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Thematic Report IV

Secondary Raw Materials (Including Mine Wastes)

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Preliminary note

This thematic report has been developed within the Minerals4EU project in the context of the first Foresight Study report (WP6) that comprises a central report and five thematic reports. These contributions were designed according to a well-defined structure to fit the purposes of the central Foresight Study report. The scope and targets of the first Foresight Study significantly determine the nature of the documents and may not be suited for unspecified or differing purposes.

The topics of the five thematic reports containing topic papers and case studies are:

1. **European raw material potential**
2. **Legislative and governmental controlled challenges with regard to European mineral raw materialdeposist**
3. **Societal challenges of mineral raw material deposits accessibility**
4. **Secondary raw materials (including mine wastes)**
5. **Developments on the raw material markets**

The following institutions contributed to WP6 in the Minerals4EU project:

- GTK (Geologian Tutkimuskeskus, Finland)
- BGR (Bundesanstalt für Geowissenschaften und Rohstoffe, Germany)
- CGS (Ceska Geologicka Sluzba, Czech Republik)
- GEUS (The Geological Survey of Denmark and Greenland, Denmark)
- LNEG (Laboratorio Nacional de Energia e Geologia I.P., Portugal)
- MFGI (Magyar Foldtani és Geofizikai Intezet, Hungary)
- PGI (Panstwowy Instytut Geologiczny - Panstwowy Instytut Badawczy, Poland)
- SGU (Sveriges Geologiska Undersokning, Sweden)
- HGI (Hrvatski Geološki Institut, Croatia)
- WI (Wuppertal Institute for Climate, Environment andEnergy GmbH, Germany)
- FhG (Fraunhofer ISI, Germany)
- SNL (SNL, Sweden (former Raw Materials Group))

Inhalt

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1 Future Raw Material Potential from Mine Wastes

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1.1 Executive Summary

Mining waste (MW) is one of the perspective parts of the secondary mineral resources, mainly in the field of building materials and some deficit resources with high utility value. Recovery and recycling of elements and other useful materials from the mining wastes are becoming increasingly important from a societal, industrial and environmental point of view. One of the best economic and environmental benefits of secondary raw material production is that it usually requires less energy to produce a specific quantity of raw material and expected environmental importance.

Mining wastes from solid mineral resources consist mainly of from waste rocks stored in heaps and tailings (, stored in tailing ponds). In the case of mining of gas or liquid raw materials, mainly natural gas and crude oil, also gas and liquid MW can be created. Products of further processing in metallurgy or products of burning in the form of slags and ashes, which can contain increased concentrations of interesting elements, are classified as MW sometimes too.

Heaps and tailings ponds contain large amounts of extracted inert material, and the location and in many cases the amount of this material which are also known. Occasionally, there are some technologically not inert wastes (hazardous to the environment) wastes. That makes the extraction of additional ore type recyclable mining waste is possible by using new technologies and reducing the environmental risk.

The term MW is not unitary, in some cases people speak rather about a by-product.

MW is legislatively delimited in DIR 75/442/EEC “on waste” and DIR 2006/21/EC “on the management of waste from extractive industries and amending Directive 2004/35/EC“, which defines only the basic terms.

Variations and classifications of MW should be different from any point of view: according to the phase and age of mining activity, according the mined or processed material, ecological and geographical acceptability, operational-technological criteria, climate conditions, possibilities of technological utilization, economical aspects and others.

Demonstrated case studies showed the key moments of the approach to future possible utilization of MW.

- The case study „Future potential from mining wastes: The role of the national inventory of Closed Mining Waste Facilities in the service of the Potential Assessment of Secondary” from Hungary shows the possibilities of the use of national inventories according to the „Future potential from mining wastes: The role of the national inventory of Closed Mining Waste Facilities in the service of the Potential Assessment of Secondary” from Hungaria ukazuje možnosti využití národních inventarizací podle Directive 2006/21/EC, Article 20, which are focused on risk assessment of the disposal sites, to selecting economical mineral potential. For example in the area of Hungary is registered 1689 disposal sites of MW. This national inventory represents a database with graphical presentation in GIS tools. On the basis of delimiting criteria and assessment of the bulk volume to 52 725 000 m3, which corresponds to more than 100 000 000 tons, these tonnages can be considered as a potential secondary raw material.

- The case study „Future minerals potential from the Cínovec/Zinnwald tailing deposit“ shows Czech parts of the abandoned deposit Cínovec, specifically the utilization of a disposal site of flotation wastes after processing of Sn and W ores. The rest of material with a high content of mica zinnwaldite did not have economical use in the time of production from the sixties to the nineties of the last century. New technologies, demand for lithium-based batteries for cars and ensuring of alternative European sources caused the present interest in primary and secondary sources of lithium. Therefore, exploration of the potential deposit was made on the tailings by a private exploration company and exploitable reserves were newly calculated – 680 000 tons of lithium ore with a content of 0.27 % Li and other potentially usable accompanying elements Rb and Cs. In present, the administrative process of getting a mining licence is already going on. The study describes an important key factor, when an industrially exploitable deposit is becoming from MW with the help of geological exploration, calculation of reserves of the utility component, economical evaluation of the accumulation and choose of a proper technology.
- „Mine waste study from Sao Domingo „ from Portugal shows the potential utilization of MW after a mining of gold by the Romans and modern mining of pyrite in the 19th and 20th century. The rests of gossans on heaps and slags contain in average 1 g/t Au and maximally 7 g/t Au and increased contents of rhenium to 3.4 g/t Re, which is thousand times higher than its content in the Earth crust. Except these elements, also Pb, Co, Cd, In, Sb and Tl are present in increased concentrations. This case study clearly shows the importance of the oldest historical mining, which is focused mainly on precious metals, and the new industrial era, where the main commodity was pyrite for obtaining sulphuric acid. Environmental aspect is also important, because this significant historical district is affected by a strong acidification from the mined pyrite, and a potential utilization would be connected also with an elimination of this environmental load.
- The “German case study” describes a survey of MW in three regions – Saxony, West Harz and Saarland. A methodical survey of tailings after mining of tin with residual economical mineralisations of tin and lithium with other critical elements is described, also evaluation of old heaps after mining and metallurgical processing and a method of preparation of deposit register for heaps with the use of advanced information technologies are described. The case study is instructive for recommending the methods of research of the economic potential of MW.

Following key factors follow from the experience of quoted case studies and already sooner done studies out of the project M4EU for a perspective utilization of MW:

1. Presence of the utility component in an economically exploitable amount, which depends on further following aspects.

2. Source of primary raw material – basic question for the source material of MW and its possible utilization. Important question is, whether the rests of mined commodity will be used, or another commodity, which was not the object of mining and processing.
3. Age of mining work with production of MW – present active operation allows installation of supplementary technologies for MW utilisation, but restoration of processing operation in abandoned sites is technologically and economically more demanding.
4. Type of MW – dumps with waste rock are more demanding concerning evaluation of utility components and processing (with higher energetic contribution). Flotation tailings are more homogeneous, lower energetic contribution is needed for their processing, but the concentrations of utility components are mostly lower.
5. Type of processing of primary raw material – manual sorting, grain size of crushing and milling, type of processing – flotation, gravitational processing, leaching, etc.
6. Environmental aspect – mining of MW should improve the environment. Some of the sites can't be mined, because subsequent insoluble environmental impacts would arise – acidity due to oxidation of dumps, flaring of coal, dustiness.
7. Technological-economical aspect – MW sites represent relatively small volumes, which are exploitable within a short time span – ca. up to ten years. On many sites, mining and processing of MW is necessary to combine with other activities and complex utilization of the site. It is needed to select efficient, but environmentally friendly technologies (mobile technologies, transport to central processing plant, etc.).

1.2 Introduction

1.2.1 Relevance of the topic

- *relevance of the topic with regard to – today and in particular future – supply and demand of mineral raw materials*

Mining waste is one of the perspective parts of mineral resources, mainly in the field of building materials and some deficit resources with high utility value. Recovery and recycling of elements and other useful materials from the mining wastes are becoming increasingly important from a societal, industrial and environmental point of view. One of the best economic and environmental benefits of secondary raw material production is that it usually requires less energy to produce a specific quantity of raw material.

We should consider mining waste as potential mineral resources from many points of view. One of the main decisive criteria should be the information about whether the potential resource has been already used within mining and processing, thus the mining waste (abbreviation MW) contains already only the technological remains of the ore, or the MW was an unused part in the beneficiation and processing process.

The term MW is not uniform in the national legislations, the directive n. DIR 75/442/EEC "on waste" doesn´t consider MW after mining and processing of resources and DIR 2006/21/EC "on the management of waste from extractive industries and amending Directive 2004/35/EC" defines only the basic terms.

Documents EPA (http://www.epa.gov/osw/nonhaz/industrial/special/mining/) speak about the formation of MW during the processes of extraction, beneficiation and processing of mineral resources (Mining wastes include waste generated during the extraction, beneficiation, and processing of minerals.)

Extraction is the first phase of hardrock mining which consists of the initial removal of ore from the earth. Beneficiation follows and is the initial attempt at liberating and concentrating the valuable mineral from the extracted ore. After the beneficiation step, the remaining material is often physically and chemically similar to the material (ore or mineral) that entered the operation, except that particle size has been reduced. Beneficiation operations include crushing; grinding; washing; dissolution; crystallization; filtration; sorting; sizing; drying; sintering; pelletizing; briquetting; calcining; roasting in preparation for leaching; gravity concentration; magnetic separation; electrostatic separation; flotation; ion exchange; solvent extraction; electrowinning; precipitation; amalgamation; and heap, dump, vat, tank, and in situ leaching. The extraction and beneficiation of minerals generates large quantities of waste.

In order to use MW as a mineral resource in the future, it is necessary to make a register, which would show the potential possibilities of utilization. The majority of so far made inventorying is focused mainly on the environmental security of the waste facilities with MW according to MW Directive. One of them is a Register of Waste Facilities of MW in the Czech Republic ("Registr úložných míst těžebních odpadů ČR"). It was made according to the law n. 157/2009 Sb., about MW treatment and about a change of some laws, which implements a European Parliament and Council 2006/21/ES regulation about MW treatment and about a change of the directive 2004/35/ES. Ministry of the Environment of the Czech Republic assigned the Czech Geological Survey (further only CGS) the task of investigating closed and abandoned waste facilities, which are a serious risk for the environment and human health, and administrating a register of these waste facilities. A closed waste facility is, according to Stanley et al. 2011, a facility where mining activity has ceased. Closed waste facilities are facilities with an identified former owner or licensee and closed according to former licences or regulations. Abandoned waste facilities are facilities without an identified former owner/licensee and/or not having been closed in a regulated manner.

In order to make this Register, a project "Investigating of closed and abandoned waste facilities, which are a serious risk for the environment or human health" was made and a financial support from the Operational Program for the Environment, financed from EU resources, was arranged. The project started 1. 7. 2010 and finished 31. 12. 2012. The main aims of the project were (Štrupl 2012):

1. to collect relevant source material for Inventorying Closed and Abandoned Waste Facilities in the Czech Republic including Methodics of their Evaluation;

2. to make Register of Dangerous Waste Facilities, which the Czech Republic was obliged to have and publish until 1. 5. 2012 according to the law about MW treatment. The register should have been made as an independent web application and should have contained information about the type and degree of risk on the localities, which have or could have serious unfavourable influence on the environment or human health.

The work has been divided into 7 workpackages (abbreviation WP), where WP1 had an organisational character. WP2 comprised saving the archival documentation and field observation to the Access database, WP3 should define the methodics of risk evaluation, WP4 and 5 comprised field exploration work on 300 chosen localities with chemical analysis of dangerous elements Ag, As, Ba, Be, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, Se, Sn, Te, Tl, V, Zn and asbestos. WP 6 processed the gained information into publicly accessible geographical informational system (GIS), accessible on the address http://www.geology.cz/extranet/sgs/ulozna-mista-tezebniho-odpadu/registr-rizikovych-uloznych-mist. WP7 field were public relations.

The result of the project was the inventorying of 7062 waste facilities, from which 632 were operating and 6430 abandoned/closed. 300 places was chemically assessed in detail and 11 from these were evaluated as dangerous. From the point of view of resources was registered:

3151 objects with MW after mining of ores

1944 objects with MW after mining of nonmetalliferous raw materials

1073 objects with MW after mining of building materials

772 objects with MW after mining of fossil fuels

122 objects with MW after mining of radioactive materials

The contribution of the project to future evaluation of MW with respect to their potential resource value is the definition of the types of the resource materials, estimation of MW volume and exploration of the environmental conditions on the waste facilities.

1.2.2 Regional Variation

- *variations of topical phenomena per geological, climatic, geographical, political, or other regional patterns*
- *statistics on regional variations, where available, and/or hypotheses*
- *reference to case studies (ch. 1.2)*

The utilization of MW is conditioned by many factors.

MW are connected with the mining site and processing site, which can be relatively far away from the mining site.

Mining-selected waste (or simply mining waste) can be defined as a part of the materials that result from the exploration, mining and processing of substances governed by legislation on mines and quarries. It may consist of natural materials without any modification other than crushing or of natural materials, processed to varying degrees during the ore-processing and enrichment phases, and possibly containing chemical, inorganic and organic additives. Overburden and topsoil are classified as waste.

From the point of view of the time of activity we can talk about historic mine waste and modern mine waste (Backstrom edit. 2013).

Closed waste facilities do not have any time element to their definition and can be divided into two generic categories:

1. Heaps or tips with waste rock

   Waste rock is an unused extraction product, which contains metal and other nonmetallic material which has too low content and is difficult to recover economically. It is usually stored in landfill sites near the mine center for the sake of transport cost savings. Usually opencast pits and quarries cause more mine waste generation than an underground mine. Waste rock is mainly generated by surface stripping to expose the shallow ore. Some oxidation processes (pyrite) are heterogeneous so they cause acidification and other physical and chemical processes.

2. Lagoons or ponds, including tailings impoundments containing tailings.

   Tailings are processed waste or mill waste, which are usually fine ground rocks from which valuable materials have been extracted. Depending on the ore properties, technologies used are very different and different units (leaching, floatation) can produce different kinds of wastes. Disposal of mine waste from hard rock metal mines is the largest environmental problem.

In the former case, waste is in a wholly solid state and not in solution or suspension (i.e., when not contained it is unlikely to move). In the latter case waste maybe in a fluid state or is material which is wholly, or mainly, in solution or suspension (i.e., likely to flow if not contained). Nevertheless, old tailings are usually thixotropic and do not flow easily.

Variations and classifications of MW should be different from any point of view.

A. *One criterion should be according to the phase of mining activity:*

   (1) Mining (extraction) produces top soils, overburden, waste rock and temporary stockpile (without chemical additives)

   (2) Processing phase (beneficiation) produces tailings or processing waste (containing chemical additives)

   (3) Another criterion results from the mined material – here is possible to distinguish MW coming from the mining of:

   (4) Ores

(5) Nonmetalliferous materials

(6) Building materials

(7) Coal

(8) Radioactive materials

C. According to the processed material:

(1) All the valued components were gained by the ore processing

(2) MW contained during the mining and processing an unused material, which is now or in future reusable

D. Ecological and geographical acceptability of the waste facility site:

(1) The waste facility site is an ecological burden or an obstacle for the site utilization

(2) The waste facility site is ecologically acceptable, it has its place in the site utilization and it is rehabilitated

E. Operational-technological criteria of waste facility:

(1) Chemical and mineralogical composition
(2) Physical properties of MW
(3) Engineering-geological conditions (mainly the stability of the MW body)
(4) Hydrogeological conditions, possibilities of water contaminations, accessibility of technological water

F. Climate conditions:

(1) Operation possible all the year
(2) Climate conditions limit the operation on the site (mountains, northern countries)

G. Possibilities of technological utilization:

In this region many new possibilities and innovative methods of intensive research are emerging. Some of the new unconventional methods are briefly described in studies of projects ProMine (promine.gtk.fi) and MinNovation (www. min-novation.eu).

1.2.3 Influencing Factors

The utilization of MW as a mineral resource, mainly critical mineral resource, in future is not a simple task.

Building materials

As the least problematic appears the utilization of MW as building materials or backfils of mines. Heaps with less quality building or non-metallic materials or overburden of coal beds are reworked without any major environmental impacts. Technical progress of mobile sorting and crushing devices also helps.

Gaining of building materials from MW after processing of ore resources is more problematic. The heap material was although mostly primarily sorted, but it can still contain bigger amount of sulphides, whose weathering products and total acidity are unacceptable for utilization in construction industry.

As for flotation ore waste utilization in building materials, it depends on the quality and purpose of the flotation process. Flotation sands are fine, with grain diameter under 0.1 mm and smaller. Currently, they are used mainly as fillers in cement mixtures, for the production of building prefabricated parts, or as a backfil material. An interesting application is utilization of fine flotation and metallurgic products for production of lightweight aggregates (Backstrom, 2013).

The overburden sands and clays after coal mining are used for building purposes without problems (i.e. in basins in the north of Czech Republic). The overburden “cypris” clays, which expand by heating to lightweight aggregates, are worldwide popular building materials.

MW after the mining of the radioactive resources as building materials are a special commodity only in few countries of EU. The Czech Republic has long experience with application of these materials. Only heaps are reworked. One of the typical working is at the heap Bytíz by Příbram in central Bohemia, where the material of the heap is crushed to a uniform size, washed with water and then the remaining radioactive material is separated. The result is a hygienically appropriate quality aggregate.

Non-metallic resources

The waste after processing of glass sands can be used by suitable separative methods as an abrasive material.

A broad application have the heaps from the overburden parts of brown coal beds. They are used as kaolin for ceramic industry or as seal, ceramic or special clays.

The problem in Czech Republic is winning of these resources due to preferential mining of lignite.

Ores

Gaining of metal elements from MW in the Czech Republic is beginning to be a subject of research and winning of Li and other elements at the locality Cínovec is in the stage of realization project (see the Case Study).

The Czech Republic is an example of a country with a rich mining history and a minig industry evolved for centuries. Many objects, mainly heaps, remained from this activity and they could be used in the future. On the other hand, the system of subsidies of the socialist economy and industrial restructuring in the nineties of the 20th century, which totally liquidated the industry of mining and processing of ores, resulted in the absence of possible processing capacities and missing scientific background in this field.

Except the mentioned MW after the mining of Sn and W ores as a source of Li, also waste after the processing of uranium ores is promising. At the locality Rožínka (Moravium), which is the only active uranium mine in the countries of EU, experiments with application of dregs after alkaline processing of the uranium ores are running. The aim is to gain proper concentrates of Nb and Ta, possibly V, which are connected with the uranium and don't go into the resulting product. This research will be finished within the consortium of national project CEEMIR until the year 2019.

Another interesting product could be the MW after magnetic and flotation processing of kaolin. The separated minerals contain an increased proportion of the elements REE, Nb and Ta. Detailed research of these materials currently begins.

In the region of mining of a historical deposit of Cu-Zn-Ag ores Kutná Hora Kaňk a research on verifying remaining content of Ag in the tailings and of Ag and In in historical heaps is prepared. Obstacles for the research are the local conditions of undermining and consolidation of natural conditions of landscape and vegetation.

The heaps after the historical as well as modern mining of polymetallic ores and uranium in the surroundings of Jáchymov and Příbram hide so far unknown potential.

A gradual incorporation of heaps and tailings into the landscape of the Czech Republic is an interesting phenomenon. At many of them were declared protected zones of nature due to particular strange structural and rock composition. However, it considerably complicates the future research and utilization of these objects.

Radioactive resources

Mining of radioactive materials dominated the former Czechoslovakian mining industry after the year 1945, the regions of Jáchymov, Příbram, Vysočina and from the sixties the region in the surroundings of Stráž pod Ralskem in the north of Czech Republic were the most important mining districts. The majority of uranium ore was mined in an underground mine, which had the consequence of heap production. Intensive mining of radioactive resources in the fifties and sixties of the 20th century resulted at the uranium mines in that many ore minerals were deposited on the heaps as gangue or waste rock, mainly at the Jáchymov and Příbram ore districts.

Mining of MW at the heap Bytíz, where the main product is stone and aggregate, gives also radioactive material as a secondary product by selection of radioactive minerals. This material is transported to the mine Rožínka for processing together with the extracted uranium ore.

During the mining of uranium ores in the northern Czech Republic in the surroundings of Stráž pod Ralskem, a method of in-situ acid leaching from the basement of Cretaceous rocks was used. After the mining was finished in 1994, a remediation of the relevant water horizons in the leached layers has begun. The original system of boreholes is used for the remediation – one part of the boreholes is used for pumping the water into the polluted horizons and other part of the boreholes is used for pumping the contaminated solution out. This solution is neutralized on a neutralization station and it is further processed by an alkaline method into a resulting product – U ammoniate – yellow cake. The inactive neutralization products, mainly in the mineralogical form of alum, are transported as a waste into the tailings, a part of this product is sold to the industry.

Current knowledge and so-far realized projects imply, that:

1. MW is a perspective source of mineral resources

2. The advantage of MW is their presence on the surface and prepared granulation to a big extent (the rock is already disconnected and partly crushed), which has a good influence on the limitation of energetic investments and limitation of the environmental burden.

3. The disadvantage of MW is the low concentration of usable parts and relatively small volume of the raw material.

4. The consequence is, that due to the economics of operation at abandoned facilities of MW, it will be necessary to use and evolve mainly more universal mobile and semimobile technology, which would allow economical utility at more places.

5. It is necessary to search for methods for complex application of MW, because application of just one component is not economically effective and we should consider the application of MW as a process of more activities at the locality.

2 Future Potential from Mining Wastes: The Role of the National Inventory of Closed Mining Waste Facilities in the Service of the Potential Assessment of Secondary Mineral Raw Materials

János Kiss, Zoltán Horváth (MFGI)

(Supporting Organisation: MBFH (Hungarian Office of Mining and Geology))

2.1 Executive Summary

By 2012, member States had to set up an inventory of closed (abandoned) mining waste facilities (Directive 2006/21/EC, Article 20). This inventory may be used for other purposes due to specified background information. One of these aims is the utilization of the waste rock as secondary raw material.

Heaps and tailings ponds contain large amounts of extracted inert material, the location and in many cases the amount of which are also known. Occasionally, there are some technological not inert (hazardous to the environment) wastes that makes the extraction of additional ore type recyclable mining waste possible by using new technologies and reducing the environmental risk.

The inventory contains the name and the coordinates of the excavated recyclable material, sometimes the mined raw material and the material of mining waste, the size of the object (area, height) and the expected volume of the heap or tailing pond. All of these data are important parameters in the estimation of the potential of these mineral resources.

The basic database of closed mining waste facilities, developed from various databases of landscape wounds, mining areas and mining wastes, contains 16 451 records. Only a small fraction of this, about 1 689 facilities are known as closed mining waste facilities, i.e. waste heaps and tailing ponds. The risk assessment and ranking of these facilities had to be carried out. The work proceeded from the hazardous facilities towards the less hazardous facilities. Out of the 1 689 mining waste facilities, 463 facilities can be regarded as potentially harmful according to the assumed non-inert or toxic material content at the date of the Internet publication on 1 May, 2012.

The registration and risk classification of inert mining wastes (e.g. the construction raw materials) started in 2012 and is still in progress. In 2013 492 pieces of inert objects were registered and undergone a selection (risk-based ranking) according to the EU directives in the proper methodological procedure. By 1 December 2013 1003 pieces of mining waste objects have been included in the inventory with GIS and other parameters[1] which are necessary for methodological selection. Recently 36 ponds and 967 mining waste heaps can be found in the inventory.

The National Inventory of Closed Mining Waste Facilities including information on risk based selection is an important base for the assessment of secondary mineral raw material potential. The fact that it is available for the public via Hungarian Office for Mining and Geology supports the social acceptance of mining activities and serves useful information for future land use planning and for investments of local and regional developments. This case study could be exemplary for those Member States where the implementation of the relevant Directive has not started yet. However, further co-operations and discussions may be initiated for those MS where the development of this type of inventories is in progress.

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[1] Mining raw material, mining waste material, area, height, volume of facilities etc.

2.2 Introduction

2.2.1 Scope

The Hungarian case study deals with today and future mineral potential of mining wastes. The National Inventory of Closed Mining Waste Facilities is an important base for the assessment of secondary mineral raw material potential. It is in close relation with the Strategic Implementation Plan (SIP, 2013) for the European Innovation Partnership (EIP) on Raw Materials.

After the introduction of the regulatory background, the inventory of closed mining waste facilities and the risk classification of the closed mining waste facilities will be presented. The pre-selection procedure (risk selection), the selection procedure (risk classification) and the representation of their results will be introduced. The result of risk assessment is summarised in an excel table, and a possible internet representation of the results is given.

The Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC in Article 20 prescribes for the Member States the registration of closed and abandoned mining waste facilities which can cause significant environmental impact or have a considerable risk to the human health or to the environment in the medium or short term. The risk-based inventory had to be made available to the public by 1 May 2012. The Hungarian Ministry of Economy and Transport (GKM) implemented the Directive to Hungarian law by Decree No. 14/2008 (IV. 3.) on Mining Waste Management, that directs the MBFH, the Mining Authority in Hungary to develop and maintain the inventory, and to carry out environmental risk assessment and the risk-based ranking of closed mining waste facilities.

In order to comply with the EU and national legislation, the Geological and Geophysical Institute of Hungary (MFGI) has delivered an inventory of mining waste facilities in Hungary, according to contract by the Hungarian Office for Mining and Geology (MBFH).

In the following, the the preparation, the content of the inventory and the basic EU regulation will be introduced. We present the background data system focusing on basic information about the mining waste facilities and on environmental issues (risk assessment), but this way it could be used directly for the potential assessment of secondary raw materials including the availability of resources. In other words an inventory of secondary raw materielas will be described as a result of the implementation of the mining waste directive that we have done.

In common usage, the mining waste facility is called rock heap in case of unprocessed coarse grained material, and it is called tailing ponds in case of processed fine grained mud. Materials in these facilities are taken from the Earth sub-surface by mining activity, which in some cases can cause environmental pressures. Mining waste facilities and their surroundings therefore have to be monitored, their effects on the environment have to be determined and, if necessary, intervention has to be made.

Prior to pre-selection it was necessary to prepare an inventory with appropriate data. This way the first step in the implementation of the inventory was a data collection. This involves the basic spatial, environmental and demographic data and data harmonization in a database system, in addition to the review of all closed mining waste facilities and their visualization in maps. Also, the data on the facilities necessary for the risk assessment had to be collected.

In Hungary, approximately 5000-6000 mining waste rock heaps and tailing ponds can be estimated on those sites that had been exploited in the past, and on mining sites currently in operation. Among them about 2000 have been surveyed based on county reports of mining waste cadastres in the 1980s, that were selected according to the size of the heaps and ponds, respectively. Accordingly, these waste rock heaps and tailing ponds represent the gross of the mining wastes as potential secondary raw materials. The other 3000-4000 mining wastes bearing objects are rather small, few hundred to few thousand m^3 in size (BŐHM és GOMBKÖTŐ 2010).

The pre-selection method of the risk assessment is based on the European Commission (EC) Guidance including the source, pathway and receptor factors, with consideration of existing known impacts. The source, pathway and receptor factors for risk assessment involve the relevant characteristic features of the facility (material content, engineering stability), the possible release and transport of the stored material, and the factors also involve the sensitive receptors (humans, waters, nature conservation areas and agriculture). For environmental risk assessment the most important aspect is the ’precautionary principle’. Accordingly, if the risk assessment was positive, or if the data or the risk classification of the facility is uncertain, the facility shall be considered risky and directed to further examination.

Those facilities which got through this pre-selection procedure and got classified for ’further examination’ have to be processed in the next step for selection procedure. This second step is the risk-based ranking. At the present, there is no harmonized method for risk ranking and classification in the European Union and thus the way of execution of this step relies on the Member States.

