Next generation urban mining – Automated disassembly, separation and recovery of valuable materials from electronic equipment: overview of R&D approaches and first results of the European project ADIR

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Keywords: recycling, reverse production, consumer electronics, robotic handling, 2D/3D measurement, laser spectroscopy, laser desoldering and cutting, hydrometallurgy

Abstract

An overview will be presented on current R&D activities of the European project ADIR – running since 9/2015 - dealing with the automated disassembly, separation and recovery of valuable materials from electronic equipment. Main focus are end-of-life cell phones and printed circuit boards from server and network electronics.

To date the material specific recycling is focused on mass stream concepts such as shredder processes and metallurgy to extract the high-value metallic constituents, i.e. copper, gold, silver. However, a series of critical elements cannot be recovered efficiently or is even lost in dust or residual fractions.

The goal of ADIR is to demonstrate the feasibility of a key technology for next generation urban mining in the scope of inverse production concepts. An automated disassembly of electronic equipment is worked out to separate and recover valuable materials. The concept is based on image processing, robotic handling, pulsed power technology, 3D laser measurement, real-time laser material identification (to detect materials by laser spectroscopy), laser processing (to selectively unsolder these; to cut off parts of a printed circuit board), and automatic separation into different sorting fractions. A data base is built up providing comprehensive information about physical and chemical features of the items to be treated.

A machine concept was worked out being capable to selectively disassemble printed circuit boards and cell phones with short cycle times to gain sorting fractions containing high amounts of valuable materials. Examples are those materials with high economic importance and supply risk such as tantalum, tungsten and neodymium.

The various processes for the ADIR demonstrator have been developed recently and will now be implemented in a set of interlinked machines to validate the novel process chain for inverse production. The current state of development will be highlighted.

1 Introduction

The UNEP report clearly points out the need to decouple the so far prevailing correlation between gross domestic product (GDP) per capita and the metabolic rate in terms of the consumption of resources per capita and year [1]. The need is to come to a so-called Kuznet-curve, i.e. the further growth of GDP shall come along with a reduced metabolic rate instead of a further increasing one [2].

On the way to such a sustainable green economy the development of technologies for next generation urban mining is considered to be a cornerstone. Figure 1 illustrates schematically various circles of backflows which a product may take to reenter the production chain. Whereas the inner circles are partly well established the greatest circle – the recycling branch – requires a further technology push by making available novel inverse product technologies to enable efficient recycling chains for industrialized countries. The lower part of Fig. 1, shown with a grey background, illustrates that trading actions generates product flows to users in the Third World, offering an extension of the life cycle by reuse and reselling. However, this only provides a postponement, it is not a principle solution for the material cycle. Since the target customers in that case are often located in developing countries, this approach endangers a thorough and efficient recycling of valuable materials (cf. dashed arrows in the lower part of Fig. 1).

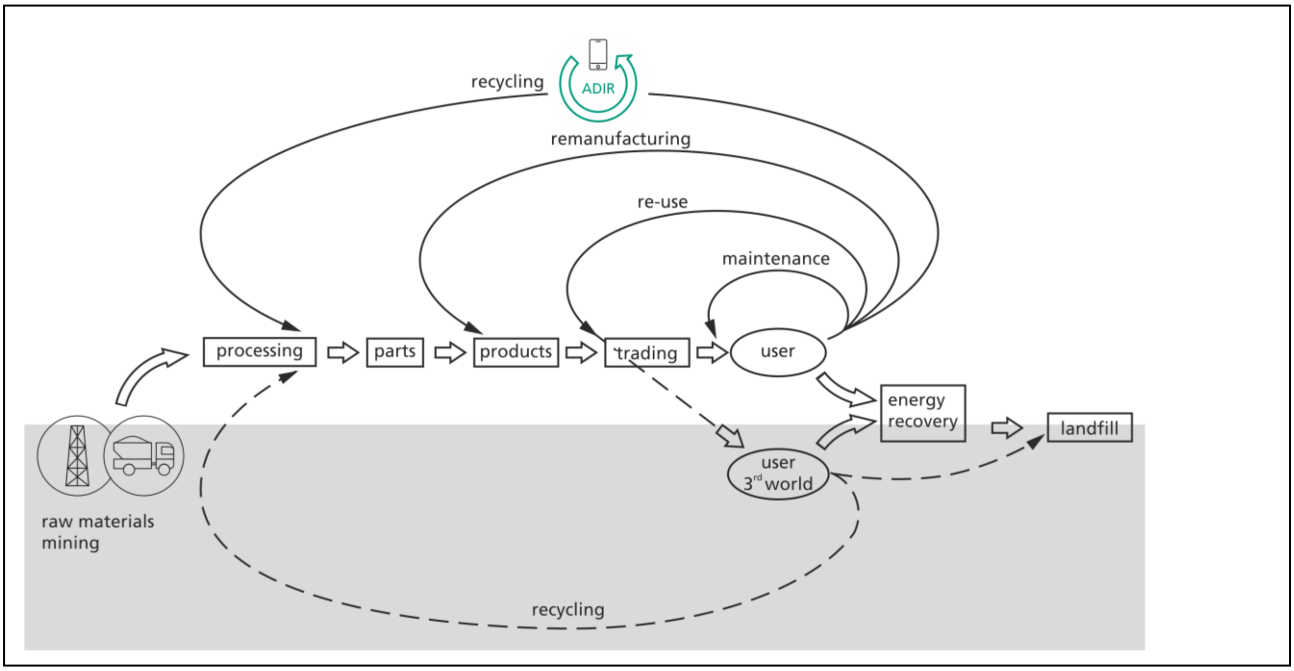

Figure 1: The circles of circular economy. The project ADIR contributes to the inverse production chain by applying novel technologies for a selective physical disassembly of electronic products and hydrometallurgical processes to improve the efficiency of recovery and to extend the range of recoverable materials. The lower part with a grey background indicates processes which are conducted mainly outside Europe under difficult economic and social conditions often dominated by low quality processes with severe consequences for health, environment and sustainability. Trading of electronic products to users in the 3rd world is a main feeding channel for these negative impacts on working conditions and environment

Moreover, the international resource panel emphasized that recycling rates for many metals are still miserably low [2]. Electronic equipment such as mobile phones and printed circuit boards contain elements with high economic importance and significant supply risk such, see Fig. 2 [3].

