as collection hubs and ran special days to raise awareness. A celebratory event took place for the school that collected the largest amount of WEEE;
2. “Re-use Collection Bag” a collection sack issued to private households. These bags were collected at the kerbside once a month;

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3. “Re-use Box” distributed to householders and businesses for collecting small household appliances and mobile phones for re-use. Once full, these boxes were returned to Recycling-Börse.

A summary of the Recycling-Börse trial is shown in Table 8 below.

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Table 8: Recycling-Börse Collections Trial Summary

Trial Host	Recycling-Börse **- Germany**
Trial Partners	Hamburg University of Technology, Fraunhofer Institute
Target Products	Display equipment, ICT, consumer electronics, small household appliances
Target CRMs	Tantalum, Neodymium
Website Link	https://www.recyclingboerse.org/it/europa-projekt-wrap-crm/
Collection Activity 1 *Re-use Olympics in Schools* Collection days in schools with a competition of which school could collect the most items for re-use. Items were assessed for re-use by Recycling-Börse with non-re-usable items being disassembled for the recovery trials.	
Details	May 2017 – Jul 2017 Herford (Germany)
Collection Activity 2 *Monthly Kerbside Sack Collections from Households* Each household received a sack which, once filled with WEEE, could be placed at the kerbside for a monthly collection.	
Details	Mar 2017 – Dec 2017 Herford (Germany)
Collection Activity 3 *Re-use Boxes for Households and Businesses* Householders and businesses could request a box for collection of WEEE. These boxes were returned to the Recycling-Börse depot, shops or collection points. For households, this was an alternative method of collection compared to the kerbside sack.	
Details	May 2017 – Oct 2017 Herford (Germany)

The Re-Use-Olympics at schools and the Re-Box provided good opportunities to engage directly with the public to provide behavior changes messages regarding WEEE. The Re-Use-Olympics demonstrated that collections in schools can be delivered with minimal disruption to the daily running of a school, but also provides excellent, hands-on educational opportunities in relation to environmental sustainability. The Re-Bag combined clothing and WEEE collections, increasing the overall value of collections and reducing product damage. The Re-Box collected mixed household items for re-use in addition to the WEEE and again, increased the overall value of collections. Table 9 below provides information with regard to the WEEE collected through each trial method.

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Table 9: WEEE Collected during Recycling-Börse Trials

	Weight Collected		Items Collected		Weight Re-use		Items Re-use	
	Kg	**%**	**No. items**	**%**	**Kg**	**%**	**No. items**	**%**
Re-Use Olympics for schools	2629.8	0.9	720.0	0.7	112.9	0.0	45.0	0.1
Re-Box for households	91.9	0.0	67.0	0.1	13.1	0.1	6.0	0.1
Re-Bag for households	193.5	0.1	262.0	0.2	16.5	0.1	29.0	0.1
Total	**2915.2**	**1.0**	**1049.0**	**1.0**	**142.5**	**0.0**	**80.0**	**0.1**

The trials were successful in increasing the collections of small WEEE in regions without an established network of separate collections and re-use organisations (other than municipalities). Depending on the region - urban or rural – the methods could offer a more convenient opportunity to return used products.

To generate sufficient amounts of material for the recovery trials, a representative amount (11.8 tons) of the non-trial local municipal collection of small household WEEE was identified, individually sorted by type of equipment and measured accordingly. During the sorting, magnets from HDDs, Tantalum capacitors and printed circuit boards (PCBs) with Tantalum capacitors were separated for the recovery trials. The results of the sorting showed that the composition of the sorted WEEE was: 35% small household appliances, 20% consumer equipment, 14% information technology (IT) and telecommunication devices, 12% lighting bodies and 12% other waste. Other sorted categories (toys, leisure and sport equipment, electronic working tools and medical devices) were less than 10% of the total sorted WEEE.

A valuable and essential database with average weights was created by this activity. These standard weights were used to calculate the total weight of the collections, so that the results for methods with a low collection performance would be comparable.

Pre-selection of defined devices with a significant CRM content for subsequent treatment and processing for CRM recovery appears to be necessary for efficiency. Both the product database and product-specific knowledge of CRM content produce related sorting criteria for daily practice, and which can be applied in pre-treatment facilities. There is also potential for these criteria to be utilized in communications for collections activities to increase their effectiveness.

3.5. Czech Republic Collections Trial

Trial host ASEKOL, is a Czech Producer Compliance Scheme who is responsible for the state-wide collection and take-back system for waste electrical and electronic equipment (WEEE), on behalf of producers and importers of WEEE. A summary of the Asekol trial is provided in Table 11 below.

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An objective of the collection model was to get as close to people as possible. Citizens in selected areas of Prague had the opportunity to drop off WEEE directly in front of their house. For these purposes, ASEKOL created two prototype mobile containers for joint collection of WEEE and textiles, which could be placed whenever and wherever needed.

The trial phase of the project (placing the containers in the streets) started in the middle of March and continued until July 2017. Mobile containers were deployed in various municipal districts within the capital city of Prague. Containers were placed in each location for at least 2 days. The trial project was also accompanied by an awareness-raising campaign emphasizing the collection trials for, in particular, CRM-rich WEEE.

Table 10: Asekol Collections Trial Summary

Trial Host	Asekol – Czech Republic
Trial Partners	Green Solution, Enviropol
Target Products	ICT, consumer electronics, small household appliances
Target CRMs	Rare Earth Metals, Platinum Group Metals, Gold, Silver (Copper and Aluminium – not CRMs)
Website Link	https://www.asekol.cz/asekol/
Collection Activity *Mobile Collection Units in Areas Not Suited to Permanent Collection Containers* Mobile collection units that accept textiles and WEEE were placed in specific areas of Prague for a 24-48 hour period. They were in areas of Prague that are unable to site permanent, stationary collection units due to the historic beauty and importance of the surroundings. The locations of these collections were advertised via posters, social media and news reports.	
Details	Mar 2017 – Jul 2017 Prague (Czech Republic)

Working with CORETEX CZ SE (a waste textiles collector) to use their secure mobile collection unit in historical areas of Prague where the siting of ASEKOL's successful permanent collection bins is not possible for aesthetic reasons. The secure mobile collection unit placed in various locations for 2 days at a time was accompanied with leaflets to promote the targeted WEEE and to provide information on when and where the unit would be available. The levels of CRM-rich WEEE from these collections were compared with the levels of CRM-rich WEEE from the permanent collection bins.

Table 11 below shows the WEEE collected by category during this trial. For collection yards, the most collected category was category 3 (IT and communication equipment) with 51.6% by weight. For the stationary containers the most collected category was category 2 (small household appliances) with 38.9% of the total weight collected. For the mobile containers the most common categories collected were 2 and 3, with very similar results. Lastly, the third most common group is category 4 representing consumer electronics.

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Table 11: Categories of WEEE as a % of Total Weight Collected by Asekol Trial

	Collection Yards	Stationary Containers	Mobile Containers
Category 2	5.09%	**38.92%**	**33.76%**
Category 3	**51.55%**	22.95%	**33.75%**
Category 4	37.86%	28.97%	26.03%

A total of 1.7 tonnes and 694 items of WEEE were collected during by mobile containers and around 26.7 tonnes through their stationary containers & collection yards. Only 3% of the collected items were suitable for re-use. Asekol's collection trial identified that:

- Collection trials via mobile containers were very time consuming and costly (actually the most expensive collection stream) due to:
  - Promotion, flyers and their distribution, staff hire costs
  - Payment of permits and parking fees (for the container placement)
  - Permits had to be issued for each site
  - It was necessary to negotiate independently with each Municipal District; these negotiations were lengthy
  - It is more likely to be a seasonal affair – it is hard to negotiate parking places during the winter time
  - Logistics - collection of e-waste and its transport (twice – firstly to the company dealing with textiles, secondly to relevant reloading site); replacing the containers from one point to another one
- The collection results were affected by an existing network of stationary containers. Mobile ones were added in places where the stationary ones couldn´t be placed (historical areas, transition to underground containers etc.).
- The collections were supported by linking with another valuable waste stream (textiles) and with the Red Cross, who supported the endeavour. Collections always work well with a respected charity involved, as in this case. The Red Cross is a credible institution and thus collections of worn clothes convinced people to dispose of e-waste as well.
- Also, other companies dealing with waste textiles became interested in adding e-waste collections.
- Re-use activities should not be done with the WEEE that is thrown into the containers and then transported to the re-use center; this is because the act of discarding, as well as each additional handling phase, increases the risk of subsequent material damage.
- Mobile containers could be applicable elsewhere as they are easy to locate/relocate. However, this collection method was the most expensive one (direct costs were 4 times higher than in case of stationary containers).

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- Mobile collections did not facilitate re-use as devices are dropped rather than placed into containers and subsequent handling phases, along with transportation, raises the risk of potential further damage (display breakage, loosening of parts, pollution etc.).

3.6. Collections Trials Summary and Conclusions

Table 12 below illustrates that the project aim, to deliver up to three collection activities in each country, was exceeded, and highlights the wide range of activities that were trialed during this phase of the project.

