European Commission

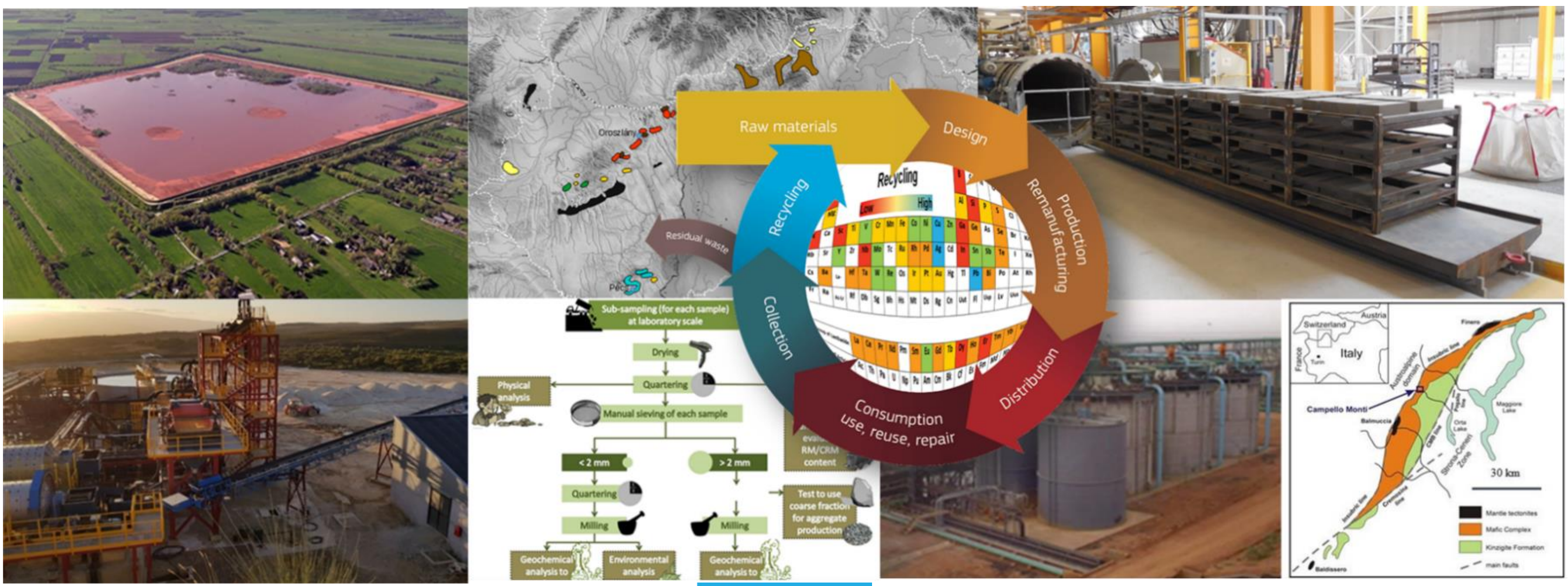
JRC SCIENCE FOR POLICY REPORT

Recovery of critical and other raw materials from mining waste and landfills

State of play on existing practices

Blengini, G.A.; Mathieux, F.; Mancini, L.; Nyberg, M.; Viegas, H.M. (Editors)

2019



Joint Research Centre

EUR 29744 EN

Contact information
Name: Fabrice Mathieux
Address: Joint Research Centre, Via E. Fermi 2749, 21027 Ispra, ITALY
Email: fabrice.mathieux@ec.europa.eu
Tel.: +39 332789238

EU Science Hub
https://ec.europa.eu/jrc

JRC116131

EUR 29744 EN

PDF	ISBN 978-92-76-08568-3	ISSN 1831-9424	doi:10.2760/600775
Print	ISBN 978-92-76-08567-6	ISSN 1018-5593	doi:10.2760/174367

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: Blengini, G.A.; Mathieux, F., Mancini, L.; Nyberg, M.; Viegas, H.M. (Editors); Salminen, J.; Garbarino, E.; Orveillon, G.; Saveyn, H.; Mateos Aquilino, V.; Llorens González, T.; García Polonio, F.; Horckmans, L.; D'Hugues, P.; Balomenos, E.; Dino, G.; de la Feld, M.; Mádai, F.; Földessy, J.; Mucsi, G.; Gombkötő, I.; Calleja,I. *Recovery of critical and other raw materials from mining waste and landfills: State of play on existing practices,* EUR 29744 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-08568-3, doi:10.2760/600775, JRC116131.

Contents

List of contributors 4
1 Introduction 7
1.1 Critical raw materials 8
1.2 Circular economy 10
1.3 Key actors in the EU 14
2 Relevant EU policy measures 16
2.1 Waste Framework Directive 16
2.2 Extractive Waste Directive and the Reference Document on BAT 16
2.3 Landfill Directive 18
2.4 Horizon 2020 18
2.5 EIT Raw Materials 23
3 Best Available Techniques for the Management of Waste from Extractive Industries 28
3.1 MWEI BREF and recovery of critical and other raw materials 28
3.2 Generic BAT applicable to the recovery of critical and other raw materials 29
3.2.1 Recovery of extractive waste 29
3.2.2 Prevention and reduction of extractive waste generation 30
3.2.3 Corporate management 30
3.2.4 Data and information management 30
3.3 Risk-specific BAT applicable to the recovery of critical and other raw materials 31
3.3.1 Design for closure 31
3.3.2 Geotechnical analysis and monitoring of the structural stability 32
3.3.3 Physico-chemical stability of extractive waste 32
3.3.4 Groundwater and soil pollution remediation 34
3.3.5 Monitoring of emissions to soil, water and air 34
4 Knowledge base needs and sources 35
4.1 The EU Raw Materials Information System 35
4.2 Overview of the knowledge base from current practices 39
5 Framework conditions and monitoring tools 42
5.1 Monitoring progress: the EU Raw Materials Scoreboard 42
5.2 Summary on framework conditions from relevant projects 43
6 Overview of the potential of recovery from landfill and extractive waste 45
6.1 Extractive waste 45
6.2 Landfill 47
6.3 Overview on existing practices: focus on technologies 50
7 Existing practices for recovery of critical raw materials and other raw materials 55
7.1 Recovery of Tantalum and Niobium from tailings of the old Penouta mine 55

7.2 Recovery of CRMs and valuable metals from inorganic industrial waste streams 69

7.3 Biohydrometallurgy for treatment of low grade resources: the Kasese site, Uganda 79

7.4 Bauxite Residue as a resource in Europe 85

7.5 Smart Ground database and protocols for data collection 91

7.6 CriticEL - Raw Material National Survey in Hungary 106

8 Conclusions and outlook 116

List of abbreviations and definitions 120

List of figures 123

List of tables 125

Abstract

The transition to a more circular economy is essential to develop a sustainable, low carbon, resource efficient, and competitive economy in the EU. In such a context, Critical Raw Materials (CRMs) are those with a particularly high importance to the EU economy and, at the same time, with a high risk of supply disruptions. First and foremost, improving the circular use of CRMs is a key strategy in improving the security of supply and not surprisingly is an objective of various policies. This report delivers on action #39 of the Circular Economy Action Plan: "Sharing of best practice for the recovery of critical raw materials from mining waste and landfills". It builds on discussions held during two 2018 workshops and gathers together six examples of existing practices for the recovery of critical, precious, and other materials from extractive waste and landfills, highlighting technological innovations and contributions to a more comprehensive knowledge-base on raw materials.

The report also provides various estimates of potential recovery of certain materials compared to their current demand. Lessons learnt from the practices include awareness that it is very unlikely that recovery processes can target one or just a few specific materials of great interest and disregard other elements or bulk matrixes. Especially in case of very low concentrations, most of the mineral resources and other bulk materials in which they are embedded must be valorised in order to increase economic viability and minimise waste disposal. As recovery processes can be very energy intensive, environmental and land use related aspects are also particularly relevant in that environmental gains may also occur and, moreover, land space can be liberated and reused for new purposes and services. Finally, availability of data and information on secondary materials as well as a harmonised legislative framework within the EU appear to be crucial for the large-scale deployment of recovery practices.

Acknowledgements

Editors would like to thank Magnus Gislev (European Commission) for proposing the idea of this report, Christian Wimmer, Jose Jorge Diaz Del Castillo, Daniel Cios, Milan Grohol and Konstantinos Georgitzikis (European Commission) for reviewing the report, Špela Bavec (Geološki zavod Slovenije, Slovenia) and Manuel Vázquez Mora (Junta de Andalucía, Spain) for inputs to the report.

List of contributors

This report has been edited by Gian Andrea Blengini, Fabrice Mathieux, Lucia Mancini (JRC Ispra - Land Resources Unit), Maria Nyberg, and Helena Viegas (DG GROW Resource Efficiency and Raw Materials Unit).

The following authors have contributed to the preparation of this report:

- Chapters 1, 2, 4, 5, 6, and 8: Gian Andrea Blengini, Fabrice Mathieux, Lucia Mancini (JRC Ispra - Land Resources Unit); Justin Salminen (Boliden); Ignacio Calleja (EIT Raw Materials)
- Chapter 2.2 and Chapter 3: Elena Garbarino, Glenn Orveillon, Hans Saveyn (JRC Seville - Circular Economy and Industrial Leadership unit)
- Chapter 7.1: Mateos Aquilino, V.; Llorens González, T; García Polonio, F., SMS, Strategic Minerals Spain, (Spain))
- Chapter 7.2: Liesbeth Horckmans, VITO (Belgium)
- Chapter 7.3: Patrick D'Hugues, Chris Bryan, Anne Gwenaelle Guezennec, and Dominique Morin, Waste and Raw Materials Unit BRGM, Bureau De Recherches Géologiques et Minières, (France)
- Chapter 7.4: Efthymios Balomenos, Mytilineos S.A., Metallurgy Business Sector/NTUA Laboratory of Metallurgy (Greece)
- Chapter 7.5: Giovanna Dino, Piergiorgio Rossetti, University of Turin (Italy); Marco de la Feld, ENCO Consulting (Italy)
- Chapter 7.6 Ferenc Mádai, János Földessy, Gábor Mucsi, Imre Gombkötő, University of Miskolc, Faculty of Earth Science and Engineering (Hungary)

The views expressed in these contributions are the authors' own and do not necessary reflect the opinion of the editors and the position of the European Commission.

Executive summary

The European Commission, in its Circular Economy Action Plan (COM/2015/614), has identified a number of measures to facilitate the transition towards a circular economy. Several of these measures regard Critical Raw Materials (CRMs), i.e., the materials with high economic importance to the EU and high supply risk. As for other materials, secondary critical raw materials can be recovered from extractive waste and landfill. This report aims to share existing practices of recovery of critical and other raw materials from these sources, consequently delivering on the Action 39 of the Circular Economy Action Plan.

The report builds on two workshops held in Brussels on May 16th, 2018: "Re-Mining of Mining Waste" and "Enhanced Landfill Mining", and on a sub-sequent call for contributions presenting relevant current practices. This resulted in six sub-chapters provided by various stakeholders and these have been collected together and analysed in the present report. Four of these chapters address technological processes for the recovery of different materials from mining tailings and industrial waste, as in the case of the Penouta mine, the CHROMIC project, biohydrometallurgy at the Kasese mining site, and the REDMUD project. Moreover, the aim of the SMART GROUND and CRITICEL projects is to improve the knowledge base on the availability of critical, precious, and valuable secondary materials.

Policy context

The Raw Materials Initiative (EC/2008/699) recognizes the importance of a secure and sustainable supply of raw materials to the EU from domestic sources, international markets, and from secondary sources, e.g., by recycling. The identification of materials that are critical for the economy has led to the list of CRMs, which has been published every three year since 2011. Improving the circular use of CRMs is also an objective under the Circular Economy Action Plan (COM/2015/614) and EU Directive 2018/851, amending Directive 2008/98/EC on waste. In addition, the Extractive Waste Directive (2006/21/EC) sets specific requirements for both minimisation and recovery of extractive waste. In support of implementation of the Extractive Waste Directive, the Commission has published the Reference Document on Best Available Techniques for the Management of Waste from Extractive Industries (MWEI BREF).

The present report should help Member States implement the proposed provisions on CRMs, especially CRMs contained in extractive waste and landfills.

Key conclusions

The experience of the present report suggests that recovery of critical and other raw materials from landfills and extractive waste is not at this stage a widely diffused practise in the EU. Nevertheless, there are some notable examples which not only demonstrate the potential but also the availability of technologies and the existence of a highly innovative sector. The general lack of a knowledge base is certainly a bottleneck as well as the framework conditions that have not been optimised yet.

Recovery from extractive and industrial waste seems to be more advanced, and has a remarkably high potential to contribute to a sustainable and secure supply whereas Enhanced Landfill Mining seems to be less developed and a less promising area as far as CRMs and related raw materials are concerned.

Cooperation with other EU initiatives and valorisation of the existing databases on Secondary Raw Materials (SRM) could certainly support the consolidation of the necessary knowledge base to boost its recovery at EU level. This suggests that systematic and adequately funded campaigns for field sampling and data collection might be a highly recommended necessary step.

Main findings

Until a few decades ago, only one or two commodities were extracted from each mine. In addition, different cut-offs practiced over time and technological constraints left behind valuable materials disposed as extractive waste. Therefore, historic extractive wastes in many European regions are a potential resource for several sought-after metals and semi-metals, including those increasingly used in modern high-tech applications.

One finding from the report is that the recovery process cannot regard a specific material alone (especially if present in low concentration), but most of the available resources must be valorised. Base metals, minor metals, and (most) of the rock matrix as industrial minerals and/or aggregates need to be recovered and valorised in order to make the process economically viable and resource efficient.

The report provides various estimates for potential recovery of various materials with respect to current demand for them. For instance, in the cases of chromium, niobium, and vanadium, slags could contribute to reducing the reliance on importing these materials by 12%, 6%, and 7%, respectively.

Energy demand required for material separation is the main challenge for the full recovery of all metals in mixed matrices or in solution. Indeed, energy consumption increases exponentially as the concentration of the target metal falls below 1 wt%. Elements that are much diluted, or which appear in a complex mineralogical form, are difficult and expensive to recover, and have a higher water footprint and higher CO_2 emissions.

In addition to the economic value of recovered materials, environmental and social aspects emerged as relevant drivers for the treatment of extractive waste. Indeed, the process can lead to the environmental restoration of abandoned mining areas and to the release of new land space. Community engagement is very important for the successful deployment of waste treatment projects as environmental risks and opportunity have to be clearly communicated.

1 Introduction

The transition to a more circular economy, where the value of products, materials, and resources is maintained in the economy for as long as possible, and generation of waste is minimised, is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient, and competitive economy[1]. In its Circular Economy Action Plan COM (2015) 614 published in December 2015, the European Commission identified a number of measures across the stages of the life cycle of products including production, consumption, waste management, and production of secondary raw materials (SRMs). The plan also included several actions to be taken in five priority areas, including one concerning Critical Raw Materials (CRMs). CRMs are of both high economic importance to the EU and have a high risk of supply disruption[2]. In addition, they need to be managed along their life cycle in a better way[3]. The plan identified several potential sources of secondary critical raw materials not only including electronic waste but also landfills and extractive waste.

Since 2015, most of the 54 actions in the action plan have been completed, and several of these concern CRMs. In particular, the report "*Critical Raw Materials and the Circular Economy*" published in 2018 identified key actions to manage CRMs better especially at end-of-life, taking inspiration from best practices in eight sectors including landfills and extractive waste[4].

The present report delivers one of the last actions due in the plan, i.e., action #39 related to "*Sharing of best practice for the recovery of critical raw materials from mining waste and landfills*". Due to the fact that CRMs contained in landfill and extractive waste are mixed with other materials, and because it is rarely commercially profitable to only target CRMs, the scope of this report has been slightly extended to cover other raw materials.

This report builds on the discussions of the two CRMs workshops on "Re-Mining of Mining Waste" and on "Enhanced Landfill Mining" held in Brussels on May 16th 2018, a call for candidate chapters to present current relevant practices which was widely distributed during summer 2018 (not only to participants at the workshops but also to the Operational Group of the EIP on Raw Materials). After the candidates had been selected, six chapters were developed by various stakeholders during autumn 2018 using a common structure. The JRC then edited the chapters to ensure consistency and extracted various lessons that are presented in the summary sections. A few introductory sections have been added to make the report as complete as possible.

The report is organised as follows: following this context setting, fundamental concepts concerning CRMs and circular economy are outlined, together with a list of key actors in this area in the EU. Section 2 briefly analyses the Waste Framework Directive and the Extractive Waste Directive (with further insights in Section 3) and summarises the research carried out by H2020 framework and EIT Raw Materials and link them with the topic of the report. Sections 4 and 5 respectively deal with the knowledge base and the framework conditions, analysing both the literature and current practices presented by external stakeholders. Section 6 presents figures on the potential of recovering CRMs from both landfills and extractive waste, and analyses the technologies that are at stake. Section 7, which is the largest section of the report, combines the six chapters on six different current practices prepared by external stakeholders, which covers technologies, framework conditions, and knowledge base. Section 8 presents the main findings and conclusions.

---

[1] EC, 2015. Closing the loop - An EU action plan for the Circular Economy. COM/2015/0614 final.

[2] EC, 2017. Communication on the 2017 list of Critical Raw Materials for the EU. COM (2017) 490 final.

[3] Mathieux, F., et. al., 2017. Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-74282-8 doi:10.2760/378123 JRC108710.

[4] EC - European Commission, 2018b. Commission Staff Working Document. Report on Critical Raw Materials and the Circular Economy. SWD (2018) 36 final.

1.1 Critical raw materials

Background and definition

Raw materials form the basis of the EU's economy today and will do so in the future, they ensure jobs and competitiveness, and they are essential for maintaining and improving quality of life. Non-energy raw materials link to all industries across all supply chain stages. They are also fundamental and currently irreplaceable in driving change, for instance, through digital technologies, low-carbon energy technologies (e.g., solar panels, wind turbines, energy-efficient lighting), sustainable mobility (e.g., electric vehicles).