During the selection procedure the relative risk classification of the facilities is defined and the character of the facility (tailing ponds or waste rock heap), the status of remediation, the size of the facility and the slope of the underlying topographic terrain is used to develop risk classes defining the overall risk rank of the facility.

In addition to the completed inventory, a further task was the presentation and public communication of the results. For the sake of efficient representation, risk classification was simplified and four classes were developed for both tailing ponds and waste heaps, emphasised by colour coding in maps (Fig. 1). The rest of preliminary screening (pre-selection) and ranking parameters (selection) can be inquired as facility attributes in the internet application.

This case study paper presents the importance of a national inventory for assessing the future potential of mineral resources from mining wastes, and its potential role.

2.2.2 Relevance of the case

Due to the statement of the SIP (2013) „The EU is highly dependent on imports of raw materials that are crucial for a strong European industrial base, an essential building block of the EU's growth and competitiveness.” the importance of the secondary raw materials is increasing. „The increasing demand for unprocessed minerals and metals and volatility in the prices of certain raw materials, as well as the market distortions imposed by some countries on a number of them, have shed light on the importance of raw materials for our economy and society (SIP 2013)” means that the mining wastes facilities should be reconsidered. The 2nd Non-technology Pillar, the Priority area II.B deals with the improvement of the Europe's waste management framework conditions and excellence.

The mining waste volumes form significant deposits of secondary mineral resources that could serve as important source of domestic supply. They can be classed by differences in the types of mining wastes and differ significantly as they have undergone various processing procedures. Using the appropriate technology and keeping the required environmental and social specifications, closed mining facilities could serve important source of construction raw materials (secondary aggregates) and chemical (e.g. critical) elements as well reducing the import dependence.

Fig. 1. shows the distribution of mining waste sites (tailing ponds), non inert mining waste heaps and inert mining waste heaps) in Hungary. The inventory lists 37 tailing ponds, 966 mining waste heaps with exact location. The inert and the non-inert mining waste heaps are almost equally frequent.

2.3 Analysis: Scope of closed mining waste facilities

2.3.1 Inventory of closed mining waste facilities

In order to comply with the EU and national legislation, the Geological and Geophysical Institute of Hungary (MFGI) has delivered an inventory of mining waste facilities in Hungary, according to contract by the Hungarian Office for Mining and Geology (MBFH).

The inventory of mining waste facilities connected to the mining activity is based on three digital registries of the MBFH, in addition to further sources of the Hungarian Geological, Geophysical and Mining Archives:

1. Database of Mining waste and Secondary Raw Material Reserves;
   This database constructed by Federal Geological Office (KFH) in 1992 contains the name of the facilities, the material of the mining waste and the size of the objects. This database was the main source database but the coordinates of the database objects were unsuitable.
2. Mining Area Registration System;
   This is the regular inventory of mining activities in Hungary, operated by Hungarian

Office for Mining and Geology (MBFH). It contains the mining areas until 2010. This database points out the places where the mining waste facilities can be found.

3. Landscape Wound Database;
   This is the database of different size near surface, local mining activities, like quarries of different size and different source materials (with or without documentations). It was constructed by Town-planning Construction Institute (VÁTI) in 1996 and based on the 1:10 000 scale topographic map sheets.

The digital databases either contain the facilities or indirectly indicate their most probable location. The joint database of the three different data set including the landscape wounds, quarries, underground mines, mining waste heaps, and tailing ponds contains 16 451 objects altogether. Out of these, as the investigation has revealed, only small portion, ca. 1 689 facilities are well determinable closed mining waste facilities (heaps or tailing ponds). In 463 cases the location identification was based on the 1:10 000 scale topographic map sheets or Google Earth aerial photos and fieldwork. The facility selection used the unified database and it was based on the pre-selection parameters (see chapter 2.2.1).

2.3.2 Risk classification of the closed mining waste facilities

According to the present method, risk ranking has two stages. The first stage is the pre-selection or preliminary risk screening, and the second stage is the selection or risk-based ranking.

2.3.2.1 Pre-selection (preliminary risk screening)

In case of the closed mining waste facilities, we determined which are not risky for the environment, and those which may be risky and need to be further examined. This selection was made for 463 mining waste heaps and tailing ponds facilities in accordance with the EC methodology (Guidance document for a risk-based pre-selection protocol for the inventory of closed waste facilities as required by article 20 of directive 2006/21/EC, Draft 2, 2010 June). The pre-selection protocol, according to the Guidance (Stanley et al. 2010), requires the exact location (coordinates) of the facilities.

In summary, in addition to the characterisation of the substances stored in the waste facilities, the engineering stability of the waste facilities also has to be studied, in addition to the possible transport routes. The location of the facilities in relation to the location of sensitive receptors is of utmost importance, such as the distance to the nearest protected ecosystem, and therefore the risks of the waste facilities posed to the environment needed to be evaluated. This requires precise coordinates and lot of reliable background information needed.

For the pre-selection questions (Guidance document for a risk-based pre-selection protocol for the inventory of closed waste facilities, Appendix) the national digital spatial databases (National GIS Database – OTAB, Digital Cartographical Database – DTA-50, Digital Elevation Model – DDM-50, Land cover and land use data – CORINE, National nature conservation areas – NATURA2000, Water Management Atlas – VGA, Population registration data – KSH) were collected, together with the MBFH mining-specific data sets. In spite of the wide coverage of these databases, there are data deficiencies and not all of the questions could be answered accurately based on these databases. Some of the data were not up-to-date and thus required an update.

For the risk assessment of facilities the most important criteria is the hazardousness.

- From the viewpoint of the mineral composition, all mining waste facilities associated with ore mining are considered potentially hazardous due to the potential sulphide and toxic metal content in the extracted ores. In Hungary, uranium ore facilities belong to this category.
- With respect to material content, the next hazardous mining waste group in Hungary is the mining waste of Mesozoic (Cretaceous) and Cainozoic (Eocene, Miocene) coals due to their high sulphur content.
- In addition to the material content, the engineering stability is a very important aspect, therefore all mine tailing pond facilities received higher risk classification than heaps irrespective of the material content.

Based on the above considerations, the pre-selection procedure was applied to the following 463 closed non-inert mining waste facilities:

- Tailing ponds – **21** facilities
- Waste heaps – **442** facilities; of these
    - Ore waste heaps – **142** facilities
    - Coal waste heaps – **300** facilities.

The pre-selection risk assessment resulted in that 10% of the closed mining waste facilities are not risky, and thus do not need further examination (**44** facilities). The majority of 90 % (416 facilities) showed that the second selection phase for risk ranking needs to be performed.

The **ArcGIS spatial database** of mining waste facilities (Fig.1.) contains all of the data sources used for answering the pre-selection questions, therefore all the data is available for control and further analysis. The completed spatial database is suitable for the unconstrained retrieval of all the data used for the pre-selection procedure.

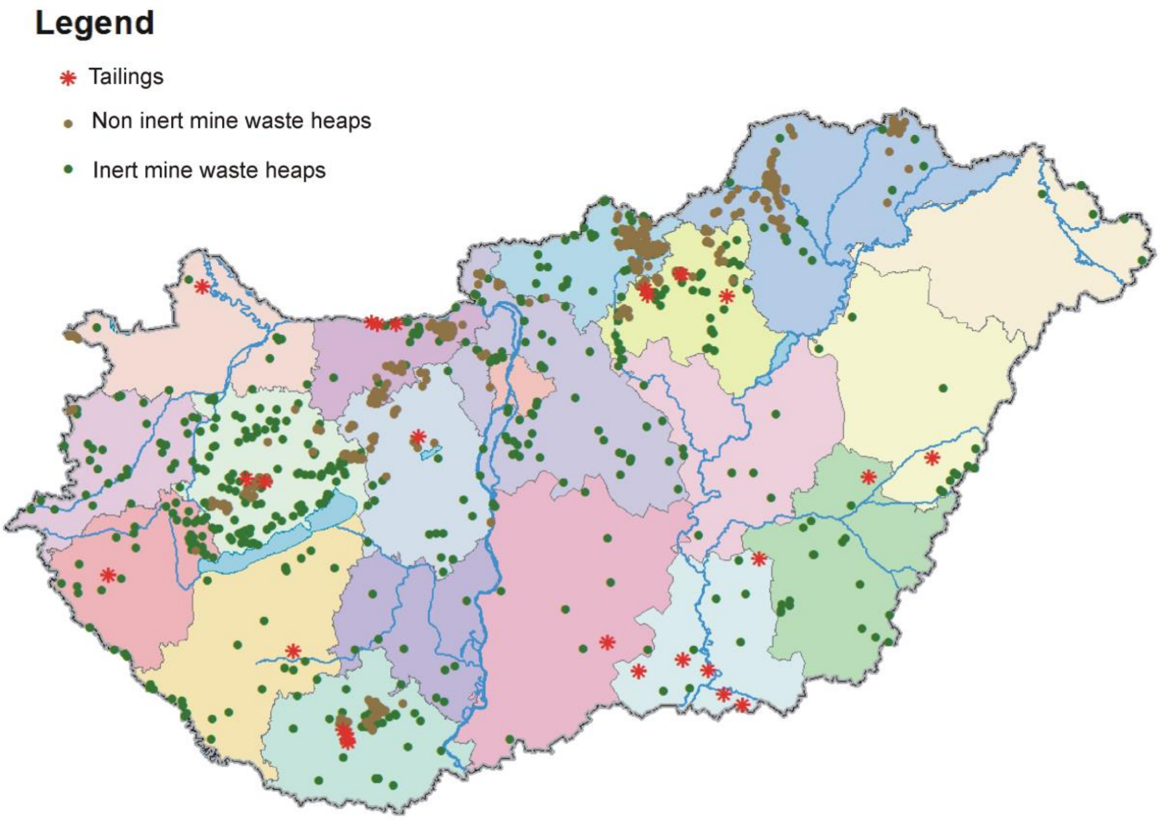


Figure 1: Distribution of tailing ponds, non inert mining waste heaps and inert mining waste heaps in Hungary based on the inventory. Administrative areas (counties) are shown by different colours.

For presentation in the internet, the ArcGIS data tables of the facilities were converted to KMZ/KML format so they can be displayed by using „Google Earth”. Only public information determined by mining authority MBFH is presented on the webpage (http://www.mbfh.hu/home/html/index.asp?msid=1&sid=0&hkl=547&lng=1).

2.3.2.2 Selection (risk-based ranking)

Risk-based ranking had to be performed on those facilities which received a „further examination needed” result in the pre-selection procedure. The selection was based on a predefined set of criteria, determined by Jordán (2011). Out of the 463 facilities only 106 ones provided information on remediation activities which was one of the most important selection parameters in the ranking method applied (as shown below).

Risk-based ranking had to be performed on those facilities which received a „further examination needed” result in the pre-selection procedure. The applied selection procedure uses essentially the pre-selection ‘source’ parameters and ‘threshold values’ such as facility type (tailing ponds or waste rock heap), and size of facility or slope of the topography.

The last step of the assessment is the risk-based ranking using the result of the pre-selection and the selection procedures. For this end, the results selection table had to be created as follows. The table contains the following worksheets:

- **SOURCE**-data worksheet

  Worksheet contains data needed to answer the pre-selection questions and the answers themselves;

- **PRE-SELECTION** worksheet

  Short answers (yes, no, unknown) to the pre-selection questions and the pre-selection results (examine further or no need to examine further);

- **REMEDIATION** worksheet

  These are data from the field site reambulation or from other sources which clarify the remediation status and classification. The name of expert carrying out the field reambulation and the date of reambulation are also included;

- **SELECTION** worksheet

  Contains the final result of the pre-selection, plus the answers to the remediation questions („exist or not”, „complete or not” and „successful or not”) and the selection code based on the size of the object and the topographic slope parameters;

- **PS_ORDER** worksheet (***p**re-**s**election*)

  Contains the facility identification code, the pre-selection classification code and the latest risk rank of the sites (it can change with changing parameter values). This worksheet also contains the ranking of facilities based on the pre-selection data;

- **S_ORDER** worksheet (*selection*)

  Contains the facility identification code, the selection classification code and the current selection risk ranking classification (it can change with the change of the parameters). This worksheet also contains the risk ranking which is based on the selection data.

- **RANKING** worksheet (common)

  Contains the facility identification code, the pre-selection and the selection classification code and the common risk ranking classification (it can change with the change of the parameters). This worksheet also contains the risk ranking which is based on the results of pre-selection and the selection procedures.

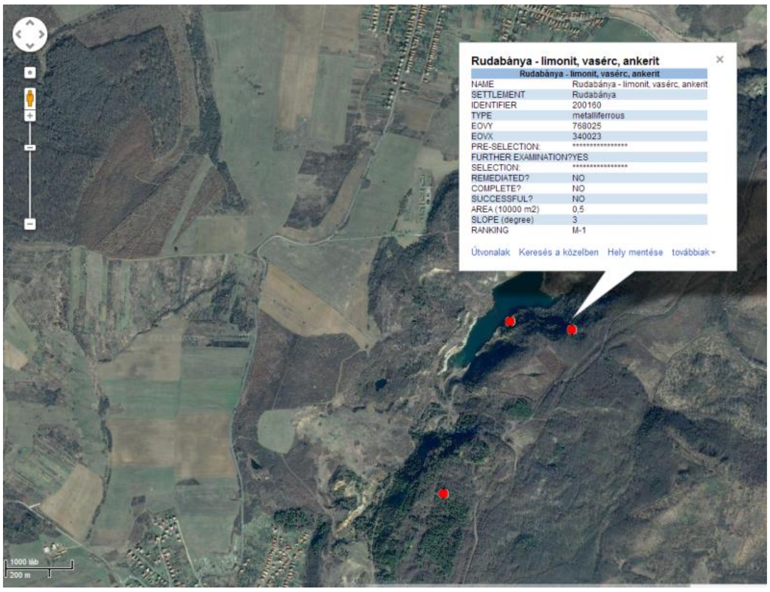
The facilities under consideration are classed according to a simplified risk classification that is applied for the tailing ponds and mining waste heaps, respectively (Table 1).

Table 1: The simplified risk classification of the facilities used in the Internet representation (Letter Z is the first letter of Hungarian word „tailings”, M is the first letter of Hungarian word „heaps”)

TAILINGS	RISK-BASED RANKING	HEAPS
Z-1	Big size, without remediation	M-1
Z-2	Small size, without remediation	M-2
Z-3	Big size, remediated	M-3
Z-4	Small size, remediated	M-4
UNKNOWN	No data, no rank	UNKNOWN

2.4 Internet representation of the results

Until 2014 the link service of maps.google.com was used for representation of the results. Unfortunately this service has been stopped by Google. The internet representation of the results now is realized by the KMZ/KML file format that can be displayed by „Google Earth” (Fig. 2).



Rudabánya - limonit, vasérc, ankerit

Rudabánya - limonit, vasérc, ankerit	
NAME	Rudabánya - limonit, vasérc, ankerit
SETTLEMENT	Rudabánya
IDENTIFIER	200160
TYPE	metalliferrous
EOVY	768025
EOVX	340023
PRE-SELECTION:	****************
FURTHER EXAMINATION?YES	
SELECTION:	****************
REMEDIATED?	NO
COMPLETE?	NO
SUCCESSFUL?	NO
AREA (10000 m2)	0,5
SLOPE (degree)	3
RANKING	M-1

Figure 2: Google map view with three mining waste facilities (red dots). The data for a selected mining waste heap is shown in a data table (North Hungary).

Another possibility to display the data graphically is the application of a GIS server. Such GIS servers (like the server of the Geological Survey) allow accessing the constructed GIS system for external users, if configured accordingly.

2.5 Discussion

This case study regarding the development of the Hungarian Risk-based Inventory of Closed Mining Waste Facilities shows that the quantity of material of the mining waste heaps and tailing ponds can be determined in order to support the estimation and assessment of secondary raw material potential.

The inventory has to include data on environmental information as well. This environmental information is not used directly for the estimate of mineral resources from mining waste facilities, however, can be used at later stages, as resolving environmental impacts can be a significant driver for the re-mining of mine heaps and tailing ponds.

- Precise methodological guidance was available for the pre-selection of the closed mining waste facilities (Stanley et al. 2010); therefore the pre-selection was relatively easy to perform once the necessary database became available. In some cases the facilities had to be investigated in some detail due to lack of information in the archive databases.

  The pre-selection risk assessment was carried out for the identified 463 non-inert facilities and, as a result, 44 facilities were found not needing further examination. In the remaining 416 facilities further examination was needed and the selection procedure was applied.

  The results of pre-selection ranking can be seen in the 3rd appendix of summary report (Kiss and Jordán 2012).

- For selection (risk ranking) the European Committee did not provide methodological guidance, therefore a risk-based ranking selection method had to be developed. This way different risk-based ranking selection methods may have been developed for each EU Member States. This means that the final results of risk-ranking could not be compared.

  This method is prioritised to the other factors (parameters) related to transport and receptors. In this context, status of remediation is assumed to play an important role in risk mitigation and accident reduction and thus it receives special attention.

  The results of selection ranking can be seen in the 4th appendix of summary report (Kiss and Jordán 2012).

463 pieces of hazardous (non-inert) by constituents' point of view mining waste objects (ore mine, bauxite, coal mine heaps, furthermore red mud and mud-tailing ponds) were recorded and have been published on the MBFH website:

http://www.mbfh.hu/home/html/index.asp?msid=1&sid=0&hkl=547&lng=1

as a public inventory of mining waste facilities in Hungary (Kiss and Jordán 2012).

The registration and risk classification of inert mining wastes (e.g. the construction raw materials) started in 2012. In 2013 492 pieces of inert objects were registered and undergone a selection (risk-based ranking) according to the EU directives in the proper methodological procedure. By 1 of December 2013, 1003 pieces of mining waste objects have been included in the inventory with GIS and other parameters[2] which are necessary for methodological selection. Recently 36 ponds and 967 mining waste heaps can be found in the inventory (Fig. 3.).

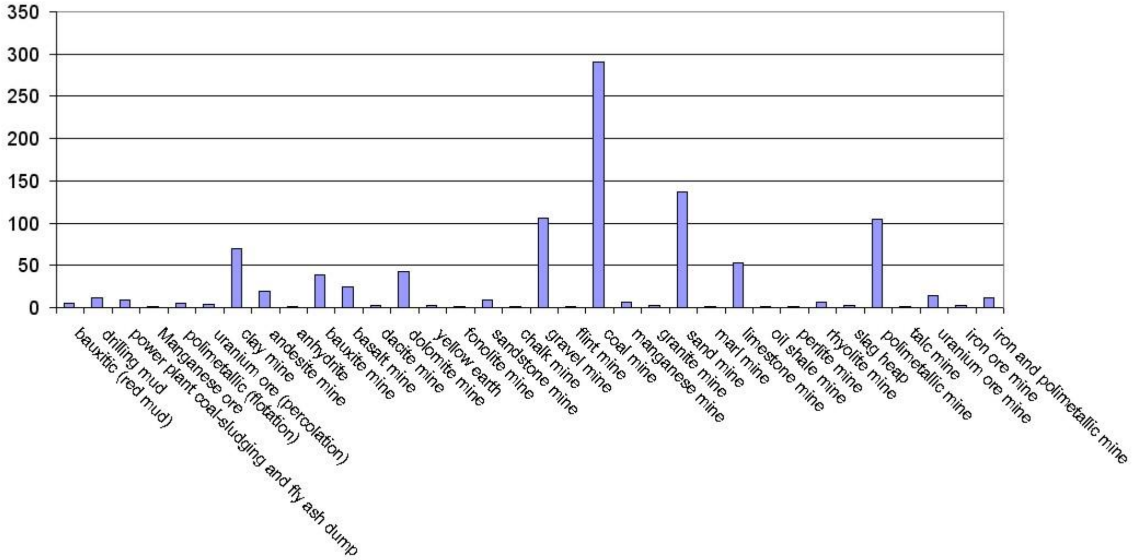


Figure 3: Distribution of 967 mining waste heaps according to their material

Based on all the registered objects (60% of them with volume data) and the estimations of missing data the total volume of the inert mining waste rock heaps amounts to 52 725 781 m^3, which can be the potential resource of secondary raw materials in Hungary. Considering that the materials in heaps are unconsolidated deposits, its estimated density is 2 kg/dm^3. This implies an overall mass of more than 100 million tons (Fig. 4.).

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[2] Mining raw material, mining waste material, area, height, volume of facilities etc.

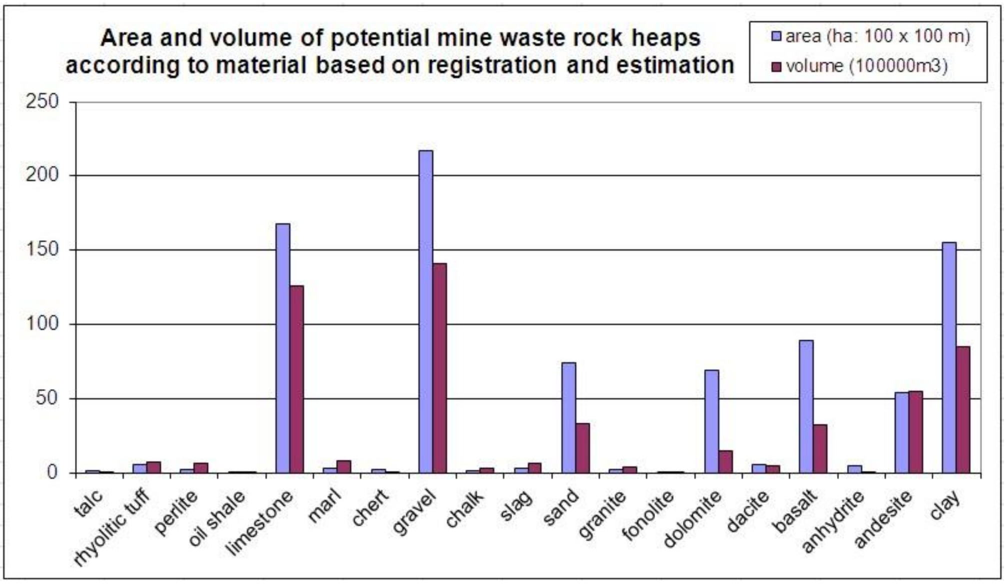

Figure 4: Inert mining waste heaps distributed by their material, the covered area and their volume (2012)

In conclusion, the National Inventory of Closed Mining Waste Facilities serves relevant data for the estimation and assessment of Secondary Mineral Raw Material potential. This case study showed what (publicly reported) information is expected/available on European level, exemplified by the case study of Hungary.

Acknowledgement

We are thankful for the review of the text by Katalin Sári (Geological and Geophysical Institute of Hungary). The financial background of the development of the National Inventory of Closed Mining Waste Facilities is based on the co-operation and agreement between the Hungarian Office for Mining and Geology and the Geological and Geophysical Institute of Hungary.

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Strategic Implementation Plan (SIP) for the European Innovation Partnership on Raw Materials Part I-II. FINAL VERSION – 18/09/2013. http://ec.europa.eu/eip/smartcities/files/sip_final_en.pdf

2.6 Appendix

Risk-based pre-selection protocol for the inventory of closed waste facilities

(Based on: GERRY STANLEY, JORDÁN GYŐZŐ, HÁMOR TAMÁS, MICHAEL SPONAR: Guidance document for a risk-based pre-selection protocol for the inventory of closed waste facilities as required by article 20 of directive 2006/21/EC, Draft 2 2010. June)

The pre-selection questionnaire is based on the risk assessment source-pathway-receptor paradigm and it has four basic sections:

0. Any known serious impacts;
1. Source (with material content and stability characteristics);
2. Pathways; and
3. Receptors.

Within each section, in case of existence of any of the risk conditions, the section as a whole has to be considered as „satisfied". In order to have the facility selected for further examination as a potentially harmful site, either the condition of section 0 or all the three conditions of the sections 1-3 have to be satisfied.

- Within each section it is enough to analyze the section questions until the first satisfied condition (first question with a 'YES' response).
- Among the sections 1-3 it is enough to analyse the facility until the first NOT satisfied condition. In this case the „source–pathway–receptor" chain is broken somewhere; therefore the facility does not have to be further examined as a harmful site.
- The questions are designed so that the YES answer indicates the presence of risk in each case.
- In the case of the lack of information for answering a question, the unfavourable case is considered which is identical to a YES response, i.e. the existence of risk.

Automatic classification based on the pre-selection parameters

A preliminary ranking is possible based on the pre-selection parameters. One of the simple ways is the numerical decimal representation of the number of 'yes' (and unknown) responses arranged in the order of importance for the main sections of the pre-selection. The SOURCE section is divided into material content and engineering stability question groups. The selection questions are in the order of importance, therefore the decimal numerical representation gives a corresponding larger value for the questions (parameters) of higher importance. The order of the questions and the associated numerical representation are shown in Table 2.

Table 2: The scheme of the preliminary ranking based on the pre-selection parameters

QUESTION GROUPS **(answers)**								
Introductory	**Material**		**Stability**		**Transport**		**Receptor**	
Y	Y	UNKNOWN	Y	UNKNOWN	Y	UNKNOWN	Y	UNKNOWN
DECIMAL PLACE OF THE NUMBER OF (YES or UNKNOWN) ANSWERS								
9	8	7	6	5	4	3	2	1

The preliminary ranking based on the pre-selection parameters has the following codes:

- the 9th (the highest) decimal rank: known general risk source;
- the 8th rank: known harmful material content;
- the 7th rank: unknown material content, potential risk;
- the 6th rank: known engineering stability risk;
- the 5th rank: unknown engineering stability, potential risk;
- the 4th rank: known transportation risk;
- the 3rd rank: unknown transportation, potential risk;
- the 2nd rank: living environmental risk;
- the 1st (smallest) rank: unknown risk of living environmental.

The pre-selection guidance document states, that if there is no pathway for contamination transport, there is no risk. In this case, in spite of the existing harmful material content or stability risk, the facility does not need further investigation.

This can be taken into account in the automatic classification, so that a TRANSPORT factor has to be placed between the 3rd and 2nd rank. The value of the TRANSPORT is 0, if the transportation pathway is broken, and it is 1, if the transport pathway is not broken. In this case every former value has to be zeroed out according to the section answer. The facility is not being analyzed further according to the pre-selection method in this case.

Risk-based selection protocol of closed waste facilities

The tailings lagoons are unambiguously considered more risky than waste rock heaps due their liquid content constrained by complex dam structures that may enable the fast accidental escape and spread of large amounts of muddy material. All of the major devastating mining waste accidents have been related to tailings. Also, due to the recent catastrophic accidents of Baia Mare (Romania) hitting downstream the Tisza River in 2000 in Hungary, and the Kolontár (at Ajka, Hungary) red mud spill in 2010, tailings lagoons are classified more risky than waste rock heaps with no exception in the selection procedure in Hungary.

The next risk ranking parameter is the status of remediation. The remediation status of the closed mining waste facility, i.e. the technologically designed, implemented and accepted remediation of the given disposal site fundamentally defines the risk of the closed facility. Remediation essentially limits or hinders material effluence and it increases engineering stability. This is also in accordance with the primer objective of the Directive and with risk assessment principles. Environmental risk has to be reduced by proper risk management and by mitigation using appropriate remediation technology.

The uncertainty also has to be taken into account for remediated waste heaps. In many cases, there has been remediation but incomplete, or there has been remediation but unsuccessful.

Remediation status can be assessed by the following questions:

- Has remediation been carried out for the mining waste facility?
- Has remediation been done for the whole facility (or only for a part of it)?
- Was the remediation successful on the remediated part of the facility?

This information is included in the selection table helping the assessment and risk ranking of the waste facility.