Table 12: Summary of Types of Collections Activities Undertaken

	Collection Activity	Prioritisation from Collection Matrix	Location	Trial Host
1	Retail take back in charity retailer	High	Greater Manchester (UK)	Axion Consulting
2	Retail take back with major electrical retailer	High	Greater Manchester (UK)	Axion Consulting
3	Retail incentivised returns	High	York and Leeds (UK)	Axion Consulting
4	Employee amnesty events in Business to Business WEEE collections	Mid/High	Various locations across Scotland and Northern England (UK)	Re-Tek
5	Primary school collection hubs	Not individually listed	Aberdeenshire (UK)	Re-Tek
6	University Halls of Residence collection hubs	Not individually listed	Glasgow, Edinburgh, Newcastle, Durham (UK)	Re-Tek
7	WEEE bins at recycling centres specifically for re-use	Mid/Low	Kilmarnock and Cumnock (UK)	Re-Tek
8	Collection events in city public squares	Mid/High	Milan (Italy)	Ecodom
9	Primary school collection hubs	Not individually listed	Milan (Italy)	Ecodom

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10	Primary school collection hubs	Not individually listed	Herford (Germany)	Recycling-Börse
11	Kerbside household collections	Mid/Low	Herford (Germany)	Recycling-Börse
12	Retail collection hubs	High	Herford (Germany)	Recycling-Börse
13	Mobile collection units in areas unable to have permanent collections	Not individually listed	Prague (Czech Republic)	ASEKOL a.s.

As shown in Table 13 below, the trials were successful in collecting the products deemed as priority (due to their high CRM content). All the trials collected consumer electronics and ICT, and three of the trials collected display equipment. This enabled sufficient testing of each of these product types in the subsequent recovery trials.

Table 13: Summary of the Priority Products Collected

	Collection pieces	Collection kg	Re-use pieces	Re-use kg
Asekol Display equipment	17	91	0	0
Asekol Consumer electronics	508	399	0	0
Asekol ICT	445	566	4	8
Asekol Gadgets	273	153	4	5
Axion Display equipment	3	15	3	15
Axion Consumer electronics	63	81	19	35
Axion ICT	236	599	88	294
Axion Gadgets	142	185	51	89
Ecodom Display equipment	26	126	11	52
Ecodom Consumer electronics	561	441	115	173
Ecodom ICT	545	742	181	250
Ecodom Gadgets	272	188	89	40
RecyclingBörse Display equipment	60	126	1	52
RecyclingBörse Consumer electronics	209	441	22	173
RecyclingBörse ICT	422	742	22	250
RecyclingBörse Gadgets	122	188	3	40
Re-Tek Display equipment	205	958	132	628
Re-Tek Consumer electronics	31	54	8	3
Re-Tek ICT	589	2416	90	353

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Re-Tek Gadgets	222	269	36	57
Total Display equipment	311	1680	147	701
Total Consumer electronics	1372	1388	164	258
Total ICT	2237	5182	385	911
Total gadgets	1031	848	183	191

Table 14 below shows the tonnages collected by collection type for each of the trials partners.

Table 14: Summary of Total Tonnages Collected by Trial Partner.

	Axion	Re-tek	Ecodom	Recycling-Börse	Asekol	Total
Instore Takeback	0.7					**0.7**
Schools/University Halls		102	943	2629		**3674**
Mobile Containers/Bring Banks			2615		1659	**4274**
Stationary Containers/HWRCs		4226			9058*	**4226**
Public Events			2008			**2008**
Collection Yards					17664*	**0**
B2B		1246				**1246**
Social Enterprise		621				**621**
Household Collections				285		**285**
Total	**0.7**	**6195**	**5566**	**2914**	**28381**	**43056.7**

In total around 43 tonnes (of which 10 tonnes were used to complete the monitoring and evaluation requirements of the project) of materials were collected through the collection trials activity which took place from June 2016 until September 2017. The project's initial aim was to collect 100 tonnes of material, but due to the size and weight of the products being targeted we felt that this would be unachievable and so requested a change to the overall tonnage figures as part of the mid-term report which was submitted in July 2017. The overall tonnage that was actually collected during the project was sufficient and allowed all supporting actions to be completed as required.

3.7. Summary

Although the cost and revenues from the individual trials are not directly comparable, they do suggest that collecting high value products (that can be resold with little or no repair) as economically as possible (via a retailer) could offer the most effective means of increasing CRM recovery. Further work should investigate the potential additional costs that could be included (i.e. revenue lost to a retailer from the loss of floor space) and whether economies

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of scale in both collection and recovery could increase the effectiveness of this method of collection.

A key insight from the trials is that retailers and charity shops have a great opportunity to increase collections of WEEE. Retailers that are part of consumer's everyday habits (e.g. small convenience stores) offer an economical way to collect small WEEE from consumers. Trusted retailers may also give consumers confidence to handover appliances where data security issues are greatest (e.g. smartphones). This also increases the potential economic returns on collections since items returned are likely to be of relatively high value.

Data from the collection trials has been utilized to inform work under WP C1 – Monitoring and Evaluation. In addition, and as part of WP C1, structured interviews were also undertaken with trials hosts to facilitate evaluation of the economic costs and benefits of the specific collection, re-use and recovery trials. A synthesis of collection/re-use trial data was undertaken to enable comparison of all results in a transparent and consistent way. This comparison is based on data from all trials, and includes information regarding 4,890 items or 9,854kg of collected products. As noted above, the overall volume of materials collection through the trial is much higher, however only data from the trials that are directly comparable have been included in the C1 evaluation.

Initial findings from WP C1 reports that, based on assessments undertaken by treatment operators, the re-use potential from the trials is as follows:

Table 15: Re-use Amount in Relation to Collection Amount Across the Trials

Product Category	% Re-usable
Televisions and Monitors	43 %
Consumer Electronics	15 %
Information and Communication Technologies (ICT)	17 %
Small Household Appliances	8 %

There was only a small observable difference in the age of products across all category groups. Over two-thirds of re-usable products were 0-3 and 3-6 years old (37% and 37% of products respectively) and 27% of re-usable products were more than 6 years old.

Further analysis will be reported through WP C1 and will include:

- Comparison and interpretation of results under consideration of the specific trial conditions;
- Environmental assessment: e.g. how the collection/re-use potential of the trials change if focus is placed on resource/CO2e equivalent savings compared to weight based environmental assessment; and
- Economic assessment.

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4. Recovery Trials B2

4.1. Recovery Trials Summary

Five recovery trials were carried out across four countries to test different methods of recovering CRMs from waste electricals. Each trial targeted one or more of the following CRMs:

- Graphite;
- Cobalt;
- Antimony;
- Tantalum;
- Rare Earths;
- Platinum Group Metals;
- Gold; and
- Silver.

During the initial stages of this work a literature review and desktop study was completed by EARN (Sven Grieger) (see Appendix 2), with input from all project partners, to understand recovery methodologies currently in use for each of the target CRMs. This review allowed for a greater understanding of methods for testing and was sent to NEEMO with the August 2016 monthly report.

4.2. Axion Recovery Trials

The approach of the Phase 2 trials was to:

- Isolate the circuit boards from the WEEE items through manual dismantling;
- Separate the components from the circuit boards through chemical depopulation using the Itrimex technology; and,
- Segregate components using various mechanical separation techniques, including size separation, magnetic separation, and density separation.

At the outset of the project, it was planned to use optical sorting as part of the component segregation process; however, as discussed later this was deemed to not be appropriate Axion used a list of circuit board components created by International Tin to visually identify fractions that may contain elements of interest.

Items, circuit boards, and components were segregated throughout the trials by item type and age group; in this way the final analyses could be matched back to the item type and age group the components had been recovered from.

When collating the items after collection it was noted that there was a large number of routers and ethernet switches, as well as a number of car radios. Since these items were

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particularly noteworthy, they were dismantled and depopulated on their own and the results are reported separately.

In total, 233 items were dismantled: 182 at E3 Recycling and a further 51 by Axion. The proportion of circuit boards recovered from the items was typically in the range 10 20%, with the exceptions of mobiles, 6+ years (34.8%) and routers (~40%). Computer towers had by far the highest recovery rate of circuit boards, at over 6 kg/hour; in comparison, most other items had recovery rates of less than 3 kg/hour, with the exception of routers (4.5-5 kg/hour). This agreed with E3 Recycling's initial assessments that computer towers were much easier to dismantle than most other items. Laptops were particularly difficult to dismantle, with some taking up to 20 minutes each.

67 kg of circuit boards were depopulated using the Itrimex technology in 77 batches. The proportion of components on each set of boards was in the range 20-30%, with notable exceptions being computer towers (40-50%) and others, 0-3 years (5.6%). Before depopulation it was necessary to manually remove large metal items from the circuit boards as these reacted vigorously with the depopulation solution. It was also noted that not all components were removed from the boards due to different adhesion methods.

Sorting segregated the components into a variety of fractions, with specific components concentrated in each. Elemental analysis confirmed that tantalum was found mostly in one specific fraction (3.15-8 mm, magnetic, 2-3 SG) and tin was found in the fine (<0.5 mm) fraction. A large (>80%) proportion of the gold present in the fractions <8 mm was concentrated in four fractions. These could be recombined to give a fraction with overall concentrations of greater than 1,500 ppm.
The key lessons learned from the recovery trials are as follows:

Dismantling:

- It was noted that the operators at E3 Recycling had well lit and ventilated workstations. This was very important to be able to see the items they were dismantling in detail.
- Operators also had many different tools and attachments, e.g., drill bits and screwdriver heads, in order to open all different kinds of fastenings. There were several screws that were unique to a manufacturer that required special tools.
- The speed at which the operators were able to process an item depended heavily on the specific dismantler's experience, and whether they were familiar with a particular item. This was reflected in the speed with which computer towers were dismantled; it may be that with more familiarity and experience with other items such as mobile phones the dismantling speed may be improved.
- Laptops in particular were very difficult to dismantle and took by far the longest of all item types. However, when taking into account the amount of circuit boards recovered, the recovery rate for laptops was comparable with many other item types, such as tablets and 6+ year old mobile phones.