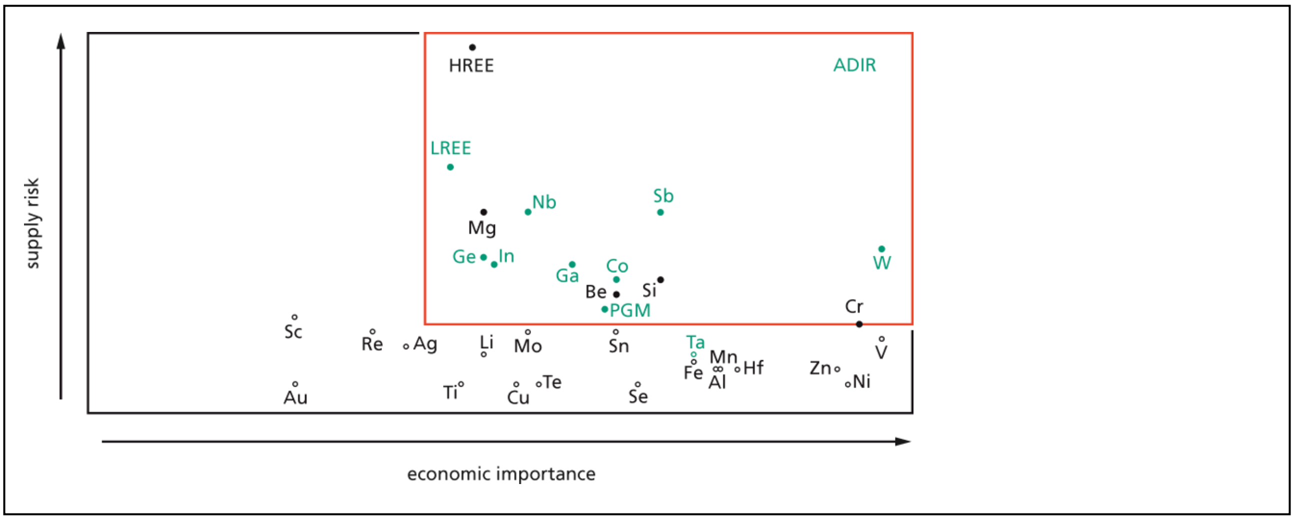

Figure 2: Assessment of raw materials with respect to their criticality; particularly important are those shown in the red rectangle [3]. The elements stated in green are the target elements of the ADIR project as e.g.: Ta, W, Pd (belongs to PGM) and Nd (belongs to LREE). HREE = heavy rare earth elements, LREE = light rare earth elements, primarily Pr, Nd; PGM = platin group metals, primarily Pd; Si = silicon metal

Electronic equipment – such as cell phones (or mobile phones, MPH) and electronic boards from computers, servers and switching electronics – comprises a lot of valuable materials. On the other hand their life cycle is becoming shorter and shorter. Thus, the amount of MPHs no longer used increases continuously reaching an accumulated level of > 190 million units in the year 2014 in the European Union [4]. The dimension of the challenge is illustrated with Fig. 3 showing the accumulated number of active mobile phones in the world as a function of time [5]. The curve shows a saturation behaviour reaching a level of 6.9 bill. in 2014. Europas share of this number is: 780 mill. in 2014. Assuming a stagnation of the market at a level of 7 billion units – see horizontal line with number 1 in Fig. 3 - and a mean time of usage of on average 4 years yields a total number of end-of-life mobile phones worldwide of 1.75 billion units per year (see green horizontal line with number 2 and right axis of Fig. 3). This number is plausible looking at the number of sold mobile phones in the year 2013 of 1.8 billion [5]. The share with respect to Europe is then about 193 mill. end-of-life MPHs per year.

A similar estimate for the world market of personal computers (this term is used here to describe the sum of desktop-PCs, laptops/notebooks and tablets; the monitor of the desktop-PC is not considered in the following) shows that this market is stagnating since 2013 at a level of about 550 mill. sold units per year [6]. Hence the estimated number of end-of-life units of PCs per year is in the order of 550 mill. units worldwide assuming a pure replacement market. Europe´s estimated share is about 61 mill. end-of-life PCs per year with a corresponding number of mainboards (printed circuit boards, PCB).

This mass flux of valuable material is often lost for the European economy by exports to Africa or Asia (cf. Fig. 1). If recycled in the EU, the conventional approach is focused on mass stream concepts such as shredder processes, partially followed by magnetic or eddy-current separators and pyrometallurgic procedures to extract the high-value metallic constituents, i.e. gold, silver, palladium and copper from MPHs and PCBs. However, a series of critical elements cannot be recovered efficiently or is even lost completely in dust or in residual fractions with high degree of dilution.