Both in the remediated and non-remediated cases further aspects are the size of the waste disposal facility and the topographic slope below the facility, in this order of significance.

These considerations yield the following risk ranking classification:

CLASS ’Z’: (’**Z**agytározó’ in Hungarian) **tailings lagoon**

1. Without remediation
    1. Big facility (>10 000m^2)
        1. On steep slope (slope>5°)
        2. On flat slope (slope<5°)
    2. Small facility (<10 000m^2)
        1. On steep slope (slope>5°)
        2. On flat slope (slope<5°)
2. Remediated
    1. Big facility (>10 000m^2)
        1. On steep slope (slope>5°)
        2. On flat slope (slope<5°)
    2. Small facility (<10 000m^2)
        1. On steep slope (slope>5°)

2. On flat slope (slope<5°)

CLASS ’M’: (’**M**eddőhányó’ in Hungarian) **waste heaps**

1. Without remediation

1. Big facility (>10 000m^2)

1. On steep slope (slope>5°)

2. On flat slope (slope<5°)

2. Small facility (<10 000m^2)

1. On steep slope (slope>5°)

2. On flat slope (slope<5°)

2. Remediated

1. Big facility (>10 000m^2)

1. On steep slope (slope>5°)

2. On flat slope (slope<5°)

2. Small facility (<10 000m^2)

1. On steep slope (slope>5°)

2. On flat slope (slope<5°)

The numbering appearing in the assessment is important, because this gives the collective risk classification of the closed mining waste objects. The meaning of the collective codes is represented in Table 3.

Table 3: Risk classification of closed mining waste facilities for selection

3 level code	Meaning of the code	Collective code
Z111	Steep, big size **tailings lagoon without remediation**	**Z-1**
Z112	Flat, big size **tailings lagoon without remediation**	
Z121	Steep, small size **tailings lagoon without remediation**	**Z-2**
Z122	Flat, small size **tailings lagoon without remediation**	
Z211	Steep, big size **remediated tailings lagoon**	**Z-3**
Z212	Flat, big size **remediated tailings lagoon**	
Z221	Steep, small size **remediated tailings lagoon**	**Z-4**
Z222	Flat, small size **remediated tailings lagoon**	
M111	Steep, big size **waste rock heaps without remediation**	**M-1**
M112	Flat, big size **waste rock heaps without remediation**	
M121	Steep, small size **waste rock heaps without remediation**	**M-2**

M122	Flat, small size **waste rock heaps without remediation**	🟨
M211	Steep, big size **remediated waste rock heaps**	**M-3**
M212	Flat, big size **remediated waste rock heaps**	
M221	Steep, small size **remediated waste rock heaps**	**M-4**
M222	Flat, small size **remediated waste rock heaps**	

(Letter Z is the first letter of Hungarian word „tailings”, M is the first letter of Hungarian word „heaps”)

Automatic classification based on the selection parameters

A classification is made by the selection parameters. The classification is made by the remediation parameters, the size of the object and the concrete leaning of the surface. In case of the size the standard background was 1 ha (10 000m^2), while in case of the angel of dip was 5°. In the determination of the last two codes, the different values of the objects were normalized with these critical selection background values. The essence of this is that, if the size of the object is smaller than 1 ha, than the value of the number on the decimal place also decreases (will be smaller than ten), if higher, than many times higher, so much higher the value. In case of the angle of dip in the same way, but there the normalization is made for 5°.

Table 4: The scheme of the ranking based on the selection parameters

QUESTION GROUPS (answers)							
Was there remediation?		**Was the remediation being completed?**		**Was the remediation successful?**		**Size of the site**	**Slope at the site**
N	NA	N	UNKNOWN	N	UNKNOWN	T / 1 ha	D / 5 degree
DECIMAL PLACE OF THE ANSWERS (NO or UNKNOWN)							
8	7	6	5	4	3	2	1

The ranking based on the selection parameters has the following codes:

- the 8th (the highest) decimal rank: no remediation;
- the 7th rank: no information on remediation status;
- the 6th rank: remediation is not completed;
- the 5th rank: no information on the completeness of remediation;
- the 4th rank: the remediation is not successful;
- the 3rd rank: no information on the success of remediation;
- the 2nd rank: size of the facility compared to the threshold 1 ha;
- the 1st rank: topographic slope compared to the threshold 5°.

3 Economic Potential of Mine Wastes from Three Major Ore Mining Districts in Germany

Compiled by: **Kerstin Kuhn (BGR)**

Contributions by: **Andreas Kamradt (Martin-Luther-University Halle-Wittenberg, Institute for Geosciences (MLU)); Philipp Büttner (Helmholtz Institute Freiberg for Resource Technology (HIF))**

3.1 Executive Summary

In Germany, more than 2000 mine waste sites from former metal ore mining activities exist. Whereas in the past these mining residues were mainly examined for their environmental impact, their economic potential as a source for valuable metals and other materials (e.g. construction materials), has been increasingly investigated during the last years. Different ore deposit districts comprising various mineral commodities were mined in Germany. Therefore, according to the specific ore deposit district, the mine wastes contain a broad inventory of metals like Pb, Zn, Cu, Sn, W, Ag, Au, Co, Ni, Bi, Mo, Sb, Li, In, Ge, and Ga. Due to the economic decline in the German mining sector in 1992, investigations concerning the economic potential of mine wastes are almost exclusively realized within state-funded research projects by universities, research institutions or government agencies such as the BGR, which are often accompanied by small to medium-sized companies mostly without mineral exploration intentions.

Within this case study results of three research projects, working in different German mining districts (Erzgebirge, Harz, Mansfelder Land) are presented. The focus lies on mining residues containing base metals and so called high-tech metals. General aspects of advantages and disadvantages for re-mining mine waste, environmental issues as well as general conditions influencing the rework of the mine waste material are presented in the discussion part of the study.

Within the last years, mine waste sites that might be economically mineable were found by the different projects. However, the metal concentrations of mining residues are characterised by a wide variability, which can be seen at sites of the same waste type and even within a single object. Factors, influencing metal content, are for instance the composition of the mined ore, the mine waste type, the time of deposition, the ore processing technology, secondary alteration processes, and the deposition of different waste materials at one site.

Additionally to the material-specific factors listed above, there are more parameters influencing the economic potential. These are the accessibility of the waste site – often they are overgrown, sealed or buildings were constructed on top of them. Complex ownership structures could complicate access to mine waste sites or those sites could be under natural or monumental protection. Moreover, the ore mining sector has ceased to exist in Germany some decades ago concurrently with a strong decline of operating mineral processing plants.

For all these reasons, the different research projects, which focused to the recoverability of metal commodities from mining residues in the last years, conclude that re-mining of mine waste in Germany on a large scale and therefore a replacement of large quantities of metal imports is hardly conceivable. However, recovery might be economically feasible for some waste sites. In order to determine such objects, a comprehensive database as well as an extensive exploration is necessary. There is no national register for German mine wastes up to now. Data of mine waste sites are collected at regional levels and contain different depths of information.

Data research is therefore difficult and time-consuming. The partners of different projects currently cooperate to create an initial supra-regional land register for larger mine waste sites of some mining regions in Germany. In order to remediate old mine waste sites even small revenues from the re-use of the still available metal content of those waste sites may be welcome to cover the remediation costs. Unfortunately, this approach has never been followed in Germany which may be because the municipalities which have to realize the restoration of mine waste sites have no experience in ore mining nor have they any appropriate industry partners.

3.2 Introduction

3.2.1 Scope

Whereas large proportion of the German demand for non-metallic mineral resources, like potash, rock salt, industrial minerals and rocks can be covered by domestic production, Germany depends on imports of metallic ore and concentrates to nearly one hundred percent. The production from German metal ore deposits is restricted to approximately 413000 t iron ore and 110 t Cu + Ag per year (BGR 2013). With the closure of the last major underground mines for non-ferrous metals in Germany in 1992, a long ore mining era ended.

In Germany, various ore deposit districts exist, which were mined for long times for different mineral commodities. From this long era, which can be dated back to prehistoric times by archaeological findings (e.g. Klappauf 1985), many mining residues are left. According to the ore deposit district, the mine wastes can still contain different valuable metals like Pb, Zn, Cu, Sn, W, Ag, Au, Co, Ni, Bi, Mo, Sb, Li, In, Ge, and Ga.

Due to the federal structure of Germany, the administration of the closed mine waste facilities are decentralised, being assigned to the municipalities and federal states. Inter-regional land registers remain in the initial stages of development. Although the location of many mine waste dumps is registered, information about the deposited materials are often absent. But this knowledge would be very important for a pre-selection of potential interesting dumps.

Recently, different state-funded research projects have been investigating the resource potential of mine wastes in certain ore mining districts in Germany and selected mine waste sites have been explored. Based on the results of these projects the economic potential of mine wastes from three major ore mining districts (Erzgebirge, Harz, Mansfelder Land; Figure 1) in Germany is presented in this study.

Advantages and disadvantages for re-mining mine waste, environmental issues as well as general conditions influencing the rework of the mine waste material are presented in the discussion part.

Within this case study, the focus lies on mining residues containing non-ferrous metals and high-tech metals. Due to low raw material prices, mass raw materials like iron and manganese, as well as residues from the stone and quarrying industry are not considered. Further information about exploration methods (e.g. with RADAR and multispectral methods) and re-mining of Fe-slags were generated by the research project “REStrateGIS” (funded by Federal Ministry of Education and Research, BMBF-funding code: 033R103; http://www.ressourcenkataster.de; 2012-2015).

Figure 1: Locations of the three mining districts, presented in this case study (map source: http://www.worldofmaps.net/en/maps.htm)

In addition, energy raw materials, like residues from hard coal or lignite mining as well as from uranium production cannot be taken into account within this case study.

According to the process by which the residues were formed, we can differentiate between different mine waste types. Coarse-grained waste rocks contain residues from the mining process itself (Figure 2A). Residues from ore processing are more fine-grained and usually originate from flotation (after 1920) or from density separation (older wastes until approx. 1940; Figure 2C+D). Residues from metallurgical treatment of the produced ore concentrates can contain slags (Figure 2B) or ashes.

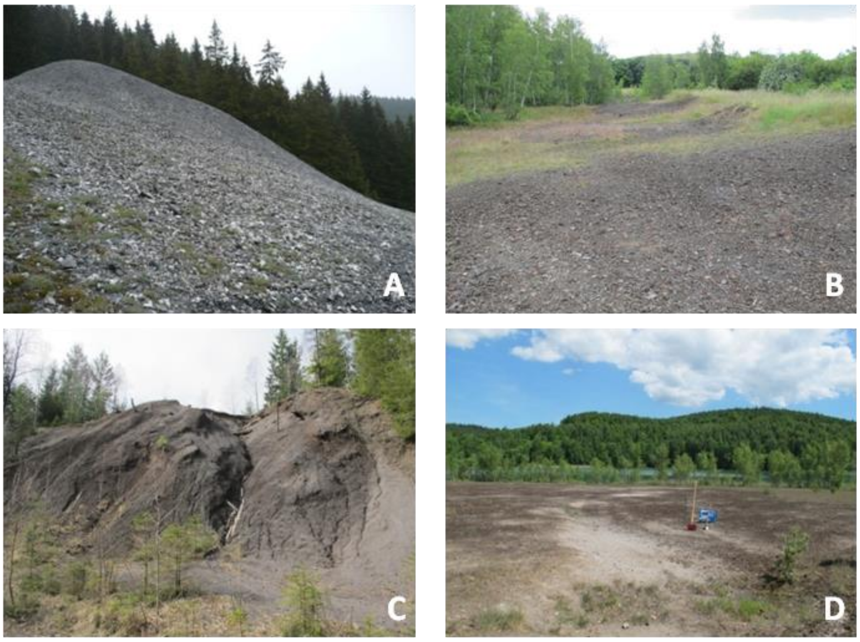

Figure 2: Examples of different mine waste types from the Harz Mountains. A: waste rock dump (heap) near Oberschulenberg. B: slag dump from Langelsheim. C: density-separated processing residues near Clausthal-Zellerfeld. D: tailing pond from flotation near Bad Grund. (Poggendorf et al., 2015)

3.2.2 Relevance of the case

In 2013 approximately 41 billion euro were spent for metal commodities, including metal ores and concentrates (17.6%), as well as for intermediate products and products from the first-stage processing. The amount of imported metals amount to 63.5 million tons (=Mt), whereby about 44 Mt of the material were metal ores and concentrates.

Since Germany is essentially dependent on metal imports, the secure supply of metals is very important. Especially the increasing demand of mineral raw materials in emerging industrial nations, the concentration of production for some raw material to a few and sometimes politically unstable countries, the influence of speculation on the commodity markets, the distortion of competition in trade (restrictive competitive practices in trade), as well as the unknown development of material-intensive technologies in the future, call for new strategies (BGR 2013).

One possibility is the reduction of metal imports by increasing the recycling of metals. In Germany the recycling of metals from scrab, steel and urban waste as well as the purchase of scrap and wastes mainly from EU members for recycling is already realized to a large extend (BGR 2013).

The economic potential of wastes from thousands of years of ore mining in Germany as a potential source for metals, high-tech elements and construction aggregates is under current investigation. These studies support the resource exploration in Germany as well as the developement of technologies and methods for exploration and processing of mineral raw materials. Due to the economic decline in the German mining sector in 1992 and the turning away from exploration of raw materials for many years, it is necessary to obtain this knowledge and develop it with new technologies. These technologies might be applied for mine wastes or ore deposits in Germany as well as abroad.

Due to the missing sector of metal ore mining it is not surprising that the investigations of metal bearing mine wastes in Germany are almost exclusively realized within state-funded research projects by universities, research institutions or government agencies such as the BGR, which are often accompanied by small to medium-sized companies mostly without exploration intentions.

In addition to the national importance to secure raw materials, the exploration of the dumps may have a regional importance. Thus, many of the waste dumps still have to be remediated, but the private owners of the closed, historical dumps, as well as the municipalities often have problems to bear the costs. The recovery of valuable materials might help to cover the costs for remediation. Additionally, the reprocessing of the material normally diminishes the amount of harmful substances like heavy metals in most cases.

3.2.3 Analysis

3.2.4 Regional Study: The Erzgebirge

3.2.4.1 Mining in the Erzgebirge

The Erzgebirge is located in the southeastern part of Germany in the Free State of Saxony. This regional study will provide an overview of major mining districts in a region in which metals mining has taken place for more than 850 years (SOBA 2015). Most important commodities include silver, zinc, lead and tin, but also uranium has been exploited on a very large scale. Mining dumps and - tailing ponds abound as a result of historic mining operations. Many of these mining and processing residues still contain significant concentrations of valuable resources. This summary will just consider the results of the BMBF-funded (Federal Ministry of Education and Research) project SMSB (Strategic metals and minerals from Saxonian mining dumps). The project initially identified the 20 mining-related residue dumps with the highest value potential. It was shown that tailings deserve particular attention, because waste rock piles usually contain very low concentrations of valuable metals and metallurgical slags in the Erzgebirge have mostly been consumed as building material for construction of roads and houses in the time of German Democratic Republic (GDR). The screening illustrates further that there are three mining districts with a particularly high potential for re-mining, including the tin-ore districts of Ehrenfriedersdorf and Altenberg, as well as the polymetallic base metal district of Freiberg. In each of these three districts there are a number of large tailing ponds containing considerable metal concentrations. All of the high potential mining dumps relate back to mining activities in the 20th century. This is determined not only by the fact that the rate of exploitation and processing reached an unprecedented scale, but also because industrial processing was much less efficient than manual and semi-manual processing.

Geology of the mining district of Freiberg

For more than 800 years, the polymetallic sulfide deposits of Freiberg have been mined for silver, lead, copper, and zinc. Polymetallic sulfide mineralization is hosted by a large number of veins with several distinct mineral associations. These originated during at least two distinct stages, one of Late Variscan, the other of Cretaceous age. Both stages contribute significantly to the metal potential of the district (Baumann et al. 2000, Tichomirowa et al. 2002). The veins are hosted by gneiss, mica-schist, and amphibolite (Baumann et al. 2000).

Geology of the mining district of Altenberg

In Altenberg the largest tin deposit of the Erzgebirge with a mining history of 550 years (1491-1991) can be found (Weinhold 2001). The deposit is a greisen-type deposit hosted by a small stock-like granitic intrusion. This granitic stock is part of the larger Altenberg-Teplice Caldera of late Variscan age (Weinhold 2001).

Geology of the district of Ehrenfriedersdorf

The Ehrenfriedersdorf tin-mine, which closed in 1990, looks back on 750 years of mining history. Similar to the Altenberg deposit, mineralization forms a greisen-type deposit. However, different to the Altenberg deposit tin mineralization in Ehrenfriedersdorf occurs within as well as outside the stock-like granitic intrusion. Tin-bearing structures occur as veins and skarns in the exocontact around the intrusion, stockwork and vein-like zones in the endocontact – within the intrusion (Hösel at al., 1994). The country rocks are metamorphic series of the amphibolite to greenschist facies, deriving from Proterozoic and Cambrian educts.

3.2.4.2 Characterization of Mine Wastes with high economic potential

Available documentation for the volumes of flotation residues deposited in the 20th Century in -tailing ponds in the Erzgebirge is rather detailed (see Table 1). This also applies to chemical and mineralogical compositions of the tailings. It has thus been a rather simple task to identify tailing ponds of high economic potential for re-mining. These include tailings in the districts of Altenberg, Ehrenfriedersdorf and Freiberg (Table 1). In addition to the two tailing ponds listed for the Freiberg District there is another big pond in Freiberg called “Spülhalde Hammerberg”. The latter has nearly the same size and content as the tailing “Spülhalde Davidschacht”.

Table 1: Tangible properties of tailings dams of particular relevance for re-mining in the Erzgebirge

District	**Name**	**Time**	**Volume**	**Metals**	**Concentration (wt.%)**	**References**
Altenberg	Tiefenbachhalde	1953 - 1966	1.95 Mm³	Sn Bi Mo	0.2 – 0.12 < 0.02 < 0.01	(Weinhold 2001)
	IAA Bielatal	1967 - 1991	10.45 Mm³			
	Schwarzwasserhalde	1938 - 1953	0.45 Mm³			
Ehrenfriedersdorf	Spülhalde 1	1942 - 1969	0.44 Mm³	*Mo - 20 ppm, Bi - 50 ppm, Sn like Altenberg (Hösel at al., 1994)*		
	Spülhalde 2	1969 - 1990	1.59 Mm³			
Freiberg	Spülhalde Davidschacht	1951 - 1964	1.3 Mt	Pb Zn	0.25 0.24	(G.E.O.S. 1993)
	Spülhalde Münzbachtal	1960 - 1964	0.83 Mm³	Pb Zn	0.10 0.18	(ACD 1993)

Figure 3: First drill campaign of project SMSB in Altenberg (TUBAF 2013)

Figure 4: Density separation experiment of tailing material at UVR FIA in Freiberg (TUBAF 2014)

3.2.4.3 Verification of historical and collection of new data

The work packages of the SMSB project, which started in 2011, include two exploration drilling campaigns on different tailing ponds in order to verify historical data and to collect new tangible information. In the first campaign a single pilot hole was drilled on each of the four ponds identified as having particular potential for re-mining. This included the Tiefenbachhalde in the Altenberg district, the Spülhalde 1 in the Ehrenfriedersdorf district, as well as the Spülhalde Davidschacht and Spülhalde Münzbachtal in the Freiberg District. Each drill core was positioned such as to intersect the respective tailing ponds near their center. The soft tailings were collected in a PVC-liner – with the aim to obtain undisturbed sample material permitting the reconstruction of compositional and textural stratification. The drill cores were sampled systematically and evenly in meter long intervals. These samples were homogenized and subsampled. Laser granulometry was applied to determine particle size distributions, whereas X-ray fluorescence analysis (XRF) and X-ray powder diffraction analysis (XRD) were applied to determine quantitative chemical and mineralogical attributes on bulk samples. The samples were further investigated using and Mineral Liberation Analysis (MLA). In general, the results obtained were in good agreement with historical data, complementing them by relevant mineralogical and microfabric information needed for the critical assessment of metal deportment and possible technological routes for revocery.

Based on the analytical results, the two tailings with the highest economic potential were selected for a second drilling campaign, namely the Tiefenbachhalde in the Altenberg district and the Spülhalde Davidschacht in the Freiberg district. The second campaign included 10 holes for each tailing. The drill holes were placed such as to cover the pond in a grid-like fashion. Every hole was drilled through to the bottom of the tailings in order to get information about the local thickness. The 10 drill cores where sampled in 2 meter intervals. All samples were homogenized and sub-sampled for XRF, XRD, MLA and laser granulometry analysis.

3.2.4.4 Technical challenges of re-ming of tailings

After verifying the historical data of the tin content in the Tiefenbachhalde Altenberg and the Spülhalde 1 in Ehrenfriedersdorf, as well as the lead and zinc content in the Spülhalde Münzbachtal and Spülhalde Davidschacht in the district of Freiberg, the results also show potential for strategic metals like indium, germanium, gallium, tungsten, molybdenum and other metals. Even if the contents of these metals are not significant high, they may be able to be extracted through the processing process (with focus on the target metals of the former mining). This is the aim of the ongoing project SMSB. One work package deals with ore processing of the tailing material. Three different methods of processing are being tested on the material, namely the chemical leaching (by TUBAF), the biological leaching (by G.E.O.S. Freiberg GmbH) and the mechanical processing (by TUBAF).

The leaching with acidophilic bacteria can be better applied for sulfidic tailing materials as it occurs in the area of Freiberg, because sulfur is needed by the microorganism for their metabolism. If this kind of tailing material was in contact with air or water for the time of deposition, oxidation processes could occur, which will impede the leaching processes. In Freiberg there is an oxidation zone in the first two meters of the tailing Spülhalde Davidschacht and Münzbachtal. In the district of Altenberg and Ehrenfriedersdorf the tailing material is oxidic and not suitable for acidophilic leaching.

Not only the mineral composition, also the grain size of tailing material plays a significant role for the success of the re-mining method. If the material is too fine, mechanical processing cannot be used, because flotation is working down to a material grain size of about 10-20 µm. Because of the borders of former flotation the material fraction with a grain size lower than 20 µm has a much higher concentration of valuable metals. Also the density separation of tailing material during the process of jetting had influence to the structure of the tailing, so that it is inhomogeneous. For mechanical processing a homogeneous input of material will be needed, so information about the structure of the tailing is very important.

3.2.4.5 *Challenges of the accessibility of waste sites and law*

With the research on tailings in Saxony, the Helmholtz Institute Freiberg wants to figure out what kind of problems can occur with the realization of re-mining waste sites. Beside the SMSB project, the institute applied for a study of a re-mining scenario as a method of rehabilitation from hazardous emissions of tailings. The potential re-use of mine wastes might be hampered by the existence of nature or monument conservation issues. Therefore together with the public authorities these aspects were discussed with regard to the relevant laws. In Freiberg for example the tailing Spülhalde Davidschacht is under restrictions by the monument conversation. The tailing was not used for any activities until it was closed in 1964. The quiet site offered the best conditions for rare animals and special plants, which can live on a contaminated soil. Some of these species are protected by EU-law, which means that re-mining will be just possible with expensive compensation measure.

The results of the BMBF-funded project SMSB (Strategic metals and minerals from Saxonian mining dumps, BMBF funding code: 033R095) will be presented in a report until March 2016. For more information, please contact the Helmholtz Institute Freiberg for Resource Technology.

3.2.5 Regional Study: Western Part of the Harz Mountains

3.2.5.1 *Mining in the Harz*

The Harz Mountains are located in the northern part of Germany (Figure 1). Due to its wealth of precious and non-ferrous metals like silver, lead, copper, and zinc mining took place for more than 1500 years (Liessmann 2010, Klappauf 1985). Additionally, iron-ore, barite, and fluorite were mined in the Harz.

There are four major ore deposit districts in the Harz Mountains. A very famous one was the Rammelsberg, a marine sediment-hosted massive sulfide deposit (SHMS), where about 27 Mt of raw metal ore were mined (Stedingk 2012). Another major ore deposit district is the Oberharzer vein district, steep dipping and mainly WNW-ESE striking veins with partially high-grade ore (Liessmann 2010). The most prominent locations of mining were Clausthal-Zellerfeld, Grund-Silbernaal, and Lautenthal. In total about 37.9 Mt of metal ore were mined (Stedingk & Stoppel 1993, Liessmann 2010). Table 2 presents the primary production data of the major ore mining districts.

Table 2: Mined base and precious metals of the main ore deposit districts (Liessman 2010, Stedingk 2012, Wilke 1952).

Ore deposit district	Mined raw ore	Amount of metals produced			
		Pb	Zn	Cu	others
Rammelsberg	27 Mt	2.2 Mt	4.6 Mt	0.54 Mt	2600 t Ag, 30 t Au
Oberharzer veins	37.9 Mt	1.9 Mt	1.5 Mt	--	5000 t Ag
Mittelharzer veins (St. Andreasberg)		12500 t		2500 t	320 t Ag

Ore containing veins are also abundant in the Mittelharz as well as in the Unterharz vein districts. However, the amount of mined ore is much smaller. The most prominent mining district of the Mittelharz was Sankt Andreasberg, which is characterised by silver-rich ore and vein mineralisations with a stronger polymetallic character (Pb-Zn-Cu-Ag-Co-Ni-ores; Wilke 1952). In the other mining districts of Mittel and Unterharz, Pb-, Zn-, Ag-, or Cu-ores and locally also Co-, Ni-, Sb-, W-, Se- or Au-ores were mined (Liessmann 2010). Additionally barite, fluorite and iron-ores were mined. Because mining in the Unterharz was less extensive compared to the other disricts and the amount of mine wastes should be negligible, it is not considered in this study.

3.2.5.2 Distribution of Mine Wastes

Ore mining in the different districts have produced all types of mine wastes. These residues of hundreds of years of mining include waste rocks, ore processing wastes with density separated residues (until 1940) as well as tailings from flotation (after 1920), and metallurgical slags.

From the three main ore deposit districts Rammelsberg, Oberharz and Mittelharz about 350 mine waste sites are known from base and precious metal mining, without dump sites from the iron-ore-, fluorite- or barite- mining. Some prehistoric and therefore very little waste sites might be missing in that list. A comparison between the distribution of different mine waste types, concerning the number of mine waste dumps and the amount of material, reveals clear differences. The number of mine waste sites per waste type reflects the different techniques of mining, processing and metallurgical treatment for the different ore types. For the massive sulfides from the Rammelsberg, for instance, there was no ore processing possible until the implementation of the flotation in 1936 (Liessmann 2010). Therefore, the ore was roughly sorted and then smelted, leading to a high throughput in the smelters and many slag dumps in the surroundings of the Rammelsberg.

In contrast to the Rammelsberg, low-grade waste rock dumps are more important for the vein-type ore mining in the „Ober- and Mittelharz“. Since these veins are heterogeneously distributed over a large area, mining took place at many locations and a lot of overburden and low grade waste rock had to be deposited. In the last decades of the 19th century the construction of a few central ore processing facilities replaced many little ones (Liessmann

2010). During the same period, ore processing residues were deposited at heaps for the first time. All processing residues produced before, had been disposed of in the adjacent rivers and led to a strong contamination of rivers and adjacent farmlands.

Except for some waste sites, the volumes of most objects in the Harz are below 100,000 m³, but economically interesting might only be the larger ones. There are, however, clusters of mine waste sites with similar material in the immediate vicinity or surrounding region, which perhaps can be re-mined together.

Most of the waste material in the Harz originates from the mining in the Oberharz. This corresponds to the higher amount of raw ore, which was mined in that area compared to the Rammelsberg. Nevertheless, the amount of metals, which could be extracted, is only half as high as at the Rammelsberg (3.4 Mt versus 7.3 Mt Pb + Zn + Cu + Ag + Au, Table 2).