Although all raw materials are important, some of them are of more concern than others in terms of a secure and sustainable supply. Critical raw materials (CRMs) are identified in the EU according to two main dimensions: 1) economic importance and 2) risk of supply disruption. A raw material is defined as being critical if both dimensions exceed a given threshold[5]. The supply risk indicator in the EU criticality assessment[6,7] is based on the concentration of primary supply from countries and their level of governance. Production of SRMs (recycling) and substitution are considered to be risk-reducing filters. The economic importance is correlated to the share of demand in an economic sector, its Gross Value Added, and the degree of substitutability of the material.

The European Commission published the first list of CRMs in 2011[8] (EC - European Commission, 2011) and the second one in 2014[7]. The third list of CRMs for the EU was released in September 2017[6] (**Table 1**) and the EC applied a revised criticality methodology which is an evolution of that used to establish the 2011 and 2014 lists. As the EC's in-house science service, the Directorate-General Joint Research Centre identified specific aspects of the EU criticality methodology and adapted them so that the needs and expectations of the resulting CRMs list would identify and monitor CRMs in the EU better. The modifications were introduced in the revised methodology giving high priority to comparability with the previous two exercises, which in turn reflects the overall objective of effectively monitoring trends and maintaining the highest possible policy relevance.

Table 1 The 2017 EU List of Critical Raw Materials (EC, 2017). (HREEs = heavy rare earth elements ([9]), LREEs = light rare earth elements ([10]), PGMs = platinum group metals ([11]))

Critical raw materials			
Antimony	Fluorspar	LREEs	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

[5] Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Peirò, L.T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., Ciupagea, C., 2017. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. Resour. Policy 53, 12–19. doi:10.1016/j.resourpol.2017.05.008

[6] EC - European Commission, 2017. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU. COM (2017) 490 final.

[7] EC - European Commission, 2014. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials

[8] EC - European Commission, 2011. Tackling the challenges in commodity markets and on raw materials.

[9] Dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium.

[10] Cerium, lanthanum, neodymium, praseodymium, samarium.

[11] Iridium, platinum, palladium, rhodium, ruthenium.

Current supply and trade situation

The value chain of CRMs is not fully and homogeneously covered by European industry and pronounced imbalance exists between the upstream steps (extraction/harvesting) and the downstream steps (manufacturing and use). Considering the very limited supply of CRMs from secondary sources, the need for access to primary sources, including ores, concentrates, and processed or refined materials is huge and crucial for the creation of wealth by – and even the survival – of European industries and their associated jobs and financial benefits.

The majority of these primary raw materials are produced and supplied from non-European countries (**Figure 1**).

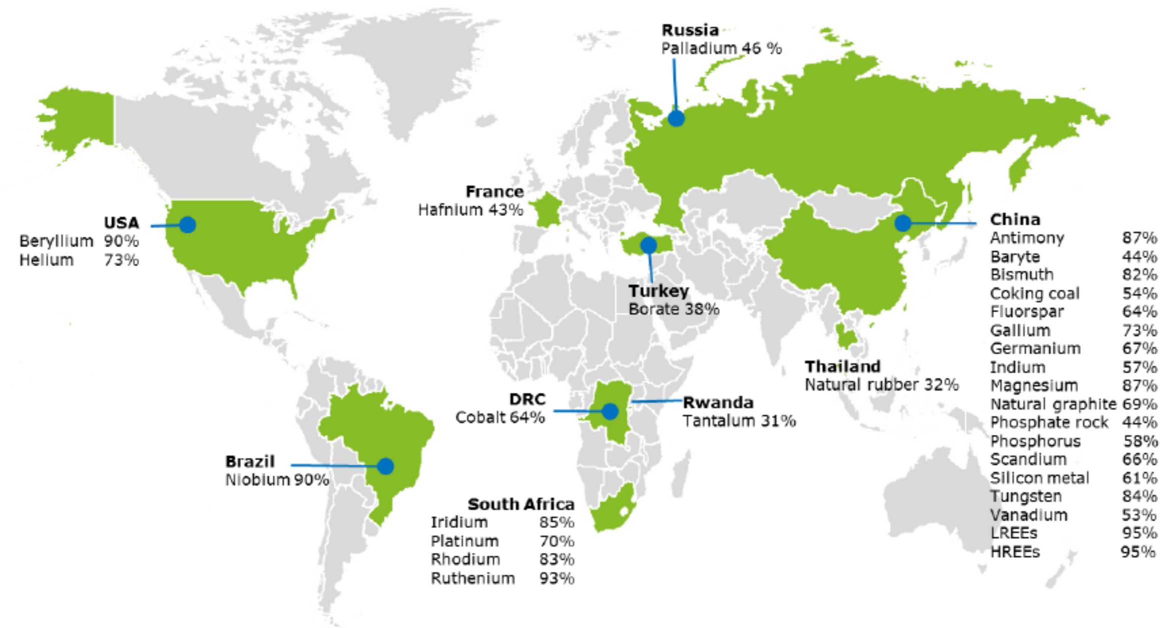


Figure 1: Contribution of primary global suppliers of CRMs to European demand: average from 2010-2014

Although China is the principal global supplier of CRMs, the analysis highlights other countries that represent important global suppliers of specific CRMs such as the USA (beryllium and helium), Russia (palladium), and the DRC (cobalt).

Many CRMs lack the upstream steps of the value chain in the EU: antimony, beryllium, borates, magnesium, niobium, PGMs, phosphorus, rare earths, scandium, tantalum, and vanadium. This is either due to the absence of those materials in the European ground or to economic and societal factors that negatively affect exploration (for deposit discovery and characterisation, estimation of resources and reserves) or extraction (closure of existing mines, reluctance to open new mines, etc.). In addition to some abiotic raw materials, natural rubber is also entirely grown and harvested outside the EU.

In order to feed its industries and markets, the EU has currently no other choice in accessing these CRMs but to import their ores and concentrates or the refined materials from other countries.

Hafnium is the only CRM for which an EU Member State (France) is the main global producer. For hafnium and indium, the Member States produce enough primary materials to avoid significant extra-European imports (See **Figure *12***).

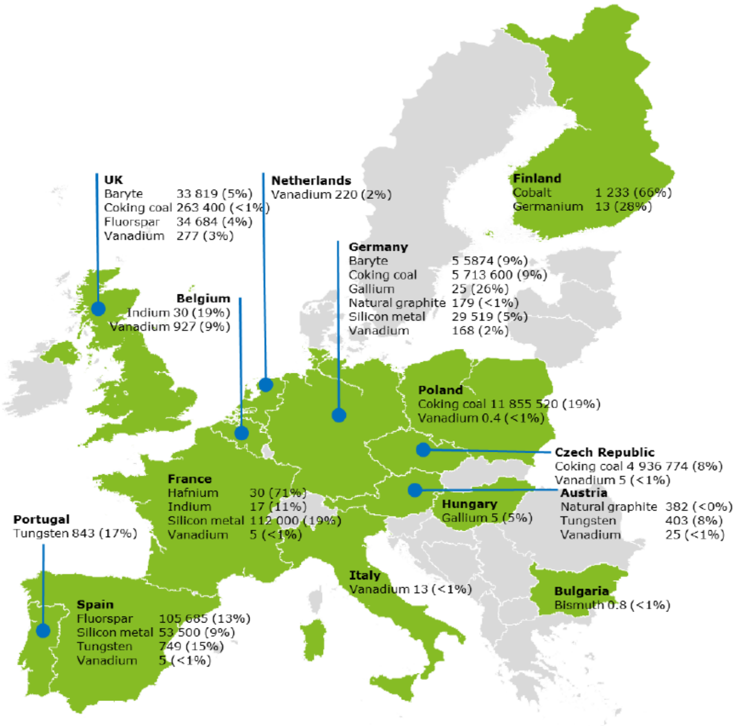


Figure 2 EU production of primary CRMs in tonnes (and share of supply to EU in %), average 2010-2014

1.2 Circular economy

The Circular Economy Action Plan[12] is an ambitious but concrete programme that stimulates Europe's transition towards a circular economy by contributing to 'closing the loop' of product life cycles. The action plan aims to simultaneously boost EU competitiveness while fostering sustainable economic growth and generating new jobs.

The measures in the action plan cover the whole life cycle of products from production and consumption to waste management as well as the market for SRMs. Innovation and investment in the field have been promoted through the H2020 programme. The appendix to the action plan sets out the timeline for completion of the actions. Among the topics included in the Circular Economy Action plan are:

- the promotion of the reparability, upgradability, durability, and recyclability of products by developing product requirements relevant to the circular economy in its future work under the Ecodesign Directive[13];
- revised legislative proposals on waste, which set targets to reduce waste and increase recycling, and which should also create incentives for better product design[14];
- boosting the market for secondary materials and water reuse.

---

[12] EC - European Commission, 2015. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy. COM/2015/0614 final.

[13] European Union, 2009. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (Text with EEA relevance).

[14] EC - European Commission, 2008. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste.

Together with food waste and plastics, the following priority action areas are addressed in the action plan:

- CRMs, where the Commission encourages their recovery and action by Member States in its revised proposals on waste;
- construction and demolition waste, where the Commission will take action to ensure the recovery of valuable resources and adequate waste management and to facilitate the assessment of the environmental performance of buildings;
- biomass and bio-based products, where the Commission will promote efficient use of bio-based resources and will establish a target for recycling wood packaging and a provision to ensure the separate collection of bio-waste in the revised waste policies.

The 2018 Circular Economy Package[15] included measures to prevent waste and where this is not possible, significantly step up recycling of municipal and packaging waste. Landfilling is to be phased out and the use of economic instruments such as Extended Producer Responsibility schemes to be promoted. The new legislation strengthens the "waste hierarchy", i.e., it requires Member States to take specific measures to prioritise prevention, reuse, and recycling above landfilling and incineration, thereby making the circular economy a reality. The package adopted an EU Strategy for plastics, developed a monitoring framework to measure progress toward a circular economy, and analysed the links between CRMs and the circular economy[16] amongst other actions.

Then in March 2019, the Final Circular Economy Package[17] containing a comprehensive report on the implementation of the Circular Economy Action Plan was presented. The report presents the main achievements under the Action Plan and sketches future developments towards a climate-neutral, circular economy where pressure on natural resources is minimised. Overall, many completed actions concern CRMs, including: initiation of standardisation work on material efficiency of energy using products[18], and publication of a standardised method to declare the presence of CRMs in products[19]; revision of waste legislative framework with a special focus on CRMs; and publication of the report "Critical Raw Materials and the Circular Economy"[16]. The present report delivers one of the last due actions of the plan, i.e. action #39 concerning "*Sharing of best practice for the recovery of critical raw materials from mining waste and landfills*".

Current circular use of critical raw materials

Recycling is an important source of SRMs. It can contribute to the security of raw materials supply and in advancing towards a more circular EU economy. A good measure of the circular use of CRMs is the recycling contribution to meeting materials demand in the EU for which the end-of-life recycling input rate (EOL-RIR) measures how much of the total material input into the production system comes from recycling 'old scrap' (i.e. post-consumer scrap)[20].

Although several CRMs have high recycling potential, and despite the encouragement from governments to move towards a circular economy, the EOL-RIR of CRMs is generally low (see **Figure 3**).

---

[15] EC - European Commission, 2018. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a Monitoring Framework for the Circular Economy. COM/2018/029 final.

[16] EC - European Commission, 2018. Commission Staff Working Document. Report on Critical Raw Materials and the Circular Economy. SWD (2018) 36 final.

[17] EC- European Commission, 2019. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the Circular Economy Action Plan. COM(2019) 190 final.

[18] http://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=search.detail&id=564

[19] https://www.cencenelec.eu/News/Brief_News/Pages/TN-2019-017.aspx

[20] Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Peirò, L.T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., Ciupagea, C., 2017. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. Resour. Policy 53, 12–19. doi:10.1016/j.resourpol.2017.05.008

This can be explained by several factors: i) for many CRMs, sorting and recycling technologies are not available at competitive costs yet; ii) it is impossible to recover materials which are in-use dissipated; iii) the supply of many CRMs is currently locked up in long-life assets, hence implying delays between manufacturing and scrapping and so directly influencing the recycling input rate; iv) demand for many CRMs is growing in various sectors and recycling contribution is largely insufficient to meet demand.

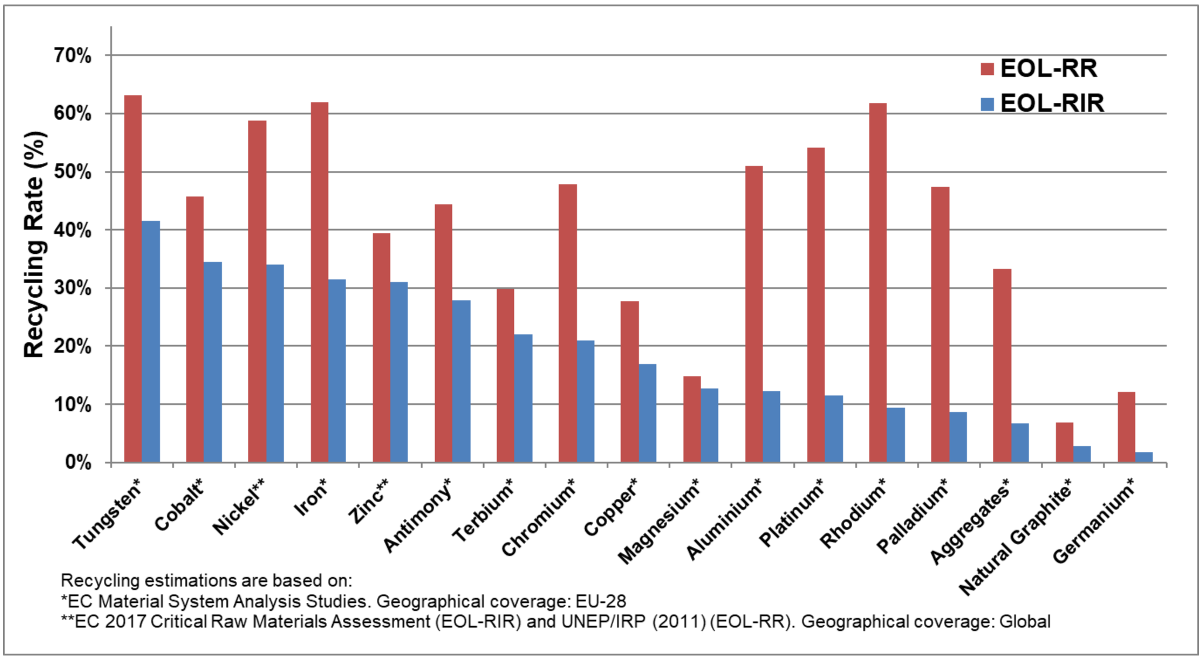


Figure 3. Current contribution of recycling to meet EU demand for CRMs: end-of-life recycling Input Rate (EOL-RIR). Source: JRC elaboration based on Deloitte Sustainability (2015 and 2017)[21,22].

A few CRMs, namely vanadium, tungsten, cobalt, and antimony have a high recycling input rate. These good performances can be explained by the fact that the collection rate at end-of-life is high: tungsten is mainly used in machine tools and vanadium in steel alloys (both mostly handled by businesses) that are consequently well collected at end-of-life; cobalt and antimony are primarily used in batteries that are well collected at end-of-life under the terms of waste legislation and the Batteries Directive.

Some other CRMs have a good rate of recycling at end-of-life (e.g. recycling rates for PGMs reaches as much as 95 % for industrial catalysts and 50-60 % for automotive catalysts) but this contribution is largely insufficient to meet the growing demand and so the recycling input rate is low (e.g., 14 % for PGMs).

When looking at an element like indium very much of which is used in flat display panels, only very small amounts of indium are currently recycled due to lack of infrastructure and the metal's volatile prices. Hence the recycling input rate is currently nil. However, exemplary recycling processes to extract indium from display panels in an economic way are currently under research and development[23].

---

[21] Deloitte Sustainability, British Geological Survey, Bureau de Recherches Geologiques et Minieres, Netherlands Organisation for Applied Scientific Research, 2017. Study on the review of the list of Critical Raw Materials - Criticality Assessment. Report prepared for the European Commission. Available at https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en. doi:10.2873/876644

[22] Talens Peiro, L., Nuss, P., Mathieux, F. and Blengini, G., Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data, EUR 29435 EN, Publications Office of the European Union, Luxembourg, 2018.

[23] Ardente, F., Mathieux, F., 2014. Identification and assessment of product measures to improve resource efficiency: the case-study of an Energy using Product. J. Clean. Prod. 83, 126–141. doi:10.1016/j.jclepro.2014.07.058

Figure 4 presents similar values for a broader range of raw materials, i.e., those that were in the 2017 EU criticality assessment[24].

Just as extraction of primary CRMs in Europe helps to ensure security of supply of raw materials to European industry, so does their resource efficient management throughout their lifecycle and the recycling of waste into secondary CRMs. Consequently, in the methodology for establishing the EU list of CRMs, substitution and recycling are considered to be risk-reducing measures. Environmental benefits of a more circular use may include, for instance, lower energy use (and associated air emissions), lower water use, and lower impacts on the biosphere (rainforests, arctic regions, ocean floors etc.) and/or less waste produced per tonne of material extracted.