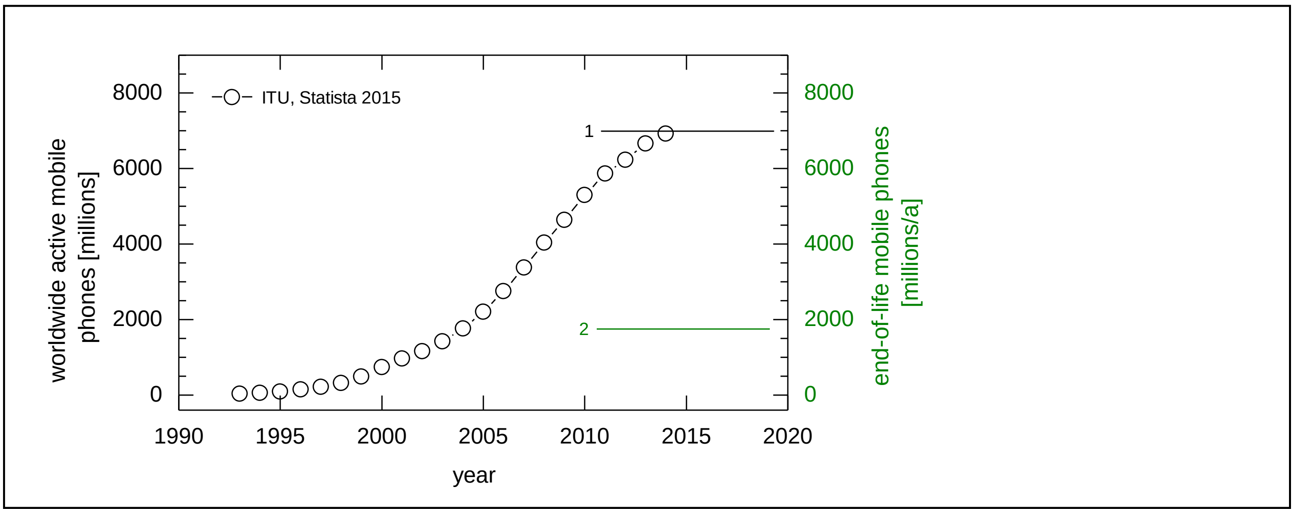

Figure 3: Number of worldwide active mobile phones from 1993 to 2014 [5]. 1 = assumed stagnation level; 2 = number of end-of-life MPHs expected assuming a 4 years period of use (right y-axis)

How can this mass flow be tackled in an efficient way? That is the point where the European project ADIR is focused on. The goal of ADIR is to demonstrate the feasibility of a key technology for next generation urban mining by selective treatment of the piece goods MPHs and PCBs (from personal computers and switching electronics of telecommunication base stations) for efficient recovery of valuable materials instead of using mechanical – such as crushing or shredding – and metallurgical methods designed mainly for recovery of the above mentioned metals only.

2 ADIR project

The overall objective of ADIR is to open the door for next generation urban mining by exploring and demonstrating innovative technologies for automated disassembly, separation and recovery of valuable materials from electronic equipment [7]. The process chain addressed by ADIR is illustrated in Fig. 4.

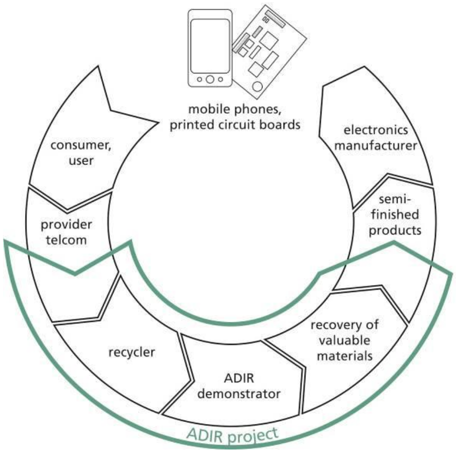

Figure 4: Process chain addressed by ADIR

Information technology, robot handling, pulsed power technology, image processing and laser technology have achieved a unique evolution in the last years in Europe. So far, their dominant application field is production technology. With ADIR these tools will be interlinked for the first time to realise a novel type of machinery enabling automated disassembly and sorting of components of electronic equipment. The ADIR system will initiate a revolution in terms of reverse production as technology basis for next generation urban mining.

Figure 5 shows the consortium members of ADIR and the installed advisory board. Coordinated by the Fraunhofer Institute for Laser Technology 10 partners are working together with specific expertises in the fields of mechanical engineering, laser technology, pulsed power technology, automation, metallurgy and recycling. The project is accompanied by an advisory board with representatives of Deutsche Telekom Technik, Vodafone and Fairphone.

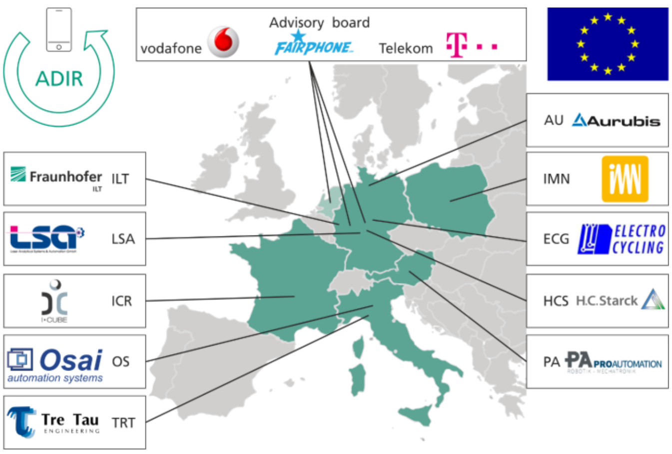

Figure 5: European coverage of the ADIR consortium

3 Overall concept

The technological concept of the ADIR demonstrator is shown schematically in Figure 6 [8].