Altogether, there are about 16 million cubic metres (=Mm³) of mine waste material from base and precious metal mining in the Harz Mountains. Ore processing residues account for most of the waste material for both the massive sulfides from the Rammelsberg as well as the vein ore from the Harz vein districts. Especially after implementation of the flotation process for the Rammelsberg and the Oberharz ore, a few, but huge tailings were built. Tailings from flotation have generally lower metal concentrations than older ore processing residues. However, the large amount of material can make them economically interesting.

3.2.5.3 *Metal concentrations of the mine waste*

The main metals of the mine waste from the Western Harz are the base metals Pb, Zn, and Cu, which occur in all mining districts with different proportions. Additionally to these metals Ag, Sb, In, Ga, Bi, Co, Ni, Sn, Se, Au, and the minerals fluorite and barite can be enriched in the mine waste of some districts. Indium, Ga, Sb, Co, and fluorite can occur with high purity, which may be of special interest because some of them belong to the so-called critical elements for the European Union (EU 2014).

In Table 3 minimal and maximal element concentrations of some larger mine waste sites are shown. Apart from two waste dumps, the concentrations do not represent average concentrations, since number of samples is too low. With regard to the suite of different ore metals, the residues of the Rammelsberg ore are probably most interesting in the Harz. Apart from the base metals, they are also characterised by elevated concentrations of In, Ga, and Sb. Germanium exists in the ore of some mining districts (Moeller & Dulski 1993). However, within the analysed mine waste sites only very low concentrations could be recorded by different anaytical techniques (ICP-MS, LA-ICP-MS).

The largest waste sites from the Rammelsberg ore are the two tailing ponds “Absetzbecken am Bollrich”, which contain about 3.4 Mm³ material. Estimations of their mineral contents, based on drill cores, revealed about 2.5 Mt metal-sulfides (Pb, Cu, Zn, Fe) and about 2 Mt barite (Woltemate 1988). From 2015 to 2018 the two tailing ponds will be investigated in detail within the research project REWITA (BMBF-funding code: 033R136; 2015-2018). Based on average indium concentrations of the sphalerite, scientists of the REWITA-project expect about 100 t Indium within both tailings (pers. communication A. Dittmar, CUTEC). Gallium concentrations of the tailing material have only been reported from one drill core meter and amount to 29 ppm (Woltemate 1988). Further by-products, additionally to the base metals, are Sb, Ag, Bi, Co, Ni, Sn, Se, and low quantities of Au (Woltemate 1988).

Other tailings in the Harz contain flotation residues from the Oberharz Pb-Zn-(Ag-Sb-Cu)-veins. For instance in Bad Grund there are two large tailing ponds that together contain about 5 Mm³ material (Table 3). Average samples, which were taken between 1988 and 1992 from the Absetzbecken II in Bad Grund, showed Zn concentrations between 0.2-1.5 % and barite concentrations between 1 - 2 % (IGU 1994). These results are consistent with analyses within the project ROBEHA, whereby single layers can have concentrations up to 4.4 % Zn.

Ore processing residues, deposited in the area of the Mittelharz could not be found. The mining period in that area ended before flotation was established in the Harz. Older ore processing dumps with residues from density-separation can only be found in the area of the Oberharz vein mining. From this mine-waste type, only four objects seem to exist, since until the second half of the 19th century all material was disposed into the rivers and streams. The existing waste sites usually have higher metal concentrations than residues from flotation and, depending on the mined vein mineralisation, are more enriched in Zn or in Pb, Ag, and Sb. Lead-antimony- and silver-rich, density-seperated ore-processing wastes occur in the Pochsandhalde Bergwerkswohlfahrt, which was investigated in detail within the research project ROBEHA (Table 3). Unfortunatly, the volume of this dump is quite low (approx. 50,000 m³). Therefore, only the re-mining of several ore processing dumps together (density-separation) might be profitable.

Table 3: Metal concentrations (minima-maxima) of larger mine waste sites or clusters of mine waste sites (Kuhn et al. 2015). With two exceptions, analyses were done on near surface samples (up to 1 m depth), which were randomly sampled. Average concentrations are only recorded for sites with a sufficient number of samples. All other concentrations represent only indications. Recorded volumina imply only rough estimates (Sources: contaminated site register of the administrative district Goslar; literature (CUTEC 1994, Woltemate 1988); own data from BMBF-funded research project ROBEHA).

	Pb (%)	**Zn (%)**	**Cu (%)**	**Ag (ppm)**	**Sb (ppm)**	**In (ppm)**	**Ga (ppm)**	**Ge (ppm)**
Residues from ore processing - flotation								
Absetzbecken am Bollrich I and II (R; 2 tailing ponds; approx. 3.4 Mm^3)	ø I: 1,15* ø II: 1,05*	ø I: 1,6* ø II: 2.40*	ø I: 0.16* ø II: 0.15*	1 core: I: 30*	1 core: I: 170*	1 core: I: 7*a	1 core: I: 29*	
Absetzbecken II Bad Grund (O; n = 49 / 15; tailing pond I and II approx. 5 Mm^3)	0.1 - 0.6	0.2 - 4.4	0.01 - 0.30	3 - 11	29 - 55	0.2 - 2	8 - 14	3 - 4
Residues from ore processing – density separation								
Pochsandhalde Bergwerkswohlfahrt (O; n = 211 / 99; approx. 50,000 m^3)	2 – 14 (ø 4.8)	0 - 1.1 (ø 0.1)	0 - 0.2 (ø 0.02)	40 – 270 (ø 126)	150 – 630 (ø 294)	0 – 1 (ø 0.2)	1 – 12 (ø 8)	1 – 4 (ø 3)
Pochsandhalde Ottiliaeschacht (O; n = 9 / 7; 1 heap; approx. 100,000 m^3)	0.4 – 1.3	1.3 – 3.0	0.03 – 0.12	7 - 15	40-88	4 - 7	12 - 16	3 - 5
Waste rocks from mining								
wast rock heaps at the Rammelsberg mine (R; n = 9 / 8; 2 heaps; approx. 300,000 m^3)	0.3 - 8.1	0.06 - 0.47	0.05 - 0.36	5 - 191	25 - 880	3 - 32	22 - 27	2 - 7
waste rock heaps in Lautenthal (O; n = 8 / 6; several heaps; approx. 500.000 m^3)	0.1 - 0.8	1.4 - 6.7	0.02 - 0.03	4 - 8	24 - 60	1 - 5	20 - 25	3 - 5
waste rock heaps near Oberschulenberg (O; n = 6 / 6; mehrere Halden; approx. 300,000 m^3)	0.7 - 3.6	1.1 - 2.8	0.03 - 0.35	6 - 29	68 - 242	4 - 37	22 - 35	3 - 4
Slags from metallurgical treatment								
slag heap in Langelsheim-Goslar (R; n = 16 / 9; 4 heaps; approx. 160,000 m^3)	0.9 - 5.7	2.3 - 18.5	0.3 - 1.5	21 - 108	108-930	18 - 63	15 - 23	2 - 4
slag heap Bleihütte Clausthal (O; n = 6 / 4; 2 heaps; approx. 120,000 m^3)	0.5 - 6.6	0.7 - 8.9	0.07 - 0.3	5 - 69	165 - 525	2 - 23	9 - 20	3 - 8

*Used abbreviations: n = x / x: number of samples from XRF-analyses / (LA-) ICP-MS-analyses; *: Data from Woltemate, 1988; a: higher concentrations are expected for other regions of the tailing pond; ø: average concentrations of the dump/pond – recorded only, if there is a sufficient number of samples; R: Rammelsberg district; O: Oberharz district*

Similar considerations apply to the coarse-grained waste rock dumps in the Harz, since many of them have volumina below 100,000 m³. Nevertheless, in several regions, like Lautenthal and Oberschulenberg, clusters of waste dumps occur. Due to the dilution with host-rocks or gangue material, metal concentrations in waste rocks are often low. However, strong variations occur. Metal-rich waste rocks for instance occur in some dumps located in Lautenthal (Table 3). Samples from these dumps contained between 1.4 - 6.7 % zinc und 20 - 25 ppm gallium.

In Cu-rich samples from Oberschulenberg indium concentrations of up to 37 ppm were measured. Although Cu-rich ore of the Pb-Zn-Cu-veins can contain Indium, average concentrations of entire waste rock dumps are likely too low to be economicially interesting. In contrast, waste rocks from the Rammelsberg district (approx. 300,000 m³ material) have mostly elevated Ga- and In- concentrations (3 - 32 ppm Ga, 22 - 27 ppm In; number of samples = 9). However, the majority of the material belongs to the Rammelsberg mine, which is listed as world cultural heritage.

Metallurgical slags can contain high metal concentrations. Especially old slags from the Rammelsberg ore contain high amounts of Zn (up to 18.5 % Zn). Further elements, like Pb, Cu, Sb, Ag, and subordinately Sn, In, and Ga can be enriched (Table 3). The volume of most slag heaps in the Harz is however problematic. Because slags were often used as construction material, for instance for streets, only re-mining of several slag heaps would generate larger amounts. Another challenge while handling slags, is the metal extraction from the material. The material is very hard and metals can be bound within sulfides, silicates and other oxides, or occur as pure metals.

The presented results about the mine wastes in the western Harz were produced within the BMBF-funded research project ROBEHA (Economic potential of mine waste on the example of the western Harz, taking into account the sustainability, 2012 - 2015, BMBF funding code: 033R105; www.robeha.de). The collaborative project involves Prof. Burmeier Ingenieurgesellschaft mbH (BIG); the Federal Institute for Geosciences and Natural Resources (BGR); Clausthal University of Technology - Institute of Mineral and Waste Processing, Waste Disposal and Geomechanics (TU-Clausthal IFAD); Clausthal Institute of Environmental Technology (CUTEC); RWTH Aachen University - Academic and Research Department Wastemanagement (RWTH LFA) as well as DORFNER Analysenzentrum und Anlagenplanungsgesellschaft mbH (Dorfner ANZAPLAN). Beside the large-scaled investigations about historical mine waste sites in the western Harz, two mine waste dumps were explored in detail. By the aid of geophysical (ERT, SIP, RADAR), geochemical (e.g. LIBS core scanner, XRF, ICP-MS, LA-ICP-MS) and mineralogical exploration methods (microscopy, REM-MLA, microprobe), the internal structure and the element distribution within the dumps, the processability of the materials regarding valuable metals and potential valuable inert residuals have been analysed. Furthermore, scenarios for the re-mining of these dumps and the environmental impact have been discussed.

3.2.5.4 Technical challenges of ore-processing

Ore-processing tests on density-seperated residues within the ROBEHA-project (TU Clausthal - IFAD) indicated that for re-mining the ore processing technique must differ from the technique which was used during origin of the mine waste. Especially due to alteration processes within the dump, sulfidic bound metals were redistributed and are now bound within different phases (sulfides, carbonates and Fe-oxihydroxides). The highest output on valuable metals of the mining residues was obtained by a combination of leaching and flotation. However, costs for these techniques are relatively high.

3.2.5.5 Challenges of accessibility of the waste sites

For many mine waste dumps in the Harz the ownership has been changed over the course of time. Only few dumps are still under the supervision of mining authorities or belong to recycling companies. The rest belongs to private owners, the state forests or municipal authorities. For some older waste sites many owners can exist, as it is the case for a larger slag heap in Langelsheim, where approximately 30 different owners exist. For such mine wastes exploration and re-mining is very difficult. Many dump sites in the Harz are also difficult to sample, since they are already remediated or overgrown, covered by buildings, are listed for natural or historic preservation, or belong to the world heritage.

3.2.6 Regional study: Mansfeld-Sangerhausen mining district

The mining of the Kupferschiefer-type black shale-hosted copper ore over a time span of nearly 800 years has formed significant legacies of mining and processing residues within the landscape of the Mansfeld-Sangerhausen mining district. Until the closure of the last mining shaft, 109 Mt of Kupferschiefer ore were mined and processed with an entirely extraction of 2.63 Mt of copper and 14,000 t of silver, as well as byproducts as zinc, lead, cobalt, nickel, rhenium and gold (Knitzschke 1995, Rappsilber et al. 2007). Mining legacies caused by the mining of ore and subsequent extraction of metal commodities comprise numerous historic small scale dumps, tabular dumps piled up from the beginning of the industrial mining age and huge conical dumps, which mark the youngest remnants of the local mining history in the socialistic era as well as tailing ponds of process residues.

Kupferschiefer mining in the Mansfeld-Sangerhausen district was generally marked by winning of the Permian stratiform black shale-hosted ore, but also stratigraphic adjacent lithotypes, namely the hanging wall Werra limestone/dolomite and footwall Rotliegend sandstone have been mined in several Mid-European Kupferschiefer-type mining districts (Richelsdorf, Lower Silesia/SW Poland, Lower Rhine Basin) and are still extensively extracted in the Polish Kupferschiefer-type deposits of the Lubin mining district. Mining in the Mansfeld-Sangerhausen area was exclusively restricted to the black-shale-hosted ore and the processing to recover copper and byproducts was entirely focused to the pyrometallurgical route, which has produced both huge amounts of waste rocks and tailings.

Artisanal mining trace the northern boundaries of both districts, where the Kupferschiefer bed outcrops, but can be tracked equally on the western rim of the Mansfeld basin. These small-scale mining shafts reached only few meters depth and left unexceptional wall rock heaps of 10 to 20 meters, because the very selective mining methods during the Middle Age (1200 – 1600). With increasing quantities of mined Kupferschiefer ore, the new shafts were sunk further basin inwards corresponding with increasing mining depths and volumes of waste rocks deposited on increasing larger heaps/dumps (mining period 1600-1800). Improvement of mining and extraction techniques led to mining depths reaching over 100 meter with appropriate volumes of wall rocks that has to excavate by the sinking of the deeper shafts. From about 1850 a new era of mining in the Mansfeld district took place and marks the change to the application of industrial mining methods. In consequence, the mining depths and the size of the dumps rose up further, inherent with increasing stoping heights and extraction of thicker portions of the Kupferschiefer bed towards the hanging wall limestone. Low-grade ore, uneconomic at that time, was stored mostly at a certain part at the top of the tabular dumps and represent nowadays an easily accessible resource. Large scale mining of Kupferschiefer starting from the technology jump after second world war and resulting in large conical dumps in both, the Mansfeld and Sangerhausen district, with heights of up to 150 meters and 300 m diameter, piled up in the Mansfeld area on top of the older tabular dumps. Table 4 summarizes the main features of the most notable tabular and conical dumps of the Mansfeld-Sangerhausen region.

Table 4: General features of mining dumps of the Mansfeld-Sangerhausen district.

District	**Shaft/Type** (conical/tabular)	**Operation time**	**low-grade ore**	**ore grades [%]**				**wall rock**	**Size/Area**
				Cu	**Pb**	**Zn**	**data**		
Sangerhausen	Thomas Münzer/ cone+tab	1944-1990	-	-	-	-	-	7,312,000 m^3	16.0 Mt
Sangerhausen	Bernard Koenen 1/ cone	1958-1990	-	-	-	-	-	5,475,000 m^3	13.2 Mt
Sangerhausen	Bernard Koenen 2/ cone	1958-1990	-	-	-	-	-	3,720,000 m^3	9.4 Mt
Mansfeld	Otto Brosowski/cone+tab	1900-1970	250,000 m^3	0.32	0.86	2.29	°	5,750,000 m^3	10.8 Mt/22.8 ha
Mansfeld	Fortschritt I/ cone+tab	1906-1967	100,000 m^3	0.79	0.58	0.73	*	8,500,000 m^3	8,600,000 m^3/ 26 ha
Mansfeld	Ernst Thälmann/ cone+tab	1906-1962	200,000 m^3	0.32	0.86	2.29	°	9,620,000 m^3	9,620,000 m^3
Mansfeld	Theodor/tab	1870-1917	59,000 m^3	0.07-0.54	1.31-2.37	1.51-4.48	*	624,000 m^3	683,000 m^3
Mansfeld	Zirkel/tab	1891-1927	450,000 m^3	0.09-0.93	1.62-2.46	1.43-2.24	*	3,230,000 m^3	3,680,000 m^3/ 15.2 ha
Mansfeld	Hermann/tab	1899-1924	460,000 m^3 (inferred)	0.08-0.75	1.13-2.76	1.09-2.38	*	4,140,000 m^3 (inferred)	4,600,000 m^3/ 19.2 ha
Mansfeld	Otto I-IV/tab	1865-1910	300,000 m^3	0.09-0.83	1.27-3.05	1.39-2.69	*	2,000,000 m^3	2,326,000 m^3/ 18 ha
Mansfeld	Eduard/tab	1864-1905	210,000 m^3	0.08-0.59	0.84-3.52	1.03-4.42	*	1,960,000 m^3	2,170,000 m^3/ 15.5 ha
Mansfeld	Martin 2 (south)/tab	1850-1900	23,000 m^3 (inferred)	0.19-0.38	1.81-2.77	1.50-3.04	*	330,000 m^3 (inferred)	353,000 m^3
Mansfeld	Max-Lademann/tab	1879-1964	800,000 m^3	0.18-0.66	0.18-2.03	0.31-1.66	*	1,000,000 m^3	1,800,000 m^3/8.4 ha
Mansfeld	Niewandt/tab	1892-1913	22,000 m^3	0.2	0.8	1.8	°	1,652,000 m^3	1,672,000 m^3/11.7 ha
Mansfeld	small artisanal heaps (northern & western margin of the district)	approx. 1400-1800	-	-			-	unknown	370,000 m^3

** BMBF-funded project "Recovery of metals and mineral products from old Kupferschiefer mine dumps, Mansfeld district, Central Germany" (033R011, 2009 - 2012)*

° Arge TÜV Bayern - L.U.B.: Umweltsanierung Mansfelder Land 1991

Other residues formed by the pyrometallurgical extraction are lead-zinc flue dusts produced by gas scrubber plants of the combustion chambers, which were usually processed further in the Hettstedt lead smelter or partially deposited in tailing ponds (Theisen sludge, e.g. disposal site Helbra) or stored in basin-like excavations layed in low-grade ore/wallrock dumps (Niewandt-shaft/ Siersleben). Table 5 displays various residues generated in regards to the pyrometallurgical processing of Kupferschiefer.

Table 5: Process residues and disposal sites of the pyrometallurgical extraction of black shale-hosted ore in the Mansfeld-Sangerhausen mining district (compiled from Arge TÜV 1991, Daus & Weiss 2002).

Type of residues	Location	Disposal type	Element conc.	Volume
Silicate slag	Helbra (Koch smelter)	slag heap	-	11,000,000 m^3
	Wimmelburg (Krug smelter)	slag heap	-	7,000,000 m^3
Theisen sludge	surrounding area of the August-Bebel-smelter, Helbra	small—scale cement cells; on top of slag heaps; large ponds	20 % Zn 15 % Pb 1.3 % Cu 1.1 % Sn	220,000 t
Zn-Pb-flue dust	Niewandtshaft-dump, Siersleben	dump internal basins (partly covered)	40% Zn 13% Cl 18%Pb 5% Cu	17,400 t
Neutralization $CaSO_4$ sludge	Niewandtshaft-dump, Siersleben	dump-attached sludge pond	0.6 - 1.2 As	19,200 t
	Lichtlöcherberg, lead smelter Hettstedt	sludge pond	0.6 - 1.2 As	?

The efficient utilization of dump material and process residues in the Mansfeld-Sangerhausen region is regulated by several factors. Generally, the recovery of low-grade ore, waste rocks and process residues is bound to their availability in respect to property rights and decision-making management organizations, respectively. Numerous dumps have been sold to private companies since the last two decades, mainly for the use to exploit crushed stone for building material such as road construction, filling material, or frost protection layers. Consequently, the real availability of in particular dump material from the Mansfeld region has been reduced to estimated 50 %. Furthermore, some of the dumps (e.g. Zirkelshaft dump or the conical part of the Ernst-Thälmann shaft dump) are subjected by stronger preservation orders of the district administrative authority. The remaining mining dumps are generally managed by the LMBV mbH (Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH) with the aim to sale, whereas management and sale of process residues disposal sites is subjected to the MDSE mbH (Mitteldeutsche Sanierungs- und Entsorgungsgesellschaft mbH). Due to the intense mining and production level during the socialistic era and before, the Mansfeld-Sangerhausen region is relatively densely populated and the accessibility to objects is granted by a well-developed infrastructure.

Most of the processing facilities have been demolished or were dismantled/exported in the early 1990's; only the copper-silver-smelter in Hettstedt has been refurbished partially, but has discontinued its production in 2002.

Several studies of the Mansfeld-Sangerhausen area in respect to the inventory of mining legacies and their environmental impact have been carried out in the 1990s commissioned by the German Federal Environment Agency (Arge/TÜV 1991, Sanierungsverbund e.V. Mansfeld 1993).

A recovery of in particular process residues is complicated by environmental issues arising by the content of radioactive or toxic components. It is well examined that Mansfeld Theisen sludges as well as neutralization sludges contain hazardous organic compounds (polycyclic aromatics, polychlorinated dibenzodioxins and - furans), which represents a serious issue for the mineral processing in respect to future recovery of metals. Also the oxidation of Zn-/Pb-sulphides contained in the sludge by weathering leads to more soluble sulfates and consequently to sewage loaded with toxic compounds. Several approaches for the remediation of the unsealed sludge ponds have tested on the disposal sites in the early and late 1990's (Reiß & Gock 2000). A promising remediation method to decrease the content of toxic organic compounds and to separate lead from zinc can be achieved by low temperature oxidation of the slugdes with hydrogen peroxides (Daus & Weiss 2002). A new concept for pressure leaching of Theisen sludge is published in 2015 (Reiß & Gock). Cu, Zn and Re will be extracted by solvent methods. In the $PbSO_4$-concentrate the radionuclide ^{210}Pb is enriched. The radioactivity is below the limit of Pb-smelters.

But approaches to recover the metals successfully from the Theisen sludge have been failed and is recently investigated by a joint research project ("Winning of economically strategic materials from fine-grained residues from copper smelting – Theisenschlamm") that is focused on the application of selective microbial leaching (Glombitza & Reichel 2014).

In thelast years, research was also focused to the recovery of value metal commodities from low-grade Kupferschiefer ore. A multidisciplinary research project, running from 2009 - 2012, has investigated the recovery of base and trace metals from low-grade black shale-hosted copper ore by resource-efficient methods in a holistic approach (BMBF-funding code: 033R011, http://www.r-zwei-innovation.de/de/604.php). The study comprises various scopes of fields of investigation from a initial dump assessment, sensor-based sorting over flotation and hydrometallurgical winning as well as marketing and sales opportunities of the extracted metals and byproduct, those were carried out on dump material from the Fortschritt I tabular dump (Kamradt et al. 2012). The main evidence is that a profitable ore processing is feasible. However, some key issues to improve the recovery rates have to be investigated more detailed. Here, the challenge is to find an appropriate communition method in order to liberate also a considerably part of the base metal sulphides occurring as minute ore particles (5 - 100 µm) in the black shale low-grade ore. Despite of the particle liberation during communition, the partially high amount of organic carbon of the black shale interfere the flotation process and also the physico-chemical properties of flotation agents that are able to carry the few micrometer-sized ore particles in the froth needs to be examined. Nevertheless, promising results in a spin-off project with the Geomicrobiology department of the BGR were achieved in regards of metal recovery by the microbial leaching of crushed black shale and limestone-hosted ore (Kamradt et al. 2013). The high recovery rates of in particular for Cu and Zn (up to 95%) generated by bioleaching have stimulated the continuation of research in regards to the metal recovery from black shale-hosted ore by microbial leaching methods initiated by precursor projects as ProMine and Bioshale and currently continued in the french-german EcoMetals-project (Kutschke et al. 2014).

3.3 Discussion and Conclusions

Mine wastes are generally easily accessible objects and some of them are characterised by a high economic potential. Some of the waste dumps are very heterogeneous, since their use has often changed during time. Thus, material was often removed and used for other purposes, or other materials were deposited at the dumps, too. Additionally, separation processes during and alteration processes after deposition can cause relocation processes of the valuable metals, especially when they occur as sulfides. Whereas Pb often precipitates in situ or close proximity very fast in compounds such as sulfates or carbonates, Zn can be transported further and therefore can be depleted in some zones and enriched in other zones. Therefore, an accurate resource estimation of a dump site needs an intensive exploration as it is also the case for primary ore deposits.

Investigations of mine residues within different projects have shown that each mine waste site is special. Even waste dumps from the same mining district and the same waste type often show different metal concentrations. The affiliation to a certain ore deposit gives evidence of the occurring elements within the waste material, but concentrations are difficult to predict.

Comparing different waste types, one can conclude that waste rocks from the mining process itself are only in special cases economically recoverable. There is often too much gangue material or host rock associated with the ore-bearing parts and due to the mostly blocky material, costs for comminution would exceed the economic benefit. Nevertheless, there are some exceptions, but since dumps with higher ore grades often have been recovered in the past they are few in number.

Ore processing residues seem to have a higher economic potential. The highest metal concentrations occur in older dumps consisting of residues from density separation, the main ore processing procedure before 1930. Unfortunately, there are only a few dumps or heaps of this type left, usually with lower volumes compared to tailings from flotation.

Tailings from flotation normally have lower metal concentrations then older ore processing residues, but huge amounts of material. This can be economically interesting, especially when the focus lies on valuable metals. The material in the large tailing ponds are often saturated by water at a certain depth. Therefore, different alteration zones can often be found within the pond, especially for sulfidic material. During injection of the residue-water slurry sedimentation processes took place and led to an increase of the fine-sized material towards the centre of the tailing. In contrast, metal concentrations decrease towards the centre.

Many slags are characterised by high metal concentrations and might be economically interesting. However, due to the hardness of the material and the binding of the metals within sulfides as well as silicates, oxides or even as pure metals, the metal extraction might be difficult. For Fe-slags, the melting of the entire slag material was tested within the research-project REStrateGIS. With this method alloys instead of pure metals are obtained. For the recovery of base metals from Zn-, Pb-, and Cu-rich slags of the Harz Mountains (ROBEHA project) leaching experiments were promising.

In most cases, older mine waste dumps have higher metal concentrations than younger ones. However, older dumps are often smaller since mining technology was not that elaborated in former times.

The regional studies demonstrate, that mine wastes are often characterised by low to intermediate metal contents and therefore often can be compared to low-grade primary ore deposits. Since quantities are normally not that high, they will not replace primary ore deposits. However, they can be considered as resources that might be recoverable if market prices for metal commodities increase or supply bottlenecks for some metals exist.

The advantages of the recovery of mine waste, compared to primary ore mining, is the easy access to the material and the low costs for re-mining. Therefore, exploration and start of exploitation would be less time-consuming. Additionally, the conservation of natural resources, the energy demand, and the emission of greenhouse gases can be reduced. There are lower amounts of residues generated compared to primary mining and already existing residues are reduced. With good separation of heavy metals, the new produced residues are less harmful and can be deposited at well-sealed landfills. Additionally, costs for a remediation could be reduced.

The most important outcome of the different research projects, working with mine wastes in Germany, is that a few mine waste sites with an elevated economic potential were found. However, there are various circumstances which limit the reworking of mine waste sites.

The main disadvantage is that there are no existing processing plants for metal ore in the neighbourhood of the waste sites. Up to the early 1990s, almost all metal ore mines in Germany were closed. Therefore, new ore processing plants have to be set up, which would raise costs enormously. A mobile system might be a good option, which enables to rework several mine waste bodies. The rework of several bodies with similar ore composition would also increase the amount of material, and thus the efficiency.