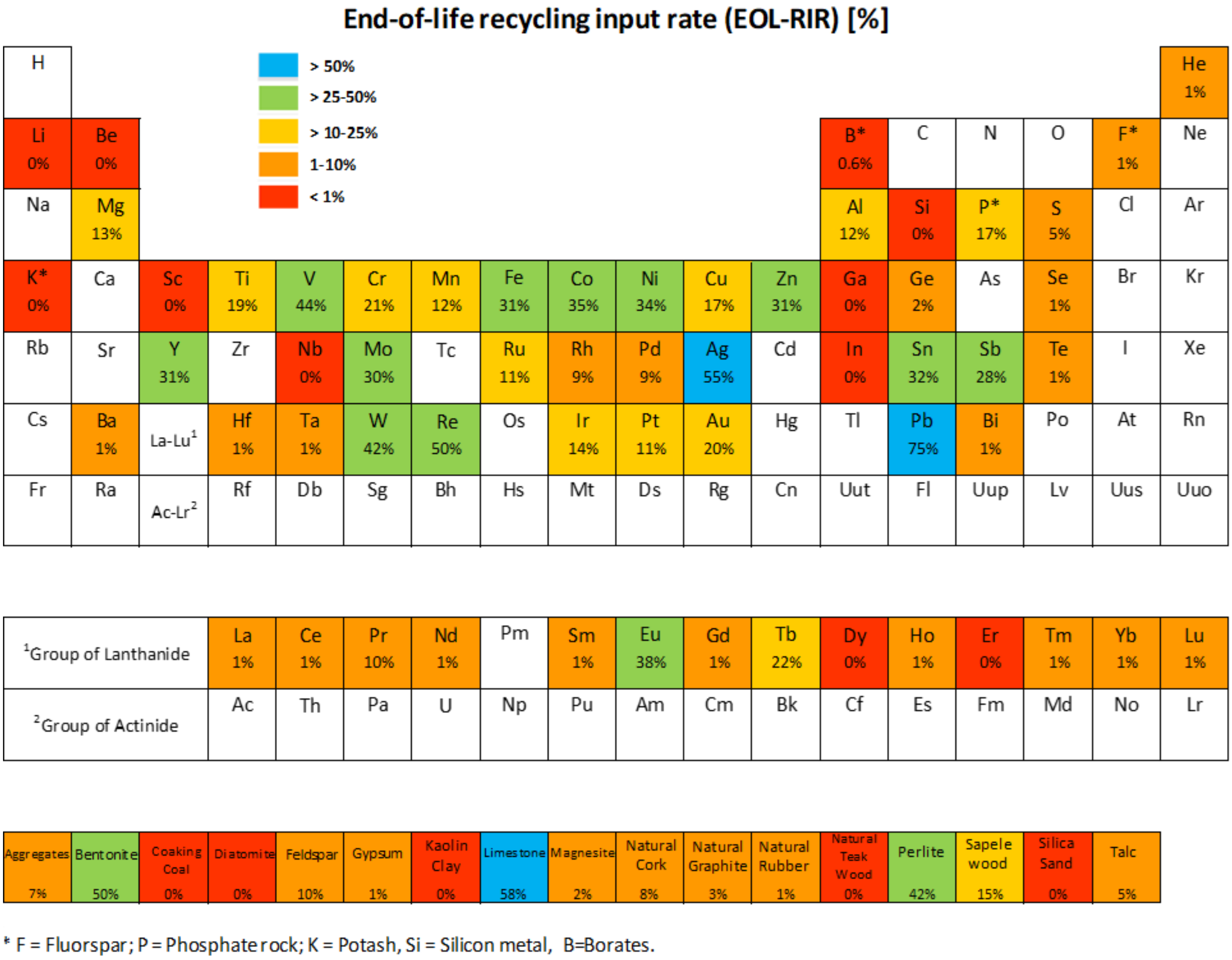


Figure 4 Current contribution of recycling to meet EU demand of CRMs: end-of-life recycling Input Rate (EOL-RIR). Source: JRC elaboration based on Deloitte Sustainability (2015 and 2017)[25].

---

[24] Deloitte Sustainability, British Geological Survey, Bureau de Recherches Geologiques et Minieres, Netherlands Organisation for Applied Scientific Research, 2017. Study on the review of the list of Critical Raw Materials - Criticality Assessment. Report prepared for the European Commission. Available at https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en. doi:10.2873/876644

[25] Talens Peiro, L., Nuss, P., Mathieux, F. and Blengini, G., Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data, EUR 29435 EN, Publications Office of the European Union, Luxembourg, 2018.

1.3 Key actors in the EU

The European Innovation Partnership on Raw Materials

The European Innovation Partnership on Raw Materials is a stakeholder platform that brings together representatives from industry, public services, academia, and NGOs. Its mission is to provide the European Commission, Members States, and private actors with high-level guidance on innovative approaches to the challenges with raw materials.

With regard to the EU industrial policy, the EIP-RM plays an important role in meeting the objectives of the Commission's flagship initiatives Innovation Union and Resource Efficient Europe. To foster innovative solutions, the EIP-RM developed its Strategic Implementation Plan (SIP)[26] which describes the specific objectives and targets as well as how their achievement is planned by carrying out a set of 95 concrete actions. These include research and innovation coordination, technologies for raw materials production, substitution, framework conditions, knowledge and skills, and international cooperation.

To implement these actions, the European Commission launched several Calls for Commitments[27] to Member States, industry, academia, and other relevant stakeholders. The Raw Material Commitments (RMCs) are joint undertakings made by several partners who commit themselves to carrying out activities that will contribute to achieving the actions and targets of the EIP within the period 2014-2020. The EC tracks the progress made by the RMCs by means of the Annual Monitoring Report[28].

Among the RMC, the European Enhanced Landfill Mining Consortium (EURELCO) should be noted. It is a multi-stakeholder network that supports the required technological, legal, social, economic, environmental, and organisational innovation for Enhanced Landfill Mining within the context of a transition to a circular, low carbon economy. Enhanced Landfill Mining is defined as "the safe exploration, conditioning, excavation, and integrated valorisation of (historic, present, and/or future) landfilled waste streams as both materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE), using innovative transformation technologies and respecting the most stringent social and ecological criteria"[29].

The EIT Raw Materials Knowledge and Innovation Community

EIT Raw Materials was initiated by the EIT (European Institute of Innovation and Technology), is co-funded under Horizon 2020, and is the largest consortium in the raw materials sector worldwide. It aims to boost competitiveness, growth, and the attractiveness of the European raw materials sector by driving and fostering innovation and empowering students, education partners, and entrepreneurs toward the circular economy. The EIT Raw Materials (RM) includes more than 120 partners from leading industries, universities, and research institutions from more than 20 EU countries. Partners of EIT RM are active across the entire raw materials value chain from exploration, mining, and mineral processing to substitution, recycling, and the circular economy. They collaborate on finding new, innovative solutions to secure supply and improve the raw materials sector in Europe. The EIT RM is expected to have a significant effect on European industrial competitiveness and innovation capacity as well as empowering students, entrepreneurs and education partners driving towards the circular economy. For instance, the EIT activities could result in the introduction of innovative and sustainable products, processes, and services as well as

---

[26] DG GROW (2013): Strategic Implementation Plan (SIP), endorsed by the EIP's High Level Steering Group on 25 September 2013. https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/strategic-implementation-plan-sip-0#Read%20EIP%20docs

[27] Call for commitments were launched in October 2013 and December 2015. The current call has been launched in June 2018. It is an open call with cut-off dates set biannually.

[28] EC - European Commission, 2017. European Innovation Partnership on Raw Materials: Annual Monitoring Report 2016, EUR 28839. ed. Publications Office of the European Union, Luxembourg. doi:10.2760/057300

[29] Jones, P.T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., Hoekstra, N., 2013. Enhanced Landfill Mining in view of multiple resource recovery: a critical review. J. Clean. Prod. 55, 45–55. doi:10.1016/J.JCLEPRO.2012.05.021

talented people delivering increased economic, environmental, and social sustainability to European society.

Among other activities, EIT RM supports innovation and education projects, and new businesses that scale up and introduce new technological solutions for recycling and optimisation of the material chains of end-of-life products.

The Ad hoc Working Group on Critical Raw Materials

The Ad hoc Working Group is an expert sub-group of the Raw Materials Supply Group, comprising representatives from the Member States, the extractive industries, intermediate user (e.g. steel), downstream industries, the recycling industry, academia, and geological survey(s).

The Ad-hoc Working Group on Critical Raw Materials (AHWG) has worked to develop the methodology for the criticality assessment since 2010, and helps the Commission in the regular updates of the CRMs lists.

European Expert Network on Critical Raw Materials

SCRREEN (Solutions for Critical Raw materials — a European Expert Network) is a Coordination and Support Action network aiming at gathering European initiatives, associations, clusters, and projects working on CRMs into a long-lasting Expert Network on Critical Raw Materials, including stakeholders, public authorities and representatives of civil society. This network will combine forces to address all CRMs issues including mining, processing, recycling, substitution, and final applications in relation to cross-cutting aspects: policy/society, technology, standards, and markets.

SCRREEN will contribute to the CRMs strategy in Europe by (i) mapping primary and secondary resources as well as CRMs substitutes, (ii) estimating the expected demand of various CRMs in the future and identifying major trends, (iii) providing policy and technology recommendations for actions improving the production and the potential substitution of CRM, (iv) addressing specifically WEEE and other end-of-life (EOL) product issues related to their mapping and treatment standardisation, and (vi) identifying the knowledge gained during recent years and easing access to this data for people and organisations outside the project. The knowledge gathered within the SCRREEN project will be collected and maintained in the Raw Materials Information System.

2 Relevant EU policy measures

2.1 Waste Framework Directive

The Waste Framework Directive 2008/98/EC lays down measures to protect the environment and human health by preventing the generation of waste, the adverse impacts of the management of waste, and the overall impacts of resource use and improving the efficiency of such use. For this purpose, the Directive provides definitions, principles, objectives, and targets as well as other requirements concerning waste management in the EU. These comprise the waste hierarchy, the polluter pays principle, the extended producers' responsibility, and recycling targets. In 2013, the 7th Environment Action Programme[30] set the following priority objectives for waste policy in the EU, drawing more ambitious targets for EU waste legislation:

- To reduce the amount of waste generated;
- To maximise recycling and re-use;
- To limit incineration to non-recyclable materials;
- To phase out landfilling to non-recyclable and non-recoverable waste;
- To ensure full implementation of the waste policy targets in all Member States.

In December 2015, the Commission adopted a proposal for changes to the Waste Framework Directive (and other waste related directives) as part of its Circular Economy package. In May 2018, the Directive 2018/851 amending Directive 2008/98/EC on waste was adopted. In its first recital the amended Directive states that "waste management in the Union should be improved and transformed into sustainable material management". Of particular relevance for this report are the provisions concerning CRMs in both recitals and articles, including that "Member States should take measures:

- To promote the re-use of products constituting the main sources of CRMs to prevent these materials becoming waste; (…)
- To achieve the best possible management of waste containing significant amounts of CRMs, taking economic and technological feasibility and environmental and health benefits into account, (…) and
- To include nationally appropriate measures regarding collection and recovery of waste containing significant amounts of CRMs in their waste management plans."

The present report should help Member States implement the proposed provisions on CRMs, especially those contained in extractive waste and landfills.

2.2 Extractive Waste Directive and the Reference Document on BAT

Although 'Circular use' of critical and other raw materials usually refers to recovery or recycling[31], a key contribution to a more circular economy may come from 'extractive wastes'[32] because they often contain valuable critical and other raw materials that have never been supplied to the economy before. Subjecting extractive waste to further extraction helps minimise waste and resource use at the same time: the amount of existing extractive waste can be reduced by further exploiting the remaining valuable fractions, which in turn minimises new waste generation thanks to a reduced need for extracting virgin resources. The potential for the recovery of raw materials from extractive waste depends on several factors such as their amount, concentration of the valuable commodities, and

[30] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013D1386&from=EN
[31] SWD (2018) 36 final, Part 1/3, Section 1.2.2, p.9.
[32] As defined in Article 2 of Directive 2006/21/EC.

mineralogy, the re-processing technology (commercially available and economically viable), and the market demand[33].

On the one hand, Directive 2006/21/EC, also called the Extractive Waste Directive (EWD), provides measures, procedures, and guidance to prevent and reduce, as far as possible, any adverse effects on the environment and human health resulting from the management of extractive waste. These represent the general objectives of the EWD. Nevertheless, according to Recitals 13 and 34 'prevention or minimisation' and 'recovery' of extractive waste are also part of these objectives. As a consequence, Article 5 sets specific requirements concerning both the minimisation and the recovery of extractive waste.

Prevention or reduction of extractive waste production and harm from them is envisaged in Article 5(2)(a) by for example considering:

- 'the choice of the waste management in the design phase and the method used for mineral extraction and treatment';
- 'placing extractive waste back into the excavation void after extraction of the mineral as far as is technically and economically feasible and environmentally sound'; and/or
- 'reusing topsoil'.

Recovery of extractive waste is envisaged in Article 5(2)(b) by encouraging:

- recycling;
- reusing; and/or
- 'reclaiming extractive waste where this is environmentally sound'.

In addition, the information on the composition of extractive waste, i.e. the type, quantity, and concentration of mineral resources left in the extractive waste because it is unprofitable at the time of extraction may be considered to be the starting point for the potential recovery of these resources in the future, when technology and market conditions allow. Hence, specific requirements on waste characterisation laid down in Article 5(3)(b) can contribute towards the recovery of critical and other raw materials.

On the other hand, pursuant to Article 21(3) of the EWD, the Commission published the Reference Document on Best Available Techniques (BAT) for the Management of Waste from Extractive Industries (MWEI BREF)[34].

The MWEI BREF focuses on the general objectives of the EWD. Nevertheless, it also includes a number of BAT conclusions contributing towards the circular economy. In this context the MWEI BREF provides useful information on BAT for the characterisation, minimisation, and recovery of non-energy mineral resources from extractive waste, e.g.:

- BAT 2 and BAT 3 on initial extractive waste characterisation, and review and verification of the extractive waste characteristics;
- BAT 6 on prevention of solid extractive waste generation;
- BAT 7 (b) on sorting and selective handling of extractive waste;
- BAT 10 on recovery of extractive waste.

Obviously, in case of re-processing extractive waste, the entire BREF is of relevance as such an activity would necessarily generate new or residual extractive waste that requires adequate management. For this reason, further information and guidance on the MWEI BREF

[33] Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. and Solar, S., Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-74282-8 doi:10.2760/378123 JRC108710.

[34] Garbarino, E., Orveillon, G., Saveyn, H.G.M., Barthe, P., Eder, P., Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries, in accordance with Directive 2006/21/EC; EUR 28963 EN; Publications Office of the European Union, Luxembourg, 2018; ISBN 978-92-79-77178-1; doi:10.2760/35297, JRC109657.

is provided in chapter 3, always with emphasis on the recovery of critical and other raw materials from extractive waste.

2.3 Landfill Directive

According to the waste management hierarchy, landfilling is the least preferable option and should be limited to the necessary minimum. Where waste needs to be landfilled, it must be sent to landfills, which comply with the requirements of Directive 2018/850 amending Directive 1999/31/EC on the landfill of waste. The objective of the Directive is to ensure a progressive reduction of landfilling of waste and to prevent or reduce as far as possible negative effects on the environment, in particular on surface water, groundwater, soil, air, and on human health from the landfilling of waste by introducing stringent technical requirements for waste and landfills.

Landfills are waste disposal sites for the deposit of waste onto or into land (Directive 2018/850[35] amending Directive 1999/31/EC). Controlled landfills are divided into three categories: landfills for hazardous waste, landfills for non-hazardous waste, and landfills for inert waste.

The Council decision (2003/33/EC) establishes criteria and procedures for the acceptance of waste at landfills.

2.4 Horizon 2020

Horizon 2020 has been instrumental in implementing the EU Raw Materials Initiative and the European Innovation Partnership (EIP) on Raw Materials. Particularly the Societal Challenge 5 on climate action, environment, resource efficiency, and raw materials (SC5) has helped to respond to the challenge of securing sustainable access to raw materials and particularly CRMs.

More than €350 million has so far been invested in R&I actions under SC5 in developing and demonstrating sustainable production of primary and secondary raw materials including CRMs in the EU. The Commission already funded at least 65 research projects and policy support actions of which more than half concern CRMs. All of the actions should help to consolidate a growing raw materials R&I community in Europe and outside.

In the latest period of 2018-2020, more than €250 million have been specifically budgeted for the actions on raw materials, of which more than €100 million is earmarked for a Circular Economy Focus Area.

Building on a first inventory of H2020 projects addressing CRMs from mineral-based waste developed by the H2020 SCRREEN project[36]. **Table 2** presents a list of relevant closed or on-going EU funded projects related to the topic of this report is shown below. The last column of Table 2 indicates whether the project refers to a technology pillar or to a non-technology pillar (Framework conditions and Knowledge base) as defined in the 2013 Strategic Implementation Plan of the European Innovation Partnership on raw materials (EIP-SIP).

[35] OJ L 150, 14.6.2018, p. 100–108

[36] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S., Lauri, L., 2018. Identification and quantification of secondary CRM resources in Europe. Deliverable 3.2 of H2020 SCRREEN Project.

Table 2 List of relevant completed and on-going EU projects addressing CRMs from mineral-based waste and landfills.