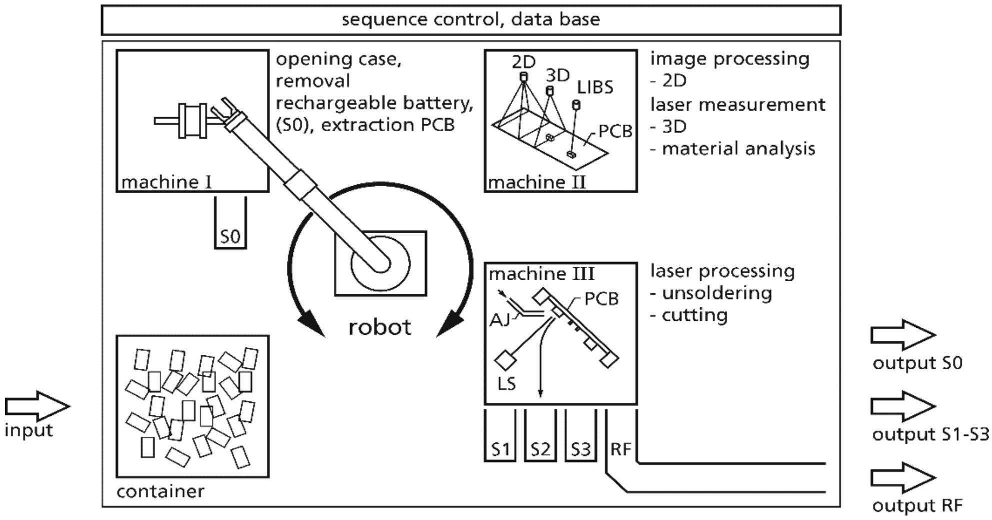

Figure 6: Concept of the ADIR demonstrator. A robot and a manipulator are picking single objects from the input stream and feed sequentially the machines I, II and III for selective disassembly of mobile phones and printed circuit boards (PCB) yielding the sorting fractions: S0 batteries, S1 – S3 enriched fractions of valuable materials, RF residual fraction. 2D/3D = two/three dimensional measurement of the geometry of PCB, LIBS = laser-induced breakdown spectroscopy for material analysis, LS = laser source and scanner for unsoldering and cutting, AJ = air jet

The collected end-of-life mobile phones are piled in a container and fed to a conveyor (not shown in Fig. 6). A robot equipped with a camera is picking a single object and positions this piece in a first machine I, where the case of the MPH is opened, the rechargeable battery is removed and put into bin S0 (“sorting fraction zero”). These actions shall be based on robotic processes, milling actions and potentially combined with pulsed power technology for fragmentation. The printed circuit board is taken out from machine I and a manipulator transfers this PCB to the next machine II. Machine II performs various measurements at the PCB. It takes 2D and 3D (by laser) images, processes these to identify interesting components potentially containing high amounts of valuable material. A laser spectroscopic measurement based on LIBS (laser-induced breakdown spectroscopy) measures inline constituents of these components, as e.g. tantalum. These data are used to feed a data base and to extract coordinates for the laser beam control to unsolder components from the PCB or to cut off parts of that PCB in machine III.

The measured object from machine II is transfered to machine III where the identified components are selectively unsoldered or cut off from the PCB. The disassembled components are discharged to the sorting fractions S1 to S3. After removal of the selected components the residual object is discharged to a residual fraction (RF).

The ADIR demonstrator yields e.g. five output streams: a) sorted fraction S0 containing rechargeable batteries (output of machine I), b) sorted fractions S1 to S3 with high-content of target materials from selectively disassembled components (output of machine III), c) residual fraction RF (output of machine III). These fractions, especially S1 to S3, are studied for efficient recovery of valuable materials by the involved R&D institute of non-ferrous metals research (IMN), the electro-recycling company (ECG) and two metal and semi-finished products manufacturers (HCS, AU).

This machine concept is scalable in various aspects: a) increase of number of sorting fractions from five to ten or more to recover further fractions of enriched target elements, b) stepwise increase of throughput of the ADIR demonstrator by reduction of cycle time based on the successively growing data base with information about types, physical and chemical parameters of MPHs and PCBs; i.e. the information gained from items inspected previously by 2D/3D measurements and material analyses (LIBS), can efficiently be used for subsequent objects of the same type without a need of a repeated inspection.

4 Composition of MPHs and PCBs, data base

From a collection of thousands of end-of-life MPHs a top ten list was determined and items of these list were studied by various analytical methods to gain information about the chemical composition of the electronic components used in these devices. Additionally, a set of modern smart phones was studied. A series of methodical approaches was deployed to establish a solid basis of the physical and chemical features of MPHs: manual dismantling, removing of battery, extraction of complete PCB and individually mounted components, photographs of each component were taken with a dedicated coordinate system; compositional analysis of electronic components by various methods: ICP-MS, ICP-OES, screening XRF; interlaboratory tests, "cherry picking" tests. The data was stored in a data base which enables queries to locate e.g. electronic components with high tantalum content on a PCB of a given MPH model.

The screening semi-quantitative XRF-based procedure was used for evaluation of the metal value contained in the material. Figure 7 shows as an example a pie chart with the average €-shares of the elements Au, Pd, Ag, Ta, Nd and Sn in electronic components on the PCB for 13 analysed MPHs (numbers are stated per average PCB from a MPH; they refer to the electronic components on the PCB only, not to the whole MPH). Additionally, the averaged percentage share of these six most valuable metals is given at the right of Fig. 7. As expected the highest share is linked to Au corresponding to a value of about 1 Euro (estimate based on market prices in 1/2017). Critical raw materials are found with shares of 5.2 % for Pd, 1.9 % for Ta and 0.4 % of Nd. Whereupon these are average numbers the studies revealed compositional shifts of MPHs depending on their year of market entry.