Whereas costs for exploration as well as recovery of the material are lower than for primary ore deposits, the ore processing might be more difficult. Especially for metals, bound to sulfides, alteration processes can lead to the redistribution of the metals to different mineralogical phases like sulfides, carbonates and other oxides. Metals, bound to oxides (e.g. cassiterite) are less affected. Additionally, the grain sizes of the waste material might cause problems. Tailing material from flotation for example is already characterised by small grain sizes. An additional grinding in order to remove alteration rims of the metal sulfides might lead to grain sizes which are difficult to flotate again. In order to extract metals of the mining residues, the ore processing must differ from the technique, which was applied during the production of the mine wastes. Therefore, a cost-effective process chain represents a challenge for the rework of mine wastes.

Additionally to the demands of the processing, there are general conditions influencing the rework of the mine waste material.

Many waste sites are difficult to explore, because for many of them there has been a change of use during time. Thus, they can contain different types of waste, are partially covered by buildings or vegetation, or have already been remediated. Some of them are also listed for natural or historic preservation. Relatively young mine waste areas are more often accessible than older ones.

Different interests for exploitation of the waste sites by the owners, the public authorities, different companies as well as the public are valid for all waste sites.

Since up to now, there is no re-mining of mine wastes in Germany, it is yet to be regulated by the authorities of the respective federal state, which approval procedure has to be applied and where residues of the re-mining have to be deposited.

As a result of the usually lower metal concentrations (apart from slags) of the mining residues, compared to the ore from primary mining, the lower volumes, as well as the external conditions, re-mining of mining residues will probably operate on the verge of profitability. Energy and raw material prices, costs for deposition of the residues after re-mining, in combination with the support from the general public are decisive factors. An already existing processing plant in the neighbourhood would raise the economic potential enormously.

Despite the restrictions listed above, there are mining residues in Germany, which are expected to be economically interesting under certain circumstances. To find these objects an intensive preparatory work is necessary, especially for the mining residues, which were deposited before the 20th Century. Information about mine wastes in Germany is dispersed over many different administrative state authorities and is incomplete for some regions. Additionally, it sometimes might be difficult to get access to the data.

Due to the lack of mining industry for metal ore, the search and exploration of potential mine waste targets is partially taken over by public-sector institutions, in cooperation with small companies within state-funded research projects. Therefore, the currently acting research projects provide good databases for exemplarily historic mining districts, which are currently summarized in an initial supra-regional register.

3.3.1.1 Hazardous Materials within the Mining Residues

Mine wastes act as a large source for pollutants. In addition to the valuable metals, also arsenic and cadmium are released and enter soils, as well as rivers and lakes in form of sediments or dissolved in water. Therefore, re-mining can be a chance for an environmental improvement. Many residues have to be remediated, but the municipalities cannot afford it.

However, a recycling of waste material might, in the short term, increase the metal discharge (e.g. as dust) of the dump site. In the long term, concentrations of most heavy metals are reduced via recycling. Additionaly, the new residues after re-mining can be deposited according to present rules.

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4 The Cínovec/Zinnwald Tailings Deposit

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4.1 Executive Summary

This case study documents the transformation process of the mining waste into a raw material. From the legislative point of view, it is the transfer of the mining waste, which is subject to the Directive DIR 2006/21/EC in transposition of national law n. 157/2009 Sb. in the category of raw materials, to so called mining law n. 44/1988 in the case of the Czech Republic. This transfer is possible on the basis of a successful survey, and the result of the survey is the finding about the economic concentration of the reserved mineral. This legal process, which is demonstrated on the example of the MW site on Cínovec, is a significant moment for the utilization of MW. In the time of the origin of the MW by processing of the ore, there was neither relevant utilization for the waste products, nor economic conditions. After a time, more than 25 years since the end of processing on Cínovec, the demand for lithium rised, because it is an important raw material for accumulators of electric cars. Rising prize of lithium on the world market allowed us to think also about neglected sources in the silicate matrix and their utilization directly from European sources. The original material with a small economic value thus became an economically expoitable secondary raw material. Potential mining is possible after a survey of the site, determination of economic content of lithium and other metals, calculation of reserves and investigation of a proper technology for optimal processing of the raw material. The process of giving the mining licence is going on with these initial parameters.

The case study describes a prepared utilization of tailings of a former Sn-W (Li) mine and processing plant in the village Cínovec on the Czech-German border. Sn-W (and potential Li, Rb, Cs, Nb, Ta, Sc) ores in Cínovec were mined with breaks from middle-ages until beginning of the nineties of the 20th century. The ore in primary deposit is formed by altered rocks – greisens and quartz veins of several ore stages. The main ore minerals are cassiterite, wolframite and zinwaldite, in some places also minerals of Mo and Bi in substantial amount. The typical hydrothermal alterations around the ore zones are partial argillitization, addition of fluorine in the form of fluoride and formation of topaz. These ores were processed from the sixties of the 20th century by flotation, where the main product was Sn-W concentrates.

The mica zinwaldite and other minerals were deposited into waste flotation sediments of the tailing pond, which was grounded in the beginning of the sixties of the 20th century. The proportions of the tailing pond are approximately 200 x 150 m and during the operation time of the tailing pond about 1023 000 tons of mining waste after the flotation processing of the Sn-W ores was deposited here in total. 860 300 tons of geological reserves is the amount of exploitable deposited mine waste according to the 2014 calculation of reserves, from that 680 000 tons are the exploitable reserves, which is a volume of 506 000 m^3, when counting with 9 m as an average thickness of the ore. The tailing pond was recultivated in pursuance of the liquidation of the mine Cínovec by depositing of waste rock from the mine and planting of coniferous trees – pines and larches.

A mining area of approximately 8.607 ha is proposed for mining, a mining time of 5-6 years is supposed when considering mining of 130 to 150 000 tons a year. Current industrial purpose of the mining is focused on gaining of Li from the zinwaldite, the average concentration of Li in the deposit is 0.27 % Li, the content of Li in zinwaldite concentrate is about 1.4 %. The final product is the zinwaldite concentrate. Metallurgical processing to lithium hasn't been solved yet; the final customer is going to do it. Possible by-products, not considered for technical utilization yet, are Rb (0.24 %), Cs (0.03 %), Sn (0.6 %), W (0.4 %), topaz, fluoride and possibly quartz.

The mining would be realised by excavators, and the original plan was to transfer the extracted material about 17 km away from the site into a prepared processing plant. However, during discussing of the EIA document, a variant of mining and processing in the site area on Cínovec was accepted, due to negative impact of the transport. The processing of the ore would probably be realized by water suspension separation in a highly magnetic environment of a superconductive electromagnetic separator. The unprocessed rest would be taken back into the tailing pond area and recultivated.

Permission administrative procedures for definition of the mining area with mining permission and construction of the processing plant are currently going on. Mining and processing operator will be the company Cínovecká deponie s.r.o., Prague.

4.2 Introduction

On this example is demonstrated the possibility of utilization of mining waste as a critical and an important raw materials source. Flotation sands after processing of Sn-W ores on the Cínovec-South deposit are the object of future utilization. The flotation sands originated as waste, containing mica called zinwaldite, which contains high concentrations of Li, Rb, Cs and other interesting elements. Zinwaldite concentrate, which will be supplied as a final product to processing factory, will be gained from mining and processing of these sands, and that became the business plan.

4.2.1 Scope

This example illustrates the transformation of a waste to a critical raw materials deposit. The Cínovec/Zinnwald deposit has been mainly a Sn, W deposit of an European importance and was mined since medieval age. Due to modern technology advance, the prices of lithium on the world market have been skyrocketing since the 1980s of the last century, when they almost tripled between 1980 (about USD2660/ton) and 2012 (about USD 4 220/ton), and therefore mining waste transformed to a promising deposit.

This case study shows also possibility of ore mining, which was stopped more than twenty years ago. Ore mining, especially gold and underground mining, is strongly restricted by strategic and environmental regulations in the Czech Republic. Surface metal mining of a former mining waste should be a new way for reuse of low grade matters or matters with important elements.

Lithium in this case should be a very important commodity in the future. Also other components, which occur together with zinwaldite, like Rb and Cs, should also have wide scope of use, which is illustrated below.

Nonbattery lithium demand includes utilizations in frits and glass, lubricants, air conditioning and medicine. Lithium could be substituted by other materials in these applications. In frits and glass, it could be substituted by sodic and potassic fluxes; in lubricants, by aluminum and calcium soaps; and lithium alloys could be substituted by engineered resins that use boron, glass, and polymer fibers. Lithium bromide, lithium chromate, and lithium chloride are used in air conditioners operating with the absorption principle. Lithium is used as a coolant and shielding material in nuclear reactors and for the production of tritium. Lithium metal is used in alloys with other metals; for example, it changes the hardness of aluminum and lead and the ductility of magnesium. Rechargeable batteries were the largest potential growth area for lithium compounds. Demand for rechargeable lithium batteries exceeds that of other rechargeable batteries. Automobile companies have been developing lithium batteries for electric and hybrid electric vehicles. Identified lithium resources for Bolivia and Chile are 9 million tons and more than 7.5 million tons, respectively. Identified lithium resources for major producing countries are: Argentina, 6.5 million tons; USA, 5.5 milion tons; Australia, 1.7 million tons; and China, 5.4 million tons. In addition, Canada, Congo (Kinshasa), Russia, and Serbia have resources of approximately 1 million tons each. Identified lithium resources for Brazil are in total 180,000 tons (USGS 2015). It would take 1.4 to 3.0 kilograms of lithium equivalent (7.5 to 16.0 kilograms of lithium carbonate) to support a 60 km trip in an electric vehicle before requiring recharge. This could create a large demand for lithium. Estimates of future lithium demand vary, based on numerous variables. Some of those variables include the potential for recycling, widespread public acceptance of electric vehicles, or the possibility of incentives for converting to lithium-ion-powered engines (Goonan 2012).

Cesium is used in small quantities in a variety of utilizations, some of which are experimental or developmental in nature. The current application requiring the most of cesium is probably a specialty high-density component in drilling mud used for petroleum exploration. Cesium also has a wide-spectrum of photoemissive properties whereby electromagnetic radiation, which includes visible light and nearby regions of the radiation spectrum, which are converted to electrical current. Thus, cesium is used in television image devices, night-vision equipment, solar photovoltaic cells, and other types of photoelectric cells. Perhaps one of its best known applications is its use in the super-accurate atomic cesium clock that is used as a standard for the world’s timekeeping systems. It is used also in the chemical process industry, primarily as an ingredient of metal-ion catalysts; in medical applications; in the removal of sulfur from crude oil in petroleum refining; and as an ingredient in specialty glasses used in fiber optics and night-vision devices. The market for cesium is very small and its amount reach perhaps less than 25,000 kilograms per year (kg/yr) in the United States, and not much more for the rest of the world. World reserves are vast, compared to apparent world demand. The mining and processing of cesium minerals are in such a small scale, that environmental hazards or damage caused by the production of cesium are minimal (Butterman et col. 2005).

Rubidium is used interchangeably or together with cesium in many uses. Its principal application is in specialty glasses, which are used in fiber optic telecommunication systems. Rubidium's photoemissive properties have led to its use in night-vision devices, photoelectric cells, and photomultiplier tubes. It has several uses in medical science, such as in positron emission tomographic (PET) imaging, the treatment of epilepsy, and the ultracentrifugal separation of nucleic acids and viruses. A dozen or more other uses are known, they include a cocatalyst for several organic reactions and in frequency reference oscillators for telecommunications network synchronization (Butterman, Reese 2003).

4.2.2 Relevance of the case

Documented case was selected because, as was already explained, it is a unique source of critical raw materials with respect to many aspects of the deposit. It illustrates the usability of well-deposited mining waste as a future deposit according to the dynamics of world market, and it also contributes to the characterisation and ways of utilization of the unique multi-element greisen deposits, which could be the source of many critical raw materials elsewhere in the world. Furthermore, it is presently prepared to be mined, which not only makes it an important actual issue and practical example of effective mining for the residents of EU, but it also provides us with well compiled archive materials and EIA documentation, which are presently available.

4.3 Analysis

Figure 5: Topographic situation of the tailing deposit Cinovec

The deposit comprises a tailing pond or setting pit of the Sn-W Cínovec/Zinnwald deposit, which is situated on the Czech-German border in Krušné hory/Erzgebirge mountains near the towns Teplice or Dresden. About 1/3 of the deposit lies in the German territory.

The tailing pond, with proportions approximately 200 x 150 m and total area about 9 ha, is situated in the southern part of the village Cínovec, at the Czech side of the top plains of Krušné hory/Erzgebirge mountains in the height of 835 m above the sea level. Climate conditions correspond to the position on the top parts of the mountains – there is a short, relatively cold and wet summer and a long, cold winter with a lot of snow, and there are rather windy conditions. Residential buildings are next to the eastern part of the tailing pond and a road and petrol station is next to its northwestern part. Soil horizon still has not developed on the surface of the tailing pond.

The Krušné hory/Erzgebirge mountains are formed mainly by rhyolites, granites and porphyres. The granites are very evolved and smaller apical parts of the plutons and their exocontact zones are known for their “greisenisation” – metasomatical ore-forming process. The mined material comprised mainly of greisens, greisenised granite and quartz veins. Mineralogy of the tailing pond is the same as the mineralogy of the deposit. Lithium was not gained during the processing of the ore from Cínovec the majority of mining time. Lithium is the main utility component in the tailing pond, but also other elements have interesting concentration in the substrate with possible utilizations as by-products – for example Rb, Cs, Nb, Ta, Sc and REE.

The Cínovec/Zinnwald deposit, whose tailing pond is the object of the study, belongs to the greisen group of deposits, which are connected to metasomatically altered granite elevations and their exocontact zones. This deposit is connected to the apical part of albitic granite intrusion (“cínovecký granite”), which is the youngest member of multiphase variscan “krušnohorský” granite pluton. This elevation is north-south elongated and 1/3 of it lies in the German territory. The surrounding Teplice quartz porphyry is hydrothermally altered (zwitterization, less kaolinization and silicification). The mineralization smoothly goes from the granite to the altered exocontact of the intrusion (porphyry). The apical part of the granite intrusion is albitized till the depth of 600 m under the surface. On the contact of the granite intrusion and Teplice quartz porphyry a pegmatite rim “stockscheider” is often developed (from few cm to 1 or 2 meters thick, formed mainly from K-feldspar and biotite). There are few rare few cm-thick aplite dykes in the western part of the deposit. From the structural point of view, the directions NW-SE and NE-SW are the most important directions for the ores and the deposit (Šrein, Küh., Hartsch, 2011).

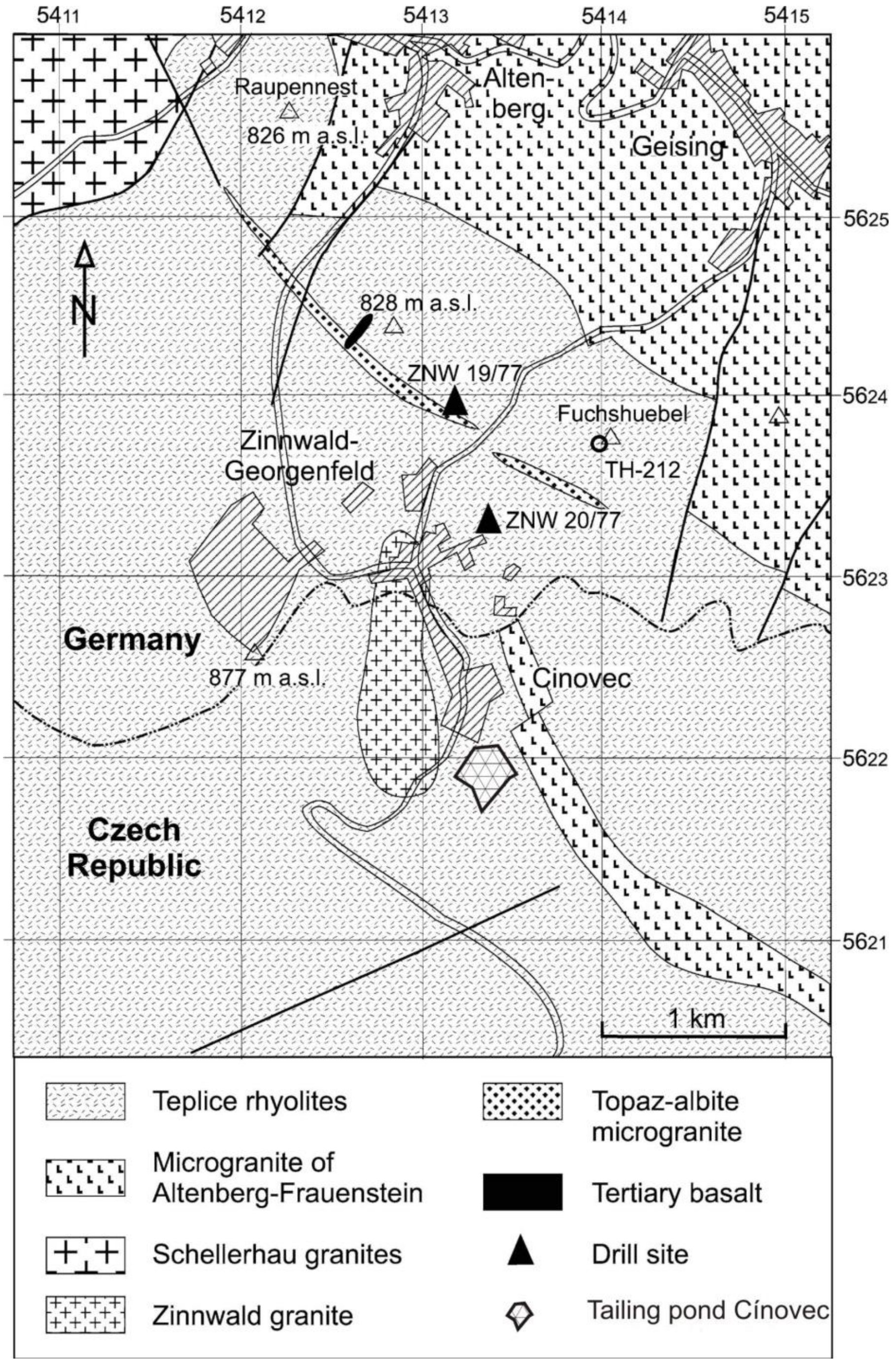

Figure 6: Geological sketch of the area Cinovec/ Zinwald (according Webster and al. 2004)

The greisens comprise two basic types – an older type, massive metasomatic greisens forming big irregular shapes with only Li mineralization (in Li mica – zinwaldite); and a younger type forming thin layers around quartz veins with also Sn-W mineralization locally (connected with the tectonically altered zones). Down to the depth of approximately 250 m mainly flat horizontal greisens around veins predominate (dips 5 – 45°), while in bigger depth until approximately 400-450 m steep greisens around veins with NE-SW direction predominate. All the types of the greisens are often present in the same area and merge in intersections into very irregular ore bodies. There are several stages of mineralization after the quartz core developed:

- greisenic stage (main ore mineralization) – quartz, wolframite, cassiterite, zinwaldite, fluorite, topaz and scheelite
- K-feldspar stage – veins of pegmatite character with adular and younger zinwaldite
- sulphidic stage – quartz with accumulations and irregular lens of arsenopyrite, tin pyrite, tennantite, sphalerite, Bi minerals, Cu sulphides, pyrite and opal
- supergene minerals stage

Mineralogy of the tailings is the same as the mineralogy of the deposit – cassiterite and rarely stannite is the source of Sn, wolframite and partly scheelite is the source of W, and all this minerals contain trace elements Ta, Nb and Sc. Li and Rb is contained in micas, mainly zinwaldite, but also K-feldspar contains some Rb and Cs. The chemical composition of the waste from the deposit Cínovec-south was as follows: Sn=0.07 %, W=0.011 %, As=0.007 %, S=0.03 %, Pb=0.01 %, Cu=0.01 %, Zn=0.06 % and Li=0.23 % (Petrů, 2014). Therefore the only potential economically interesting product of the mining is Li. During the original usage of the tailing pond Li was not gained as a mining product, therefore it was deposited in the tailing pond, where now the average concentration of Li is 0.27 %. Li is concentrated in micas (zinwaldite group) and complicated K, Li, Fe, Al silicates (the volume of zinwaldite in the tailing pond is about 20 % and there is 1.4 % of Li in zinwaldite). Zinwaldite is evenly distributed in the pit. The area of the tailing pond is approximately 8.6 ha (86 065.5 m^2), the pit volume is 506 063 m^3. The total amount of geological reserves on the tailing pond deposit is 860 307 t, from that mineable is 679 643 t (Cetl et al., 2014; Petrů, 2014). According to David J. (1991), the total amount of reserves in the tailing pond is 1 023 527 t, that means 2 958 t of Li (0.289 % Li), 2 487 t of Rb (0.243 % Rb), 297 t of Cs (0.029 % Cs), 645 t of Sn (0.063 % Sn), 379 t of W (0.037 % W), 819 845 t of SiO_2 (80.1 % SiO_2), 20 154 t of topaz (1.969 % topaz), 3 301 t of fluorite (0.323 % fluorite).

History

The first historical piece of information about the mining of Sn ores in Cínovec dates from 1378, when flat horizontal veins were mined. The mining began in the Czech territory, but was developed on the German side soon too. The deposit was mined down to the level of third floor until the beginning of 19th century, then the mining flourished during the century, on the Czech side under the control of Lobkowitz and Clary families. A change happened in 1879, when also W ores started to be extensively mined and slag heaps and dumps on the surface started to be reused (on Czech as well as German side). During the First World War was the mine under military control and was extensively mined (mainly the second and third floor), then the mining was suppressed in the years 1918 – 1931 and the mine was only kept going until the beginning of the Second World War, when it was again mined to the highest extent and the fourth floor was opened. Li mica (zinwaldite) was also mined on the Czech side during the Second World War and in the 50’s of the 20th century, and on the German side from 1890 till the end of the Second World War. The mining in the German side was stopped after the end of the Second World War and the mine was definitely closed in 1967. From 1945 till 1968 in the Czech side the lower horizons (5th, 6th and 7th floor) were explored and in 1958 the mine was taken over by “Rudné doly (Ore Mines) Příbram”. The veins and surrounding greisens were mined, and also an experimental chamber mining was realized. The vein deposit on the Czech side was mined out in 1977 and gradually liquidated, but there was a study of impregnating greisens in the bedrock of the veins realized by Geoindustrie until 1960, which was positive, thus a new deposit Cínovec-south was opened in 1981 by a pit with two floors (8th and 9th). The mining on the Czech side was supported by state grants until 1989/1990, when the communist regime fell and the mining had to be stopped because of economic reasons. The deposit was wetly secured and it still contains about 53 millions tons of Sn-W ores and interesting contents of Li, Rb, Nb, Ta, Sc, Cs and other elements. The deposit on the Czech side is now under the control of Diamo Příbram. In the 60’s of the 20th century a tailing pond was grounded, which was in function until the end of the mine production in 1990.

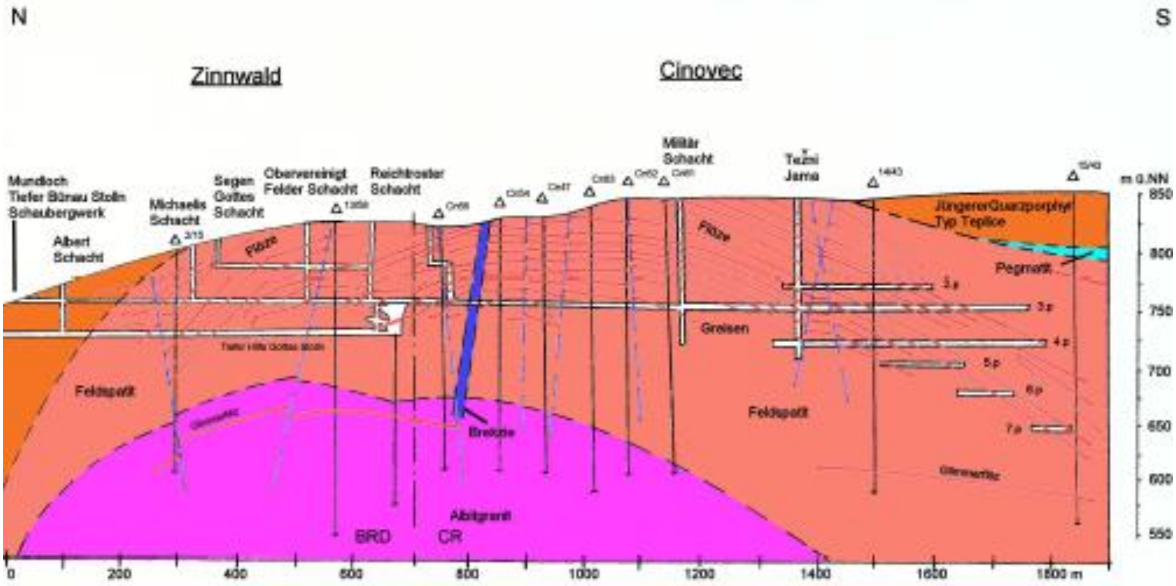

Figure 7: Geological profile with mining works

Mining project

Lithium is the lightest metal in the periodic table of elements, whose world reserves in available deposits are estimated at 20Mt. The world consumption of lithium is more than 6kt a year and a gradual increase is expected. The prices of lithium on the world market have been skyrocketing since the 1980s of the last century when they almost tripled between 1980 (about USD 15/pound) and 1998 (about USD 45/pound). At present, the price of Li on the world market is approximately 5.015 USD/kg (lithium carbonate) and 6.620 USD/kg (lithium hydroxide), the price of Rb and Cs is even higher (U.S. Geological Survey, 2015).

The company Cínovecká deponie, a.s. (Czech Republic) is planning the extraction of the deposit. They suppose the maximum mining capacity a year of 130 000 – 150 000 t (cca 700 t a day), which should result by the amount of reserves mentioned previously in about 5 to 6 years of mining. The plan is to build an open pit of several floors, which will be after the end of mining recultivated to a similar surface, which was there before.

Figure 8: Present stage of the tailing pond (left). (from project documentation)

For processing lithionite, there are, in general three possible methods. The first is gravity separation based on the different densities of individual components of the processed ore. The second is flotation method (silicates are varied with regards to flotability). The conditions for the selectivity of the silicate flotation can be created by selective activation or deactivation of the separated minerals in an acid or alkaline environment. In the case of zinwaldite (contrary to other lithionites), the most suitable method for its extraction seems to be the process of magnetic separation in some of the known types of magnetic separators (Botula et al., 2005). Zinwaldite has significant magnetic properties due to a relatively high content of iron (12%) which enables its transformation into a magnetic product. On the other hand, the results of laboratory tests executed in the laboratories of VŠB – Technical University of Ostrava give clear evidence that the flotation process using the amine-based cationic collector is suitable for the separation of lithium mica - zinwaldite. This technology may also be employed in case of possible continuation of Sn-W ore extraction in the region of Krušné hory. With respect to the specific mineralogical and chemical composition of Czech Li-micas (zinwaldite), some other processing technologies may be applied besides flotation (with lower operational costs). Zinwaldite features significant magnetic properties; therefore, it can also be gained by magnetic methods (Samková, 2009). The pit volume is 506 063 m^3 and the amount of total geological reserves in the tailing pond is 860 307 tons (out of that 679 643 tons are mineable). The recovery factor in zinwaldite concentrate is 83 %. Approximately 13 % of the deposit is composed of clay and heavily clayish sand layers, which should be removed. The tailing pond was already partly recultivated with vegetation and soil (Fig. 5).

Figure 9: Recultivated surface of the tailing pond

A treatment plant was originally planned to be built approximately 17 km from the spot in an unused areal of a former mine in the locality Újezdeček u Teplic. After a public discussion about the EIA documentation, the municipalities demanded limitation of the transportation of the raw material to the processing plant. Therefore the project was modificated and it is planned to build the processing plant directly on the site. Also other objects connected to mining must be built, as well as a drainage mechanism and communications, and capping must be removed. Sands after the separation should be used as a by-product (Botula et al., 2005).