Depopulation:

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- When the solution was fresh, it was able to depopulate circuit boards well. However, after a few batches the efficiency dropped and the solution needed replenishing more often than had been anticipated.
- Many boards contained large pieces of metal (e.g., aluminium heat sinks). These reacted vigorously with the depopulation solution and gave off nitrous oxide, which is hazardous, and accelerated the aging of the solution. To complete the trials, larger pieces of metal were removed before adding the boards to the solution, however this would not be practical at commercial scale.
- Many of the components had to be removed by scraping the boards with a chisel or screwdriver. At a commercial scale this could be achieved using a tumbling drum or a similar process.
- Even with fresh solution, there was still a noticeable amount of smaller components left on the boards.
- An alternative depopulation process could be to heat and agitate the boards in order to melt the solder. This process is under development by several companies and further work could be carried out to trial this method.

Component separation:

- Size separation was successful in segregating the components, and was able to concentrate the components that had been identified as potentially interesting into the smaller size fractions (<8 mm)
- Magnetic and density separation further segregated the components in the 3.15 8 mm size fractions; in particular, chips tended to have a density of 2-3 SG, while tantalum capacitors and crystal oscillators tended to have a density >3 SG.
- Elemental analyses showed that a large (>80%) proportion of the gold present in the fractions <8 mm was concentrated in four fractions. These could be recombined to give a fraction with overall concentrations of greater than 1,500 ppm. Tantalum was found in one other fraction, while a large proportion of tin was found in the fine fractions.
- Given the gold content in both magnetic and non magnetic fractions of the 0.5 3.15 mm size range, there appeared to be little advantage to this separation.
- There was also a large proportion of gold containing chips and pins present in the fractions >8 mm. There did not appear to be an advantage of screening at 16 mm.

Feasibility of establishing a full scale processing operation

Gold and copper are found in large quantities across almost all fractions, with no correlation between composition and fraction and/or category. There are very few fractions where there is a significant concentration of other CRMs.

Additionally, given the number of components remaining on the circuit boards after the depopulation trials, it is likely that these partially depopulated boards will still contain relatively high proportions of gold and copper.

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It is probable that every one of these fractions would be sent to the traditional processing route for recovery of gold and copper; therefore, it is unlikely that a specialist processing plant to treat these fractions and recover other CRMs would be viable.

4.3. Re-Tek Recovery Trials

The aim of the recovery trial was to develop "proof of concept" benchtop experiments that would use biological and chemical separation techniques to extract gold, silver and cobalt from PCBs. The gold (Au), silver (Ag) and cobalt (Co) enriched solutions, would then be passed through a proprietary ElectroChemical Cell (EC Cell), manufactured by UWS to recover the elements of interest.

The laboratory work strands are summarised below:

Biological separation: Three different types of microbe were selected (acidophiles, fungus and cyanogenic) to determine whether they would selectively extract gold, silver and cobalt from ground PCBs.

Chemical separation: Three chemical separation techniques were explored to extract gold, silver and cobalt, these were i) acid dissolution, ii) sulphide precipitation, and iii) particle size distribution. A fourth extraction method which used hydroquinone to extract solely gold was also considered.

EC Cell: Fourteen proprietary EC Cells were manufactured for the recovery of gold, silver and cobalt from reference solutions.

The initial aim was to wholly carry out the experiments on PCBs collected during Phase One. However, this methodology was subsequently refined for the EC Cells and hydroquinone experiments. For the former, reference solutions of gold, silver and cobalt of a known concentration were produced in order to calculate hypothetical recovery rates and help to determine the success of the concept. Reference solutions of gold were also produced for the hydroquinone experiments.

The key findings from the above work are now summarized in the following sections.

Biological Separation

The results from the initial Aspergillis Niger microbial leach, were inconclusive and the laboratory work would need to be repeated in order to determine the effectiveness of the microbes.

The cyanogenic bacteria had limited success at mobilising gold and silver. The cobalt results were very variable and would need to be explored further. Further investigations looking at a sodium hydroxide wash to remove copper should be considered as a sequential step in the process.

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For the 2-step process, the acidophilic treatment with A. ferrooxidans resulted in significant recovery of Au (up to 70%), Co (up to 96%) and Cu (copper) (up to 99%) with minor additional recovery in the subsequent cyanogenic stage. Due to a problem with the laboratory instrumentation, it was not possible to analyse silver. The results indicate that gold was typically bioleached into solution, whereas Cobalt and Copper were associated with the biomass (biosorption/ bioaccumulation) rather than in solution.

These results indicate some promising findings, however further work would be required to confirm the measured recovery rates in light of elevated abiotic controls

Chemical Separation

Extracting gold using hydroquinone was relatively straightforward to set up with recovery levels higher than expected.

Particle size distribution analysis was undertaken to establish of this could be an aid in establishing whether specific types of metals accumulated in particular size ranges of PCB after shredding e.g. showing CRM-rich areas of the PCB.

Multi-elemental analysis showed that gold and cobalt increased in concentration with decreasing particle size and thus there may be the potential for physical separation from Cu and Zn (Zinc) which increase in concentration with increasing particle size. The results for silver were inconclusive.

Optimum pH recoveries for gold, silver, cobalt and copper were determined, however the results should be treated with caution, due to suspected contamination.

EC Cell

The EC Cells were tested using model solutions, made up to a known concentration. This enabled accurate recovery rates to be determined. The results utilising the reference solutions appear promising, with gold, silver and cobalt recovery rates at 99%, 95% and 98% respectively. The cells appear to be effective at recovering these metals at concentrations as low as 1ppm.

There appears to be some contamination of gold, silver and cobalt arising from the EC Cell itself, but the cause is currently unknown and requires further investigation.

Potential Next Steps:

Chemical Separation

Hydroquinone Extraction: The next stage would be to look at the composition of the Gold using surface analysis techniques to ascertain the exact composition of the extracted product and identify potential sources of contamination or oxidation states. The current

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analysis was carried out on a certified gold standard, and further analysis would assess the selectivity of the method when there is a mixture of metals present.

Precipitation analysis: Further analysis could be carried out on a Certified Reference Material to determine the % recovery after digestion and precipitation in order to assess the efficiency of the precipitation method. This should also account for the significant levels of variability between samples which may be a source of error resulting in lower/higher % recoveries than expected.

Further work looking at the “accidental” recovery of Scandium and Indium from PCBs to determine whether the recovery of these elements increases the economic and commercial viability of the methods explored during this trial. Any future work packages could actively consider these CRMs.

Biological Separation

The results from the Aspergillis Niger were too variable to draw any significant conclusions and it is recommended that the same work be repeated, before more definitive conclusions can be reached.

Results from the study of the mixed culture of cyanogenic bacteria (C. violaceum and B. megaterium) indicated that they were capable of bioleaching Cu, Ag, Co, Mg (Magnesium), Ca (Calcium) and Zn from mobile phone, notebook and computer PCBs. While high recoveries were recorded for some metals such as Co, Mg and Zn, the bioleaching process needs to be optimized to achieve higher recoveries for Au, Ag and Cu. The particle size of the PCBs appeared to have had significant effects on the metal recovery efficiency of mixed cyanogenic bacteria, but this needs to be investigated further for reproducibility. Interestingly, although recovery of Magnesium was not an objective of this study, high recovery of Mg by cyanogenic bacteria was reported for the first time which could have various industrial applications, and may help to make this process more economically viable.

The acidophilic treatment with A. ferrooxidans resulted in significant recovery of Au (up to 70%), Co (up to 96%) and Cu (up to 99%) with minor additional recovery in the subsequent cyanogenic stage. Further studies, which include a wider range of control studies, are recommended to further explore these potentially promising results with A. ferrooxidans.

EC Cell

The EC Cells appear to be achieving high recovery rates from single-elemental solutions, however results suggest that there is contamination or interference from the Electrochemical Cell. The reason for this is still unknown and this will require further work and form part of the basis for stage 2 of the project.

Once the source of contamination has been identified, the next steps could focus on recovery from multi-elemental solutions.

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General:

Set up a small-scale laboratory experiment involving a pre-treatment step of the ground PCBs with a sodium hydroxide solution, to determine whether this selectively removes copper into solution. If successful, this may increase the applicability of the EC Cell to recover gold, silver or cobalt selectively, and enable the copper to be recovered.

Carry out a range of "baseline" work using a variety of techniques, to determine total concentrations of CRMs (and other elements of interest). Non-destructive X-Ray methods could also be used to identify areas and components of PCBs with particularly high concentrations of CRMs. This data could be used to maximise recovery rates and gain a more accurate prediction of the economic viability of the recovery methods that are being proposed.

Based on the complexity of trying to recover CRMs from a heterogeneous PCB, it would appear to be economically and environmentally sound to ensure that collection schemes enable as many items as possible to be processed for reuse markets, prior to recovery/ recycling.

These trials were proof of concept, and although some of the results appear promising, it will be necessary to obtain further funding to refine the processes of interest.

4.4. Italian Recovery Trials

The ECODOM Recovery Trials aimed to increase CRM recovery of the target materials of Graphite, Cobalt, Gold, Silver and Platinum Group Metals and to develop a new hydrometallurgical process to recover Cobalt and Graphite from batteries. The trials were implemented in close collaboration with their other partners; AMSA, STENA Technoworld, ENEA and S.E.VAL S.r.l..