In a similar manner the composition of the residual PCB (when all electronic components are removed) and of the modules such as vibration alert, loudspeaker, microphone, camera were analysed. Looking at the modules only value shares of 22.5 % for Nd, 6.5 % for Pd and 6.5 % for W were found manifesting the significant enrichment of these critical metals in these parts.

The generated physical and chemical data are put into a data base which allows queries to indicate e.g. the position of electronic components on the studied PCBs where e.g. a defined threshold of tantalum content is surpassed. Figure 8 shows a screen shot of such a data base query chosen for the MPH model Siemens A55.

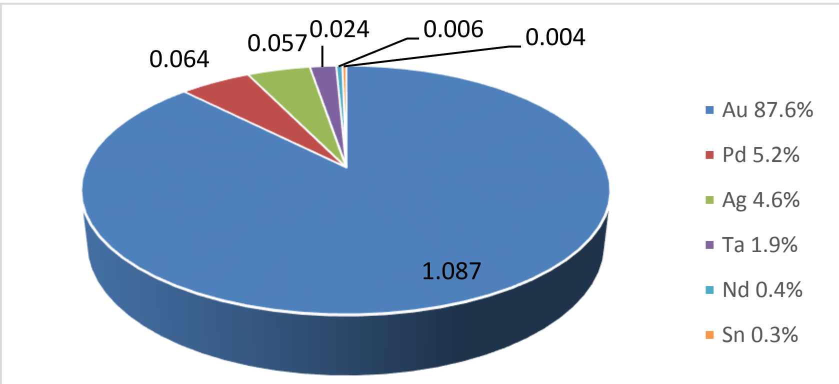

Figure 7: Pie chart of the average Euro-shares of the six most valuable target elements based on an analysis of the extracted electronic components from 13 MPHs (i.e. the values refer to the electronic components only and are given per PCB of a MPH). On the right side the average percentage shares are shown

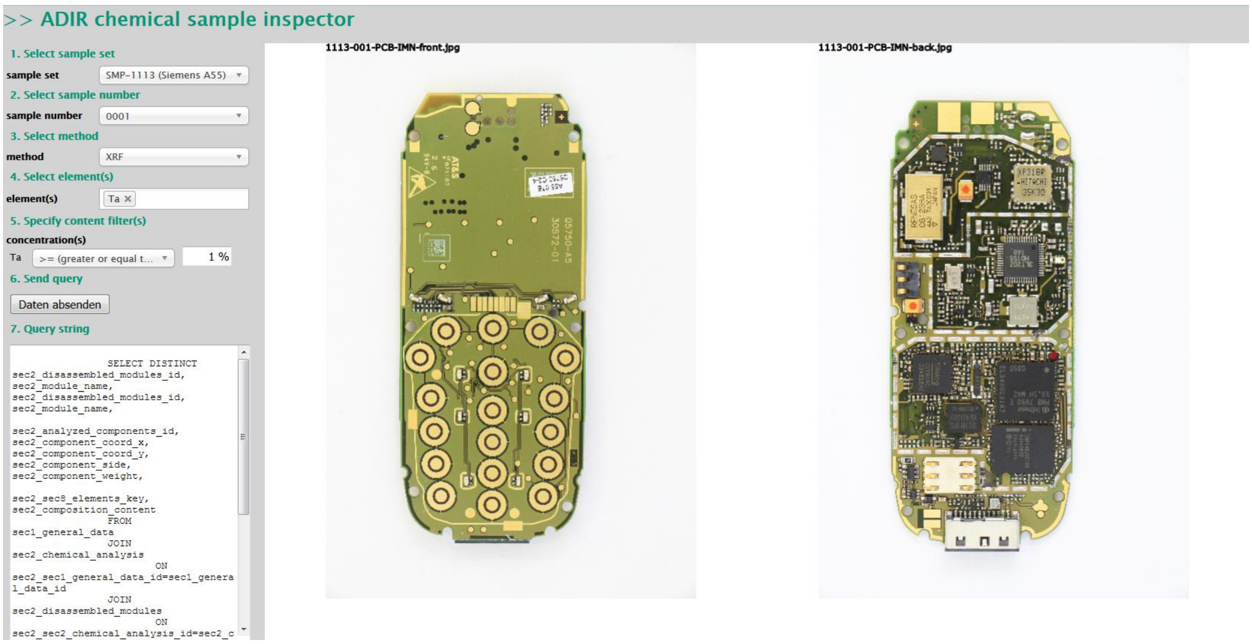

Figure 8: Screen shot of a query at the ADIR data base. High-resolution images of the front and backside of the PCB from the MPH model Siemens A55 are displayed. By a data base query (top left) compositional data with respect to e.g. tantalum are selected. In the shown example electronic components on the PCB are marked by a red dot where the tantalum content is greater or equal 1 %

5 Object charging and handling

A first design study of the ADIR demonstrator was worked out based on an interlinking of three machines, a feeding unit and a periphery for operation in a recycling plant. These machines will be set-up in 2017/2018. Objects to be recycled – such as MPHs – are singularized on a conveyor belt and from there picked by a robot. In the same way larger PCBs from network/server electronics are fed to the ADIR system. In a first machine the MPHs are placed in a clamping unit where by milling the casing is opened to get access to the internal components. A robot picks the battery and assigns it to a first sorting fraction. Step by step the MPH is disassembled. Finally, the extracted PCB is given over to a manipulator which transports this PCB to subsequent machines for 2D/3D-measurements, laser spectroscopic analysis and laser processing to selectively desolder or cut out electronic components of high material value. Figure 9 shows the robotic picking of a MPH from a belt conveyor.