4.4 Discussion

The deposit Cínovec-tailings is formed by the deposited material from a processing plant of the ore mined in the ore district Cínovec from the sixties of the 20th century till the end of operation in the year 1990. The mined material comprised mainly of greisens, greisenised granite and quartz veins. Lithium was not gained during the processing of the mined ore, and it is the main and so far the only utility component in the deposit. Lithium is concentrated in micas (zinwaldite group) and complicated K, Li, Fe, Al silicates, transient members between Fe siderophyllite and Li polylithionite. The average concentration of Li in the deposit is 0.27 %. Zinwaldite concentrate is obtainable by wet magnetic separation. The supposed content of zinwaldite (with 1.4 % Li) in the deposit is 20 %.

The demand for lithium grows from the year 2000, mainly because of its significant electrochemical potential. The utilization of Li in Li-Ion cells and accumulators in consumer electronics and instruments reached the dominant position in the year 2007. This accumulators are used recently also for saving solar energy and in electric cars. Moreover, lithium has a broad application in many industries, mainly in chemical, metallurgical and electrical industry. About 30 % of Li world consumption is used also in glass and ceramic industry and mainly in modern technologies (air-conditioning, hightemperature lubricants, production of oxygen for submarines and spacecrafts, …). Its potential for nuclear fusion and nuclear energetics in general is examined. The demand for lithium increased in the whole world between the years 2000 and 2008 on average by 6 % a year. In the year 2008 the price of this commodity partly decreased due to the financial crisis. Nevertheless, in the next ten years an exponential growth of demand is expected. According to some estimates, the demand for lithium could increase till the year 2020 on average by more than 20 % a year. Therefore efforts to satisfy the increasing demand for this element again spread, not only from the point of view of searching for new sources and methods for its winning, but also from the point of view of reassessing old deposits and potential sources.

The current main world raw materials for lithium are mainly minerals (petalite, spodumene, lepidolite, eukryptite and amblygonite), and the main source of Li in the world are currently mainly pegmatite deposits in Canada, USA, Russia, China, Spain and salt brines in USA and China. Then it is also some skarns, pneumatolitic deposits of albitites, Li-rich sediments, evaporites, brines and mineral waters, sea water and other.

From the point of view of the European Union, a significant shift in the evaluation of raw materials security and politics happened during the last ten years. Strategic (or critical) raw materials (CRM) were defined, which could be significantly deficit in the future, and therefore could endanger the economic integrity of the EU. This strategy gradually pass on the national politics, also on the raw materials politics of the Czech Republic. Lithium is also in the group of the EU strategic raw materials, therefore an effort to reassess the reserves of some raw materials and also mining wastes with Li and the other elements content emerged. On the basis of a Ministry of industry and business decision, realization of a project of research and development with registration number FF-P2/057 called “Recycling of waste raw materials with content of lithium” was started in the year 2003. A part of the project was an initial technical-economic study, of which basis was also the parameters of Cínovec tailing pond, the data about sampling from the tailings with Li and summary of the processing methods of waste raw materials with a content of Li.

A substantial mining of Li in Cínovec took place during the Second World War, when it was used mainly in lubricants. Another expansion of the Li mining was in the fifties of the 20th century. In 1957-1967 was the Li concentrate gained by flotation from gravitational waste from processing of ores from the deposit Cínovec – old company (vein deposit). The material from the processing plant was transported into the tailing pond in a floated form by a system of pipes and pumps. The purchaser of the Li concentrate was the national company Spolana (Kaznějov), which processed the concentrate to lithium carbonate. The production of Li concentrate was growing, from 1200 tons in 1958 increased to 4000 tons a year in the beginning of the sixties, but from 1963 it began to decrease again to 2300 tons a year. The quality of the concentrate was 1.23 – 1.32 % Li. The production of Li concentrate was finished in 1967 on the basis of end of demand for purchase of it from the side of Spolana, but the mining in the deposit Cínovec continued and in 1976 was established a mining area Cínovec. The Czechoslovakian government approved in june 1990 a decision about inhibition and liquidation of mining industry of ores and industrial minerals, and subsequently the state subsidy for Li concentrate prices gradually decreased and cancelled, and the mining in Cínovec was finished. Another consequence of this inhibition was also a loss of a technological base for processing of ore and industrial minerals raw materials (Scientific and development base RD Příbram, s.p., ÚVR in Mníšek pod Brdy, UNS in Kutná Hora, atd.), the research in the field of processing technology practically stopped in our country (except rare exceptions). It was decided to write off the reserves of Sn, W, (Li) ores and in the case of Cínovec-south deposit it was done in the form of transfer of the reserves from economic to non-economic. The majority of primary Sn, W deposits with accompanying content of Li was removed from State mineral balance of CR by extraction of the reserves from the register. The national company Rudné doly Příbram – závod RD Teplice, which was the original keeper of the deposit Cínovec, secured and liquidated the mine, and the mining area Cínovec was cancelled in 1993. A Protected deposit area (CHLÚ is the abbreviation in Czech) of Sn, W, Li ores in Cínovec was established within the borders of the mining area Cínovec in 1992. No company could profitably exploit the primary Sn-W deposit Cínovec. The mining works were liquidated or secured, the underground was flooded and the surface partly recultivated. A fixing material for planting was used on the tailing pond, and it is currently partly covered with vegetation and partly formed by sand plains with mountain pines. The national company DIAMO became in 2001 the successor to national company Rudné doly Příbram and it ensures a long-term monitoring of the former mines.

The project of the tailing pond mining means in the all-European scale utilization of one of the top technologies for mining – recycling of mining waste and utilization of a raw material with low grade of the utility element.

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5 Mine Waste: Tomorrow’s mines

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5.1 Executive Summary

Mines of yesteryear were mainly centered on producing single, specific commodities that were sold and exported. However, the complexity of geological environments and mineral deposits invariably led to the occurrence of more than one mineral phase. Many different ores are thus found in regional proximity. Tackling mine wastes issues in old mine sites is presently a trade-off of the environmental impact vs its potential economic value of critical or scarce raw materials content. Thus, the recovery of valuable by-products, including e.g., rare earths, makes mine wastes valuable assets while minimising their environmental footprint by reducing their volume and potentially hazardous content. Ores with metal concentrations, which were too low to be mined then, may now become valuable as technology changes, and demands on the market of mineral resources is polarised by majority interests.

The São Domingos Mine site complex, a paradigmatic example of Acid Mine Drainage (AMD) can also be studied in function of the enclosed economic potential.

Mining in São Domingos is documented from before the Roman colonisation of the Iberian Peninsula. It can be is divided into three distinct periods that are characterised by the ruling powers: 1- the Phoenicians and Carthaginians in the Calcolithic (copper age) period, which began 4300 ago; 2- the Romans who intensified the production of copper on a large scale (12 to 397 AD), and 3- a modern period that started in 1850.

The mining complex that is located near Mértola on the Iberian Pyrite Belt is approximately 4.5 km long. Due to the long-lasting mining history, it is surrounded by significant amounts of mine dumps and tailings dumps that span many periods of occupation. The material contained in the dumps are residues obtained along the mining supply chain and these are in various stages of treatment/processing, from raw extracted rock to milled ore to roasted ore to slags. In general, mining wastes may be classified according to their mass/volume as follows: industrial landfill > country rocks > gossan wastes > leaching tanks > modern slag > Roman slag > brittle pyrite > smelting ashes > pyrite blocks > iron oxides.

São Domingos wastes are known carriers of gold, rhenium, and other metals: 1- Gold: – gossan and roman slag wastes in excess of 1 Mt contain have 1 g/t Au but there are also values reported for wastes up to 7 g/t Au; 2- Rhenium - research thus far conducted indicates that in São Domingos concentrations of this rare element can reach as high as 3.4 ppm (i.e. a thousand times higher than those of the crust) and 3- Other metals: – São Domingos also contains other metals, amongst others minor and trace elements, in Cu-bearing sulphides. These include Pb (≈0.12 wt.%), Co (≈0.18 wt.%), Cd (≈400 ppm), In (≈300 ppm), Sb (≈200 ppm) and Tl (≈1400 ppm); the concentrations of some metals, such as indium, germanium and gallium, are often below detection limit.

In spite of the present day knowledge gaps, the Iberian Pyrite Belt, given its metallogenic character, is a target area for important elements such as indium, germanium and selenium and the large volumes of waste materials that are present in other areas such as Aljustrel and Caveira greatly elevate the potential of this whole mining area.

5.2 Introduction

Beneficiation, or value-added processing, involves the transformation of a primary material (produced by mining and extraction processes) to a more finished product, which has a higher sales value. Beneficiation involves a range of different activities including:

- Large-scale, capital-intensive activities, such as smelting;
- Sophisticated refining plants; and
- Labour-intensive processes, such as craft jewelry, metal fabrication and ceramic pottery.

Mineral beneficiation should be a priority for governments of resource-rich as well as resource-poor countries. It is the one process that significantly increases the value of the material along the value chain. Each successive process step provides a higher value for the output (product) than for the input.

The value chain in the mining industry begins with exploration (long time windows, very high investment, high risks, low margins) through the actual mining (first income, mine tailings), with the focus on refining and extraction of the raw materials in question.

We have to be individually aware of the role of beneficiation with regard to the optimization of the value chain, depending on the raw material. Each “substance” or raw material will have particular characteristics and require specific processes that are specific for processing this “substance”. Also, the processing involved in different European countries might differ (due to the raw material composition, the target end product, local/regional conditions, e.g. availability of additives, etc.), hence, a global overview of these processes for each “substance” should be obtained and analysed.

Mines of yesteryear were mainly centered on producing monomineral commodities that were sold and exported. However, the complexity of geological environments and mineral deposits lead to the occurrence of more than one mineral phase. Many different ores - for many different metals - are thus found in regional proximity.

Mine waste is generated by almost any mining activity. Accordingly, mine wastes can be found at/near almost every mine. In Portugal, several mine sites and mine waste is documented across the country. The mine waste can appear in different conditions and forms that influence the economic and technical options to deal with the mine waste. Reasons to treat the mine waste are various:

- Inertisation of environmental harmful substances

- Reduction of waste volumes (landscape form, slope stability)
- (Secondary) extraction of commodities, e.g. metals
- Land rehabilitation
- Job creation

Tackling mine wastes issues in old mine sites is presently a trade-off of the environmental impact vs its potential economic value of critical or scarce raw materials content. Thus, the recovery of valuable by-products, including e.g., rare earths, makes mine wastes valuable assets while minimizing their environmental footprint by reducing their volume and potentially hazardous content. Ores, which showed concentrations below the cut-off grade at the time of mining, may become valuable due to technology changes, and elevated market prices for the metals contained in the ore.

Assessment of environmental issues and economic value of wastes is also important for the decision making of civil authorities, municipality plans and stakeholders. The quantitative diagnosis of mine sites, i.e. how much of what is where, is a key-issue to deal with safety, remediation, recovery and, where applicable, adequate mine closure planning.

The São Domingos mine is a case study that shows typical challenges for mining wastes (dumps and slags) from Volcanic-Hosted Massive Sulphide (VHMS) deposits and provides a positive example on what can be achieved by best practice.

The São Domingos mine: A brief historical outline:

Mining in the São Domingos area is known to have started before the Roman colonisation of the Iberian Peninsula that took place in approximately 218 BC. It's mining history can be divided into three distinct mining periods.The first, attributed to the Phoenicians and Carthaginians in the Calcolithic (copper age) period, which began 4300 years ago, is the least investigated. Archaeological finds of three polished stone axes, similar to ones found in Rio Tinto (Spain), indicate the presence of pre-Roman mining activities at São Domingos.The second mining period is clearly attributed to the Romans who intensified the production of copper on a large scale. Thirty-nine Roman coins depicting emperors from Augustus (27 BC - AD 14) to Theodosius (AD 379-395) were found on site attesting to the Roman presence. Mining activities are deemed to have lasted, from AD 12 - 397 (for a period of 385 years).

Sao Domingos is located in a desert-like region that offers few possibilities of arable and livestock farming. The main reason for the Romans to establish themselves in such a harsh environment was gold and silver mining, which was greatly demanded by the Roman economy. Copper mining, however, was a subordinated reason since it was already intensely explored in other areas of the Roman Empire, and the demand by the Roman economy was relatively low for copper, compared to gold and silver. It is calculated that the Romans processed some 3 Mt of ore based on the volume of the mining waste dump(s) at the Sao Domingos site (Fig. 1) and based on the amount of slags found, it is estimated that some 750 000 tonnes of pyrite and copper ore were removed from São Domingos in this period. Pyrite was used as educt for sulphur winning. Mining took place up to a depth of 40 m below earth´s surface, and the average concentration of the copper and sulphur ores was 2.75% and 46%, respectively. In the 1850s, the third mining period started by exploration in the "Santo Domingos area" on behalf of the Tharsis and Calañas Mines.

Figure 10: Mine waste materials (light grey / dark brown in left of image) in the eastern side of the open pit at São Domingos.

In 16 June 1854, the Municipality of Mértola received a concession request by Biava for the São Domingos area that was subsequently granted. He later transferred his concession to Deligny, who in 1855, created La Sabina Mining Company with Spanish and French capital with a concession area of 798 km^2. Later, in January 1959, Mason & Barry, with their headquarters in London, lease the concession from La Sabina following economic interests favourable to both parties and a process of industrialised mining at São Domingos takes off on its third and final period. Between 1859 and 1867 mining operations consisted of underground operations by prolonging the existing shafts, haulages, drives and stopes using the relic infrastructures found on site. Average grades of 3% Cu and 50% S were mined in this period and the pyrite was shipped to England, via the Pomarão Harbour where, through ustulation (a process that causes the loss of volatile components) for the manufacture of sulphuric acid, the copper was extracted. Heavy maritime traffic at the Pomarão Harbour, 18 km south of the mine, and lower metal prices, prompted (James) Mason to build a treatment plant to process poorer ore at Achada do Gamo. From 1868 till its closure in 1966, due to exhaustion of the ore, São Domingos continued both as an open cast and underground mine.

It is calculated that during the mining for all the periods more than 25 Mt of copper were extracted. The amount of S produced in unknown. The mine waste material, however, is estimated at several hundred thousand tons. With this large amount of accumulated mine waste, significant environmental problems are associated that are distributed across an area of around 50 km^2.

5.2.1 Scope

Raw materials are fundamental to Europe's economy, and they are essential for maintaining and improving our quality of life. Securing reliable and undistorted access of certain raw materials is of growing concern within the EU and across the globe, from both foreign and domestic sources. This case study demonstrates the importance of mining wastes as secondary resources in Portugal. It depicts a phenomenon of historical mining wastes that are originated from pre-Roman times to today. They allow "re-mining" or reusing available resources that are easily accessible in existing mine waste materials, at times, covering significant geographical areas.

5.2.2 Relevance of the case

In the S. Domingos mining area in south Portugal, Iberian Pyrite Belt, a significant environmental footprint has been left after intensive exploitation of massive sulphides, since pre-roman times until ceasing activity in 1966. Earth Observation techniques have detailed the waste materials mapping over the area of exploitation and ore processing until the shipment of the ore within an area of approximately 50 Km^2 (Quental et al. 2011). The geochemical content on local studies of the waste materials has already shown valuable elements, and more recent research detects the presence of scarce metals in debris from the ancient sulphur factory of S. Domingos mine. This preliminary research highlights the need of develop more accurate studies concerning global waste areas in order to assess their economic value.

Historical mine waste sites can reveal/comprise significant secondary deposits, in particular in areas where mining has an ancient history. Like S. Domingos, there are a number of equally challenging and interesting target areas in the Iberian Peninsula (and elsewhere in Europe) where the mine wastes contain additional co-products valuable minerals that increment the value chain. Some of these metals have been assessed as critical elements. Such an example may be the huge mine waste dumps at the Panasqueira mine in central Portugal that have documented contents of Rhenium (Silva et al., 2013a).

While the coverage of the mine waste deposits are limited in Europe, there is further analysis needed in the assessment whether and to what degree they can contribute to mitigate raw material scarcity.

5.3 Analysis

a. General introduction

1999 marked the start of the research in Portugal into the environmental impact of abandoned mines in the south of the country. Thirty three abandoned mine sites were carefully investigated and categorised by dimension and the elements extracted (Matos and Rosa, 2001).

The São Domingos mining complex is made up of four main nuclear areas located along 4.5 km orientated in a N-S direction and represents the first parts of a sequence within the industrial copper supply chain:

1- Open pit area – This is the most northerly mining nucleus situated east of the São Domingos village. A village near this nucleus housed the mine workers. Within the village there is an area with an open pit mine, access to an underground mine, mine headgears, workshops and a preliminary ore milling facility (Fig. 2).

Figure 11: (clockwise from top left): (1) Open pit, (2) Present day village on edge of open pit, (3) ruins of ancient Mine workshops, (4) Preliminary ore milling facilities (5) Access to underground works, (6) Ventilation shaft headgear.

2- Moitinha milling station – A large milling facility for treatment (Fig. 3) of the copper ore before it arrived at the next station: Achada do Gamo factory area.

Figure 12: Right of the hill: Panorama of the Moitinha milling plant. Workers houses are up on the hill.

3- Achada do Gamo factory area (Fig. 4) – In this area the milled ore was pyrometallurgically treated and copper and sulphur extracted. Two large factory complexes exist on site in this area that is surrounded by waste materials and acid mine drainage from the waste dumps.

Figure 13: (Clockwise from top left): (1) Achada do Gamo factory furnaces, (2) Achada do Gamo factory vents, (3) Fe- rich waste material, (4) Acid mine drainage (AMD), (5) Milled pyrite and sulphur crystals, (6) Mellanterite crystals on edge of AMD pond.

4- Telheiro nucleus area – A set of offices built for management and control of the produced ore that was shipped to the Pomarão harbour (where ore was loaded on ships for transport to England).

In total this mining complex is approximately 4.5 km long. Today, it is surrounded by significant amounts of mine waste and tailings dumps that cover several periods of occupation. The materials show differing stages of treatment/processing, from raw material (ore), to milled ore, to roasted ore, to slags (Fig. 5).

In general, the differing types of mining wastes may be ordered according to their mass/volume as follows: industrial landfill > country rocks > gossan wastes > leachingtanks > modern slag > Roman slag > brittle pyrite > smelting ashes > pyrite blocks > iron oxides (Pérez-López et al., 2008).

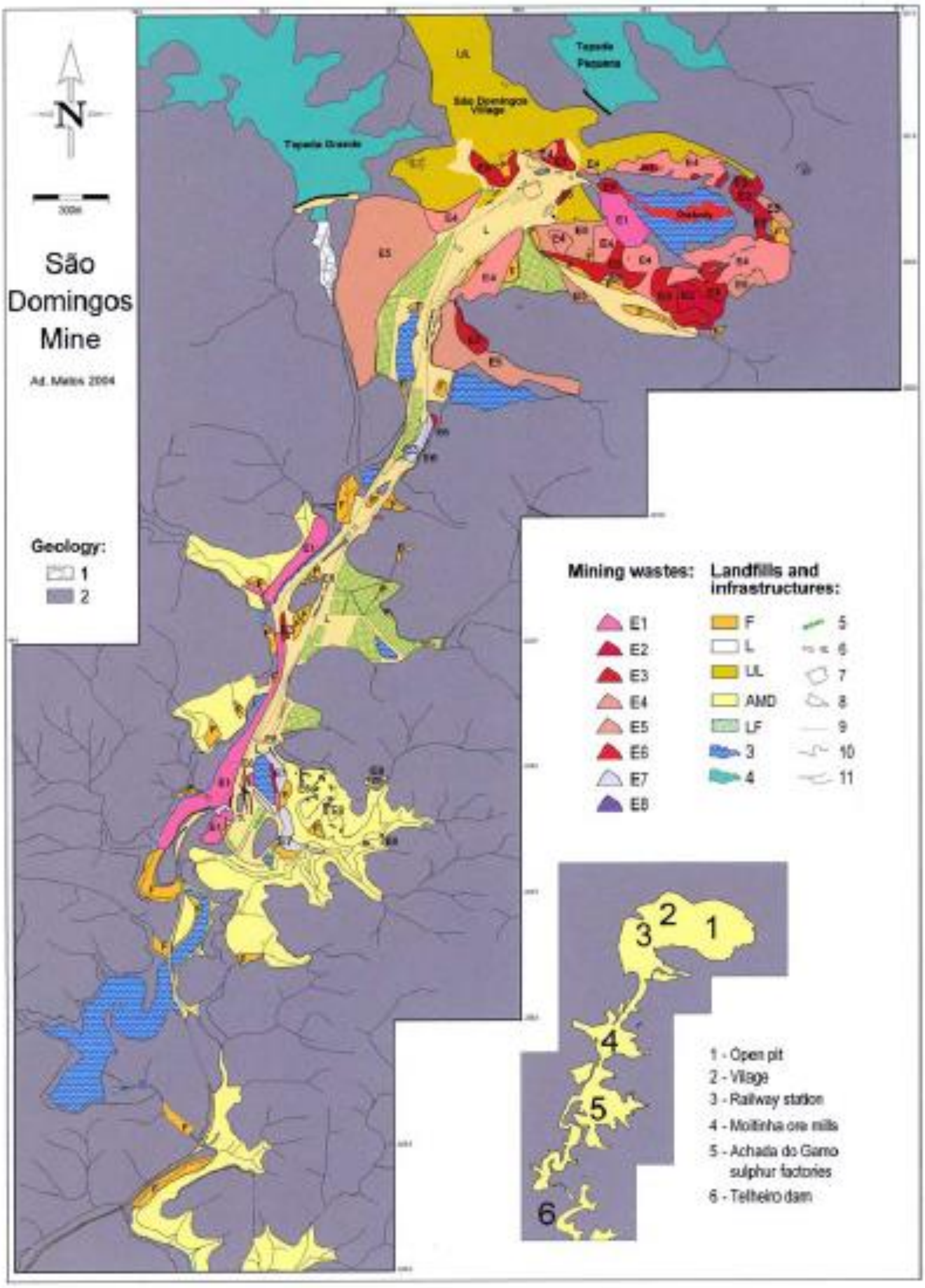

Figure 14: Geological and mining map of the São Domingos area, including the cartography of the main type of wastes. Geology: (1) Quaternary alluvium sediments; (2) Palaeozoic Basement (South Portuguese Zone): Mértola Fm. (Upper Visean); Volcano Sedimentary Complex (Late Famennian–Late Visean); Phyllite-Quartzite Group (Frasnian–Late Famennian); Represa Fm. (Late Famennian); Barranco do Homem Fm. (Famennian?); Gafo Fm. (Lower Frasnian).

Mining wastes: Tailings: E1— Modern slag; E2—Roman slag; E3—Gossan; E4— Volcanics + shales; E5— Shales; E6—Brittle pyrite ore; E7—Roasted pyrite ore (sulphur factories ashes); E8—Iron oxides (hematite roasted pyrite).

Landfills and infrastructures: F— Leached materials in seasonal flooded areas; L— Mine landfill; U—Urban contaminated landfills; (AMD) unvegetated area affected by extreme acid mine drainage; (LF) Pyrite ore leaching plateau; (3) Acid water dam/lagoon; (4) Clean water dam; (5) Cu cementation tank; (6) Orkla sulphur factories; (7) Railway station; (8) Power plant; (9) Abandoned mine railway; (10) Mine channel; (11) Stream. (After Álvarez-Valero et al., 2008).

b. Metal contents of waste materials

Due to renewed interest in precious metals and high tech metals as a direct result of their market quotations, research was carried out into metal concentrations and the metal contents of these waste materials, estimated to be in excess of 5 Mt, has focused initially, on the precious metals, namely Au, and more recently high-tech metals, such as Re. In the following, a short recap on key metals is given.

Gold – For the Sao Domingos complex, Matos and Rosa (2001) report maximum dump concentrations of this metal as 238ppb Au. However, a second sampling campaign, showed in significantly higher concentrations. Matos et al (2006) report gossan and roman slag wastes in excess of 1Mt with gold concentrations 1 g/t Au. Under certain conditions, local gold concentrations can reach values up to 7 gt/t Au (Pers. Com. Matos, 2014).

Rhenium – Rhenium is one of the rarest elements in the crustal abundance, its presence is manifested in the range of 1-10 ppb. It does not form discrete minerals but is preferentially hosted by molybdenite[3] (Silva et al., 2013a; b; Figueiredo et al., 2013b) from porphyry copper deposits. Research thus far conducted indicates that in São Domingos concentrations of this rare element can reach as high as 3.4 ppm (i.e. concentration a thousand times higher than those of the crust) (Figueiredo et al., 2013a) but reaching values as low as 1.34 ppm (Figueiredo et al., 2014).

Other metals – Besides gold and rhenium, the São Domingos complex contains also minor and trace elements in Cu-bearing sulphides: average values for selected metals are as follows: Pb (≈0.12 wt.%), Co (≈0.18 wt.%), Cd (≈400 ppm), In (≈300 ppm), Sb (≈200 ppm) and Tl (≈1400 ppm); the concentrations of some metals, such as indium, germanium and gallium, are commonly below the detection limits. Compositional maps show that In, Ge and Ga exist in Cu-bearing sulphide phases; Ge occurs also in Pb-bearing phases.

There is an indication that In in the São Domingos complex is positively correlated with Zn and Cu, but its low concentration makes it impossible to ascertain; the same is valid for a possible correlation of Ga with Cu and Pb (Mateus et al., 2011).

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[3] natural molybdenum sulphide; MoS_2

c. Extrapolation to other areas

The São Domingos complex illustrates the variety of ores associated to historical mining wastes. The Iberian Pyrite Belt, that can, due to its metalogenic character, be a treasure trove for precious metals and other important elements. For example, the massive sulphides at Neves Corvo and Lagoa Salgada contain, amongst others, indium (Benzaazoua et al., 2003; de Oliveira et al., 2011). The late stage (later mineralised in relation to the other known deposits such as Neves Corvo or Aljustrel) copper deposit of Barrigão is a carrier of germanium (Reiser et al., 2011), and in the Lousal mine there is evidence of significant gold (de Oliveira et al., 2011; 2013) contents and important showings of selenium that are presently under investigation, and further results are expected in the coming months.

5.3.1 Discussion

Because of the accommodating sulphide mineralogy and the elemental associations, priority exploration targets shall be defined for on a national scale for Portugal, like the Iberian Pyrite Belt, or other deposits that contain large volumes of mining waste materials, such as Aljustrel and Caveira (& Rio Tinto).

The São Domingos complex is an example where the interlinkage between the economic and environmental factors can be observed as the place has been abandoned for such a lengthy period. It is a site that on the one hand clearly shows that there is a potential for the exploitation of domestic mine waste as secondary mineral resources. On the other hand it also shows today´s shortcomings due to the knowledge gaps that still exist.

Ideally, a more comprehensive and clearer picture of the mineral potential of the São Domingos complex is required. This implies deeper research in the evaluation of the mineral potential on different levels.

Volumetry - A lack of reliable volumetric data for the mining wastes is still missing. This alone would require systematic sampling and analysis of the waste piles by applying an adequate method, e.g. a sampling grid should be applied over the target areas, namely the dumps, slag piles and tailings. These should be cored samples that would then need to be split into appropriate smaller and representative samples and reanalysed with multi element packages and the whole resource properly evaluated.

Assay values – A more complete set of element analyses are required to accurately calculate the value in situ of the ores present. Nowadays comprehensive, inexpensive multi element packages exist that analyse all the precious, transition and base metals as well as the high-tech metals. This allows quick and inexpensive screenings of the drill cores available and would be an inexpensive first step into gathering this knowledge.