Project acronym	**Full name**	**Status**	**Relevance concerning CRMs in mining waste and landfill**	**Links**	**Priority areas**
CHROMIC	effiCient mineral processing and Hydrometallurgical RecOvery of byproduct Metals from low-grade metal contaIning seCondary raw materials	On-going until 2020	By smart combinations of existing methods and new technological innovations, CHROMIC aims to develop new processes to recover chromium, vanadium, molybdenum, and niobium from industrial waste. So it enhances recovery of certain CRMs from waste flows and reduces their storage in landfill.	http://www.chromic.eu/	Technology
SCALE	Production of Scandium compounds and Scandium Aluminum alloys from European metallurgical by-products	Ongoing until 2020	The SCALE project aims to develop and secure a European Sc supply chain by developing technological innovations which allow the extraction of Sc from European industrial residues, namely bauxite residues from alumina production (5 Million tonnes per year in Europe on dry basis) and acid wastes from TiO_2 pigment production (1.4 Million tonnes on dry basis per year in Europe). SCALE develops and demonstrates the value chain. SCALE develops innovative technologies that can extract economically and sustainably Sc from dilute mediums (<100 mg/L) and upgrade them to pure oxides, metals, and alloys at lower energy or material cost.	SCALE	Technology
RemovAL	Removing the waste streams from the primary Aluminium production and other metal sectors in Europe	On-going until 2022	In term of technological aspects, RemovAl will process several by-products from the aluminium sector and from other metallurgical sectors in Europe (SiO_2 by-products, SPL, fly ash, and others). The different waste streams will be combined to allow for optimal and viable processing in different technological pilot nodes. In most cases the technologies and pilots have already been developed in previous or ongoing projects, and they will be pooled together by RemovAl and used in a European industrial symbiosis network. In term of societal or non-technological aspects, RemovAl will gather key sectors like the non-ferrous metal and cement sectors in order to secure a true industrial symbiosis by using	RemovAL	Technology

Project acronym	Full name	Status	Relevance concerning CRMs in mining waste and landfill	Links	Priority areas
			a top-down approach also considering legislation and standardisation at European level in order to facilitate the implementation of the most promising technical solutions.		
ERA-MIN	Research & innovation programme on raw materials to foster circular economy	On-going until 2021	ERA-NET Cofund on Raw Materials (ERA-MIN 2) is a public-public partnership funded under Horizon 2020. ERA-MIN 2 aims to implement a European-wide coordination of research and innovation programmes on raw materials to strengthen the industry, competitiveness, and the shift to a circular economy. So far, ERA-MIN has funded several projects which deal with secondary mineral resources and CRMs, within topic areas such as Recycling of mining and smelting residues (including historical dumps and tailings), and extraction, minerals processing, mine closure, and rehabilitation.	https://www.era-min.eu/node/3	All
EURARE	EURARE (Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits')	Closed in 2017	EURARE was a project for the 'Development of a sustainable exploitation scheme for Europe's rare earth ore deposits'. Some elements concerned secondary rare earths from mining waste although the main focus was on primary resources.	http://www.eurare.eu/	Framework conditions and Technology
METGROW+	Metal Recovery from Low Grade Ores and Wastes	On-going until 2020	METGROW+ aims to develop innovative metallurgical technologies to unlock the use of potential domestic raw materials. Within this project, both primary and secondary materials are studied as potential metal resources. Economically important nickel-cobalt deposits, low grade polymetallic wastes, and iron containing sludges are being focussed on. Concurrently, METGROW+ targets innovative processes to extract important metals including Ni, Cu, Zn, Co, In, G, and Ge in a cost-effective way.	https://metgrowplus.eu/	Technology
MICA	Mineral Intelligence Capacity Analysis	Closed in 2018	MICA developed the European Raw Materials intelligence Capacity Platform (EU-RMCP) with an innovative visualization interface that guides the user to a 'recipe' for how to find answers to particular mineral raw material related questions. MICA enables the user to explore data, acquire information,	http://www.mica-project.eu/ http://metadata.mica-project.eu/mmd/	Knowledge Base

Project acronym	Full name	Status	Relevance concerning CRMs in mining waste and landfill	Links	Priority areas
			and build up knowledge. CRMs and secondary mineral resources are topics covered by MICA.		
Minerals4 EU	Minerals Intelligence Network for Europe	Closed in 2018	The project aimed to develop an EU Mineral intelligence network structure delivering a web portal, a European Minerals Yearbook, and foresight studies. Some datasets of the platform concern the potential of obtaining secondary (critical) raw materials from mining waste[37].	http://minerals4eu.eu/ http://minerals4eu.brgm-rec.fr/	Knowledge Base
Min-guide	Minerals Policy Guide	Closed in 2019	The MIN-GUIDE project was designed to contribute to establishing a policy framework promoting innovative and sustainable approaches to tackle challenges in the mining value chain. Some of the recommendations concern CRMs and SRMs from mining waste.	https://www.min-guide.eu	Framework conditions
MINVENTORY	The Minventory metadata portal	Project closed	The Minventory metadata portal is a directory of statistical data holders, the characteristics of the data they hold and – where possible – links to where the data may more easily be located. It covers the EU28 and a number of neighbouring countries. The portal contains links to data holders on CRMs and on mining waste and landfill stocks.	https://ec.europa.eu/jrc/en/scientific-tool/minventory	Knowledge Base
ORAMA	Optimising data collection for Primary and Secondary Raw Materials	Running until 2019	The ORAMA project focuses on optimising data collection for primary and secondary raw materials (including CRMs from mining waste) in Member States.	https://orama-h2020.eu/	Knowledge Base
ProSUM	Prospecting Secondary raw materials in Urban mine and Mining wastes	Closed in 2017	ProSUM developed the very first EU-wide and open-access Urban Mine Platform. This dedicated web portal is populated by a centralised database containing all readily available data on market inputs, stocks in use and hibernated, compositions, and waste flows for all EU 28 Member States	http://www.prosumproject.eu/ http://www.urbanmineplatform.eu	Knowledge Base

[37] http://minerals4eu.brgm-rec.fr/node/45538 [accessed on 05/02/2019]

Project acronym	Full name	Status	Relevance concerning CRMs in mining waste and landfill	Links	Priority areas
			plus Switzerland and Norway. ProSUM covered batteries, electronics, vehicles, and mining waste and looked at waste composition, including CRMs.		
RESLAG	Turning waste from steel industry into valuable low cost feedstock for energy intensive industry	Running until 2019	The European steel industry still generates large quantities of steel slag as waste, out of which 24 % is landfilled or self-stored. The landfilled slag represents a severe environmental problem. The main aim of RESLAG is to prove that there are industrial sectors able to use the 2.9 Mt/y of landfilled slag effectively if properly supported by the right technologies. In proving this, the RESLAG project will also prove that there are other very important environmental benefits from "active" use of the slag in industrial processes such as CO_2 savings and elimination of negative impacts associated with mining (from the recovery of valuable metals and from the production of ceramic materials).	http://www.reslag.eu/	Technology
SCRREEN	Solutions for Critical Raw materials — a European Expert Network	On-going until 2020	SCRREEN aims to gather European initiatives, associations, clusters, and projects working on CRMs into a long-lasting Expert Network on CRMs, including stakeholders, public authorities, and representatives of civil society. This network combines forces to address all the CRMs issues including mining, processing, recycling, substitution, and final applications in relation to cross-cutting aspects: policy/society, technology, standards, and markets. Some deliverables of the projects concern secondary CRMS resources in Europe, also obtained from mining waste[38].	http://scrreen.eu/	Knowledge Base
SMART GROUND	SMART data collection and inteGRation platform to enhance availability and accessibility of data and infOrmation in the EU territory on SecoNDary Raw Material	Closed in 2018	SMART GROUND aimed to improve the availability and accessibility of data and information on SRMs in the EU. The project integrated the data from existing sources and new information in a single EU database, covering extractive waste, municipal solid waste, and industrial waste.	http://www.smart-ground.eu/ http://smartground.atosresearch.eu/home	Knowledge Base

[38] http://scrreen.eu/wp-content/uploads/2018/03/SCRREEN-D3.2-Identification-and-quantification-of-secondary-CRM-resources-in-Europe.pdf

2.5 EIT Raw Materials

In order to enable sustainable competitiveness of the European minerals, metals, and materials sector along the value chain, EIT RawMaterials encourages structured collaboration within the Knowledge Triangle, composed of academia, research institutes, and business. It facilitates an exchange of needs, ideas, research results, and best practices. Initiatives with innovative ideas are supported by EIT Raw Materials to turn their ideas into business opportunities through an innovation system. **Table 3** below establishes a list of relevant on-going technological upscaling EIT Raw Materials funded projects concerning the topic of this report. Projects are either technological, or related to internationalisation, Regional Innovation Schemes, or to Wider Society Learning.

Table 3 On-going EIT Raw Materials projects (completed and on-going projects addressing CRMs from mineral-based waste)

Project acronym	Full name	Status	Relevance concerning CRMs in mining waste and landfills	Links	Focus
CarsiFer	Innovative Recycling solution for waste containing Carbon, Silicon and Iron.	Running until 2022	Nowadays, most ores and metals are imported to Europe, which, inherently, already constitutes a growing geopolitical concern. In the meantime a great deal of valuable industrial waste with high metallic content are also unused, diluted with other waste streams or dumped in landfills. However, most of the time, these wastes contain a mix of carbon/graphite, iron, silicon and valuable metals as manganese, copper and nickel, which could be valorized by the industry. This project aims to develop a new concept: the production of raw materials dedicated to foundries from wastes containing carbon/graphite, silicon and metals such as carbon, silicon and iron (CarSiFer). To transform waste into a useful metallurgical product for foundries, the project will be addressing several aspects ranging from the identification and collection of waste streams to the actual treatment of the material through briquetting, and finally deliveries to foundries for validation.	https://eitrawmaterials.eu/project/carsifer/	Technology
Go-4-0	From iron and manganese oxides wastes to valuable metal alloys using novel carbon sources materials.	Running until 2019	This project aims at reducing the need for landfill deposits by turning waste streams from the metal industry into valuable products. Waste streams targeted originate from carbothermic production of silicon & ferro-manganese alloys and from metal and carbon containing waste streams from steel and metal recycling activities.	https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/iron-and-manganese-oxides-wastes-valuable-metal-alloys-using-novel-carbon-sources-materials	Technology
Morecovery	Modular recovery process services for hydrometallurgy and water treatment.	Running until 2021	The need for raw materials, especially rare earth Elements (REE), is increasing rapidly in EU and globally. At the same time, the amount of mine waste is increasing drastically. Mining industry can achieve more eco-efficient and selective raw material production by enhancing the utilization of side streams and mine waste. There is a need to develop more efficient recovery methods and to efficiently remove dissolved metals from mine water streams, while securing the surrounding environment and ecosystem. The main objective of the project is to enhance the eco-efficient and sustainable use of natural	https://eitrawmaterials.eu/project/morecovery	Technology

Project acronym	Full name	Status	Relevance concerning CRMs in mining waste and landfills	Links	Focus
			resources through creating a modular recovery process service package for hydrometallurgy and water treatment.		
PhosForce	Market ready technologies for P-recovery from municipal wastewater.	Running until 2021	While EU imports 92% of its phosphorus, this project aims to offer a unique solution to recover this essential CRM from urban wastewater for recycling as fertilizer. This project aims at giving a solution to German middle-sized waste water treatment plants by up-scaling a new phosphorus recovery process scheme in waste water treatment plants sludge stream and demonstrating its technical and economical performances at large scale. The process targets > 50% phosphorus recovery and will be cost-effective, easy to implement, eco-friendly and will present low health safety risks. An industry-driven consortium will prove the process competitiveness through prototype and demo phases, product analysis and modelling work leading to market take off.	https://eitrawmaterials.eu/project/phosforce/	Technology
SlagVal	Slag valorization for multi metal recovery and mineral resource production.	On-going until 2021	The project will provide a ready for implementation solution for the growing challenge of waste management in the companies which produce white slag by complete transformation of its volume into construction material, thus eliminating the environmentally hazardous material, and at the same time providing additional profit to the companies thanks to the recovery of base (Zn, Pb, Cu) and by-product (Ag, Sb, Sn) metals which are contained therein.	https://eitrawmaterials.eu/project/slagval/	Technology
Vivimag	A novel magnetic route for phosphorus and iron recovery from sewage sludge.	Running until 2020	Phosphorus (P) use has to become more sustainable and should include P-recycling from secondary resources. This will not only prevent eutrophication of surface waters, but will also minimize costs for disposal of phosphorus rich wastes. Phosphorus is a key nutrient in fertilizers and therefore essential for our food production. Phosphate rock is mined and processed to produce phosphorus containing fertilizers, like PK-fertilizers. However, exploitable phosphate rock reserves are found in just a few countries. The EU itself has hardly any phosphate rock reserves and depends nearly entirely on the import of this crucial resource; in 2005 the primary P import of the EU-27 was 1777 ktonne. The EU has therefore added phosphate rock to the list of CRMs. This project will demonstrate recovery of the iron phosphate mineral vivianite from sewage sludge. Through a controlled dosing strategy in	https://eitrawmaterials.eu/project/vivimag/	Technology

Project acronym	Full name	Status	Relevance concerning CRMs in mining waste and landfills	Links	Focus
			combination with sludge digestion the formation of this mineral in sewage sludge can be stimulated.		
IRTC	International Roundtable on Materials Criticality	On-going until 2020	IRTC is an international network of experts in CRMs who work on definitions and assessments on which materials are or will be critical in the future. Since "criticality" depends on the perspective – e.g. how scarce a material is in one's own region, or how much of it is needed in an economy or a technological sector – these approaches differ. The IRTC project provides a platform for international researchers to exchange, hold events at international conferences with interested participants, and publish their joint research. The project will also educate junior researchers, engage with industry and advice authorities on how to integrate the topic in strategies and policies on a national and global level. Its final goal is a long-lasting international collaboration.	https://irtc.info	Internationalisation
USEPGM-NET	USA-Europe platinum Group Metal Network	On-going until 2020	The project aims at delivering a joint research and innovation agenda between USA and Europe to improve the platinum group metal supply from primary and secondary resources. This will be achieved by analysing PGM value chains, identifying bottlenecks limiting their production and proposing joint R&D&I tracks to fix them. The work will be based on knowledge already existing with the Partners or being generated within EU or USA actions or projects.	https://eitrawmaterials.eu/project/usepgm-net/	Internationalisation
RIS-CuRE	Zero waste recovery in copper tailings in the ESEE region	On-going until 2021	The activities of the RIS-CuRE project are based on an innovation model merging all relevant stakeholders within the knowledge triangle in the field of industry, research, and education in order to increase regional competitiveness based on a regional scale, taking into account the latest know-how of the RIS-CuRE consortium. This innovative approach is based on the zero waste paradigm, which means that, once valuable raw materials such as CRMs and other metals are extracted, the residues can be recycled for the construction sector.	https://eitrawmaterials.eu/project/ris-cure/	Regional innovation scheme
RIS-RECOVER	Regional innovation scheme for zero	On-going	The RIS-RECOVER project activities are based on a quintuple innovation helix approach merging industry, research/education, government, the general public and environment sectors in order to increase regional competitiveness based on a regional background	https://eitrawmaterials.eu/project/ris-recover/	Regional innovation scheme

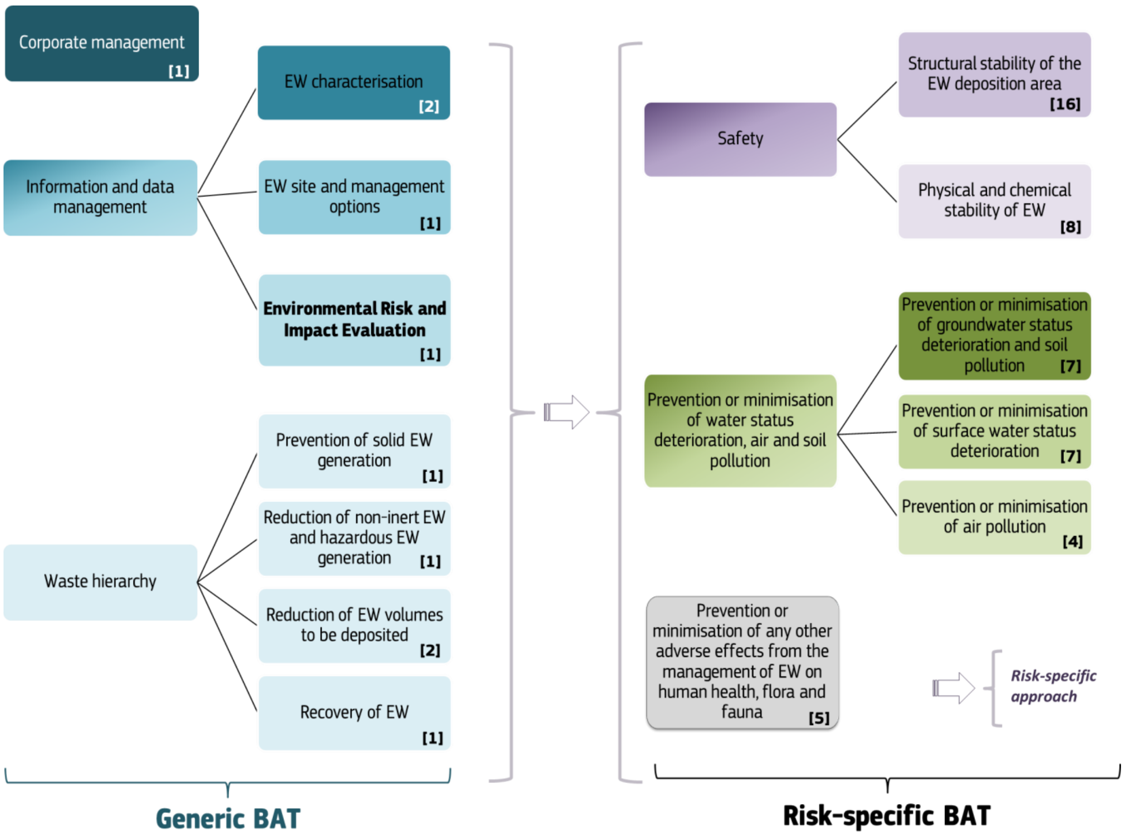
Project acronym	**Full name**	**Status**	**Relevance concerning CRMs in mining waste and landfills**	**Links**	**Focus**
	waste extraction of critical raw materials	until 2021	and the latest know-how of the RIS-RECOVER consortium. The innovative approach is based on the zero waste paradigm, which means that, once valuable raw materials like CRMs and metals are extracted, the residues can be recycled for the construction sector. Such holistic eco-innovative approach of the extraction of CRMs and other metals and the beneficial use of residues from old environmental burdens provide a guarantee for the development of regional innovation scheme which is based on the optimal positioning of the management of old landfills. This will lead to development of encouraging environment for boosting entrepreneurship and entrepreneurship in three region based on exploration of secondary deposits. The final output of the project will be a regional innovation scheme based on validated and fact-based data including a study of the potential economic, technological, organisational (legislative), environmental and social impacts of applying the innovative methodology of zero waste extraction of valuable materials in Macedonia.		
AWARE	Raising public awareness on electronic waste as a source of valuable materials.	On-going until 2020	The focus of the project will be on education and involvement of school children, both to raise the awareness of end-of-life electronics as a resource, and through them to bring the message into families and the society as whole. The aim of the project is to increase the share of waste ending up in official take-back systems instead of loosing the resource to waste disposal or incineration plants and collection outside official take-back systems.	https://eitrawmaterials.eu/course/aware-raising-public-awareness-on-electronic-waste-as-a-source-of-valuable-materials/	Wider Society Learning

3 Best Available Techniques for the Management of Waste from Extractive Industries

3.1 MWEI BREF and recovery of critical and other raw materials

Critical and other raw materials can be recovered from both authorised extractive waste facilities in operation/closure and from abandoned extractive waste facilities, i.e. extractive waste facilities left by the operator and not properly closed. Authorised facilities are covered under the Best Available Techniques Reference Document for the Management of Waste from the Extractive Industries, abbreviated as MWEI BREF[39], while abandoned facilities are excluded from its scope. Nonetheless, this reference document may also be useful in the case of re-mining abandoned or closed sites, considering that the same measures on the management of the newly generated extractive waste from re-mining, or any residual extractive waste, will basically apply to prevent or reduce as far as possible any adverse effects on the environment and human health.