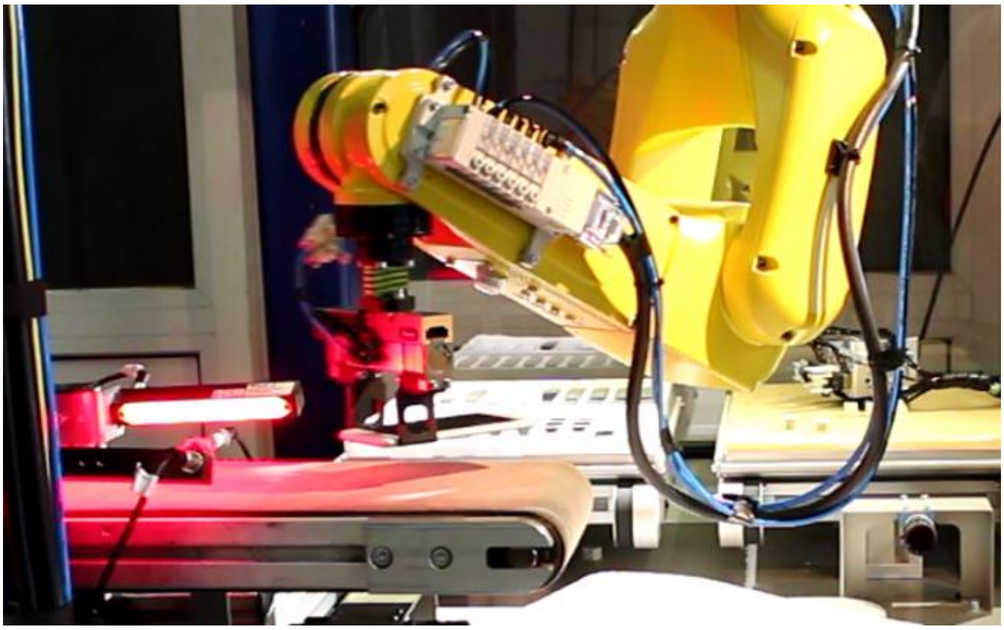

Figure 9: A singularized MPH transported on a belt conveyor, is first identified by a camera (see illumination above the conveyor) and then picked by a robot to transport the MPH to a clamping station for mechanical processing to open the casing to get access to the interior parts

The MPH is moved to a clamping unit and will then be processed by a milling tool to open the casing and to get access to the interior parts. After the opening the battery is extracted, see Figure 10, and sorted to a first sorting fraction. Finally, the PCB is taken out.

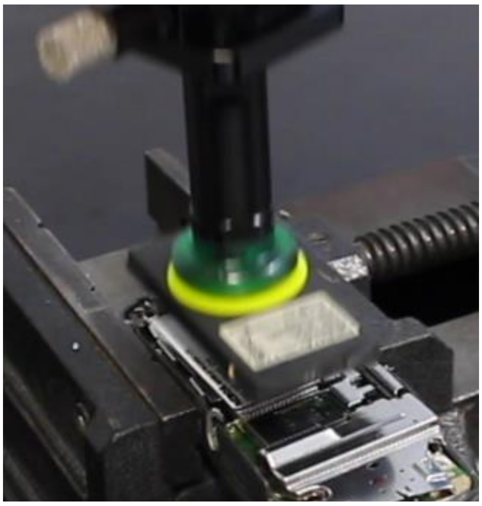

Figure 10: Withdrawal of a battery for an opened MPH by a suction cup

6 Image processing and laser spectroscopy

The data base (cf. Sect. 4) will be further extended with measured physical and chemical data of PCBs to be gained with the machine II of the ADIR demonstrator. The principal set-up of this machine is shown in Figure 11.

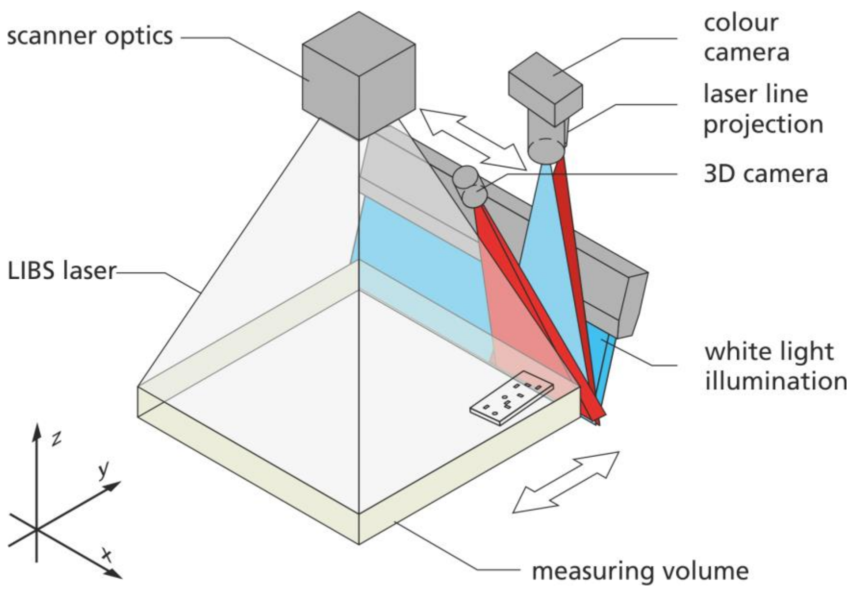

Figure 11: Principal set-up of machine II of the ADIR demonstrator. The PCB to be measured are positioned in a measuring volume. By a relative movement of a 2D- and a 3D-camera high resolution images of the PCB are taken. With a scanner optics a laser beam is then scanned to selected electronic components to measure a chemical information (LIBS)

For test purposes a raster scan of a complete PCB from a MPH was performed where a step size of 2 mm was deployed for the LIBS measurement to determine spectroscopic signals from e.g. tantalum as a function of the xy-position on the PCB. Figure 12 shows the result. The laser spectroscopic method enables a multi-element analysis in a very short time. The measurement time per spot is in the order of 2 s.