Database build up - A nationwide and large enough database of the volume characterisation and metal contents would allow us to affirmatively say that today's waste is tomorrow's mine.

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6 Recyling

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7.1 Executive Summary

The provision of secondary raw materials by closing material loops and recycling is an increasingly important factor in the European raw materials market. From an economic as well as environmental, resource efficiency-based point of view, the European Union has emphasized the necessary transition towards a "circular economy" (European Commission 2014). Unlike energy raw materials that are "consumed" irreversibly through their use, (non-energy) mineral raw materials offer, in principle, the possibility of re-use, recycling and recovery in different forms. Within the Roadmap for a Resource Efficient Europe, the European Commission has set the goal to manage all waste as a resource until 2020 by closing the loop for raw materials used for production and contained in product waste streams. As a consequence an increased supply of secondary raw materials will lower the demand for— predominantly imported — primary raw materials by Europe. Nevertheless empirical data for the recovery rates of sixty metals show that for less than a third of the sixty metals the rate is above 50% (the majority of metals are in the >25–50 % group, and three more in the >10–25 % group). For the majority of metals, little or no end-of-life recycling is occurring at all. The reasons behind this are diverse: it is not economic, or no suitable technology exists (UNEP 2013).

This report focuses on the recycling of waste electrical and electronic products (WEEE) as one of the major potential sources for an increased recovery of critical metals and one of the fastest growing fractions of municipal solid waste (United Nations University et al. 2007). It highlights the regional variations especially for the collection of waste products that are caused by different institutional set ups, economic incentives and socio-economic factors: In Sweden more than 16 kg per capita are collected, also in Denmark and Norway high amounts of 13 kg and 15 kg, and on the other hand Romania only 1 kg per capita. It also discusses relevant influencing factors for the treatment phase of discarded products: The technical recyclability of a given material or metal combination, accessibility of components for manual dismantling, economic viability either through market value of the recovered metals or through regulation/subsidies by public authorities and of course the availability of sufficient processing capacities. The efficiency of recycling chains and thus the available amount of secondary raw materials crucially depends on these two parameters analysed in this topic report: (I) waste collection and (II) waste treatment.

Based on the analysis in this chapter it becomes clear that recycling could potentially play a more important role for the European supply with raw materials, but there is still significant work to be done towards establishing closed material loops (especially for critical raw materials) in Europe. Even assuming metal-containing waste can be effectively collected and optimally pre-treated, losses either in quality or in quantity at the metallurgical stage still remain an important issue taking into account the thermodynamic limits of recycling.

The report also addresses serious data challenges: Available waste statistics are not a suitable source of information on raw material contents in different waste streams and do not provide an assessment of the available potentials for recycling. Against this background this foresight topic report especially helps to identify relevant influencing factors and regional/ temporal variations that need to be taken into account for a sound assessment of future provisions of secondary resources.

7.2 Introduction

7.2.1 Relevance of the topic

The provision of secondary raw materials by closing material loops and recycling is an increasingly important factor in the European raw materials market. From an economic as well as environmental, resource efficiency-based point of view, the European Union has emphasized the necessary transition towards a "circular economy" (European Commission 2014). Unlike energy raw materials that are "consumed" irreversibly through their use, (non-energy) mineral raw materials offer, in principle, the possibility of re-use, recycling and recovery in different forms.

Within the Roadmap for a Resource Efficient Europe, the European Commission has set the goal to manage all waste as a resource until 2020 by closing the loop for raw materials used for production and contained in product waste streams. As a consequence an increased supply of secondary raw materials will lower the demand for— predominantly imported — primary raw materials by Europe. The expectations linked to this aspired transition from securing disposal towards a sustainable resource management in a circular economy could not be higher: „Moving to more circular economic models promises a much brighter future for the European economy" (European Commission 2014). Economic analysis has shown the potentials of a more circular economy to adress challenges of global pressure on resources and rising insecurity of supply by closing material loops and treating waste as a resource (see EMF 2012).

However, despite the ongoing initiatives to transform Europe into a "recycling society", the reality shows still a clearly different picture. In 2011, the total waste generation in the European Union (EU) amounted to approximately 2.5 billion tonnes. In the case of municipal waste, the diversion of municipal solid waste from landfill towards recycling and recovery has been significant during the last two decades, and this trend of diversion is well established. In spite of this positive progress, only the minor part (40%) of waste generated in the EU was recycled, with the rest being landfilled (37%) or incinerated (23%). Around 500 million tonnes of this rest could have been otherwise recycled or reused (see Eurostat 2013 and figure 15). This refers to mixed municipal solid waste with high shares of plastics, paper and biowaste – but with also relevant amounts of recycable metals. Data availability for the specific composition of municipal solid waste is very fragmented and thus the loss of specific raw materials by landfilling or incineration without recovery from the ashes is difficult to assess. Nevertheless, figure 15 shows the diversity of starting positions of the EU member states on their paths to a recycling society.

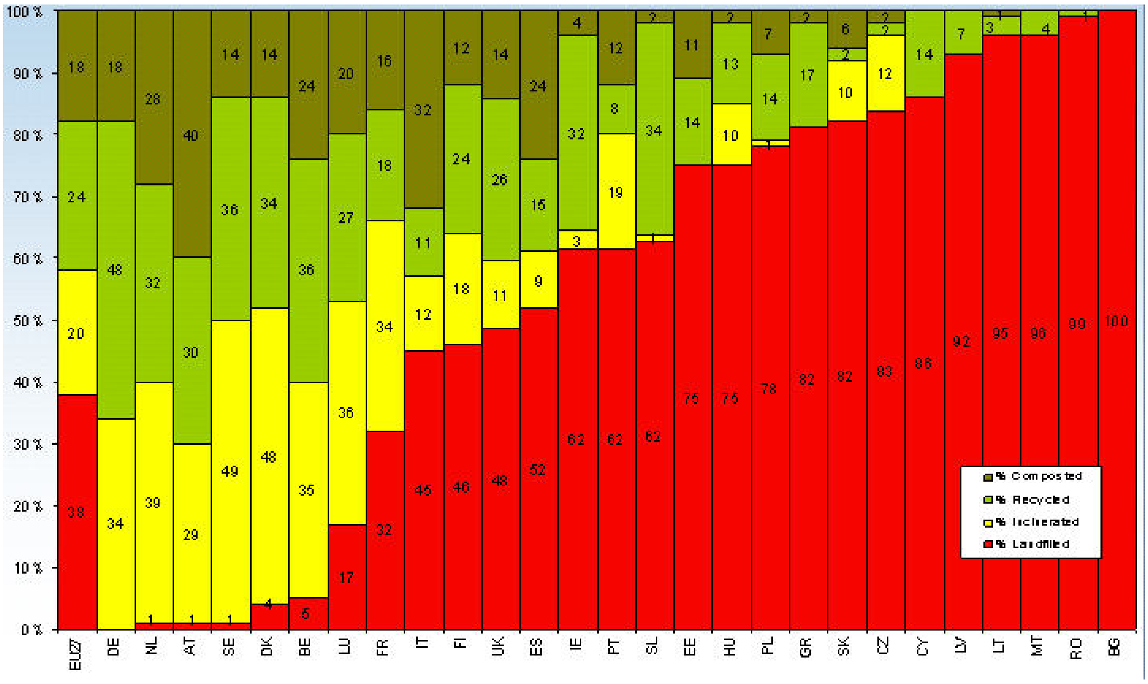

Figure 15: Treatment of municipal solid waste in/across EU countries in 2009 (based on Eurostat 2013).

Obviously, the EU still loses a significant amount of the secondary raw material potential contained in waste streams through the large shares of municipal solid waste (MSW) which are landfilled or incinerated. Moreover, the share of MSW, which is recycled (lime green in figure 15), is not comprehensively managed in a optimum way. This means there is room for improvement regarding the overall optimal treatment that would lead to a more circular economy with significant environmental and economic benefits (see Bastein et al. 2013).

7.3 Recycling of critical raw materials

Raw material losses due to lacking recycling technologies or infrastructures are especially relevant for many of the so-called critical raw materials. Figure 16 shows global average end-of-life recycling rates (EoL-RR)[4] for sixty metals. The figures refer to functional recycling, that is, recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use, thus excluding downcycling (with deterioration of the value) and losses. The table highlights that the estimated EoL-RR for less than a third of the sixty metals is above 50% (the majority of metals are in the >25–50% group, and three more in the >10–25% group). For the majority of metals, little or no end-of-life recycling is occurring at

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[4] The EoL-RR refers to functional recycling and includes recycling as a pure metal (e.g., copper) and as an alloy (e.g., brass). In contrast, a non-functional EoL-recycling rate describes the amount of metal that is collected but lost for functional recycling and that becomes an impurity or “tramp element” in the dominant metal with which it is collected (e.g. copper in alloy steel, see UNEP 2013).

all. The reasons behind this are diverse: it is not economic, or no suitable technology exists (UNEP 2013).

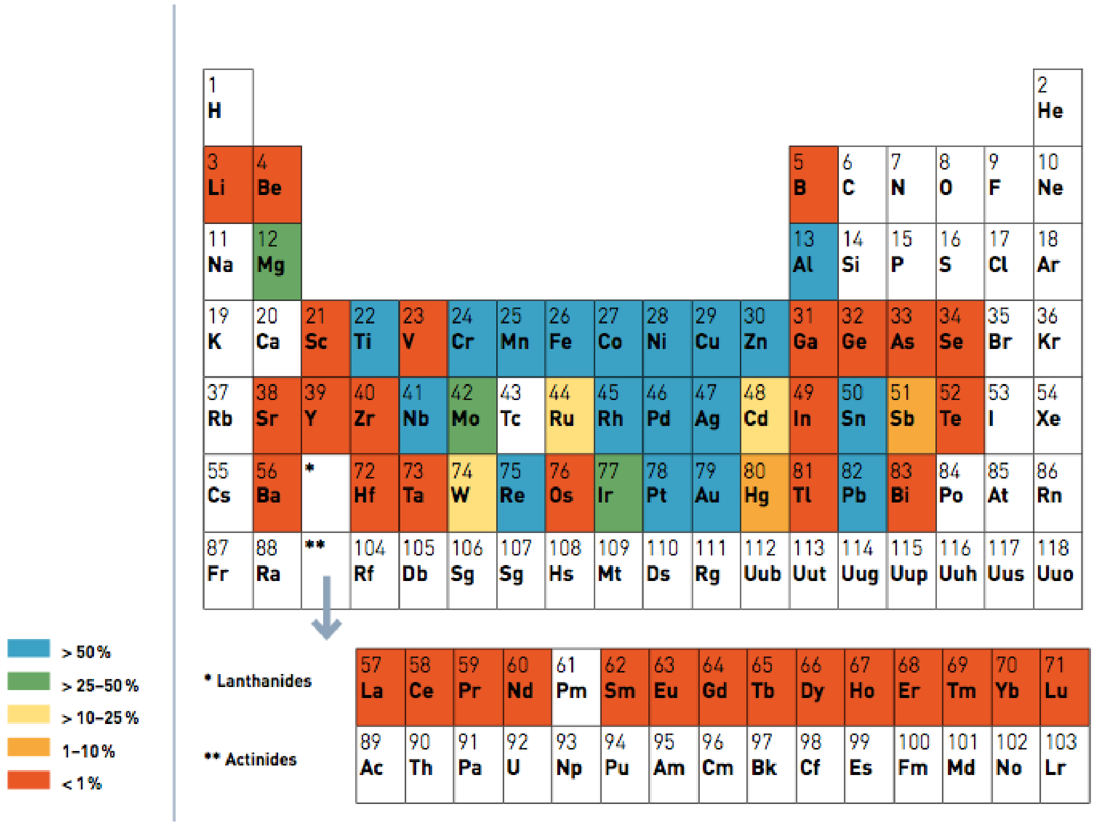

Figure 16: Estimated end-of-life recycling rates (EoL-RR) for sixty metals. (UNEP (2013).

Given the EU priority on the circular economy, it is a challenge that requires action not only at production processes, but along the overall supply chain. In practice, this means that a multitude of waste flows need to be optimised from a system-analytic view for an enhanced recovery of the metals and other raw materials.

7.4 Illustration by WEEE as an important recycling flow

This report focuses on the recycling of waste electrical and electronic products (WEEE) as one of the major potential sources for an increased recovery of critical metals and one of the fastest growing fractions of municipal solid waste (United Nations University et al. 2007). Considering the multitude of actors and products, the rapid changes of technology, product design and related material composition, as well as the rather opaque life cycle chains, WEEE is also one of the most complex waste fractions in terms of its highly heterogeneous mix of materials. Essential constituents of much EEE include precious metals (gold, silver, and palladium) and special metals (indium, selenium, tellurium, tantalum, bismuth, antimony) (cf. Chancerel 2010). Computer chip technology can be seen as exemplary for this development: In the 1980s, computer chips were made with a palette of twelve elements; a decade later, already 16 elements were employed. Today, as many as 60 different elements are used in fabricating computer chips that consist of integrated circuits (cf. Committee on Critical Mineral Impacts on the U.S. Economy et al. 2008). A large share of these elements are used as alloys or compounds, connected with other elements and exhibiting unique electrical, dielectric, or optical properties. These can pose a severe challenge for recycling processes. Here, we examine potential improvements along the recycling chain that would lead to an increase in recovery rates for distinct metals in WEEE. The efficiency of recycling chains and thus the available amount of secondary raw materials depends on parameters in two areas that will be analysed in this topic report: (I) waste collection and (II) waste treatment (see UNEP 2013).

Waste collection and waste treatment are both of general importance for the overall efficiency of the recycling chain, while the level of importance varies from waste stream to waste stream. The relative importances of these two factors is illustrated in 17 using the global copper flows in discards as an example. It is obvious that losses at the waste collection generally are not available for the pretreatment of the waste stream. The same applies consecutively for the following steps: The copper losses during separation and dismantling (the pretreatment phase) are not anymore available for recovery during smelting and refining, respectively. This means that losses along the recycling (supply) chain diminish the amounts of recycled copper. Thus, resource efficient recycling systems strive in general for low losses and play a key role in so-called “zero waste” concepts (see European Commission 2014). Only properly collected and pre-processed copper scrap can be treated at these facilities and it is the efficiency of the entire chain which determines the extent of metal recycling.

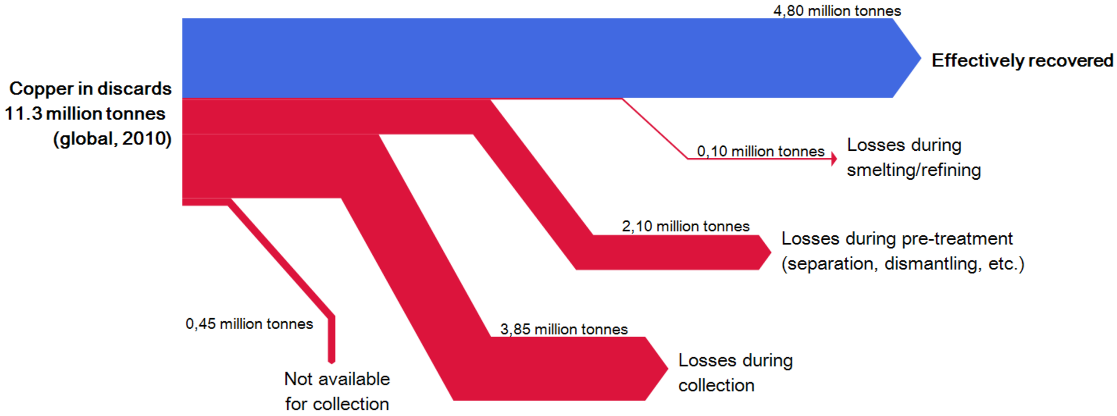

Figure 17: Estimated losses of copper along the recycling value chain. Modified after Glöser et al. (2013).

Thus, it is the smart combination of regulatory and organisational aspects (affecting strongly the collection and pre-treatment of metal-containing scrap), together with technical aspects (determining the efficiency of metal recovery) that leads to the complexity of waste management towards a “circular economy”. The estimates shown in the example of the global copper recycling (Figure 17) point to waste collection as the weakest link in the copper recycling chain, followed by the pre-processing (measured by the volume of losses), while the copper losses at the smelting/refining stage are very small. These relations between the three losses, shown in red for the example of copper (Figure 17) are basically valid also for other metals (see Chancerel 2010) and of similar relative magnitude e.g. for aluminium and steel[5]. Thus, both areas, waste collection and waste treatment, provide significant options for action for an optimal contribution by secondary resources to the overall supply of raw materials.

Therefore, in the following, the areas waste collection and waste treatment will be analysed with regard to regional variation (chapter 2), and temporal variation (chapter 3), respectively. While chapter 2 addresses the regional differentiation across the EU member states (cf. figure 1), chapter 3 addresses the temporal interconnections in this markedly dynamic part of the economy.

7.5 Regional Variation

This chapter depicts aspects of regional variation separately for the areas waste collection (2.1) and waste pre-treatment. As recycling processes are productf/substance-specific, and recycling systems are organised nationally/regionally, it is a comprehensive challenging task to address the overall recycling processes. For practical reasons, this report focuses on WEEE, and abstracts to the degree possible to derive general statements/conclusions.

7.5.1 Regional variation of waste collection

The first step of every successful recycling chain is the coordinated and separated collection. In general waste collection schemes can be differentiated into two groups: pick-up (e.g. curbside collection) or bring systems (e.g. municipal recycling centres) In practice, a variety of practical implementations exists, in most cases carefully adapted to regional circumstances, i.e. differences in waste formation, taking into account financial aspects etc. Waste formation, infrastructure, and economic capabilities determine the organisation of collection schemes, including the level of waste separation: The separation into more and thus generally purer waste streams often offers opportunities for economically viable, high-quality recycling chains. At the same time, these systems require more area (a specific challenge for urban regions with high rent costs per square meter) and cause additional costs for collection. In the case of household waste, another limiting factor is the behaviour of consumers (who have to be able to understand why specific waste products have to go into which bin).

7.5.1.1 Regional variation of WEEE collection

In the case of WEEE, the WEEE Directive 2002/96/EC (article 5) calls upon Member States to set up systems allowing holders and distributors to return WEEE at least free of charge. The induced

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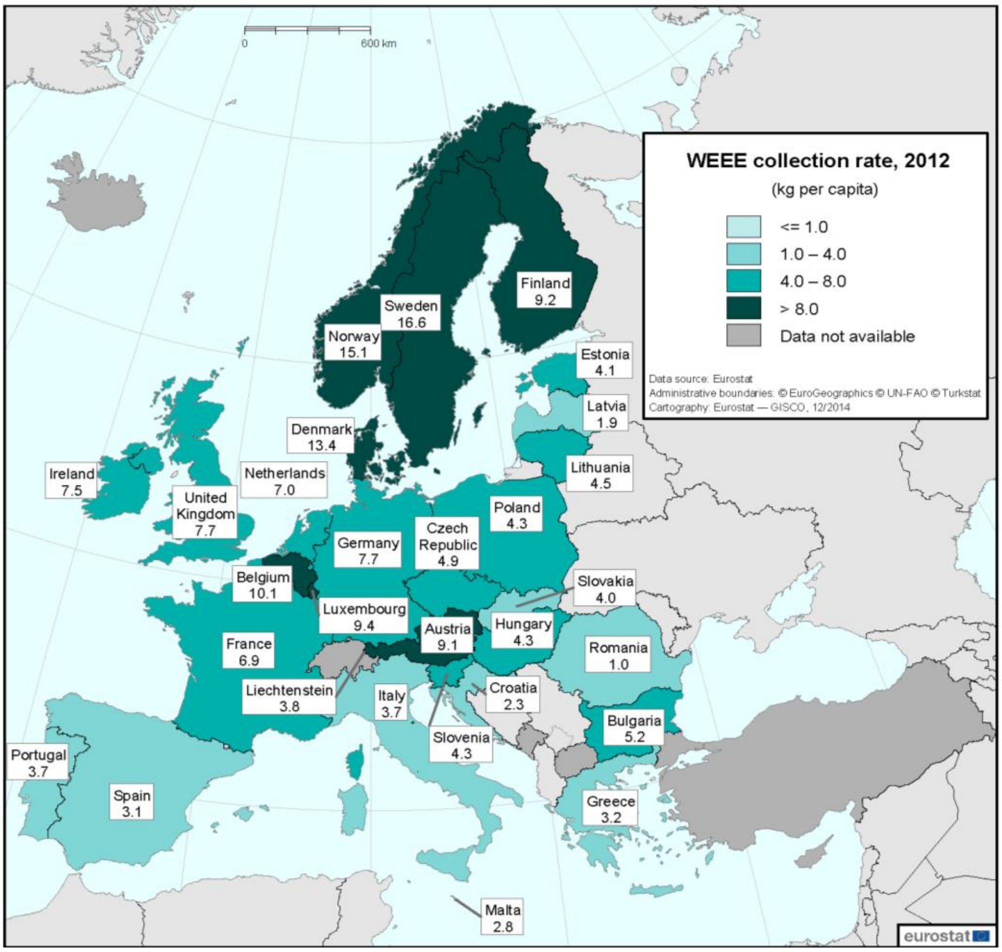
[5] EoL RR for copper is reported between 43% and 53%, between 42% and 70% for aluminium and between 70-90% for steel, see UNEP 2011.

WEEE system is based on the principle of an extended producer responsibility (EPR), financially and physically obligating the producer or importer of electronic or electrical products to take care of the end-of-life phase of its products. It mainly defines mandatory targets but leaves the specific implementation to the member states. In the following we will describe the regional variations in how these collection schemes for WEEE are set up and organized in different member states (see European Commission 2008), in some cases, schemes are also organized on a regional level (e.g. in Belgium). The chosen examples Austria, Sweden and Romania cover the whole spread of collected amounts with Sweden as frontrunner in this field and Romania as an example with a just recently installed system.

- **Austria** as one of the frontrunners in this field organizes WEEE collection by two different take back schemes: Consumers can bring their discarded products to collection points in the communities; there is at least one in every political district. The second possibility is through trade – every consumer has the right to give back an old device when buying a new device of the same function. With regard to the responsibility of the producers, the Austrian law offers two options: An individual take-back scheme in which every producer only handles the products he put on the market, or as second option a collective system in which producers commission private companies to set up a common collection scheme financed e.g. by market shares of the different producers. Both systems co-exist in Austria, however the majority of producers participate in the collective take-back systems; no single manufacturer is fulfilling the obligations individually. In Austria also producers of EEE for non-household use have the possibility to participate in a collection and recycling scheme (see FHA/ TB Hauer 2013).
- In **Romania** the local public authorities have to undertake separate collection of WEEE from private households and to establish locations for collection points for producers, namely: one for each county (41), one for each town with more than 20 000 inhabitants (104) and one for each district of Bucharest (6). There are 347 operational collection points/WEEE centres where households and distributors can bring WEEE at least free of charge—some collectors even pay for products with high contents of valuable materials like mobile phones. Distributors are required to establish a system to take back WEEE at least free of charge or against a payment that takes account of the value of the reusable components. Producers have set up and operate individual and/or collective take-back systems (6 of them have been licensed) for WEEE from private households (see European Commission 2008).
- In **Sweden** a collective waste scheme for WEEE exists since 2001 in cooperation with country's municipalities. The municipalities provide staffed reception centres for households WEEE, which is further preliminary treated and recovered. The fees charged to members based on the volumes marketed finance this. The Electronic Waste Recovery Association collection scheme (EWRA) came into operation in 2008. Collection points can be found in the outlets of associated members. The free of charge one to one return system is obligatory, however, it was not examined the way in which such free-of-charge return in implemented. No alternative provisions have been adopted. At

present, no individual or other collective take-back systems for WEEE from private households have been set up. However, certain property owners have entered into agreements with recovery undertakings concerning waste collection near their premises. Also WEEE from sources other than private households is included in the collective waste collection scheme.

The regional variations in the collection systems are reflected, amongst other, by differences in the collected amounts of WEEE from households. All WEEE collected, irrespective of the collection path, are officially reported by the national statistical offices, and on EU level by Eurostat. Figure 18 shows the WEEE collection rates for the EU member states on per capita in 2012:



Data source: Eurostat
Administrative boundaries: © EuroGeographics © UN-FAO © Turkstat
Cartography: Eurostat — GISCO, 12/2014

Figure 18: WEEE collection rates per capita in EU member states, 2012 (Graphic taken from EUROSTAT 2015)

There is a tremendous range across the member states: In Sweden more than 16 kg per capita are collected, also in Denmark and Norway high amounts of over 13 kg and 15 kg, and on the other hand Romania only 1 kg per capita but also countries like Spain, Malta or Greece that still struggle to fulfill the target of 4 kg per capita. It is important to notice that these differences are not only based on different collection schemes but also on the amount of products placed into circulation (market saturation) and the average lifetime of the EEE products. Against this background the European Commission decided to base future collection targets on the amount of products put on the market in each country instead of common targets for all member states.

7.6 Regional variation of waste treatment

Once collected, waste needs to be pre-treated before the metal(s) can be recovered at a later step. Pre-treatment steps (e.g. dismantling and sorting) are often a combination of manual and mechanical processing and can already be carried out at a very small scale, resulting on a plurality of actors (often SMEs) operating at the local, regional or inter-regional level (Hagelüken 2014). In contrast, building and operating efficient and environmentally compliant metal recovery facilities for EoL waste generally requires considerable investment and know-how. As a consequence, these facilities tend to be few, large-scale and operate by processing the pre-treated scrap from different local and foreign sources. Therefore, while scrap pre-processing is a regionally distributed process, metal recovery from complex EoL waste is limited to few facilities in Europe. More facilities exist for less complex EoL materials such as comparatively large, easily identifiable copper or brass pieces that can be directly melted and reused without the need for smelting and refining. However, these facilities also tend to be large and very few (to use economies of scale) compared to pre-sorting facilities.

7.7 Influencing factors

7.7.1 Waste collection

With regard to the disposal of WEEE together with municipal waste it seems clear that a relevant section of small domestic appliances are not separated from the domestic waste stream and go to mixed domestic waste treatment (typically landfill or incineration). But a large proportion of WEEE by weight comprises large or medium appliances from domestic waste which are easily distinguished from general domestic waste and are in practice already sorted by consumers throwing away their WEEE as most of these products have material value for recycling. They also often just do not fit into waste bins, thus highlighting the size of products as an important factor in proper separation and collection.

In its impact assessment for the WEEE directive, the European Commission (2008) estimates that 13% of the WEEE arising are not separately collected and thus the rest 87% of the WEEE arising is being separately collected (whether reported or unreported). One of the most important sources of uncertainty are shipments of WEEE outside of the the EU, legally as well as illegally. WEEE can be treated in accordance with the Directive outside the EU, if treated to standards equivalent to those in the Directive. Trade statistics show that 25,000 tonnes of WEEE is reported as legally shipped out of the Community yearly. Nevertheless this number is significantly lower than the assumed total export. Various pieces of evidence suggest that very large volumes of WEEE are shipped out of the EU illegally for sub-standard treatment in the developing world. These shipments are often disguised as export of used equipment, but in fact are shipped for their material value. Due to the illegal nature of these shipments there is no data available on the overall volume of the shipments. The UNU study (UNU et al. 2007) mentions reports on shipments of WEEE disguised as goods from the port of Hamburg and refers to findings that 28 % of businesses (collectors and exporters) were found to be exporting WEEE illegally from the Netherlands. There are well-established markets for recycled metals and some markets for some of the plastics. Transport costs for WEEE are low in comparison to the value of the materials, thus allowing a global market for WEEE recycling. In many developing countries, (for example in Africa, the Indian sub-continent and in China) the costs of WEEE processing are low, partly due to low labour costs with manual dismantling, but also very often because it involves sub-standard treatment practices. These low recycling costs compared to recycling in the EU, makes trade of WEEE to developing countries (usually illegal) profitable.