The recovery trials aimed to achieve four main goals:

- test and prepare for reuse the products having reuse potential;
- implement recovery activities to increase current CRM recovery;
- perform a new hydrometallurgical process to recover Cobalt and Graphite from batteries;
- analyze the overall increase in CRM recovery throughout the entire recycling chain.

Testing the preparation for reuse of flat panel screens

Within the activities of the CRM Recovery project focused on the identification and implementation of new WEEE collection procedures, special attention was paid to flat panel screens (FPDs). Specifically, collected FPDs (43 items) became the subject of investigation for the researchers of ENEA, the Italian National agency for new technologies, Energy and

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sustainable economic development. The target of their research was the elaboration of a dedicated procedure to establish the re-use potential of these devices. ENEA developed a set of detailed procedures to test the reuse potential of FPDs. A generic software procedure for the functional performances test of a monitor was integrated into a more comprehensive procedure for the test and the performances evaluation of functional component blocks of the whole monitor system. The procedure was articulated in two successive evaluation moments. Firstly, the examined flat screen undergoes a visual inspection: namely, the screen and the external body of the device are closely checked out and damages, breakage or surface scratches are identified. Secondly, a functional test is performed. Through the support of an open access MONITOR TEST software, 19 different parameters were evaluated and corresponding tests were performed, such as: monitor geometry test, geometry and convergence test, basic color convergence test, speed and persistence test, character reading test, test of the viewing angle.

The result following the testing procedures found that 8 out of 43 screens were fit for preparation for reuse (7 of which declared not reusable by citizens).

The availability of an organized, reliable and accurate methodology to test the reuse potential of flat screens, results in a 100% ‘recycling’ rate of the CRMs contained within the unit (considering that the reuse approach allows to keep CRMs in the product’s second life, avoiding CRMs losses that currently occur through traditional WEEE recycling routes), and also produced a business opportunity in the reselling. The procedure developed is currently and successfully implemented in the STENA Technoworld WEEE treatment facility, allowing the identification of reusable flat screens to be sent for a second life in new markets. This has led to one full-time job at the Stena plant.

Precious Metal Recycling

The WEEE collected during the trials was sorted, separated and pre-processed into CRM-rich and non-CRM-rich fractions in the STENA Technoworld facility equipped with PMR technology. These fractions then passed through the different steps of the STENA’s existing precious metal recovery process. The output materials were sent to a specialized laboratory to identify the amount of Cu (%), Au, Ag, Pd, Pt, Rh (g/ton) recovered: CRM levels have been assessed to determine if the method of collection and levels of sorting lead to an overall increase in CRM captured.

A general increase in respect to the traditional mix performance of 102% of Au, 29% of Ag, 42% of Platinum Group Metals and 2% of Cu was achieved. These results (increase in recovered materials) could bring to the conclusion that the separate treatment will increase the recovery performances of the treatment plant. Note this was the difference between the two batches processed in the recovery trials – the first being ‘CRM-rich’ and the second being a standard ‘traditional’ (low-CRM content) mix. After scrutinising the results, we further investigated the composition of the regular municipal mix (feedstock from day-to-day collections), and discovered that STENA normally performs a pre-treatment step on high grade products by removing the printed circuit boards (the ones easily removable) contained in the flow before shredding them.

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Qualitatively, visual inspection of the standard of the output materials, STENA operators declared that there was an improvement in the quality, so we can conclude that, with the new treatment mix, it is possible to increase recovery rate of targeted CRMs.

Treatment of the batteries

An additional recovery activity was developed at the SEVAL plant, implementing laboratory scale processes to extract CRMs from rechargeable batteries. The batteries were treated after putting in place various specific treatment activities:

- liberation of the batteries from their packaging: extraction of lithium batteries from mobile phones and laptops;
- pre-treatment: stabilization in cryogenic and material separation (shredding);
- lab analysis: material characterization;
- secondary treatment: advanced separation and components dissolution;
- recovery and purification: separation of high value components/elements.

From the WEEE collected during the trials, 30 kg of batteries were extracted. Pre-treatment activities have been performed in SEVAL plant in Colico.

After the secondary treatment, consisting of a reduction leaching process, the results of the recovery trial of batteries was: a liquid solution characterized by a very intense colour compatible with a high Cobalt concentration (the reducing leaching is expected to have an efficiency about 98%); a solid fraction, this is the fraction that contains the Graphite, and represented the 12% of the total input material.

The recovery of the Cobalt dissolved in solution was obtained using the selective solvent CYANEX 272. In fact, the obtained solution contains dissolved lithium as well, and it is necessary to address the Cobalt uniquely.

The selective extraction through CYANEX needed to be performed in a kerosene solution with pH 6. For the optimization of the results, two extraction cycles were required. The output Cobalt was in a crystallized solid form. The efficiency of this selective extraction is estimated to be 90%. Therefore, the output cobalt is estimated to be 8% of input material.

Conclusions

The most effective result was realising the possibility of preparation for reuse, and it was reasonable to further investigate and implement the set up an organized, reliable and accurate methodology to perform the preparation for reuse of flat screens. This reuse allows for a ‘recovery rate’ for CRMs of 100% from the monitors and TVs that successfully passed all the testing. While the results concerning the Recovery Trials at Stena’s PMR plant, as well as the Recovery Trials done on batteries at the Seval laboratory, demonstrated that good recovery performances of CRMs can be achieved, and that these fields deserve further investigation. The positive impacts of the proposed activities are

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meant to be a driver to effectively promote circularity in European businesses, ad hoc policy ideas and business improvements.

4.5. German Recovery Trials

This recovery trial focused on bio-leaching of tantalum from capacitors as well as the generation of homogeneous neodymium-based magnet material from computer hard disks by hydrogen decrepitation and melt spinning.

Two bio-leaching experiments were carried out for Tantalum recovery trial. First, an amount of Tantalum capacitors was used as an input for the bio leaching. Second, PCBs with Tantalum capacitors were treated by electrohydraulic fragmentation (EHF), a process aiming to remove the mounted components from the PCB.

According to the EU standard method EN 13656, Tantalum content in the wasted Ta-capacitors was 185.9 g/kg. The characterization was done by chemical digestion with aqua regia and hydrofluoric acid. Only aqua regia (without HF) was also tested under the same condition, but did not leach enough amount of Ta (0.31 g/kg, 0.17%). The result of Tantalum recovery trial by bio-leaching from Tantalum capacitors were negative, Tantalum essentially could not be leached out by Pseudomonas putida (DSM No. 6125, maximum leaching rate: 0.33 g/kg, 0.18%) and Bacillus subtilis (DSM No. 1088, maximum leaching rate 0.34 g/kg, 0.18%) even under favored growth conditions. Penicillium simplicissimum (DSM No. 1078) has the ability to leach Tantalum, but the leaching rate was still limited (maximum leaching rate: 1.25 g/kg, 0.67%). An unknown species got the highest leaching rate (9.88 g/kg, 5.31% in 15 days, and 28.65 g/kg, 15.41% after 70 days), under 25 °C and 150 rpm, bulk density 0.1%, but the trial was unable to isolate and identify this species. It has been suggested that DNA testing could take place to try to establish what the containment is but as this is out of scope of the contract it would need to be look separately from the projects recovery trials. We would recommend that this is subject to further research.

In the third bioleaching trial, PCBs were used as the raw material. It transpired that only Penicillium simplicissimum leached 0.29 g/kg Ta from PCB particles in 15 days, and all the other results were 0, or under detective range of ICP. As the content of Tantalum in PCBs was extremely low, the exact leaching rate could not be calculated. Regarding the low content of Tantalum in PCBs, it is not commercially viable to recover Tantalum as a single metal directly from PCBs without the combination of other metal recovery process, but as the bioleaching process also has the ability to leach a high percentage of base metals (Copper, Nickel, Aluminum and Manganese), the combined multi-metal recovery process can be taken into account. The potential of Tantalum recovery by bio-leaching is shown (especially from separated Tantalum capacitors), but more research needs to be carried out. The EHF is under further development, so that in future, devices such as Tantalum capacitors can be removed more selectively.

Results Trial Neodymium from HDD

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Hydrogen decrepitation (HD) process was carried out for Neodymium recovery trial. The main contents of the recycled Nd-Fe-B powder after the Hydrogen Decrepitation process (from Neodymium recovery trial) were: Fe 45.17%, Nd 14.32%, Co 2.06%, Ni 1.22%, Dy 1.07% and B 0.95%. The flakes can be directly used as the raw material for new Nd-Fe-B magnet production.

Conclusions

The overall recovery potential of Ta and Nd was determined based on the collected PCs and laptops within the trials, since the recovery trials were focused on a good accessibility and identification of Ta and Nd containing components. Therefore, mobile phones, smartphones and tablets were not taken into consideration.

The Ta recovery potential per unit PC or laptop is 0.0011g Tantalum (70 days leaching). Thirty six units were collected in the trials, so the Tantalum recovery potential is 0.04g.
The Nd recovery potential per unit PC or laptop is 0.65 g Neodymium. Thirty six units were collected in the trials, so the Neodymium recovery potential is 23.4g.

Both figures are a very positive outcome, since the current recovery of these elements from WEEE is almost zero. In terms of Ta and Nd recovery, high-grade printed circuit boards as well as HDDs are traded in the WEEE sector as specific and individual fractions. This shows a high chance to channelize these mass flows and to become essential sources for Ta and Nd from the WEEE flow.