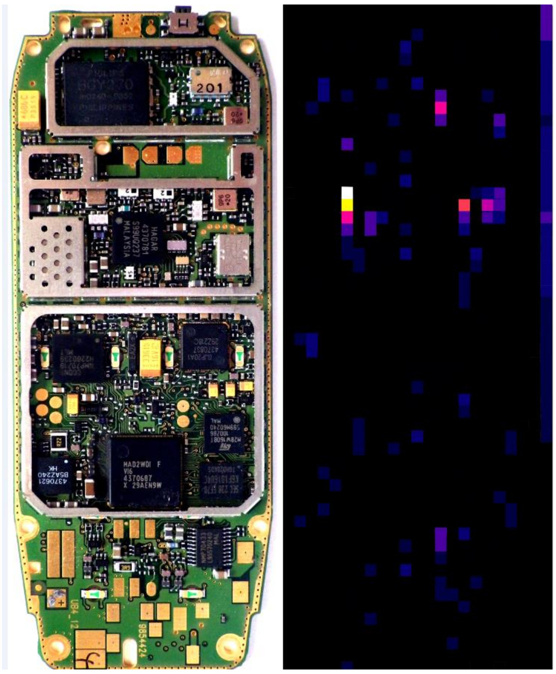

Figure 12: Left: photograph of the front side of a MPH, right: raster scan by laser-induced breakdown spectroscopy showing in false colors a chemical image of spectroscopic signatures of tantalum. An overlay of geometric-2D-image and chemical-2D-image yields the identified valuable components

Based on these data fed to the data base a component list is generated comprising a set of coordinates to be used for the subsequent processes of selective laser desoldering and cutting off of electronic components from PCBs.

7 Laser desoldering

Figure 13 illustrates the laser desoldering of a tantalum capacitor within fractions of a second. A continuous wave laser is scanned via a galvanometer head across the soldering pad of the SMD component to be desoldered. By heat conduction the solder is partly liquefied and the component is pushed by a gas momentum to a defined sorting fraction. It was shown in laboratory experiments that with this process SMD components in the size range typical for PCBs from MPHs and network electronics can be selectively desoldered and sorted within a short cycle time.

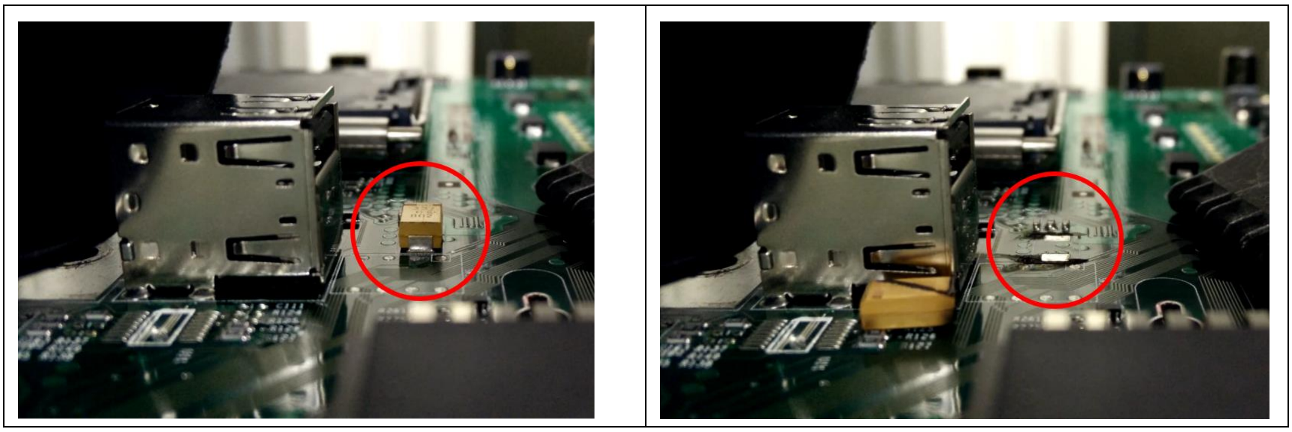

Figure 13: Left: snap shot of video sequence showing a tantalum capacitor to be desoldered (red circle), right: some tenths of a second later, the capacitor is desoldered and can be seen just left of the red circle

8 Metallurgical treatment

For determination and development of effective and efficient process routes for metallurgical recovery of valuable metals from separated components a selection of relevant fractions was made after thorough analysis of content of individual elements in the sample material and after economic evaluation of the metal value. Based on the work performed in analysis of the total composition and composition of individual parts and components from the selected objects of the sample material it was observed that the highest potential for economic recovery of metal value can be seen in individual separation of Ta, W and Nd containing components, while the remaining part of the components on the boards should be removed together as one fraction and then treated for precious metals recovery. Recently conducted studies showed the following appropriate sources of those metals:

- capacitors for recovery of Ta;
- vibration motors for W recovery;
- apeakers for Nd recovery;

The economical aspect of Ta recovery from SAW filters (surface acoustic wave) still has to be investigated and evaluated.

Because vibration motors contain both W and Nd it was decided that W recovery should be the first process to be applied and then recovery of Nd has to be performed. All the developed processing routes are based on hydrometallurgical treatment. That approach will bring added value from production of currently lost Ta and Nd on the one hand and will reduce costs of recovery of Au, Ag and PGM due to the shorter hydrometallurgical method of their treatment than the currently applied combined pyrometallurgical and refining route, as the treatment time of such high value metals has a significant influence on the profit margin.