Against this background, the following three product characteristics can be seen as key influencing factors for collection rates of discarded electronic products:

- product size and weight as they determine the share of products discarded as residual waste
- material value as it sets incentives for an export of used and waste products
- and for the same reason the re-use value in emerging and developing countries

7.7.2 Waste treatment

Pre-treatment (disassembling, shredding, sorting) of collected scrap is a key step in the recycling chain and one where different priorities can be set depending on the added value that can be generated by manual labor and mechanical pre-treatment.

Metal-recovery facilities generally focus on one or few main metallic products (e.g. steel, copper, aluminium, lead & zinc) and are very efficient at recovering these (generally on the order of 95% or higher). It is, however, generally more laborious and sometimes impractical to recover minor metals in these processes. In particular, there are material combinations that are practically unseparable by metallurgical processes, leading to irreversible losses if not separated in advance (Castro, M. B. G. et al. 2004). Nevertheless, the recovery of minor metals can be very attractive despite the additional effort, as is the case for precious metals. The following concrete examples help to illustrate the plurality of possible fates of minor metals during recycling:

- In the case of steel recycling, alloying elements (some of them considered critical raw materials) remain in the cycle but the identity of the original alloy is generally lost in the process (unless the steel can be sorted pior to secondary steelmaking). Zinc partly reports to the dust formed in the furnace and can be recovered in non-ferrous metal smelters provided its concentration is high enough. Any aluminium present reports to the slag and is so lost. Essentially all copper and tin remain dissolved in the steel and are detrimental to steel quality (increasing brittleness)—this can only be addressed by appropriate sorting prior to the metallurgical plant (Fleischer et al. 2000).

- In the case of aluminium recycling, any magnesium contained in the aluminium (such as in cans) is lost through oxidation when remelting the aluminium (Westengen 2006).
- Recycling of copper and lead opens the door to recycling of other metals especially precious metals, contained in the scrap streams by introduction of additional processing steps. For example, modern recycling facilities (e.g. those operated by Aurubis, New Boliden and Umicore)[6] are also able to recover precious (gold, silver, platinum group metals) and other metals (e.g. tin, nickel, and tellurium).

The three examples outlined above are prototypical for the types of losses of minor metals in recycling and are illustrated in Figure 19. Note that there are cases where the value of the minor metals contributes significantly to the profitability of recycling. In these cases, it is attractive to conduct more/different pre-processing steps often with increased use of manual labour to separate the most valuable parts from end-of-life products. Examples are the sorting out of motors from machinery/vehicles (for their copper content; steel and aluminium are the main metals in this case), removing the catalytic converter from end-of-life vehicles (for their platinum content) or the separation of printed circuit boards from PCs (for their precious metal content).

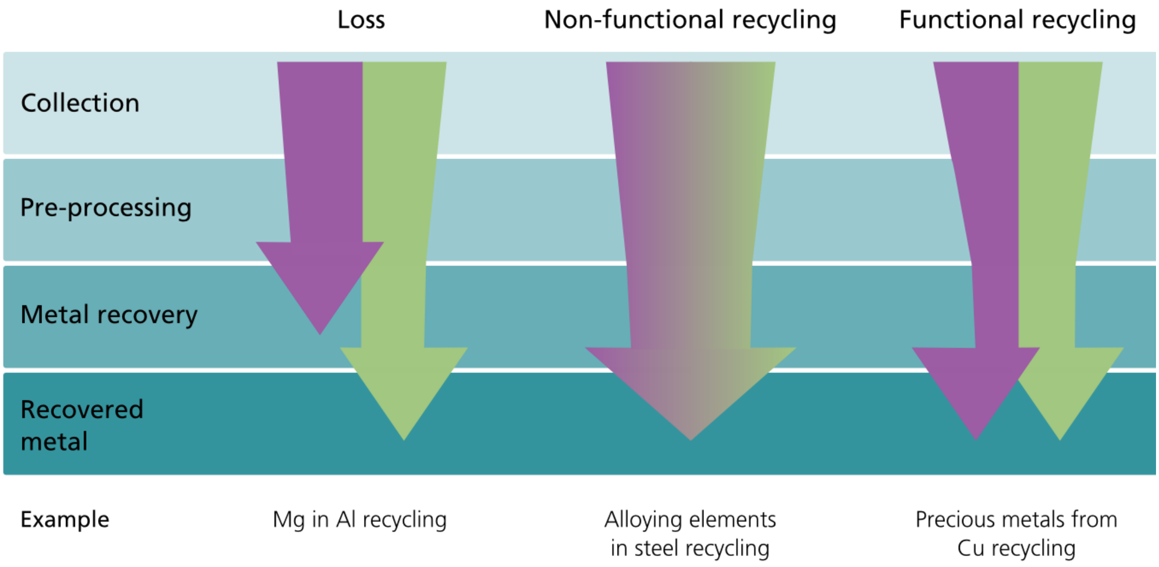


Figure 19: Three cases for losses of minor metals during recycling together with main metals. In some cases, it is possible to minimize losses of minor metals by dedicated separation/pre-processing steps (e.g. removing the catalyst from end-of-life vehicles prior to compacting and/or shredding).

Hagelüken (2014) identifies the following conditions to be met for effective recycling in Europe:

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[6] See for example Kawohl (2011), New Boliden (2010), and Vanbellen (2010)

- The material or metal combination must be technically recyclable (see examples above)
- If disassembly is required (e.g. lead-acid batteries and catalytic converters in cars), accessibility of the components for manual dismantling
- Economic viability either through market value of the recovered metals or through regulation/subsidies by public authorities
- Establishing effective collection mechanisms and ensuring that items remain in the recycling chain at the necessary seggregation level[7] through to metal recovery (see also discussion above)
- Availability of sufficient processing capacities.

Although the general features of the recycling chain are known (in some cases to great detail, as is the case for the metallurgical processes), there are still significant gaps regarding data and understanding of the decisions of individual actors at the early stages of the recycling chain which, in sum, determine the flows of scrap within and exiting Europe, as well as stocking and destocking processes along the recycling value chain (starting at individual homes).

7.8 Knowledge Gaps

7.8.1 Important sources of information and data

The WEEE Directive obligates all EU member states to report data on the annual amounts of products put on the market per product category, the amount of collected discarded products, recycling as well as reuse rates. As outlined above, these figures give a sound overview on the fate of properly discarded products but are of only limited relevance for the recovery of raw materials from these procuts.

7.8.2 Data challenges

Knowledge gaps are an especially influential factor in the field of WEEE collection, making the assessment of current and future supply of secondary resources extremely challenging. In its report "Towards Sustainable WEEE Recycling", the European Electronics Recyclers Association claims that only 20 to 33% of the amount put on the market is accounted for as being reported as separately collected by Member States (EERA 2007). Yet, the evidence suggests that the great majority of WEEE (by weight) is being separately collected rather than becoming part of the mixed municipal waste stream: but not reported as separately collected. EERA sees the following explanation: significant proportions of WEEE going to unauthorised treatment and illegal export as illustrated in the following diagram showing the different flows of consumer WEEE. The full (green) arrows represent streams that are properly monitored and reported; evidence suggests that this could be the minority of streams. The dotted (red) arrows represent streams whose volumes, destination and/or treatment are not reported. It is therefore

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[7] This is particularly relevant for precious metals in WEEE: shredding laptops and mobile phones (with a comparatively high content of precious metals) together with large appliances such as refrigerators (with a much lower content of precious metals) leads to much higher precious metals losses.

uncertain if and to which extent these stream are subject to sub-standard or even illegal treatment and trade.

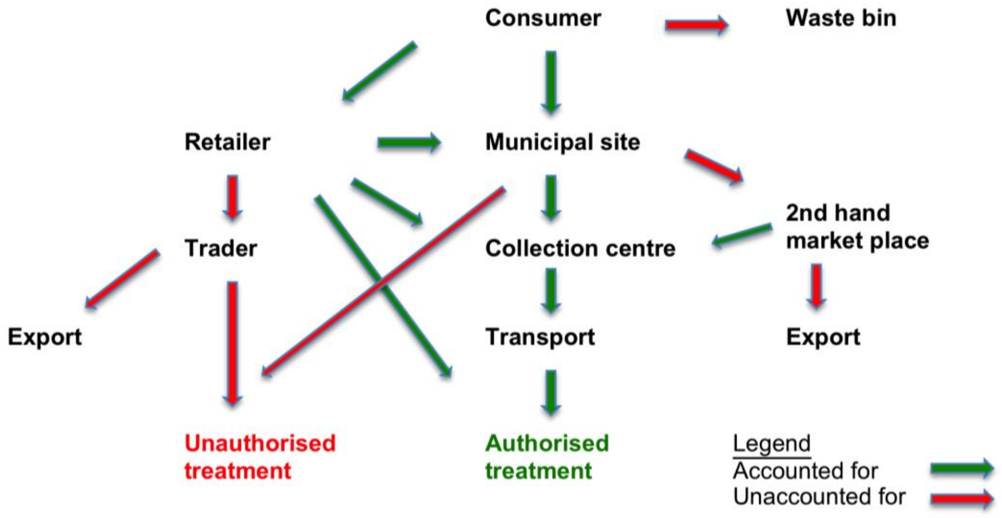

Figure 20: Possible leaks in return logistics of WEEE from households. Graphic based on EERA (2007).

7.8.3 Data opportunities

These data challenges have been adressed in Minerals4EU especially in WP 4, the Minerals Yearbook. Based on several case studies including different electronic products the chapter on secondary resources aims to develop a methodology that brings together available waste statistics on collection and recycling rates with necessary information on raw material contents and specific recovery rates.

Against this background this topic report especially helps to identify relevant influencing factors and regional/ temporal variations that need to be taken into account for a sound assessment of future provisions of secondary resources.

7.9 Conclusions and outlook

7.9.1 Overall assessment of the topic

Based on the analysis in this chapter it becomes clear that recycling could potentially play a more important role for the European supply with raw materials, but there is still important work to be done towards establishing closed loops (especially for critical raw materials) in Europe. Taking WEEE as an example, significant gaps regarding collection as well as treatment were reviewed in this chapter. The same applies to copper (a material vs. a particular waste stream). At the same time, these two stages in the recycling chain (collection and pre-treatment) offer the larger opportunities for increasing the overall efficiency of material recovery in Europe. While collection and pre-treatment can be seen, in general, as the key issues for an overall improvement of recycling chain efficiencies, it is important to address the apparently massive differences in both waste collection and treatment across Europe. This was illustrated in this chapter using data on the fate of municipal solid waste and collection amounts of WEEE per capita across the EU countries.

Assuming metal-containing waste can be effectively collected and optimally pre-treated, losses either in quality or in quantity at the metallurgical stage still remain an important issue taking into account the thermodynamic limits of recycling (Gößling-Reisemann 2008). There are effective processes in place for major industrial metals and alloys (steel, aluminium, copper, brass, etc.). However, for metals used in low quantities (whether alloyed or not), the losses are high and sometimes complete, despite their high specific value. Precious metals are an exception to this because their chemical properties make a recovery of even small quantities with good efficiency feasible and their high specific value makes this profitable. In sum, the technology is available to recover a variety of metals and metal alloys; however, there are losses that are unavoidable.

7.9.2 Next steps

The available waste statistics are not a suitable source of information on raw material contents in different waste streams and do not provide an assessment of the available potentials for recycling. For this, modelling tools (e.g. the WEEE-generation model presented by Huisman et al. 2012 or, more fitting for the purposes of minerals intelligence, dynamic material stock & flow models like that of Glöser et al. 2013 for copper) could provide additional information by generating estimates for discard streams / material in discard streams. The limited suitability of current waste statistics arises from their design for completely different purposes (avoidance of illegal disposal, coordination of responsibilites, etc.) than for providing intelligence on secondary raw material potentials in Europe. For a deeper analysis of these issues and possible next steps in order to improve raw material intelligence please see the secondary raw material case studies in WP 4.

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8 Zero Waste Mining

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8.1 Executive Summary

Raw materials are fundamental to Europe’s economy, and they are essential for maintaining and improving our quality of life. Securing reliable and undistorted access of certain raw materials is of growing concern within the EU and across the globe. In light of the pressure being placed across players due to monopolies of certain countries that are producers of, for example, critical, high technology and rare earth metals, this topic highlights the importance of the concept of “Zero Waste” when applied to mining activity in the EU.

Zero Waste mining means designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources. The redesign of resource life cycles and the emphasis on waste prevention instead of its management involves creating new commodities out of traditional waste production and contributes to the supply and demand of raw materials in the future.

Pegmatite is a igneous rock type that provides optimal conditions to exploit the idea how to achieve zero mine waste to use whole the commodities contained: tantalum and niobium minerals (columbite, tantalite, niobite) are often found in classic pegmatite deposits that contain primary mineralization consisting of spodumene, lepidolite, tourmaline, garnet and cassiterite; typical minerals in which pegmatites are often enriched. Present mining in Portugal are essentially for quartz content and feldspar ignoring the “accessory” mineralogy. Optimizing the processes and utilizing the majority of these “daughter (by-) products” leaves very little or almost no waste to be discarded.

Pegmatites are a case in point because they result from the crystallization of differentiated magma and can incorporate several distinct minerals, most of which have significant value and market niches. In most cases, pegmatite deposits are generally linear features that can extend for several kilometers spanning more than one country. Pegmatite bodies are reasonably well “zoned” in terms of mineralization and normally dyke swarms are regionally similar making these easier to mine in terms of primary, secondary and accessory minerals as they result, generally, from one pulse of magma. Therefore, the concept of regional differentiation does not come into play. In Portugal, there are several lithium deposits located in the northern part of the country. Traditionally, lithium minerals have been extracted and sold for use as fluxes in the ceramics industry together with quartz and feldspar.

The “Zero Waste” concept offers big potential in energy savings and preservation of embodied energy. This concept can be affected by several factors, namely, innovation and efficiency in the value chain, market demand, increasing overtime, extraction company policies , technology advances, technology readiness level and political constraints and regulatory exploration conditions.

Evaluation of potential and strategic mineral production streamlining for establishing this concept is invariably linked to the quantity of data available. The more reliable data, the greater the confidence with which decisions can be taken. The Zero Waste Mining is a concept that will tend to be developed sustained by European Directives and policies.

8.2 Introduction

8.2.1 Relevance of the topic

Raw materials are fundamental to Europe's economy, and they are essential for maintaining and improving our quality of life. Securing reliable and undistorted access of certain raw materials is of growing concern within the EU and across the globe. In light of the pressure being placed across players due to monopolies of certain countries that are producers of, for example, critical, high technology and rare earth metals, this topic highlights the importance of the concept of Zero Waste when applied to mining activity in the EU.

Zero Waste means designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources[8].

The redesign of resource life cycles and the emphasis on waste prevention instead of its management involves creating new commodities out of traditional waste production and contributes to the supply and demand of raw materials in the future.

The relevance of the Zero Waste concept is given by its implications:

1) A new approach how to deal with mine wastes facilities and quantity of mine wastes, avoiding the trend to increase

2) The contribution to comply with European directives, initiatives and strategies , including but not limited to:

   Directive 2006/21/EC and DIRECTIVE 2008/98/EC– minimisation, security and recycling of wastes

   Raw Materials Initiative – secure the European supply

   Circular economy concept – input for a more competitive resource-efficient economy due to minimisation of costs of extraction

8.2.2 Ilustration by a case study

Pegmatites in Portugal

Pegmatite is a igneous rock type that provides optimal conditions to exploit the idea how to achieve zero mine waste to use whole the commodities contained: tantalum and niobium minerals (columbite, tantalite, niobite) are often found in classic pegmatite deposits that contain primary mineralization consisting of spodumene, lepidolite, tourmaline, garnet and cassiterite;

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[8] Partial definition given by the working group of the Zero Waste International Alliance in 2004.

typical minerals in which pegmatites are often enriched. Present mining in Portugal is predominantly for quartz content and feldspar ignoring the “accessory” mineralogy. Optimizing the processes and utilizing the majority of these “daughter (by-) products” leaves very little or almost no waste to be discarded.

The wide variety of commodities contained in pegmatites include critical materials or strategic resources. Lithium pegmatites (containing lepidolite for instance) are used as an example how it can improve the value chain in the extraction of pegmatites.

In Portugal, there are several lithium deposits located in the northern part of the country. Traditionally, lithium minerals have been extracted and sold for use as fluxes in the ceramics industry together with quartz and feldspar. Total lithium production, estimated in 570 metric tons for 2013 (USGS, 2014) is consumed in the ceramics industry and used in the manufacture of tiles, sanitary and table ware. Presently, there is also a focus on garden embellishment using lepidolite in paving areas. However, the transformation to lithium carbonate and ultimately lithium metal could mean significant added value.

The foreseen increase of lithium demand, particularly high in batteries for HEV/PHEV/EV, in the range 2009-2025, as referred by Greenlight Resources, as well as the increase in price, following the econometric model ARIMA(1,1)](Grosjeana et al. 2012) justify the development of the “Zero Waste” concept applied to lithium deposits in Portugal.

8.2.3 Regional Variation

Pegmatites are a case in point because they result from the crystallization of differentiated magma and can incorporate several distinct minerals, most of which have significant value and market niches. In most cases, pegmatite deposits are generally linear features that can extend for several kilometers spanning more than one country.

- Political constraints such as country borders, different government regimes and regulation/legislation will govern the way access to mineral deposits might occur. This is aligned with individual internal regulations, strategic views of own mineral industry, market conditions and export and import policies, amongst others.
- Mineral extraction policies are governed by market place conditions. Strategic minerals to one company are not the same for another due to the specific markets that each company is feeding or might have access to.
- Geological bodies or mineral deposits vary in composition depending on the local geological conditions active at the time of mineral deposition or paragenetic sequencing. The latter leads to regional variation that has to be taken into account before major decisions are taken.

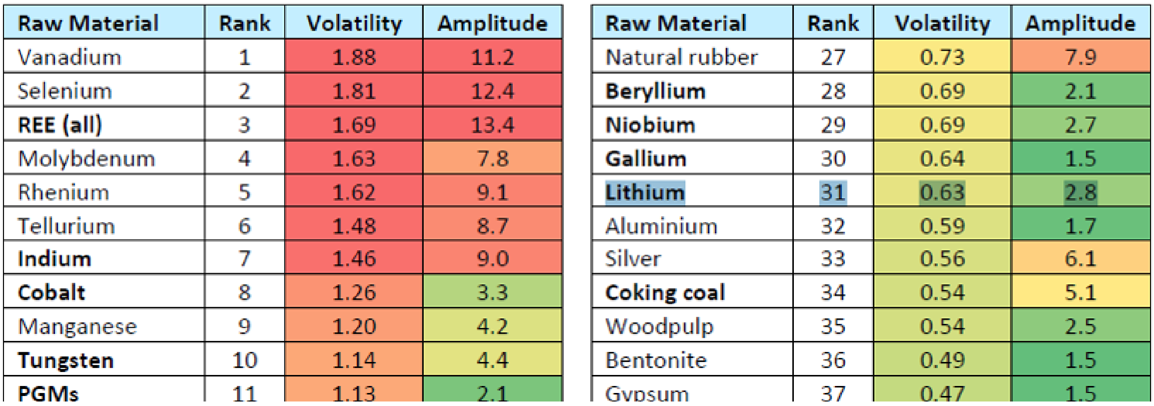
8.2.4 Temporal Variation

Temporal variations arise naturally as a result of trends that can be partially dictated by market conditions and which in turn are conditioned by several other factors. Also, switching of strategic mineral extraction policies might and does occur. This may come about due to the extinction of a certain mineral phase in the existing mining concessions that are in operation. The replenishment of that same mineral phase might, and often does, come from another geological and geographically distinct area for which the company does not yet own the mining concessions or is owned by a competitor. This will trigger a switch in internal mining policies resulting in a new product being developed for market.

Invariably, switching of commodity within a mining company is a process that takes time and often overlaps with other strategic plans and prevailing favourable market conditions.

8.2.5 Variations of topical phenomena over time

Concerning "volatility" specific statistics related to the zero waste concept have not been found, as this is highly dependent from data provided by private companies that are mainly focused on production yields and waste minimisation. Nevertheless, there are studies ranking many of the commodities that are enclosed in the considered geological environment, e.g. pegmatites (Figure 1), whereas commodities such as Nb, Ta, Rare earths (COM COM(2014) 297) are considered essential. Concerning the lithium example specifically from the case study (Chapter 1.2) the volatility of the substance is ranked considered relatively low. More specifically lithium is ranked again depicts



Raw Material	Rank	Volatility	Amplitude
Vanadium	1	1.88	11.2
Selenium	2	1.81	12.4
REE (all)	3	1.69	13.4
Molybdenum	4	1.63	7.8
Rhenium	5	1.62	9.1
Tellurium	6	1.48	8.7
Indium	7	1.46	9.0
Cobalt	8	1.26	3.3
Manganese	9	1.20	4.2
Tungsten	10	1.14	4.4
PGMs	11	1.13	2.1

Raw Material	Rank	Volatility	Amplitude
Natural rubber	27	0.73	7.9
Beryllium	28	0.69	2.1
Niobium	29	0.69	2.7
Gallium	30	0.64	1.5
Lithium	31	0.63	2.8
Aluminium	32	0.59	1.7
Silver	33	0.56	6.1
Coking coal	34	0.54	5.1
Woodpulp	35	0.54	2.5
Bentonite	36	0.49	1.5
Gypsum	37	0.47	1.5

Figure 21: Historical price volatility index for key raw materials over the past ten years (extracted and adapted after Chapman, A et al. 2013).

Concerning the same substance, forecasts for the lithium demand tend to increase (Angerer, 2009; Thielmann et al., 2010, 2012; Grosjeana et al. 2012).

8.2.6 Regional differentiation

Pegmatite bodies are reasonably well “zoned” in terms of mineralization and normally dyke swarms are regionally similar making these easier to mine in terms of primary, secondary and accessory minerals as they result, generally, from one pulse of magma. Therefore, the concept of regional differentiation does not come into play.

8.3 Influencing Factors

Zero Waste has an important impact on the management of energy flows in the economy. In the life cycle of most products the most energy intensive moments are in the extraction, production and use phase; hence from an energy point of view Zero Waste reduces emissions associated to extraction and production thanks to feeding-back most nutrients and resources back into the natural cycle –soils- or technical cycle -reuse and recycling-. The emissions associated to the use phase are reduced with better product design and ecoinnovation.

Therefore, Zero Waste offers big potential in energy savings and preservation of embodied energy. LCA studies have given evidence that the magnitude of saved energy through reuse or recycling largely outperforms the energy which may be obtained through incineration (be it conventional or non-conventional).

The factors herein considered are not they are not directly comparable depending on most of them are not quantified in terms of consequences affecting the zero waste mining. The analysis follows a bottom-up approach based on a specific geological environment.

There are some factors that inevitably will or can influence this zero waste concept. These could be:

- Temporal variations arise naturally as a result of trends that can be partially dictated by market conditions and which in turn are conditioned by several other factors. Also, switching of strategic mineral extraction policies might and does occur. This may come about due to the extinction of a certain mineral phase in the existing mining concessions that are in operation. The replenishment of that same mineral phase might, and often does, come from another geological and geographically distinct area for which the company does not yet own the mining concessions or is owned by a competitor. This will trigger a switch in internal mining policies resulting in a new product being developed for market.
- The sale of Li minerals, traditionally used for flux in the ceramics industry is also influenced by special orders from specific customers. One such example is the growing European and oriental demand for purple coloured rocks and gravel for garden embellishment. Clearly, the market opportunity presented makes the supplier/producer switch from traditional markets to a more exotic market.

- Producers of Li minerals often opt for secure sales in lower price markets rather than the more complex (higher prices) markets.
- Changes in technology or very high commodity prices drive market demand (nothing new here)
- Substitution will undoubtedly play a significant as we do not know what the future will hold in terms of power supply devices.

These we would term as external factors but ultimately the strongest external factor is demand.

Demand is primarily driven by the development for new technologies:

- Innovation and efficiency in the value chain
- Market demand, e.g. Increased demand in battery powered vehicles
- Increasing overtime
- Company policies – exploration or mining companies (can dictate the production by client demand, technology requirements or surplus material)
- Technology advances – refined products
- Technology Readiness Level
- Political constraints and regulatory exploration conditions (report to temporal variation)

In a more specific way, and considering specifically the case study in chapter 1.2:

- Switching of strategic mineral extraction policies - extinction or lower grade of a certain mineral phase in the existing mining concessions in operation. The replenishment of that same mineral phase might, and often does, come from another geological and geographically distinct area for which the company does not yet own the mining concessions or is owned by a competitor. This will trigger a switch in internal mining policies resulting in a new product being developed for market.
- Market opportunities – Sale of Li minerals (e.g. lepidolite) for flux vs. sale for garden embellishment.
- Ease of sales – Quick selling of Li minerals to “easiest” customer rather than more complex markets.
- Changes in technology - Substitution – What does the future hold in terms of power supply devices?

8.4 Knowledge Gaps

8.4.1 Important sources of information and data

Evaluation of potential and strategic mineral production streamlining is invariably linked to the quantity of data available. The more reliable data, the greater the confidence with which decisions can be taken. Therefore, reliable sources of data should be the data providers that know, understand and manipulate these data: the several national Geological Surveys and the exploration companies operating on site.

These are the players that can make knowledgeable life cycle assessment decisions and how to streamline and optimize this in light of the resources being dealt with.

8.4.2 Data challenges

Historical and forecasted demand and financial values of specific commodities leads to the logical evidence towards Zero Waste concerning mining activity. However it is a big challenge concerning data availability focused specifically in this area as this data is often held by private companies ruled by strict non-disclosure company policies and internal options.

In many instances, marginal deposits, studied and evaluated for single mineral commodity production need to be re-evaluated for multiple mineral commodities. In cases such as these, competent teams, made up of geological survey personnel and private company staff, need to undertake grassroots studies to define the potential of these deposits or mineral occurrences. These studies might involve the acquisition of new data, re-evaluation and reinterpretation of older data.

8.4.3 Data opportunities

It is an opportunity to develop specific case studies with values concerning production and different options taken based on available Life Cycle Assessment (LCA) in order to enhance/highligth/demonstrate the added value of the zero waste mining approach. Therefore, detailed economic values should be given in order to support and motivate the decisions to move towards Zero Waste.

8.5 Conclusions and Outlook

8.5.1 Overall assessment of the topic

The insights presented here are not new. The concept of “zero waste” is an objective sought by all who produce minerals – less waste means greater profit margins. However, this utopic state remains often unachievable due to variable geological conditions, company policies, national and international mineral policies and ultimately market driven factors (commodity prices which is the motor of all industry).

Our vision of Zero Waste mining stems from the fact that pegmatitic mineral resources are potentially enriched in a series of other minerals, namely: Quartz, Optically pure quartz, garnets, tin, Nb, Ta, REE, feldspar, Li and other micas. Were all these to be extracted from one single deposit, minimum waste (Zero) would be generated.

The mining of a specific mineral, or set of minerals, that allows one to achieve this rather easily, is also rarely available at every deposit. Pegmatites, due to their nature are perhaps the ones that come closer to achieving this, should they be mineralised in the minerals described above. Finding one such mineralised body optimised for zero waste mineral extraction is something all would like to have.

8.5.2 Next steps

The Zero Waste Mining is a concept that will tend to be developed sustained by European Directives and policies. Thus, detailed studies can support it at several levels:

- Develop case studies by combining in close partnership the mining companies and national geological surveys to show the advantages and other long term potentialities in order to extract the maximum value of the deposit.
- Interact with different parts in order to achieve the TRL required.
- The knowledge of mineral resources flow in mining companies dedicated to waste minimisation can help on to weight the impact factors and contribute to paradigm shift for other mining companies.

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