4.6. Czech Republic Recovery Trial

Three fractions with the highest potential for recovery were chosen for the testing of recovery methods. Precious metals, rare-earth elements (Ce, Dy, Ho, La, Nd, Pr, Sm) and copper were categorised among elements of interest. Trials were based on classical physical methods using different particle sizes, density, conductivity and electromagnetic properties.

Non-reusable WEEE was processed on a small WEEE processing line. The three fractions from the WEEE processing which have the highest concentrations of CRM were identified and then further refined to increase the CRM content of these fractions. Trials were based on classical physical methods using different particle sizes, density, conductivity and electromagnetic properties. Processes included crushing, magnetic separation, electrostatic separation and sensor separation of metals.

Precious metals, rare-earth elements (Ce, Dy, Ho, La, Nd, Pr, Sm) and copper were categorised among elements of interest. Each of the output fraction material was evaluated focusing on amount, particle size and contents of elements of interest.

Output fractions from the treatment line (dusts, plastic fractions and fine ferrous fraction) contained low concentrations of CRMs and remained waste fractions. To achieve environmental goals and economic recycling of CRMs, additional treatment phases of the

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material needs to be done in order to increase contents of CRMs to become salable product.

Only 3 fractions from 9 were suitable for next treatment phases. High enough amounts of the fractions were produced, and the particle sizes were suitable for subsequent treatment as these fractions contained enough CRMs.

Plastic fractions with a particle size < 0.5 mm or 0.71-1.5 mm are suitable mainly for recovery of precious metals and copper. For this purpose, we developed a suitable method - electrostatic separation or combination of milling and electrostatic separation. This method is automated and simple to do.

In the case of plastic fractions with a particle size of 0.71-1.5 mm, better results were reached in the batch samples from the stationary and the mobile containers. Content of Au was increased 9 times with recovery ratio ~ 59 %. And content of Cu was increased 10 times with a recovery ratio ~63 %. But more stable results for single elements were reached for samples from the collection yards. Content of Au, Ag and Cu was increased ~ 6times.

Plastic fractions of sizes < 0.5 mm contained higher concentration of precious metals. Their content was increased ~10 times. We reached our goal and we developed a suitable method for recovery of precious metals and copper from plastic fractions. Plastic fractions were suitable for the next phase of increasing of CRMs after primary treatment on the line.

Concentration of rare-earth elements in plastic fractions was very low. Product had to contain min. 3 % of element for sale purpose. Plastic fractions of < 0.5 mm from the containers contained ~117 mg/kg La. It meant that we needed to increase content approximately 300 times. We were not able to reach these results through our tested methods.

Fine ferrous fraction chosen for the trials focused on rare-earth elements. This fraction contained the highest concentration ~ 0.13 % of Neodymium. The highest concentration that we reached was ~ 0.6 % of Nd in the fine fraction after sieving. This concentration was not enough for sale. The only option for increasing of content of Nd is another subsequent treatment phase. Our tested methods were not enough for recovery of CRMs in fine ferrous fractions. New methods for recovery of fine ferrous fractions needs to be developed.

5. Summary

5.1. Linking Collection to Recovery

The overall aim of the trials was to ascertain whether there was a demonstrable link between the collection phase and the recovery phase of the trials and the lessons this may give for a wider rollout across Europe.

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There is an argument that collecting greater amounts of WEEE increases the chances that it will be captured, rather than it being hoarded by households or ending up in landfill. However, the corollary of this is that if you don't collect WEEE in an appropriate manner for the end process then many of the products that could have been re-used will be too damaged and CRMs that could have been extracted if they had been sorted and disassembled at an early stage are more likely to be lost due to WEEE shredding. Therefore the quality of the collection is as important as the quantity that is collected.

Based on the recovery systems trialed, it appears to be economically and environmentally sound that collection systems enable as many items as possible to be processed for re-use markets, prior to recovery/ recycling. If re-use is the final form of CRM recovery then the evidence from the trials is that collections need to target newer, high specification items with a relatively high resale value.

However, depending on the CRM recovery process it may be optimal to target older WEEE that have a high concentration of components used, e.g. PCB's. Development of a product database including knowledge of embedded CRM content will produce sorting criteria that could be used much earlier in the collection stage, for example in the marketing of the collections, encouraging citizens to just bring CRM-rich WEEE for collection and reminding them of the need to handle their products with care.

Recovery trials set out to separate CRMs from the items collected that had not gone to re-use. New technologies were trialed and demonstrated on a small scale and there were notable successes in achieving high enough concentrations of CRMs for recovery in some cases. The recovery trials were each different and did not produce comparable results.

The evaluators of the project, Wuppertal Institute, offered reflection on the difficulties in quantifying the results of the trials consistently for the different technologies that were being demonstrated. The amount of metals recovered cannot be clearly determined for several reasons:

- The technological approaches used in the recovery trials were very different. For instance, Asekol tested different separation methods and identified the fractions with the major part of CRM contents, but they did not really recover CRMs.
- Most of the trials did not test recovery methods for all the product types collected. Even if we could calculate the quantities recovered, they do not apply to all the types of equipment collected and can therefore not be extrapolated.
- Many experiments were carried out on a laboratory scale, so it is completely unclear to what extent the recovery rates will change if, for example, the input varies on an industrial scale.

Following the evaluation of the project, and the exercise carried out to assess the socio-economic impacts of the work, a number of recommendations have been identified for further work. These are summarised here:

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There is potential to scale-up some of the recovery technologies that achieved positive outcomes during the trials, where it was demonstrated that the technology worked successfully at a very small scale. As above, the laboratory nature of the trials for this project means that conclusions about operationalising the technology on a larger scale cannot currently be drawn. Further trials would look to demonstrate viability on a larger scale.

The trials analysis highlighted the current challenges of CRM recovery technologies due to the low cost of virgin materials (compared to the peak 2012 (http://hwwi-rohindex.de/). Some of the proof of concept laboratory experiments demonstrated high recovery rates of the materials of interest. However, further laboratory work is required before these separation techniques would be suitable for use within a commercial environment. The work has for instance shown that bioleaching resulted in high potential recovery rates, but lacks commercial viability at this stage. However, considering the significantly reduced environmental impact of bioleaching compared to conventional pyrometallurgical processes, both the real costs and operational risks are lower than those associated with chemical leaching.

As a result, we can conclude that it is important for national and local governments (as well as non-governmental organisations) to partner with R&D projects to encourage the adoption of sustainable methods of CRM recovery such as bioleaching. Furthermore, it is important that the private sector is made aware of the feasibility and benefits of adopting this approach to CRM recovery, versus traditional metal recovery techniques.

6. Conclusion

This report has provided a summary of the collections and recovery activities undertaken as part of the Critical Raw Material Closed Loop Recovery project. The outcomes from trials have demonstrated a link between collections methods and effective recovery of critical raw materials.

The recovery trials set out to separate CRMs from the items collected that had not gone to re-use. New technologies were trialed and demonstrated on a small scale and there were notable successes in achieving high enough concentrations of CRMs for recovery in some cases. The recovery trials were each different and did not produce comparable results. The amount of metals recovered cannot be clearly determined for several reasons:

- The technological approaches used in the recovery trials were very different. For instance, Asekol tested different separation methods and identified the fractions with the major part of CRM contents, but they did not really recover CRMs.
- Most of the trials did not test recovery methods for all the product types collected. Even if we could calculate the quantities recovered, they do not apply to all the types of equipment collected and can therefore not be extrapolated.
- Many experiments were carried out on a laboratory scale, so it is completely unclear to what extent the recovery rates will change if, for example, the input varies on an industrial scale.

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Information gathered during the trials has informed key project deliverables including those for work packages C1, C2 (monitoring and evaluation), B3 and B4 (policy and infrastructure plans).

http://www.criticalrawmaterialrecovery.eu/wp-content/uploads/2019/10/B3.1-Policy-Report-D.pdf

http://www.criticalrawmaterialrecovery.eu/wp-content/uploads/2019/10/Pan-European-Infrastructure-Development-B4-FINAL-D.pdf

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Appendix 1 - Collection Matrix

		kerbside (range of methods to maximise reuse and material recovery) *	Retailer takeback	collection events	incentivised returns**	business collections	Postal returns	HWRC collections* **	house clearance	third sector donations	bulky collections	other?
Products		all	all	all	all	all	SMW, consumer electronics	all	all	all	all	
Tonnage	high 3/medium 2/low 1	2	2	2	2	2	1	3	1	2	1	
reuse potential (value)	high 3/medium 2/low 1	1	3	2	3	2	2	1	3	2	2	
CRM recovery potential	High 3/medium 2/low 1	3	3	3	3	3	2	3	2	2	2	
cost relative to collection potential	high 1/medium 2/low 3	2	3	2	3	2	2	2	1	3	2	
Replicability	yes/no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	
Data security/risk of theft	risk high 1/medium 2/low 3	2	3	3	3	3	2	1	2	3	3	
Innovative	yes 2/no 1	1	1	1	1	1	1	1	1	1	1	
Potential for use of an incentive	yes/no	yes	yes	yes		yes	yes	yes	no	?	yes	
good practice evidence	examples and location											
Score		**11**	**15**	**13**	**15**	**13**	**10**	**11**	**10**	**13**	**11**	

* this could include targetting particular products or how they are separated on collection vehicle
** is this the same as retailer takeback but with an incentive?
*** this could include targetting particular products, the containers use or the categories by which the product are selected