With the aim of protecting the environment and ensuring the safety of the storage facility while managing extractive waste, the MWEI BREF provides up-to-date information and data on extractive waste management and Best Available Techniques (BAT). The 57 BAT have been divided into generic BAT (10), generally applicable regardless of the site, and risk-specific BAT (47), applicable to sites where specific risks of adverse effects on the environment or human health are identified (see **Figure 5**).



[number of BAT conclusions in each section]; EW = extractive waste

Figure 5. Overview of the generic and risk-specific BAT presented in the MWEI BREF by applying a risk-specific approach.

[39] Garbarino, E., Orveillon, G., Saveyn, H.G.M., Barthe, P., Eder, P., Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries, in accordance with Directive 2006/21/EC; EUR 28963 EN; Publications Office of the European Union, Luxembourg, 2018; ISBN 978-92-79-77178-1; doi:10.2760/35297, JRC109657.

Whereas the MWEI BREF is focused on the whole life cycle of extractive waste management - including planning and design, operation and closure & after-closure phases - several BAT conclusions hold particular relevance for the recovery of critical and other raw materials from extractive waste. These include:

- Generic BAT conclusions on corporate management [BAT 1].
- Generic BAT conclusions on information and data management:
  - Extractive waste characterisation:
    - initial extractive waste characterisation [BAT 2];
    - review and verification of the extractive waste characteristics [BAT 3].
  - Extractive waste site and management options [BAT 4].
  - Environmental Risk and Impact Evaluation [BAT 5].
- Generic BAT conclusions on the circular economy/waste hierarchy:
  - Prevention of solid extractive waste generation [BAT 6].
  - Reduction of non-inert extractive waste and hazardous extractive waste generation [BAT 7] and particularly sorting and selective handling of extractive waste [BAT 7.b].
  - Recovery of extractive waste [BAT 10].
- Risk-specific BAT conclusions to ensure safety:
  - Design for closure [BAT 11].
  - Additional Organisational and Corporate Management tools [BAT 12].
  - Geotechnical analysis of the extractive waste deposition area [BAT 22].
  - Monitoring of the structural stability of the extractive waste deposition area [BAT 23].
  - Conformance checks [BAT 24].
  - Solid/liquid control of extractive waste [BAT 27].
  - Stabilisation of extractive waste for placing back into excavation voids [BAT 28].
  - Compaction, consolidation and deposition of extractive waste [BAT 29].
  - Prevention or minimisation of pollutant leaching [BAT 30].
  - Prevention or minimisation of Acid Rock Drainage (ARD) [BAT 31].
- Risk-specific BAT conclusions for the prevention or minimisation of water status deterioration, air and soil pollution:
  - Covering [BAT 38].
  - Groundwater and soil pollution remediation [BAT 39].
  - Extractive waste influenced water generation prevention [BAT 42], particularly landscaping and geomorphic reclamation [BAT 42.d] and use of reagents or chemicals with a low environmental impact [BAT 42.e].
  - Monitoring of emissions to soil and groundwater [BAT 40], of emissions to surface water [BAT 48] and of emissions to air [BAT 52].

The BAT conclusions listed above are discussed in more detail in the following sections.

3.2 Generic BAT applicable to the recovery of critical and other raw materials

3.2.1 Recovery of extractive waste

The MWEI BREF contains a generic BAT on the re-processing of extractive waste, in order to recover valuable resources. The aim of this BAT is to encourage the re-use and recycling of solid extractive waste and application of circular economy principles in general.

Extractive waste is usually re-processed by means of mineral processing techniques. These include comminution techniques (i.e. crushing, grinding, screening, etc.) and beneficiation techniques (i.e. sorting, gravity concentration, magnetic separation, electrostatic separation, flotation, leaching, etc.). In addition to the recovery of valuable raw materials, operators and society may benefit from site rehabilitation. This may be particularly relevant in the case of abandoned sites, since the residual extractive waste generated by the re-processing will be properly managed, allowing in turn to properly close the site.

A recovery example is provided in the case study of the old Penouta mine (see Section 7.1). Tailings deposited in old dumps and ponds are re-processed by means of gravimetric separation and the following material streams are produced:

- tantalum and niobium (an Sn-Ta-Nb concentrate), which are CRM;
- quartz, mica, feldspar and kaolin, which are valuable industrial minerals; and
- residual extractive waste, which is used for the final rehabilitation of the Penouta site.

Another feature is the site rehabilitation which helps reduce the environmental impacts of the formerly abandoned mine.

It has to be emphasised that the occurrence of CRMs may not per se justify a re-mining activity. In determining what part of the deposited extractive waste can be considered in a mineral resource estimate, the evaluation of the cut-off grade may include both the critical and other valuable raw materials to be recovered. Furthermore, the recovery of critical and other valuable raw materials may be neither economic nor sustainable without solving the issue of the residual extractive waste. Maximising the mineral yield with little or no regard for the generation of extractive waste streams is not an option from an environmental point of view. Instead, the valorisation of the residual extractive waste is a key aspect leading towards a more sustainable circular economy model.

3.2.2 Prevention and reduction of extractive waste generation

In addition to the recovery of valuable raw materials, the MWEI BREF also focuses on prevention and on appropriate planning and management of the different streams, including a proper waste characterisation. This should avoid the discarding of valuable critical and other raw materials, which can be used for construction or rehabilitation purposes, into waste deposits. The appropriate planning of the extractive waste management options is ensured by drawing up an Extractive Waste Management Plan, according to Article 5 of Directive 2006/21/EC.

A further example is the BAT on sorting and selective handling of extractive waste, which aims at reducing the generation of non-inert extractive waste and hazardous extractive, and possible ARD.

3.2.3 Corporate management

Some of the potential environment and human health impacts linked to the management of extractive waste can be reduced substantially by considering the whole life cycle of the extractive site and the waste facilities. This also applies to the recovery of critical and other raw materials from extractive waste.

Operators responsible for the management of extractive waste can improve overall management efficiency by implementing systematic procedures at management level. This includes the application of an Organisational and Corporate Management system, encompassing risk management or operational management tools, and an Environmental Management System.

3.2.4 Data and information management

To support the decision making process and the corporate management, appropriate data and information management is important. When it comes to assess the feasibility of a recovery project of critical and other raw materials from extractive waste, a detailed analysis of the techno-economic and environmental issues is needed. This includes the assessment of any adverse effects on water, air, soil, fauna and flora, landscape or places of special interest, and of any resultant risks to human health. If the latter is the case a proper risk assessment may be needed. The final rehabilitation of a site, by using the residual extractive waste is part of the recovery project, as for example described in the Penouta mine case study (see 7.1).

A multi-criteria analysis is usually performed to assess the feasibility of the recovery process and can be supported by the application of the following BAT to determine the potential environmental risks and impacts resulting from the management of extractive waste:

- Initial characterisation of the extractive waste, followed by review and verification. According to this BAT, the behaviour and characteristics of representative samples of the extractive waste are investigated according to the provisions of Commission Decisions 2009/359/EC and 2009/360/EC as well as the guidance documents developed by CEN/TC 292 (see **Table 4**).
- Identification of the extractive waste site and management options, e.g. deposition on heap versus underground storage. This BAT concerns the identification of distinct site options, handling/transport options (e.g. conveyor belts, pipelines, trucks), treatment options and deposition options (e.g. temporary storage in heaps or ponds, permanent deposition in heaps, ponds or excavation voids) considering the whole life cycle of extractive waste management.
- Environmental Risk and Impact Evaluation. This is the core BAT of the MWEI BREF, as it translates information about the project into decisions on suitable BAT. It consists of a structured, dynamic and often iterative process, where all the environmental risks and impacts resulting from the extractive waste management (including source-pathway-receptor linkages) are identified, analysed and evaluated over the whole life cycle, in order to identify the risk-specific BAT that are most appropriate for the project.

Table 4: Guidance documents and standard on extractive waste characterisation developed by CEN/TC 292

Standard	**Description**
CEN/TR 16376:2012	"Characterization of waste. Overall guidance document for characterisation of waste from the extractive industries"
CEN/TR 16365:2012	"Characterization of waste. Sampling of waste from extractive industries"
CEN/TR 16363:2012	"Characterization of waste. Kinetic testing for assessing acid generation potential of sulphidic waste from extractive industries"
CEN/TS 16229:2011	"Characterization of waste. Sampling and analysis of weak acid dissociable cyanide discharged into tailings ponds"
EN 15875:2011	"Characterization of waste. Static test for determination of acid potential and neutralisation potential of sulphidic waste."

3.3 Risk-specific BAT applicable to the recovery of critical and other raw materials

3.3.1 Design for closure

The design for the closure and after-closure approach is a risk-specific BAT, which helps to ensure the short-term and long-term structural stability of the extractive waste deposition areas such as ponds, dams and heaps. It deals with the inclusion of an initial closure and after-closure planning which may contain the following:

- an assessment of costs related to the proposed and alternative closure strategies;
- a cost-benefit analysis of recovery processes carried out at a later stage;
- a preliminary identification of the covering techniques, for example, by specifying whether or not a dry cover (e.g. a permeable or impermeable cover) will be implemented or whether or not a free water cover is preferable;

- the identification of the type of rehabilitation of the extractive waste deposition area or the extractive site, which may be progressively carried out during operation or entirely implemented in the closure phase;
- details on the final landform and surface rehabilitation, also taking the BAT on geomorphic reclamation into consideration. This is also relevant in the case of a recovery project, where the residual extractive waste is used for the final rehabilitation of the site, as in the Penouta mine case study (see 7.1);
- the identification of techniques for preventing and controlling water and wind erosion, ensuring long-term stability of the deposition area and monitoring.

The final design of an extractive waste deposition area or an extractive site is carried out appropriately by considering the various closure options from the planning and design phase, by updating the design assumptions during operation and by providing a final plan at the closure phase.

3.3.2 Geotechnical analysis and monitoring of the structural stability

In the risk-specific BAT on geotechnical analyses, all of the mechanisms that can negatively affect the partial or total structural stability of the extractive waste deposition areas are considered, in order to help ensure the short and long-term structural stability. Furthermore, BAT is to monitor the structural stability of these areas and to support the monitoring measures through conformance checks, reviews, audits and safety evaluations. These BAT also apply to a recovery process where old deposition areas of extractive waste may be re-mined.

3.3.3 Physico-chemical stability of extractive waste

In order to help ensuring the physical stability of extractive waste, the following BAT can be applied:

- the solid/liquid control of extractive waste, by using one or a combination of techniques such as mechanical screening, hydro-cycloning, thickening and clarifying and dewatering by means of a pressure gradient or a centrifugal force;
- the stabilisation of extractive waste before placing it back into excavation voids;
- the compaction, consolidation and deposition of extractive waste by using techniques such as thickened/paste extractive waste subaerial deposition, wet or dry filter cake deposition (or dry stacking), placing extractive waste back into excavation voids, mud farming and co-disposal.

For example, in the case study of the old Penouta mine (see 7.1), the residual extractive waste is placed back in the old tailing ponds and in the excavation voids of the old open pit mine for the final rehabilitation of the site.
Solid/liquid control techniques such as thickening and clarifying or dewatering by means of a pressure gradient or a centrifugal force, followed by wet or dry filter cake deposition (or dry stacking) or mud farming, are particularly relevant for extractive waste from alumina refining (red muds). Red muds can either be used as a secondary raw material in certain circumstances or re-processed to recover critical or other valuable raw materials (IAI 2015[40]). Examples of CRMs potentially recoverable from red muds are rare earth elements (for example, see the EURARE, BRAVO[41], and REDMUD[42] projects and Section 7.4), scandium (see the ongoing SCALE[43] project), vanadium and gallium (for example, see the BRAVO project). Other raw materials potentially recoverable are, for example, metals such as iron, titanium, and aluminium. Furthermore, red muds can also be

[40] IAI (2015). Bauxite Residue: Management Best Practice, International Aluminium Institute & European Aluminium Association. http://www.world-aluminium.org/media/filer_public/2015/10/15/bauxite_residue_management_-_best_practice_english_oct15edit.pdf

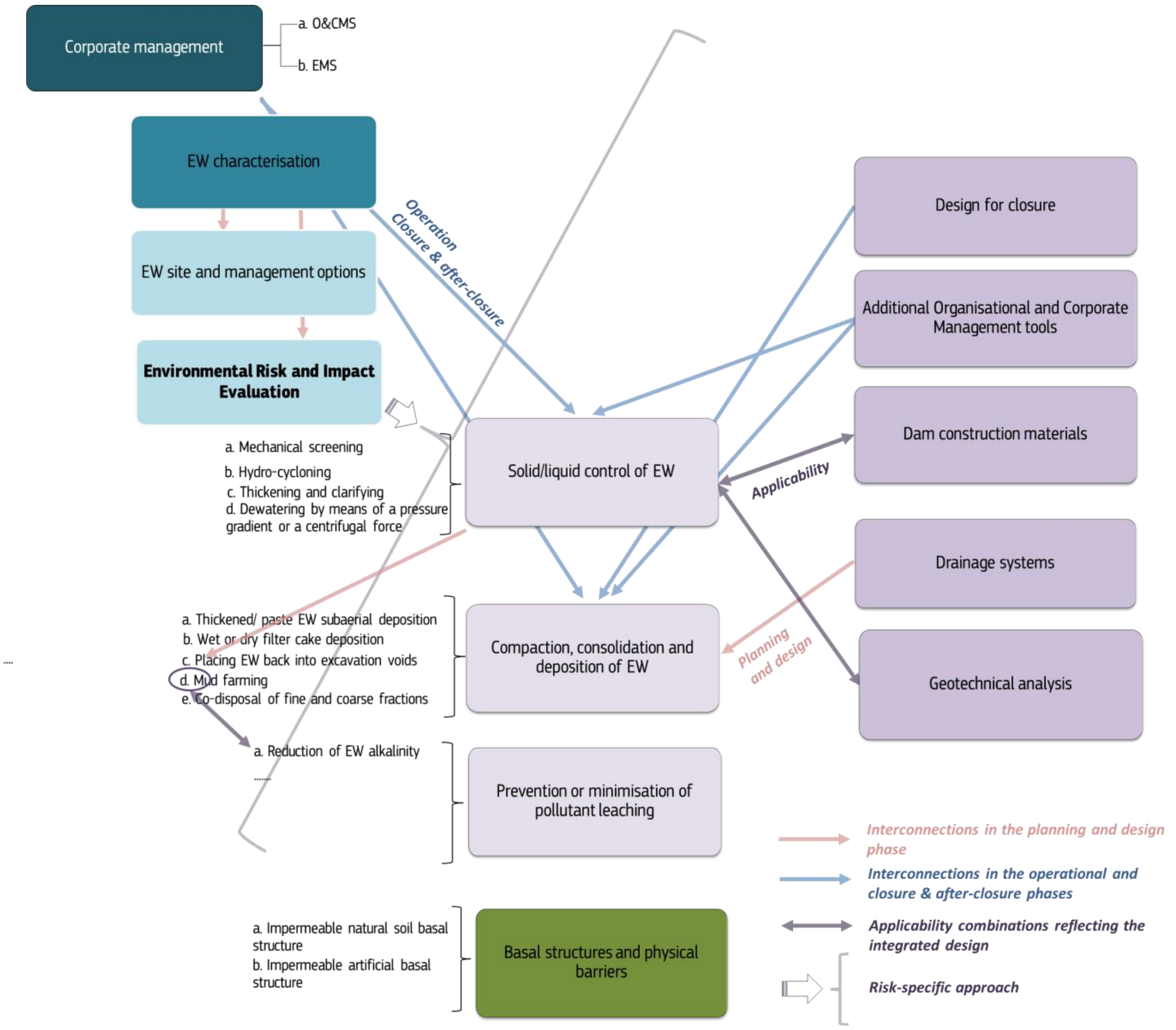
[41] BRAVO - Bauxite Residue and Aluminium Valorisation Operations http://bravoeip.eu/

[42] REDMUD - European Training Network for Zero-waste Valorisation of Bauxite Residue https://cordis.europa.eu/project/rcn/193432/factsheet/en

[43] SCALE Production of Scandium compounds and Scandium Aluminum alloys from European metallurgical by-products http://scale-project.eu/

recovered as a source of iron and alumina for cement production, as a constituent in brick production, or as a soil improver.