It was also decided that for proper closing of all relevant loops the residual streams generated in processing of individual fractions, i.e. Ta, W, Nd and precious metals, will be directed together with bare PCBs to the currently applied pyrometallurgical processes.

The preliminary flowsheets of individual processes were developed and tested in the laboratory scale, and are currently validated.

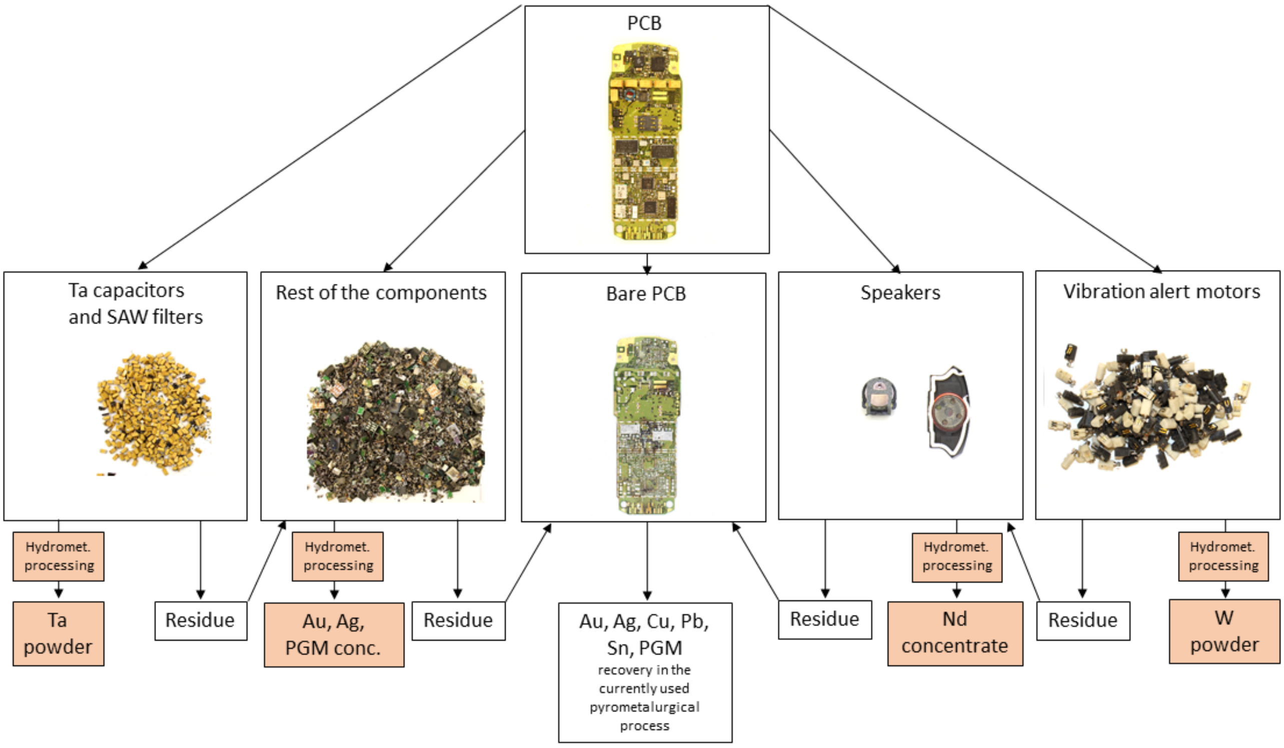

Figure 14: General overview of distribution of fractions and flow of processing streams with marked hydrometallurgical processes

9 Summary

Within the European project ADIR new technologies are explored to enable an efficient urban mining by deploying novel inverse production schemes. Treated items are end-of-life mobile phones and printed circuit boards from network/server electronics. The goal is to physically separate components of these products containing highly enriched contents of valuable materials. The elementary processes for feeding singularized items, automatic disassembly, 2D/3D measurement, laser spectroscopic analysis, laser desoldering and cutting were worked out and there capability was checked successfully in laboratory scale. Basic hydrometallurgical tests were performed demonstrating that the recovery of elements from sorted fractions such as tantalum, tungsten, neodymium is possible achieving recovery rates of > 90 %.

In the next step the set of interlinked machines will be set-up and integrated to the ADIR demonstrator. The latter will then be tested in field tests at a recycling plant to show the capability of an automatic disassembly, separation and recovery of valuable materials from electronic equipment.

References

[1] Decoupling natural resource use and environmental impacts from exonomic growth, United Nations Environmental Programme (UNEP), Ed. Int. Resource Panel, ISBN 987-92807-3167-5, 2011

[2] E. von Weizsäcker, Zukunftsfähigkeit der Green Economy, Forum Umweltwirtschaft NRW, Düsseldorf, 2.2.2017

[3] Report on critical raw materials for the EU, European Commission, May 2014, 41 p.

[4] http://www.handy-clever-entsorgen.de/hintergrundinformation/index.htm

[5] http://de.statista.com/statistik/daten/studie/192704/umfrage/absatz-von-mobiltelefonen-welt-weit-seit-2005/. IDC Corporate USA, 5 Speen Street, Framingham, MA 01701IDC, Gartner

[6] http://de.statista.com/statistik/daten/studie/183419/umfrage/prognose-zum-weltweiten-absatz-von-pcs-nach-kategorie/. IDC, 25.11.2014

[7] www.ADIR.eu

[8] Patent of Fraunhofer Society, DE 10 2011 012 592, 15.10.2015