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IT		kerbside (range of methods to maximise reuse and material recovery) *	Retailer takeback	collection events	incentivised returns**	business collections	Postal returns	HWRC collections* **	house clearance	third sector donations	bulky collections	other?
Products												
Tonnage	high 3/medium 2/low 1	2	2	3	3	2	2	2	1	2	2	
reuse potential (value)	high 3/medium 2/low 1	1	3	3	3	3	3	2	2	2	2	
CRM recovery potential	High 3/medium 2/low 1	3	3	3	3	3	3	3	3	3	3	
cost relative to collection potential	high 1/medium 2/low 3	2	3	3	3	2	2	3	1	1	2	
Replicability	yes/no	yes	y	y	y	y	y	y	y	y	y	
Data security/risk of theft	risk high 1/medium 2/low 3	2	3	3	3	3	1	1	3	3	3	
Innovative	yes 2/no 1	1	1	1	1	1	1	1	1	1	1	
Potential for use of an incentive	yes/no	yes	y	y	y	y	y	y	y	y	y	
good practice evidence	examples and location											
Score		**11**	**15**	**16**	**16**	**14**	**12**	**12**	**11**	**12**	**13**	

* this could include targetting particular products or how they are separated on collection vehicle
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		kerbside (range of methods to maximise reuse and material recovery) *	Retailer takeback	collection events	incentivised returns**	business collections	Postal returns	HWRC collections* **	house clearance	third sector donations	bulky collections	other?
Products												
Tonnage	high 3/medium 2/low 1	2	3	3	3	2	2	3	1	2	2	
reuse potential (value)	high 3/medium 2/low 1	2	3	3	3	2	3	2	2	2	2	
CRM recovery potential	High 3/medium 2/low 1	3	3	3	3	3	3	3	3	3	3	
cost relative to collection potential	high 1/medium 2/low 3	3	3	2	2	2	1	2	1	3	2	
Replicability	yes/no	y	y	y	y	y	y	y	y	y	y	
Data security/risk of theft	risk high 1/medium 2/low 3	2	3	3	3	2	1	1	2	2	3	
Innovative	yes 2/no 1	1	1	1	1	1	1	1	1	1	1	
Potential for use of an incentive	yes/no	y	y	y	y	y	y	y	y	y	y	
good practice evidence	examples and location											
Score		**13**	**16**	**15**	**15**	**12**	**11**	**12**	**10**	**13**	**13**	

* this could include targetting particular products or how they are separated on collection vehicle
** is this the same as retailer takeback but with an incentive?
*** this could include targetting particular products, the containers use or the categories by which the product are selected

7.4.1 Collections Trials Matrix

		kerbside (range of methods to maximise reuse and material recovery) *	Retailer takeback	collection events	incentivised returns**	business collections	Postal returns	HWRC collections* **	house clearance	third sector donations	bulky collections	other?
Products												
Tonnage	high 3/medium 2/low 1	3	3	3	3	3	1	3	2	2	3	
reuse potential (value)	high 3/medium 2/low 1	2	3	3	3	2	2	2	2	2	2	
CRM recovery potential	High 3/medium 2/low 1	3	3	3	3	3	3	3	3	3	3	
cost relative to collection potential	high 1/medium 2/low 3	3	3	2	2	2	1	2	1	3	2	
Replicability	yes/no	y	y	y	y	y	y	y	y	y	y	
Data security/risk of theft	risk high 1/medium 2/low 3	2	3	3	3	2	1	1	2	2	3	
Innovative	yes 2/no 1	1	1	1	1	1	1	1	1	1	1	
Potential for use of an incentive	yes/no	y	y	y	y	y	y	y	y	y	y	
good practice evidence	examples and location											
Score		**14**	**16**	**15**	**15**	**13**	**9**	**12**	**11**	**13**	**14**	

* this could include targetting particular products or how they are separated on collection vehicle

** is this the same as retailer takeback but with an incentive?

*** this could include targetting particular products, the containers use or the categories by which the product are selected

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Appendix 2 -Recovery Process Map and Recovery Mechanisms

Entity, location	***Process name***	***Description***	***Input material***	***Output material***	***Capacity of input material [ton/y]***	***Annual production of target materials***	***URL***	***Source***
Heraeus, Hanau, Germany	No information publicly available	No information publicly available	Concentrates (from mining and smelting industry, about 1-3% precious metal content in the material) - Mining concentrates from - Platinum Group Metals (PGM) mines PGM concentrates from copper and nickel smelters Secondary Concentrates (from intermediate refiners) - Concentrates, precipitates - Prepared and unprepared sweeps - Bullions Spent Catalysts (chemical, pharmaceutical &	Ag, Au, Pt, Pd, Rh, Ru, In, Re	No information publicly available	Rough figures valid for Hanau/Germany site: Pt: 15 ton/year Pd: 18 ton/year Au: 2 ton/year Ag: 130 ton/year In: 0.6 ton/year Rh: 1.5 ton/year Ru: 14 ton/year Re: 2 ton/year	www.heraeus.com	https://www.heraeus.com/media/media/hmm/doc_hmm/HMM160003_Broch_HMM_Layouts_final_Preview_002.pdf

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			petrochemical industries) - Heterogeneous catalysts on various substrates (i.e. carbon, alumina oxide) - Homogeneous catalysts in different solutions - Ion exchange resins					
			Alloys (jewelry, dental, magnetic data storage and medical industries) - Sputtering targets - Residues - Electrodes from implantable devices - Dental and jewelry alloys and sweeps - Remelt of bars Industrial Waste (electronics, automotive) Production scrap - Crucibles - Connectors - Electronic components - Strips and capacitors - Pastes, powders - Surplus materials from production processes					

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Umicore, Hoboken, Belgium	Integrated smelter refinery process ("Hoboken Process")	Smelter, the copper leaching and electrowinning plant and the precious metals refinery	Industrial wastes, copper and precious metal rich electronic waste fractions	Cu, Ag, Au, Pt, Pd, Rh, Ru, Ir, In, Se, Te, Pb, Sn, Sb, Bi	350,000 t/y in 2014	?	http://www.umicore.com	http://annualreport2014.umicore.com/management-review/group-review/economic-review/case-hoboken-expands-to-meet-market-needs/
Boliden, Sweden	Kaldo technology	The Kaldo furnace is essentially a slightly leaning cylinder which rotates during the smelting process. The material is fed in and tapped out through the mouth of the furnace. There is no need to input any energy into the furnace: the plastic in the input raw material provides sufficient energy for the smelting process. The large	The smelters are supplied with concentrates from Boliden's own mines and with concentrates and secondary raw materials from external suppliers. Boliden's internal copper concentrate production covers approximately 30 per cent of the smelters requirements, while the corresponding figure for zinc smelters is approximately 65 per cent.	Ai, Ag,	120,000 t/y	?	http://www.boliden.com	http://www.boliden.com/Operations/Smelters/E-scrap-project/

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		amounts of energy released are recycled and converted to electricity or district heating. The smelted electronic scrap, known as black copper, is integrated with the smelter's main copper flow for further refining and the extraction of copper and precious metals. Boliden Rönnskär's electronic scrap recycling operations expanded substantially in conjunction with the investment in the new material processing and						

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		smelting facilities that were commissioned in early 2012. An e-Kaldo plant complements the existing Kaldo plant, yielding a combined annual production capacity of 120,000 tonnes.						
Aurubis, Lünen/ Hamburg, Germany	Kayser recycling system (integraded smelter refinery process)	Smelter, the copper leaching and electrowinning plant and the precious metals refinery	Industrial wastes, copper and precious metal rich electronic waste fractions	Cu, Au, Ag, PGMs, Sb	Globally: 2,300,000 ton/y copper concentrates 730,000 ton/y recycling of secondary raw materials (scraps incl. WEEE fractions). 15-20% of secondary materials are fractions from WEEE: 40,000 ton PCBs, 50,000 ton equipment scrap such as PCs and other devices Lünen (Germany): about 100,000 ton/y	Lünen: capacity around 210,000 ton/y copper cathodes	www.aurubis.com	2016_09_08 WEEE Idea camp, Aachen Germany. Presentation "Aurubis AG The leading integrated coller producer" by Dr. Marcus Eschen

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					secondaries from WEEE			
PPM Pure Metals, Lengelsheim, Germany	specific recycling processes, no information available	Production of Sb, but no recycling	Ga containing scraps, residues and slurries from - GaAs crystal pulling - wafer processing - epitaxial processing - other gallium containing materials Various Ge and In containing residues	Ga, In, Ge	?	?	http://www.ppmpuremetals.de	
H.C. Starck, Goslar, Germany	production of technology metals	Hydrometallurgy (chemical processing Ta capacitors) Powder metallurgy Metallurgy Vacuum arc melting	Ta capacitors	Ta	?	?	www.hcstarck.com	
Saxonia		smelting, hydrometallurgy	precious metal containing material and residues	Au, Ag, Pt, Pd	?	?	http://www.saxonia.de	

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Recovery mechanisms

EARN

wrap earn European Recycling Platform KTN Wuppertal Institute for Climate, Environment and Energy

Index

- Overview general recovery mechanisms
- Current status of recovery (by type of equipment input)
  - Display
  - Consumer electronics, ICT, SHA
- Current status of recovery (by critical raw material)
  - Graphite
  - Cobalt
  - Antimony
  - Tantalum
  - Rare earths: Nd
  - Others: Ga, Ge, In
  - Gold, silver, PGM
- Priority recommendations on recovery trials in Germany and Turkey