Given the growing interest in red muds recovery, a more in-depth discussion of the BAT for their treatment and deposition is provided below and a scheme illustrating them is shown in **Figure 6**. BAT on solid/liquid control and BAT on compaction, consolidation and deposition are applicable based on the results of a proper Environmental Risk and Impact Evaluation. Their application is related to the principle of an integrated design, which takes into account all the relevant parameters in order to optimise the overall environmental, human health and safety aspects of a project. For example, the level of dewatering and so the selection of the appropriate solid/liquid control technique will depend on the design criteria of the extractive waste facility, including the selection of dam construction materials, the geotechnical analyses and the characterisation of the extractive waste. Finally, these BAT are implemented in the operational phase, together with systematic corporate management systems and procedures (see Section 3.2.3) whose application helps to improve the overall environmental performances.



EW = extractive waste; O&CMS=Organisational and Corporate Management System; EMS=Environmental Management System

Figure 6. Scheme of the BAT for management of red muds according to the MWEI BREF.

Another objective of the BAT conclusions is to help ensuring the chemical stability of extractive waste. For this purpose, the following BAT can be applied:

- prevention or minimisation of pollutant leaching by reducing the extractive waste alkalinity, combined with other techniques such as compaction, consolidation and deposition of extractive waste, progressive rehabilitation and temporary covers;
- prevention or minimisation of ARD by using one or a combination of techniques such as ARD management system, segregation of Potentially Acid Generating (PAG) and Non-Acid Generating (NAG) extractive waste by sorting and selective handling/deposition, desulphurisation and blending with buffering materials. Moreover, these techniques are used in combination with others whose main objective is not necessarily to ensure the chemical stability, yet contribute to it. Examples are impermeable basal structures, progressive rehabilitation, temporary cover, or permanent dry or wet covers.

3.3.4 Groundwater and soil pollution remediation

BAT is to apply remediation techniques such as phyto-technologies that use plants to treat or capture contaminants in various media (see also the BAT on aerobic or anaerobic wetlands), in order to prevent or minimise groundwater status deterioration and soil pollution. This BAT is relevant for Potentially Acid Generating (PAG) extractive waste or for extractive waste with metal leaching potential. It is applicable on the basis of a proper Environmental Risk and Impact Evaluation, and in combination with the BAT on coverings. It is applicable during operation or in the closure and after-closure phase of an extractive waste deposition area, but it could also be applied in recovery operations of critical and other raw materials from extractive waste.

Phytomining or phytoextraction is an emerging technique similar to phyto-technologies used for groundwater and soil remediation. The technique uses plants to take up contaminants with the transpiration stream. Plants called hyperaccumulators are used to mine/extract specific metals from the extractive waste or contaminated soil. These plants can absorb from 10 to 100 times higher levels of metals than other species. Therefore, phytomining could be considered as an emerging technique for the recovery of raw materials and CRMs.

3.3.5 Monitoring of emissions to soil, water and air

Operators of the extractive industries apply monitoring and management controls in order to prevent or minimise water status deterioration, air and soil pollution and to identify any adverse effect that their operations may have on the environment or on human health. BAT on monitoring emissions to soil and groundwater, surface water and air are provided in the MWEI BREF. It has to be underlined that, differently from emissions to surface water where point sources are generally identifiable, emissions to soil and groundwater and emissions to air resulting from the management of extractive waste are usually diffuse emissions, also encompassing fugitive emissions.

A monitoring plan for emissions to soil, water and air is developed in the planning and design phase and implemented during operation as well as in the closure and after-closure phase. Having in place a systematic monitoring plan for the extractive waste characteristics, for the structural stability of the deposition area and for emissions is indispensable to the Environmental Risk and Impact Evaluation. This core BAT is indeed reviewed in the case of changes influencing the management of extractive waste (see Section 3.2.3) and based on the monitoring findings.

4 Knowledge base needs and sources

4.1 The EU Raw Materials Information System

Securing the undistorted supply of raw materials and particularly CRMs is crucial and requires a sound and continuously updated knowledge base, namely the European Raw Materials Knowledge Base (EURMKB), as highlighted and stressed in the EU Raw Materials Initiative (RMI)[44]. This need was further recognised by the Strategic Implementation Plan of the European Innovation Partnership on raw materials (EIP-SIP) of 2013, particularly in Action area No II.8[45] (EC, 2017). In this context, and responding to a specific action of the 2015 Circular Economy Communication, the DG JRC of the European Commission in close collaboration with DG GROW is developing the EU Raw Materials Information System (RMIS). The Action Plan on Circular Economy (EC - European Commission, 2015) is explicitly calling for the 'further development of the EU Raw Materials Information System', in particular, to develop and share knowledge and data on SRMs and material flows and stocks.

The first version (RMIS 1.0) was launched in March 2015, then an advanced RMIS (RMIS 2.0) followed in 2017, identifying knowledge needs for strategic industrial sectors, with focus on the monitoring of recycling of relevant materials and the availability of data in key sectors[46]. The purpose of RMIS is to become a one-stop information gateway and knowledge service centre for non-energy, non-food primary and SRMs.

Figure 7 Front page of the EC's Raw Material Information System (RMIS 2.0)

[44] EC - European Commission, 2008. Communication from the Commission to the European Parliament and the Council. The raw materials initiative: meeting our critical needs for growth and jobs in Europe. COM(2008)0699 final.

[45] EC - European Commission, 2017. European Innovation Partnership on Raw Materials: Annual Monitoring Report 2016, EUR 28839. ed. Publications Office of the European Union, Luxembourg. doi:10.2760/05730

[46] Commission Staff Working Document on the implementation of the Circular Economy Action Plan, SWD(2019) 90 final.

The ambition behind RMIS 2.0 is (a) to support European Union (EU) policy with tailor-made applications like the periodical Raw Material Scoreboard[47] and criticality assessments, and (b) to help coordinate other EU-level data and information on raw materials (EUKBRM). This will be made directly available in the RMIS from different data sources. It will be facilitated by enhanced cooperation with Member States, industry representatives, and other stakeholders. The other functionalities of RMIS 2.0 will also directly serve the implementation of the circular economy policy, examples include: material flow analysis (MFA) including the EC material system analysis (MSA); the new trade policy application; information and data on SRMs; and content about sustainability issues and research & innovation. The RMIS is already "connected" through the gateway[48], that is, through hyperlinks to other relevant components of the EURMKB such as national agencies, European data services, and European H2020 projects. More dynamic connections with other data platforms are under development and in the near future should allow visualisation of relevant data in the RMIS, for example, data on SRMs.

Secondary Raw Materials

As stated in the 2015 Communication "Closing the loop - An EU action plan for the Circular Economy"[49], the European Commission aims to further develop the Raw Materials Information System (RMIS) in order to improve the availability of data on SRMs and support EU-wide research on raw materials flows.

The section of the RMIS on SRMs[50] provides an overview of (1) the relevant definitions and European policies concerning SRMs (policies and definitions), and (2) the actions proposed in the Circular Economy (CE) action plan that will contribute to boosting the market for SRMs, focusing on each step of the value chain, from production and consumption to waste management, including reuse, repair, and remanufacturing, and SRMs that are fed back into the economy (from waste to resources). It also provides an overview on available data of SRMs in specific industry sectors such as Electrical and Electronic Equipment, and mobility, including batteries.

Material Systems Analysis 2015 and 2018 update

A large raw materials system analysis (MSA) study[51] was carried out in 2015 and investigated the flows and stocks of 28 raw materials from 'cradle-to-grave', that is, across the entire material life cycle from resource extraction to materials processing to manufacturing and fabrication to use and then to collection, processing, and disposal/recycling (**Figure 8**).

The study was carried out by DG GROW and included consultation with experts and stakeholders. It is a follow-up of the 'Study on Data Needs for a Full Raw Materials Flow Analysis', launched by the European Commission in 2012 within the context of the European Raw Materials Initiative's policy. This policy aims at securing and improving access to raw materials for the EU. The MSA study aims to provide information on material stocks and flows and to assist the European Commission in developing a full MSA for a selection of key raw materials used in the EU-28, some of which are critical.

[47] EC - European Commission, 2016. Raw materials scoreboard. European innovation partnership on raw materials. Luxembourg. doi:10.2873/85546; EC - European Commission, 2018. Raw materials scoreboard European innovation partnership on raw materials. Publication Office of the European Union, Luxembourg. doi:10.2873/686373; http://rmis.jrc.ec.europa.eu/?page=scoreboard2018#/

[48] http://rmis.jrc.ec.europa.eu/?page=rmkg

[49] EC - European Commission, 2015. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy. COM/2015/0614 final.

[50] http://rmis.jrc.ec.europa.eu/?page=policies-and-definitions-2d5b5e

[51] Deloitte Sustainability, 2015. Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. Available at https://ec.europa.eu/jrc/en/scientific-tool/msa.

In 2018 this first MSA study was complemented by a JRC study on the MSA of three other raw materials: copper, aluminium, and iron[52]. This study was specifically used to update the values of recycling rates used in Indicator 16 of Scoreboard 2018[53].

By tracking materials throughout their full life cycles, MSAs can help to quantify potential primary and secondary source strengths, support monitoring of their 'level of circularity' in the EU-28, and manage metal use more wisely. This is particularly important for CRMs for which public information on their trade is sometimes unknown, their uses are not well understood, and their recovery and reuse once discarded is problematic. An accurate assessment of global and EU-wide mineral resources must not only include the resources available in ground (reserves), but also those that are present as stocks within the technosphere and become available through recycling. The data resulting from the MSA study for CRMs provides an important base of background information from which future materials criticality can be addressed more effectively, and sustainable development pathways with an EU-wide scope designed.

The MSA study was an excellent source of information to estimate the potential of stocks of CRMs in tailings and in landfills, as shown in Mathieux et al. (2017)[54] and shown in dedicated boxes in Chapter 5. Such figures were computed by analysing the stocks of each critical raw material in tailings and in landfills (see flows and stocks B.1.4, B.1.5, F.1.5, and F.1.6 in Figure 7).

[52] Passarini, F; Manfredi, S; Ciacci, L; Nuss, P, Material flow analysis of aluminium, copper, and iron in the EU-28. JRC Technical report, EUR 29220 EN, 2018. https://publications.europa.eu/s/kThJ

[53] http://rmis.jrc.ec.europa.eu/?page=scoreboard2018#/ind/16

[54] Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. and Solar, S., Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-74282-8 doi:10.2760/378123 JRC108710.

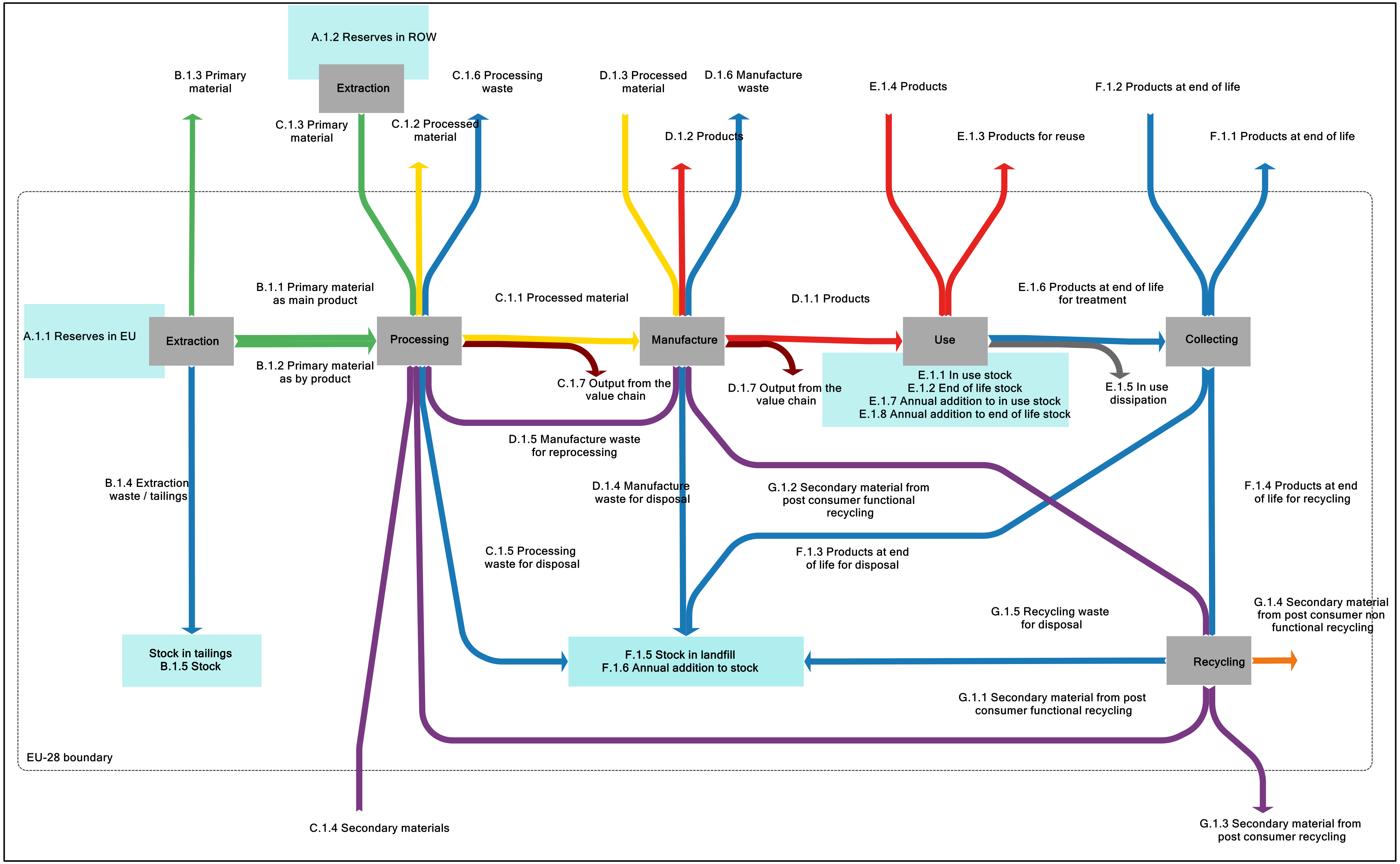


Figure 8 MSA framework and flows/stocks considered

4.2 Overview of the knowledge base from current practices

Knowledge is fundamental…

Knowledge on the quality and quantity of resources available in any waste disposal facility is necessary to accurately evaluate the potential SRMs that can be extracted and so support decisions on investments. Similarly, building the knowledge base at a higher level (at the regional, national, or even EU level) is also necessary to define appropriate legislative and technical tools.

Some knowledge in the area is available today because Eurostat collects and reports relevant data, for example, on volumes of extractive wastes and statistics about the flows of municipal solid waste disposed of in landfills. Some initial assessments of the potentials of available CRMs in tailings and landfills are also available (see boxes in Chapter 5). Current knowledge also includes the list of sources of data in Member States: the ORAMA H2020 project has recently completed a detailed description and analysis of the sources of data on mining waste (including data formats, accessibility of data) and of the competent authorities for four member States (Hungary, Ireland, Norway, Slovenia)[55]. The report also contains an overview of the sources of data for the other Member States.

…But there are still huge data gaps

As shown in the Smart Ground example, very little knowledge is currently available concerning the potentials for SRMs that can be found in mining waste, municipal solid waste, and industrial waste. Despite statistics on waste flows being available from the Eurostat website, no systematic and consistent collection of data relevant to (critical) raw materials contained in these wastes flows is carried out[56].

These data gaps are not only demonstrated by the practices analysed in this report but also by other initiatives. For example, the SCRREEN H2020 project has recently drew conclusions about the insufficient information about CRMs compositions and volume characteristics in mining waste, both in abandoned mines and mines in operation[57]. Compositional data (including the presence or not of CRMs) is currently only available for a few sites in Europe[58].

These data gaps are usually observed for both abandoned mines and for mines in operation. Historical information is an important bottleneck as there is barely accessible historical information about the existing mining resources in abandoned tailing ponds and dumps, as shown for example by the Penouta example.

Currently data and knowledge on resources available in municipal landfills such as CRMs content is also largely missing. However, the likelihood of finding CRMs in old municipal solid waste deposits remains low to negligible.

[55] Jaco Huisman, Kees Baldé, Špela Bavec, Michelle Wagner, Amund Loevik, Lucia Herreras, Perrine Chancerel, Johanna Emmerich, Kristine Sperlich, Roja Modaresi, Maria Ljunggren Söderman, Vanessa Forti, Paul Mählitz, Henrik Schillerup, Zoltan Horvath, Silvia Bobba, Pasi Eilu, Maria Anta, Kari Aasly, Gerry Stanley, Vigh Csaba, János Kiss, Katalin Szabó and Violeta Nickolova. Deliverable 2.2. of ORAMA poject. Inventory Analysis of data collection methods and sources for the improvement of SRM statistical datasets and recommendations for improving SRM datasets and harmonisation. Available on https://orama-h2020.eu/downloads/#tab-id-2

[56] Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. and Solar, S., Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-74282-8 doi:10.2760/378123 JRC108710.

[57] Anna Ladenberger,A., Arvanitidis,N., Jonsson, E., Arvidsson,R., Casanovas,S., Lauri,L. Identification and quantification of secondary CRM resources in Europe. Deliverable 3.2 of H2020 SCRREEN Project. http://scrreen.eu/wp-content/uploads/2018/03/SCRREEN-D3.2-Identification-and-quantification-of-secondary-CRM-resources-in-Europe.pdf

[58] See Footnote 48.

Some on-going initiatives to build the knowledge base

Being aware of these data gaps, in 2014 the European Commission launched a call for research projects in the framework of the H2020 programme aiming to set up inventories of SRMs, including from waste deposits. Several projects were selected and they have contributed in elaborating innovative structural answers to these data gaps.