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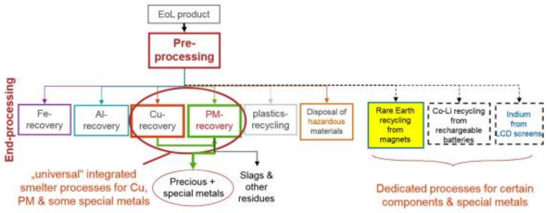
Overview general recovery mechanisms



C.Hagelüken, EIT-KIC seminar, Leuven, 14.9.2012

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Display (LCD)

- General methods:
  - Mass-flow processing by crushing and material separation (e.g. BluBox)
  - Semi-automated processing (e.g. Electrocycling)
  - Manual Dismantling

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Blu Box

- Simultaneously recycles lamps and flat panel displays
- Fully automatic recycling process
- Latest technology to ensure the safe recycling of hazardous lamps and electrical waste
- High capacity: 1000 kg/h flat panel displays and 500 kg/h lamps
- No need to manually disassemble FPDs
- Process Plasma screens up to 55" and LCD/LED/OLED screens up to 95"
- Secure data destruction
- Converts hazardous waste into valuable raw materials
- Highest safety standard – the whole system works constantly under negative pressure
- Easy transportation – the entire BLUBOX technology is built into a 40ft HC container

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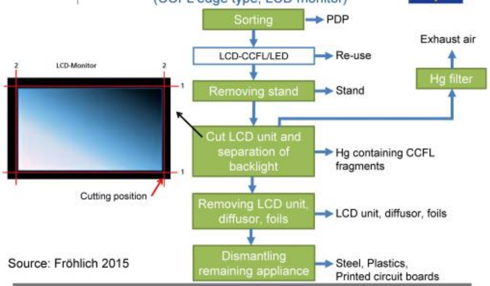
Semi-automated processing (CCFL edge type, LCD monitor)



Source: Fröhlich 2015

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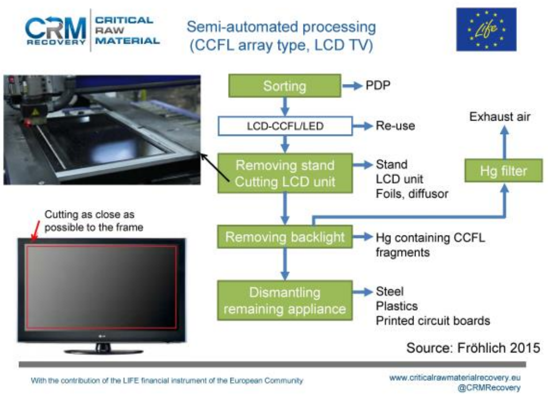

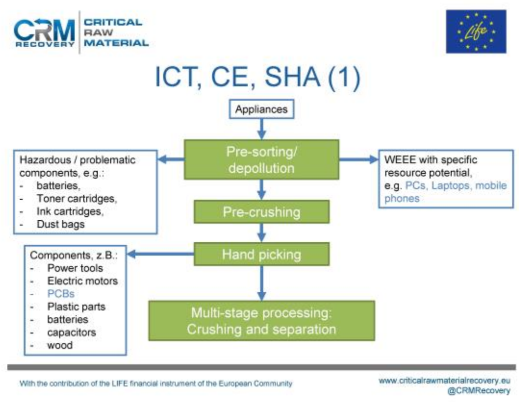

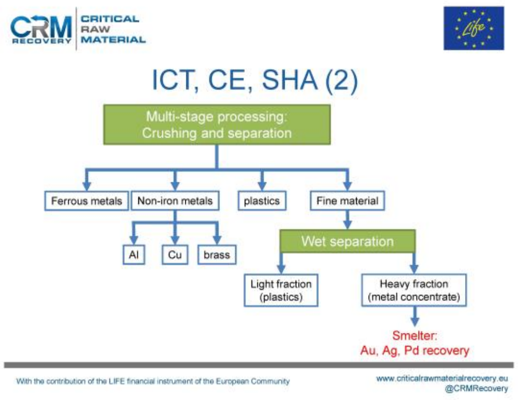

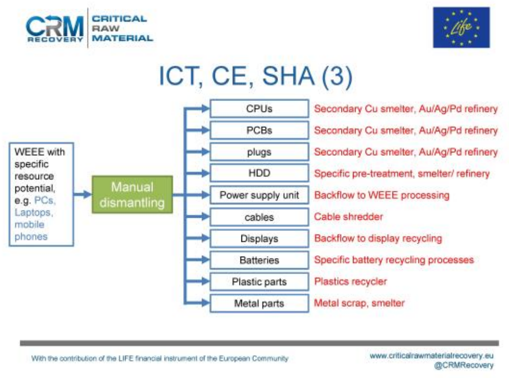

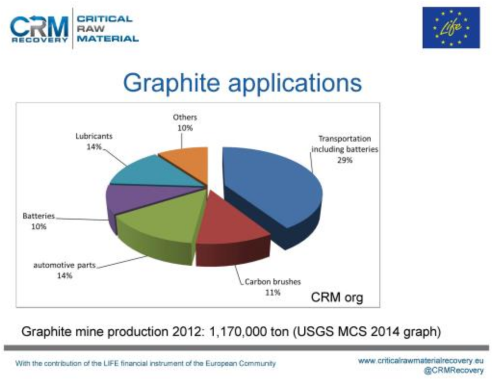

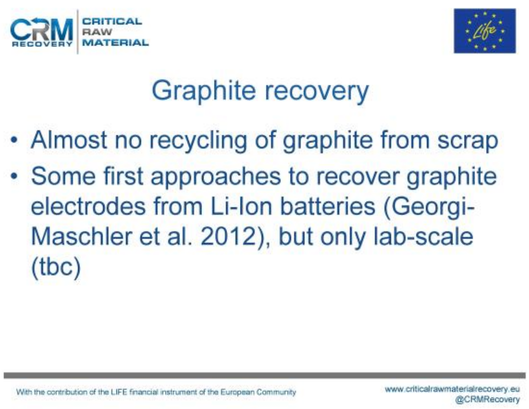

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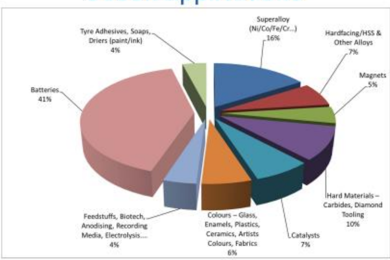
Cobalt applications



Refined Cobalt availability 2014: 91,754 ton (CDI 2015)

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Cobalt recovery

- In 2015, cobalt contained in purchased scrap represented an estimated 28% of cobalt reported consumption (USGS MCS 2016)
- UNEP data (UNEP 2011, based on Shed 2004)
  - Old Scrap Ratio 50% (end-of-life metal collected and enters into recycling chain)
  - Recycled Content 32% (share of secondary material in the fabricated metal)
  - End-of-Life recycling rate 68%

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Cobalt recovery: The Umicore Battery Recycling process

Tytgat 2011

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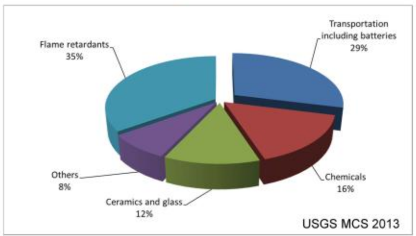
Antimony applications



Sb mine production 2012: 174,000 ton (USGS MCS 2014)

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Antimony recovery

- Majority of the secondary Sb stems from lead battery recycling. Amount of secondary Sb per year around 40,000 t (Roskil 2007)
- Recycling of Sb from flame retardants is not existing, since not economically feasible and high dissipation of the flame retardants in different plastics applications

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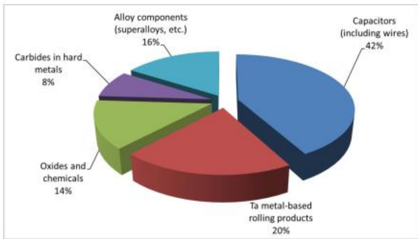
Tantalum applications



Ta demand around 1,400 – 2,000 ton/y

Thomé-Kozmiensky 2012

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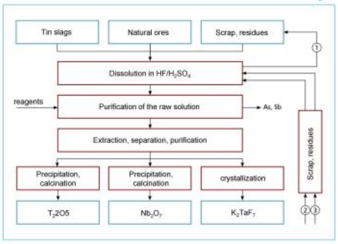
Tantalum recovery



Hydrometallurgical processing of tantalum and niobium from raw materials to the oxides and potassium tantalum fluoride (K_2TaF_7)

Thomé-Kozmiensky 2012

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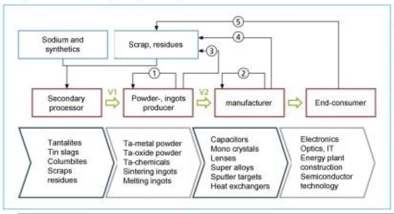
Tantalum recovery

Material flows and cycles within tantalum product processing (Thomé-Kozmiensky 2012)



Percentages of losses (V1, V2) and material flows (1-5):

V1: 2-4% loss
V2: 5-8% loss
(1) Internal recycling at powder and ingot producer: 8%
(2) Internal recycling at manufacturer of end products: 4%
(3) Backflow from powder producer to secondary processor: 17%
(4) Backflow form end-product manufacturer to powder/ ingots producer: 18%
(5) Backflow from end-user to powder and ingot producer: 17,5%

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Tantalum recovery

- Tantalum content in a mobile phone around 157 ppm (Luidold et al. 2013)
- Overall Tantalum recovery ratio from end-of-life products below 1% (Luidold et al. 2013)

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Tantalum recovery

- Biggest recycling potentials as well as challenges at post-consumer wastes from ICT products. Ta is quite diluted in these items. No economically and ecologically feasible recycling possible for the time being.
- Pre-consumer cycles of Ta scrap occurring at the production of electronics (capacitors e.g.), carbides or super alloys established (USCS MCS 2013)
- In order to secure long-term raw material security, new collection, dismantling and recycling strategies must be developed

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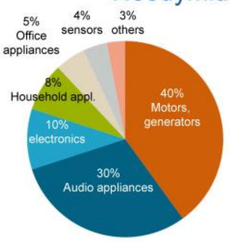
Neodymium applications



Annual production of Nd (2012): 21,000 ton

91% from China (Roskill 2013)

Nd-Fe-B applications
(Zepf 2013; Ningbo Heli Magnetic Technology Co., Ltd. 2014; Brown et al. 2014)

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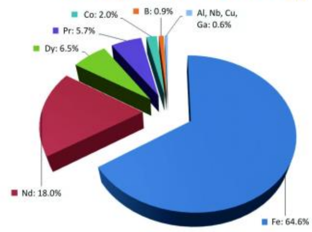
Neodymium recovery



Chemical composition of a Nd-Fe-B magnet from the scrap (Data in mass-%)
Source: Diehl et al. 2016

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Neodymium recovery

- Currently, no process is established on industrial-scale allowing the recycling of rare earth permanent magnets from end-of-life products. The rare earth elements dissipate in metal scrap.
- Three principles to recycle scrap magnets:
  - direct reuse
  - elemental recycling
  - alloy recycling

Source: Diehl et al. 2016

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Neodymium recovery

- Once the magnets are dissipated in metal scrap after conventional shredding or mixed with other magnet materials (e.g. Fe-B), any separation of individual magnet materials is technically ambitious and not economically reasonable.
- Separating Nd magnet material from WEEE, sintered magnets can be pulverized by hydrogen decrepitation (Zakotnik 2006)
- HyProMS (TSB project in the UK (2008-2010):
  Hydrogen Processed Magnet Scrap
  Partners: PowdermatriX (Project Managers),Secure IT Recycling Ltd, Less Common Metals Ltd, Magnet Applications Ltd, Precision Magnetics Ltd, Birmag Ltd, Arnold Magnetics.

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Neodymium recovery

- Direct reuse
  - Best solution from economic and ecological point of view
  - Difficult due to specific shape, irreversible damages (e.g. corrosion)
- Elemental recycling
  - extraction of single elements or compounds
  - Research on pyro- and hydrometallurgical processes
  - partly used in primary production (very energy-intensive)
  - Gas phase reactions and bioleaching
- Alloy recycling
  - → melt spinning technology

Source: Diehl et al. 2016

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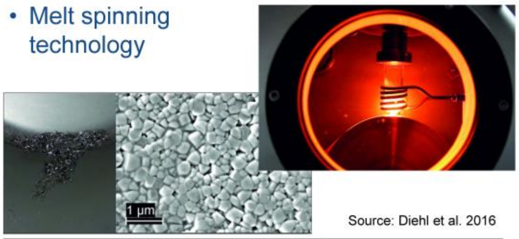
Neodymium recovery

- Melt spinning technology



Source: Diehl et al. 2016

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Neodymium recovery

- Melt spinning technology
  - inductively melted in a crucible
  - heated to more than 1200°C
  - thereafter cast via a nozzle, located in the bottom of the crucible, onto a fast rotating copper wheel (water cooled).
  - the melt drop solidifies on the rotating wheel as a thin flake.
  - The rapid cooling prevents an atomic arrangement in the otherwise typical crystalline lattice.
  - Lab scale at Fraunhofer IWKS
  -

Source: Diehl et al. 2016

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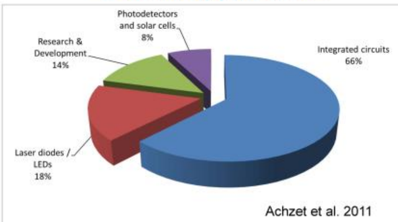
Gallium applications



Ga production around 85 ton in 2011 (World Mining Data 2013)

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Gallium recovery

- Ga recovery from end products not implemented (or very limited):
  - Ga concentration in end products is quite low
  - recycling processes very extensive
  - Ga used in new technologies, so that the end products just started to get disposed
- Recycling potential of Ga around 200t globally, mainly from GaAs semiconductors and electrical appliances (LEDs, photo detectors, solar cells)

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Gallium recovery

- Recovery of Ga mainly installed in the production process, especially at GaAs-Chip production: high percentages of losses during process (around 30% during wafer production)

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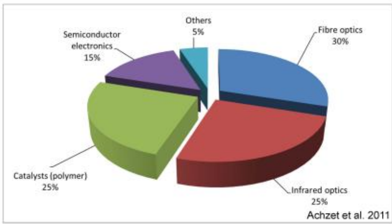
Germanium applications



Ge production around 128 t in 2012 (USGS MCS 2014)

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Germanium recovery

- Due to high dispersion of Ge in different products and applications at quite low concentrations, the Ge recovery from end-of-life products is > 1%
- wastes from production processes (dust, sludges, glass fibres, intermediates, …) are collected carefully and recycled. Around 25-30% of the Ge used globally originates from production waste recycling (USGS 2005)

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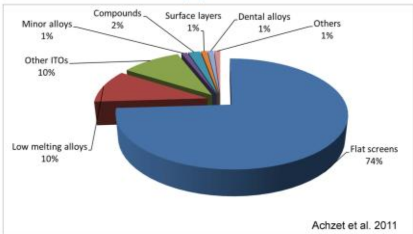
Indium applications



In production around 670 t in 2012 (USGS MCS 2013)

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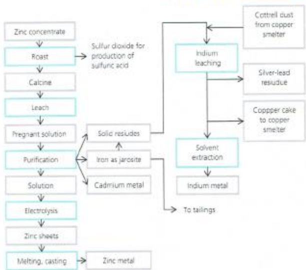
Indium recovery



Generalized beneficiation flow diagram based on the Kidd Creek operations (Gunn 2014)

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Indium recovery

- Majority of the recycled In stems from production wastes (e.g. ITO targets). During sputtering, only 30% of the ITO is settled on the target. According to Swiss Academy of Technical Sciences, 60-65% of the Indium is recycled globally from these wastes.
- About 1,000 ton secondary In is produced globally (Gunn 2014)
- In recycling from end products is lower than 1%
- Mainly Umicore is able to refine In from disposed materials.
- The recovery of In from LCD applications is still on lab stage/ pilot plant stage (e.g. German BMBF Project "In Access", or Yang 2015). It is based on leaching processes. It can be expected, that the In concentrate generated by these processes can easily be fed into existing In recovery processes (e.g. at Umicore). Source: EMPA 2015

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Au, Ag, PGM recovery

- These metals are "best performers" in the recovery by established processes at smelters (Umicore, Aurubis, Boliden). See Hoboken Process (e.g. Umicore), source: Gunn 2014:
  - Pt, Pd over 95% metallurgical yield
  - Rh, Ru, Ir slightly lower than for Pt, Pd
- Some research on hydrometallurgy, e.g. HydroWEEE project http://www.4980.timewarp.at/sat/hydroWEEE/
- Bioleaching (biooxidation, BIOX® process for sulfidic-refractory gold concentrates) in Au mining established since 1986 (Brierley 2013), but not applied in case of recycling (secondary processing)
- Some research on bioleaching, e.g. Project Ecometals http://www.ecometals.org

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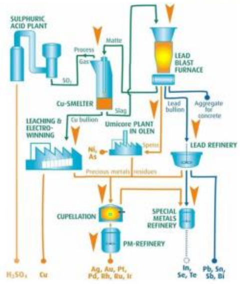
Hoboken Process at Umicore



- Hoboken universal process at Umicore
- Integrated smelter-refinery process; Cu, Pb and Ni act as collectors for precious metals
- Large orange arrows: recycling material can be fed into the process, depending on concentration and properties
- Main feed stream goes into the smelter (upper left arrow)

Source: Hagelüken in: Gunn 2014

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Recommendations for recovery trials (Germany)

Product/ component	Targeted CRM	Process	Potential candidate
Display	In, Au, Ag, PGM	Semi-automated dismantling, leaching of ITO	Electrocycling + TU Clausthal
ICT, CE, SHA	Au, Ag, PGM, Co, Ta	Pre-crushing, hand-picking, final processing	Coolrec (Liege, BE)
ICT, CE, SHA	Au, Ag, PGM, Co, Ta	Crushing and final processing	Coolrec (Liege, BE)
ICT, CE, SHA	Au, Ag, PGM, Co, Ta	Dismantling	ZME
HDD	Nd, Co	Crushing and hand-picking	ZME
	Nd	Crushing, hydrogen embrittlement	Fraunhofer IWKS
PCBs	Au, Ag, Ta, Sn, PGM	Crushing and optical sorting	Axion (contracted)
Fractions from display, ICT, CE	Co, Au, Ag	Bioleaching	Re-tec (contracted)
Li-Ion Batteries	Co, Graphite	Mechanical pre-treatment with hydro- and pyrometallurgical process steps	RWTH Aachen, IME (Prof. Friedrich) with UVR-FIA and Accurec

Analytics:
- Technical University Hamburg Harburg (Institute of Environmental Technology and Energy Economics)
- Fraunhofer IWKS

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