For example, the Smart Ground project (See Section 7.5) has specifically developed important components such as data collections plans for both municipal solid waste and extractive waste, a database (the Smart Ground platform) to gather relevant data and information on waste deposits, and some training materials. One of the main features of the Smart Ground Platform is the development of a data model to store the relevant information of waste deposits.

Initiatives to address data gaps have also been developed in Member States. For example, in Hungary the CriticEl project developed a database of data on available SRMs, in particular from waste materials contained in landfill (e.g. fly ash from thermal power plants). The database still serves as a basis for several follow-up research projects.

A recent SCRREEN report[59] also identifies some encouraging practices in some Member States such as Sweden: following the Swedish Mineral Strategy, an overall geological investigation of both primary and secondary raw materials is being undertaken in all important mining districts in Sweden. A preliminary conclusion of this investigation is that CRMs are to be found both within the old known mining districts, along with extensively explored brownfields, but also outside them. Based on the information collected and evaluated, it clearly emerges that there is significant potential for CRMs secondary resources in Sweden.

Other relevant initiatives in Member States include one in Spain[60]: the Regional Mining Administration of Andalusia region is involved in an ambitious plan to restore abandoned mining waste deposits, funded by the ERDF (European Regional Development Fund). This initiative includes work in the scope of the implementation of the EWD Directive, that is, compulsory characterization and classification measures regarding CRMs in the waste deposits of active mines. Mining waste in active mines need to be characterized for the presence of CRMs and this information should be part of the waste deposits documentation, and also to facilitate an economic assessment of future recovery. Every mining waste deposit needs to be classified regarding the presence and content of CRMs (yes/no; % content). Moreover, characterization and classification measures regarding CRMs in abandoned mines waste deposits should be implemented on a voluntary basis.

Further efforts needed

Despite all these initiatives, many problems remain. For example, to support the future development and consolidation of data on quantities of resources available in waste deposits, several data models have been developed, including the Smart Ground one and the ProSUM data model. Unfortunately, multiple harmonisations and data models for sharing waste deposits datasets at EU level make the use and comparison of shared data very complex for the time being.

Reviewing existing data from several EU reporting systems (Directive 2006/21/EC, but also recent initiatives such as ProMINE, ProSUM, and Smart Ground projects), the ORAMA project recently reiterated that there is still a lack of deposit-level data and poor spatial

[59] Anna Ladenberger,A., Arvanitidis,N., Jonsson, E., Arvidsson,R., Casanovas,S., Lauri,L. Identification and quantification of secondary CRM resources in Europe. Deliverable 3.2 of H2020 SCRREEN Project. http://scrreen.eu/wp-content/uploads/2018/03/SCRREEN-D3.2-Identification-and-quantification-of-secondary-CRM-resources-in-Europe.pdf

[60] "Personal Communication from Manuel Vázquez Mora, Junta de Andalucía, Dirección General de Industria, Energía y Minas., Spain, 2018".

coverage (not all EU countries were covered by the above-mentioned initiatives)[61]. ORAMA H2020 project is currently elaborating various recommendations on how to overcome this evident knowledge gap.

Because information has never been collected, building this knowledge from scratch often remains the only option in the majority of cases. This implies that massive characterisation campaigns might be needed to systematically sample current and past extractive waste deposits. Data collection plans including sampling methods, sample preparation, and analyses protocols developed in the context of the Smart Ground project could be very useful in such campaigns.

These massive much needed characterisation campaigns can only be enhanced through appropriate legislative provisions (see the examples of the Andalusia region and of Sweden above) and/or incentives. Moreover, the identification and promotion of several successful business cases (e.g., the Penouta case) could be very helpful in motivating further efforts in building a coherent and as complete a knowledge base as possible in the area.

---

[61] Jaco Huisman, Kees Baldé, Špela Bavec, Michelle Wagner, Amund Loevik, Lucia Herreras, Perrine Chancerel, Johanna Emmerich, Kristine Sperlich, Roja Modaresi, Maria Ljunggren Söderman, Vanessa Forti, Paul Mählitz, Henrik Schillerup, Zoltan Horvath, Silvia Bobba, Pasi Eilu, Maria Anta, Kari Aasly, Gerry Stanley, Vigh Csaba, János Kiss, Katalin Szabó and Violeta Nickolova. Deliverable 2.2. of ORAMA poject. Inventory Analysis of data collection methods and sources for the improvement of SRM statistical datasets and recommendations for improving SRM datasets and harmonisation. Available on https://orama-h2020.eu/downloads/#tab-id-2

5 Framework conditions and monitoring tools

5.1 Monitoring progress: the EU Raw Materials Scoreboard

The Raw Materials Scoreboard is an initiative of the European Innovation Partnership on Raw Materials. It provides information on the EU's overall raw materials policy context. The two editions of the Scoreboard, published in 2016[62] and 2018[63], consist of 24 indicators grouped in five thematic clusters (**Figure 9**).

Three thematic clusters, and some of the underlying indicators, are relevant for the recovery of CRMs and other secondary raw materials from extractive waste and landfills.

Two indicators in the thematic cluster "Circular economy and recycling" are particularly interesting for this report. The indicator on recycling's contribution to materials demand shows that the contribution of recycling of almost all CRMs is moderate to negligible. The indicator on WEEE management, a waste stream that contains significant amounts of CRMs, provides further information on collection and recycling. It shows that the levels of collection, reuse, and recycling of WEEE vary considerably across EU Member States, indicating significant potential to improve resource efficiency.

The indicator on national minerals policy framework in the thematic cluster devoted to "Framework conditions" highlights that a stable and efficient raw materials policy framework remains crucial because it can either impede or expedite the development of primary and secondary raw material operations.

Finally, the indicator on extractive waste in the thematic cluster on "Environmental and social sustainability" suggests that there are no comparable datasets available on volumes and quantities that would adequately support decision makers at EU level.

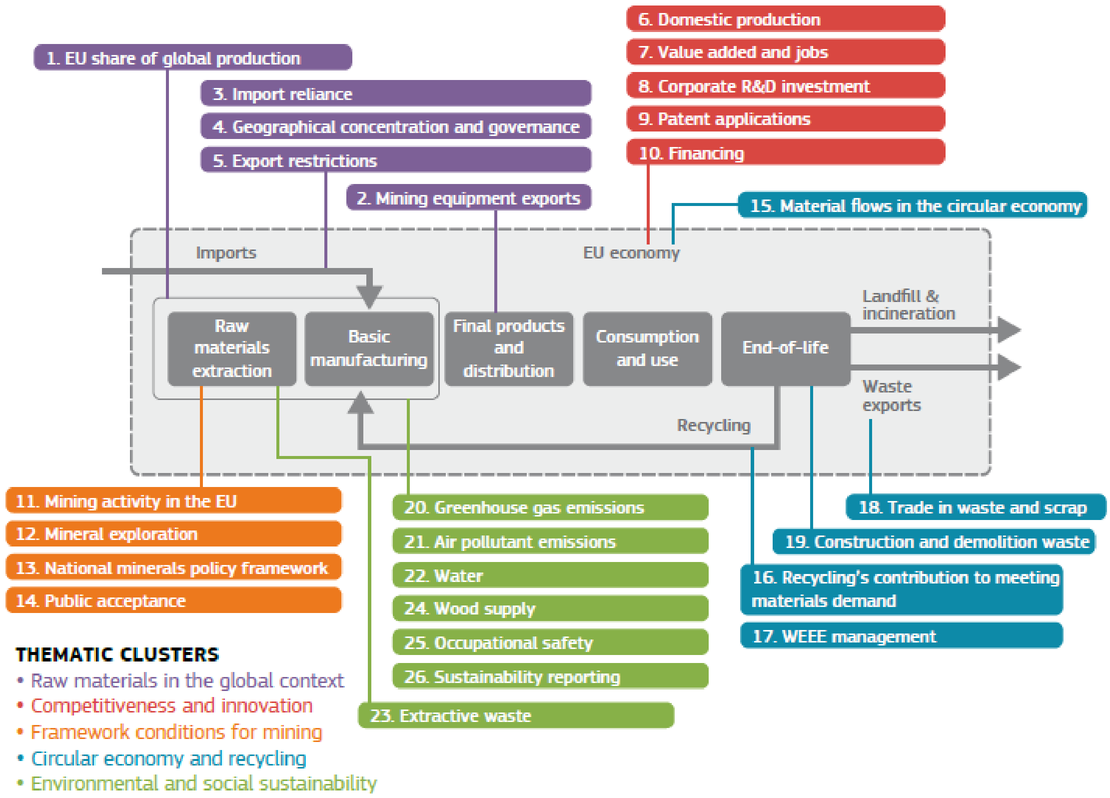


Figure 9 Indicators and thematic clusters of the 2018 Raw Materials Scoreboard

[62] EC - European Commission, 2016. Raw materials scoreboard European innovation partnership on raw materials. Luxembourg. doi:10.2873/85546

[63] EC - European Commission, 2018. Raw materials scoreboard European innovation partnership on raw materials. Publication Office of the European Union, Luxembourg. doi:10.2873/686373

5.2 Summary on framework conditions from relevant projects

A clear and stable Legal framework is the most important element for decision-making.

Based on the experience collected during the workshops and subsequent contributions from participants, the legal framework is flagged as the most important element for decision-making. In addition, in order to support effective decision-making, changes in legislation must be predictable. In particular, clarity on how landfilled waste material would be used as secondary raw material is needed and the legal use of products obtained from waste materials also needs to be clear. Improved harmonisation and mutual recognition of end-of-waste criteria should be considered. Moreover, in the recovery of CRMs, elements of concern (e.g. As, Cd, Hg) often need to be taken into account. Safe and legal outlets (use or final deposition) must be clear and practicable for both operators and public authorities. When recovering valuable and critical elements from industrial landfilled residues, the elements of concern are often concentrated and therefore need to be disposed of safely. Recovery processes also require energy.

Political and regulatory conditions are not the same in every region. One of the main regulatory bottlenecks is the heterogeneity of standards and requirements for recycling, reuse, and transport of waste materials within the EU. Homogenisation of regulations across Europe could facilitate market introduction and replication of technologies. Stakeholders stated that performance-based regulations are better suited to taking account of actual risks or technical requirements. For instance, the potential use of slags should be based more on their composition as well as on their environmental and technical performance rather than on their origin (type of slag). In general, the use of high quality slags from secondary sources should be promoted

A timeline to sort out the legal authorisations is key to coping with volatile markets.

Operators said that the administrative timelines for resolving any type of consultation or request, as well as licences and permits, are currently extremely lengthy and uncertain from a regulatory point of view. This is also influenced by political changes. Given the strong dependence on the success of a holding with the price of the raw materials, it should be a much simpler and faster process. In fact, it is essential when launching a project to exploit the phase of prices upwards, when the project can be profitable, so that the periods of low profitability can be supported. Measures have been proposed by national and regional governments to speed up these procedures and to promote the development of mining in certain strategic sectors.

Technology is available, but not always supported by adequate investment.

Recently, a number of new pyrometallurgical methods (Ausmelt TSL, ISASmelt, Plasma, various types of box fumers etc.) have been developed to treat metals containing waste materials and side products from non-ferrous industries. This has created a boost in resource efficiency and enhanced recovery of metals. Nevertheless, this developing field requires large amounts of investment and legislation that enables waste utilization in the first place. In addition, energy availability and price plays an important role for large industrial operations including waste treatment processes for multi-metal recovery. According to the operators, Europe is lagging behind in investment. In addition, the pyrometallurgical method requires electricity and a reducing agent like coal or natural gas. The use of non-fossil reducing agents, biocoal, biogas, hydrogen, or non-recyclable plastics should be studied further so as to make them renewable reducing agents.

Similarly, biohydrometallurgical processes have become an industrial reality in the main mining areas of the world by allowing the exploitation of these resources, sometimes at a lower cost, and with a smaller environmental footprint. Again, the potential prospects for the development of bioleaching operations will depend on the ability to address various economic, technical, and scientific limitations.

Technology and the legal framework can sometimes support each other

If on the one hand SRMs are desired and incentivised, sometimes legal requirements for such things as environmental protection can be seen as a barrier. In some cases, e.g., residues where recovery or recycling is currently not allowed due to exceedance of the leaching criteria, removal of metals can help to reduce the environmental impact and enable recycling. With the example of the Kasese site in mind, by contributing to the stabilisation of wastes, biohydrometallurgical operations can also drastically decrease the Acid Rock Drainage (ARD) discharge into the environment. In fact, tailings and mining waste containing residual sulphides and metals, often responsible for ARD issues, are potentially a very good target for biomining activities.

Special and/or situational conditions can trigger/boost new projects

Sometimes the framework conditions are not favourable to starting the recovery, so some other elements or synergies can play a role. For instance, in the case of the Penouta project, the existence of old facilities such as mining pools, water connections, and the old pit face, now flooded, have facilitated water catchment authorization and discharge authorization.

Accessing SRMs is often not the only driver: indeed, land space can be liberated and reused for new purposes and services, such as recreational and outdoor activities, industrial or urban redevelopment including commercial activities, areas for new landfills, or new opportunities to access the original orebody.

In general, a multidisciplinary analysis which considers economic, social, and environmental impacts must be followed, considering both the risks associated with actual waste production (challenges) alongside the potentialities of recovering CRMs and SRM from waste exploitation (opportunities).

Social acceptance or social pressure can be a powerful driver

High social acceptance can sometimes compensate for a less effective legal framework. For instance, the Penouta project has benefitted from a good environmental and social acceptance for its authorization and start-up. The previously existing mining jobs have favoured the acceptance of the local environment for the reopening of the mine.

An important aspect of the CHROMIC project is community involvement. Treatment of large amounts of waste materials often raises public concerns, and so proactive interaction with the general public is needed from the start to ensure societal trust.

The legal framework sometimes lacks a knowledge-base

Lack of information about the SRM contained in waste deposits is also a bottleneck in view of a better framework. Moreover, building the necessary knowledge base needs financial support and the return of investment is not always guaranteed.

Projects such as CriticEl and Smart Ground have identified several bottlenecks or barriers that are inhibiting utilisation of secondary mineral resources. These barriers are mostly legislative and economic in correspondence the structure and diversity of the resource industry in Member States. Data for supporting investment decisions for large scale exploration projects are available but in the case of CriticEl, they are from the 1960's and 1970's and so are outdated in terms of the complexity involved in serious financial decisions today.

6 Overview of the potential of recovery from landfill and extractive waste

6.1 Extractive waste

Extractive waste may include mineral excavation wastes (e.g. overburden or waste-rock), mineral processing/treatment wastes (e.g. tailings, waste gravel, waste sand, and clays) and drilling muds and other drilling wastes (e.g. discarded drill cuttings). As the management of extractive wastes may pose risks to the environment and to human health, minimum requirements are laid down in Directive 2006/21/EC, the Extractive Waste Directive, in order as far as possible to prevent or reduce any adverse effects on the environment or on human health brought about as a result of the management of extractive wastes[64].

Extractive waste is a potential source of valuable materials that are currently not recovered routinely, including CRMs. In certain cases, extractive wastes, such as discarded tailings, may contain CRMs in relevant amounts and concentrations (for example, indium or germanium in residues of treated zinc ores, or gallium in bauxite residues) which could be recovered at a profit as long as the market demand exists and the commodity price makes the re-processing economically viable[65]. Important influencing variables are the amounts of CRMs, their concentration, the mineralogical composition of the extractive wastes as well as the grading and fabric of the extractive waste that resulted from the treatment processes performed earlier.

In certain cases, increased recovery of CRMs from extractive wastes can reduce the need for active or passive treatment and storage of extractive waste and the associated environmental impacts. Moreover, it can decrease the need for primary extraction. At this stage, recovery of CRMs from extractive waste in the EU is rather low due to economic and technological barriers.

The potential for the recovery of CRMs from extractive wastes depends on the volumes of extractive waste and their concentrations. Since 2004 Eurostat has been collecting and reporting data, bi-annually, on volumes of extractive wastes divided into two categories (hazardous, non-hazardous). However, no systematic and consistent collection of data relevant to CRMs contained in extractive wastes is carried out.

[64] EC (2006), 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 (Extractive Waste Directive), OJ L 102

[65] See for example https://www.lkab.com/en/news-room/news/Mine-waste-will-now-be-utilised/

Availability of data on CRMs stocks in extractive waste[66]

At present no database at EU or Member State-level reports:

- the volumes of the extractive waste deposits (for closed and active mines), disaggregated by mineral exploited and/or by waste types;

- the volumes of the different extractive waste streams.

For the above reasons, only rough estimates of the (bi-)annual flows and extrapolations of the accumulated amounts are possible, such as the one provided by the MSA study[67]. The MSA study forms a comprehensive data inventory of the material flows in industrial and societal uses in the EU-28, where extractive waste is depicted by two parameters:

- 'Extractive waste disposed in situ/tailings' is the annual quantity of the element in the extractive waste disposed in situ. This indicator refers to tailings, i.e., 'the waste solids or slurries that remain after the treatment of minerals by separation processes (e.g. crushing, grinding, size-sorting, flotation, and other physical-chemical techniques) to remove the valuable minerals from the less valuable rock' (Extractive Waste Directive 2006/21/EC);

- 'Stock in tailings' is the quantity of the element in tailings in the EU. This amount corresponds to the 'extractive waste disposed in situ/tailings' accumulated over time.

A preliminary analysis from the MSA study[68] on annual flows and stocks of CRMs in extractive waste over the last 20 years is reported in **Figure 10**. Quantities are indicative and mostly derived from mass balances and expert assumptions. Moreover, CRMs accumulated in tailings have likely undergone chemical and physical changes, which must be further evaluated under several aspects in view of their possible recovery. Due to natural attenuation processes, revegetation, and internal cementation or compaction, the opening of some historical extractive waste sites for recovery can be at higher risk because they may reactivate pollution sources and pollution pathways than if the 'don't touch it' principle is applied.

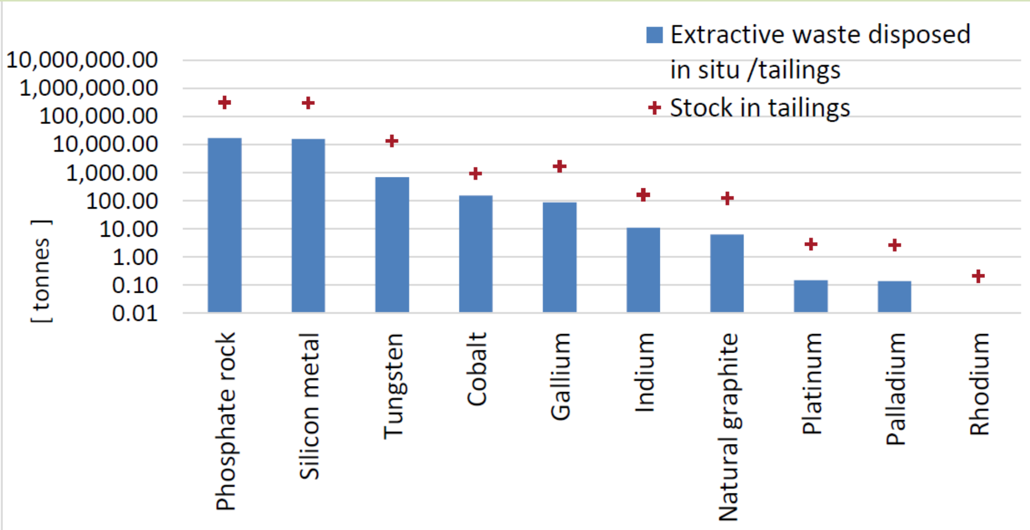


Figure 10 Estimated amounts of various CRMs in the EU-28 in 'Extractive waste disposed in situ/tailings' and 'Stock in tailings'. Source: JRC elaboration based on the 2015 MSA study[44]

[66] Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. and Solar, S., Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017

[67] Deloitte Sustainability, 2015. Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. Available at https://ec.europa.eu/jrc/en/scientific-tool/msa.

[68] *Ibidem*

6.2 Landfill

Landfills were and are used for a variety of waste, nowadays representing an accumulation of large amounts of very different materials, including CRMs and other valuable materials. Overall there are between 150,000 and 500,000 landfills in the EU, the majority of which are not active anymore[69]. However, no systematic collection of data specific to CRMs ending up in landfills has ever been carried out and so statistics are largely unavailable.

Landfills are waste disposal sites for the deposit of waste onto or into land (Directive 2018/850[70] amending Directive 1999/31/EC). Controlled landfills are divided into three categories: landfills for hazardous waste, landfills for non-hazardous waste, and landfills for inert waste. The quantity and composition of waste in landfills across the European countries reflect differences in the economic structure, consumption patterns, and the various waste policies of Member States. The number of active landfills in the EU has decreased in the last decades from the numbers of the late 1970s[71]. At the same time, the average size of the landfills has increased. Other estimates[72] indicate that the total amount of landfills in Europe is most likely to be even bigger, 90% of those being landfills[73] predating the Landfill Directive in 1999 and essentially containing municipal solid waste (MSW). Only 20 % are landfills contain more specific industrial waste and residues.

Eurostat[74] provides yearly statistics about the flows of MSW disposed of in landfills. These statistics show a trend of reduction of waste landfilled, declining from 144 million tonnes in 1995 to 61 million tonnes (– 58 %) of waste landfilled in 2015 by the EU-27, even though more waste has been generated over these years.

[69] http://www.smart-ground.eu.
[70] OJ L 150, 14.6.2018, p. 100–108
[71] For example, in Italy the number of active landfills has decreased since the 1980s from the 900 to current 28 (13 non-hazardous waste landfills, 13 inert waste landfills and 2 hazardous waste landfills). In the same period, the number of landfills in the UK decreased from 2,300 non-hazardous landfills and 938 hazardous landfills to 200 and 12 respectively [data from SMART GROUND H2020 project].
[72] http://www.eurelco.org/infographic.
[73] Sanitary landfills are sites where waste is isolated from the environment and managed in a safe way.
[74] Eurostat, Municipal waste statistics (http://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics).

Availability of data on CRMs stocks in landfills[75]

Only rough estimates of the flows and amount of CRMs ending in landfills are presently possible, for example, the one provided by the MSA study[76], a comprehensive data inventory of the material flows in industry and society in the EU-28, through two parameters:

- The 'Annual addition to stock in landfill' that quantifies the amount of an element that is annually added to landfill (in the EU), including the processing waste, the manufacturing waste, the products at end of life, and the recycling waste sent for disposal; and
- The 'Stock in landfill' that quantifies the amount of an element in landfill (in the EU). For the calculation of the stock, the amount of material accumulated in landfill over the last 20 years ([77]) are considered to be a maximum level.

The estimated amounts of CRMs annually sent to landfills and the estimated accumulation in landfill over the last 20 years in the EU are plotted in **Figure 11.** The quantities reported in Figure 7 are indicative and are mostly derived from mass balances and expert assumptions. Moreover, CRMs accumulated in landfills have probably undergone chemical and physical changes for which their possible recovery must be carefully evaluated from several points of view.

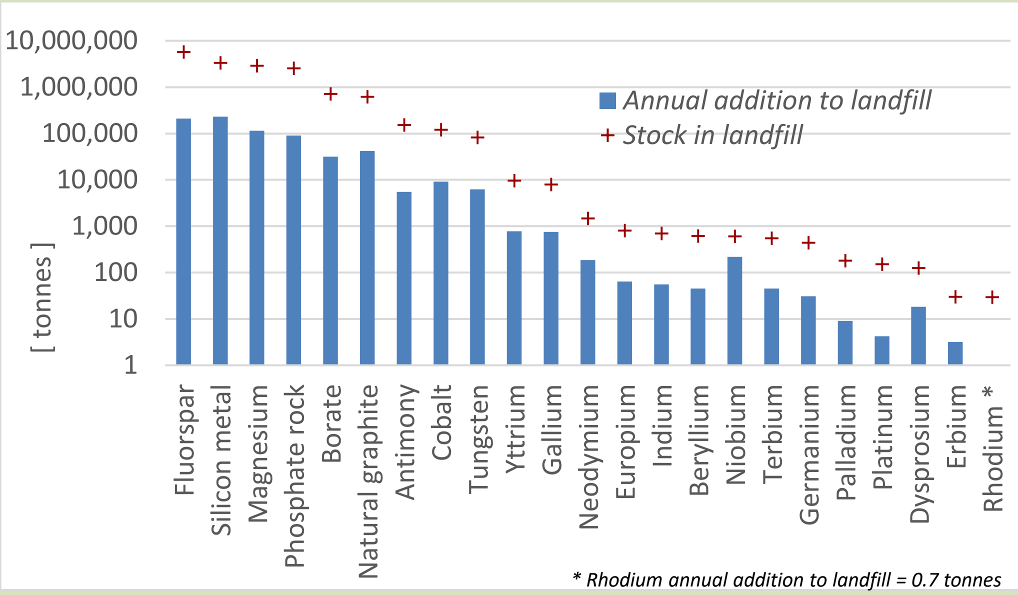


Figure 11. Estimated amounts of various CRMs as 'Annual addition to stock in landfills in the EU' and 'Stock in landfill in the EU'. *Source:* JRC elaboration based on 2015 MSA study[78].

[75] Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. and Solar, S., Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017

[76] Deloitte Sustainability, 2015. Study of Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. Available at https://ec.europa.eu/jrc/en/scientific-tool/msa

[77] This period of 20 years can be shorter if the material is used in a specific product that did not exist 20 years ago. For example, steels with niobium have been used for construction for more than 20 years but buildings and bridges have not yet reached end of life, and therefore there are none of these flows to landfills. Indium has been used to make flat panel liquid crystal displays (LCD) in electronics for about 18 years. LCD waste started to arise about six years later (i.e. 12 years ago).

[78] Deloitte Sustainability, 2015. Study of Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. Available at https://ec.europa.eu/jrc/en/scientific-tool/msa.

Enhanced Landfill Mining (ELFM)

Enhanced Landfill Mining (ELFM) is defined as "the integrated valorisation of landfilled waste streams as materials and energy, using innovative transformation and upcycling technologies and respecting the most stringent social and ecological criteria"[79].

With emphasis on non-sanitary municipal solid waste (MSW) landfills predating the EU Landfill Directive (1999), ELFM is seen as a promising pathway for a more sustainable management option than traditional remediation and aftercare. Recent research[80] shows that such a strategy could be a potential way to facilitate remediation of malfunctioning landfills, reclaim valuable urban land, and to a lesser extent, bring significant amounts of dormant metals and minerals back into use in society.

However, besides a few pilot trials there is still a general lack of full-scale projects validating the feasibility of ELFM.

A first question mark is the economic feasibility of ELFM. As for most emerging environmental innovations, ELFM can be negatively exposed to current market conditions. However, whether or not ELFM projects will prove to be economic feasibility depends on multiple factors, including the objectives and priorities set.

The lesson learned so far is that recovery of SRMs is never the main driver, and that expenditures for the recovery would in any case exceed the revenues. Conversely, the main drivers are either environmental remediation or recovery of the land for other uses, in which case recovery of secondary materials could become a complement in view of the full valorisation of the resource. In fact, in current secondary materials markets, only a minor share of the processed materials will generate a significant income (metals), while the remains will likely correspond to low revenues or even disposal costs.

A controversial aspect remains the likelihood of finding significant quantities of CRMs in old landfills because the large-scale use of many CRMs in products only began a few years ago, so they could not have reached end-of-life before the 1990s.

In addition, the environmental gains are sometimes controversial. The only impact that has been comprehensively studied is global warming[81], and recent finding for that environmental concern even conclude that climate impact varies considerably from case to case, ranging from large emission savings to significant net contributions to global warming.

In any case, developing cost-efficient and societally-motivated ELFM practices relies on extensive investments in know-how and technology innovation, policy support, and market interventions. According to EURELCO, in order to stimulate investments in the area and enable policy support and market interventions, ELFM needs to become institutionalised and recognised as a potential option for landfill management.

Directive 2018/850 amending Directive 1999/31/EC on the landfill of waste *does not specifically regulate landfill mining,* and the European Commission does not currently envisage amending the Directive in this regard. However, landfill mining is allowed if carried out in line with Article 13 of Directive 2008/98/EC[82] on waste and subject to a permit in accordance with Article 23 of that Directive.

ELFM is therefore not expressly regulated at EU level, but neither is it excluded as one of the possible practices for a more efficient and circular use of resources, in compliance with the current environmental legislation.

---

[79] http://www.eurelco.org/infographic
[80] https://new-mine.eu/
[81] https://new-mine.eu/
[82] OJ L 312, 22.11.2008, p. 3–30

EURELCO Raw Materials Commitment

EURELCO (European Enhanced Landfill Mining Consortium) is one of the Raw Material Commitments (RMCs) ([83]) that have been recognised within the European Innovation Partnership (EIP). The RMCs is a joint undertaking by several partners, who commit to activities aimed at achieving the EIP's objectives between 2014 and 2020. In particular, the goal of the EURELCO RMC is to be an open, quadruple-helix (multi-stakeholder) network that supports the required technological, legal, social, economic, environmental, and organisational innovation with respect to 'Enhanced Landfill Mining' within the context of transition to a circular, low carbon economy.

Partners of EURELCO also committed to focus on the separation and recovery of valuable raw materials and CRMs from landfilled industrial residues by using hydrometallurgical routes with the aim of recycling both the recovered metals as well as the matrix material. In February 2017, 58 organisations from 13 EU Member States were in EURELCO. In the area of waste management, EURELCO intends to remain a key driver by running the projects NEW-MINE, COCOON, NEW RAWFILL, and NEMO.

6.3 Overview on existing practices: focus on technologies

This section provides an overview of the existing practices described in chapter 7.

- **Recovery of Tantalum and Niobium from tailings at the old Penouta mine**

The Penouta Mine is located in the Ourense province in Spain and was one of the most important tin mines in Spain. The mine had several owners and was definitively closed in 1985. It was exploited using open pit methods and in a poor selective way. Mineral wastes were deposited in dumps and tailings ponds, which have not been rehabilitated at all. These mining wastes still contain interesting amounts of metals such as tin, tantalum, and niobium as well as significant quantities of industrial minerals. Tantalum and niobium are known as rare metals because of their scarcity in nature. Moreover, they have exceptional properties and are used in important high tech applications (e.g., in science and medicine). Tantalum and tin are "conflict minerals"[84] so reduced reliance on imports of these metals is particularly important.

The Spanish company Strategic Minerals Spain S.L. (SMS) conducted feasibility studies and started exploiting the mining wastes in early 2018. During the processing of tailings from waste-rock heaps and ponds of the old Penouta mine, around 1% of tin, tantalum, and niobium metals has been obtained, and 99% is mining tailings. The latter are mainly composed of silicate minerals that can be reprocessed, obtaining around 70% industrial minerals, namely quartz, mica, feldspar, and kaolin. The company has currently generated around 70 direct jobs, and 30 indirect jobs through subcontracting in an area that is suffering the continuous economic decline and depopulation. From an environmental perspective, the design of a modern processing plant allows the efficient use of energy and water resources. The use of chemical substances is avoided because it is an exclusively gravimetric process. The exploitation of the tailings and waste-rock heaps will be carried out during the next 10-12 years of operation and the turnover is expected to exceed 12 million Euros in the short term.

Technological highlights and challenges

Development of new technologies from an evolution of old mineral separation techniques by applying the best available techniques.

[83] https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/call-commitments.

[84] In politically unstable areas, the minerals trade can be used to finance armed groups, fuel forced labour, and other human rights abuses, and support corruption and money laundering. Tin, Tungsten, Tantalum, and Gold are the so called "conflict minerals" according to the EU Conflict Minerals Regulation (Reg. 2017/821).

Design and development of an optimized, effective, and efficient gravimetric process, allowing the maximum use and valorisation of residues without any chemicals or waste hazardous to the environment. Therefore, there are no chemicals in the wastes generated.

More efficient use of energy and water resources: the water supply for the exploitation plant is possible by capturing surface water in old water ponds and at the old pit face, which is currently flooded. The processing plant has a closed circuit water system so that water recovery reaches 70%, being recirculated to the circuit.

Innovative technologies for the recovery of metals have developed by combining electrostatic and high intensity magnetic separation together with pyro and hydrometallurgical techniques.

- **Recovery of CRMs and valuable metals from inorganic industrial waste streams (CHROMIC)**

The CHROMIC H2020 project focuses on the recovery of chromium, vanadium, niobium (CRMs), and Molybdenum from three model streams, namely: stainless steel slags, carbon steel slags, and ferrochrome slags. The CHROMIC consortium is composed of 11 partners which include research institutes, universities, and industries working together to develop processes that are scalable and economically viable.

From a technological point of view, CHROMIC aims to improve both mineral processing and (hydro) metallurgical technologies applied to low-grade secondary resources to increase the energy, material, and cost efficiency of the overall metal recovery process. The recovery of metals from secondary sources would reduce primary extraction (and associated costs and environmental impacts), reduce dependency on imports, avoid landfilling, and reduce the cost of raw materials. However, metal recovery from low-grade (secondary) resources is only economically viable if the large bulk material (residual matrix) can be commercialized. Potential applications for the residual matrix are the traditional uses as aggregates and fillers in the construction sector and more high-value options such as novel binders. Other potential bottlenecks include, e.g., the heterogeneity of standards and requirements for recycling, reuse, and transport of waste materials within the EU and public acceptance in local communities, which requires tailored communication of the project.

Technological highlights and challenges

Development of an innovative approach to recover Cr, Mo, V, and Nb from stainless and regular steel slags as well as ferrochrome slags without impairing the properties of the residual matrix material for valorisation.

The residual matrix materials can be used in more high-value options such as novel binders with a market value of 40-60 €/t compared to only 0-5 €/t for aggregates. Granulation and pelletisation are used to increase the particle size of novel binders. Cleaned slag can be used to produce carbstone blocks using an innovative technology producing building materials from slags and CO_2 by carbonation.

- **Biohydrometallurgy: cobalt-rich sulphidic tailings and residues at Kasese, Uganda**

Biohydrometallurgy is a well-established technique for treating certain sulphide minerals, for the leaching of low grade copper ores or mine tailings (bioleaching), and the pre-treatment of pyritic gold ores and concentrates (biooxidation). Tailings and mining waste containing residual sulphides and metals, often responsible for ARD (Acid Rock Drainage) issues, are potentially a very good target for biomining activities.

Biomining was used in the re-processing of a sulphidic mine wastes at the Kasese site in Uganda where cobalt was produced from old copper mining waste tailings using stirred tank bioleaching technology. By contributing to the stabilisation of those wastes, this biohydrometallurgical operation has also drastically decreased the ARD discharge in the environment. The "Kasese project" started in the BRGM facilities at Orléans in 1988 with the first laboratory-scale test work. The objective was to demonstrate that the recovery of cobalt from Kasese pyrite using (bio)hydrometallurgy was technically and economically feasible. In 1998, ten years after the first tests in the BRGM laboratory, the project became a reality with the inoculation of the bioleach tanks on site. Since 2000, BRGM was involved in numerous EU European project targeting the optimization of this technology on various mineral targets including mining waste.

This practice has proven to be viable (technically and economically) at industrial scale in tackling acid mine drainage problems, it has high cobalt recovery rates, and has limited environmental impacts.

Technological highlights and challenges

The biooxidation plant at the Kasese Cobalt operation was a world first. Well established technologies (bioleaching and biooxidation) were successfully adapted to reprocess sulphidic mine wastes at the Kasese Cobalt Company site in Uganda.

Treating mining waste for their metal content is also a way of reducing very detrimental environmental impacts associated with the phenomena of ARD. This also made a great contribution to eradicating the environmental black spot caused by the stockpile on the edge of a natural reserve

- **Bauxite Residue as a resource in Europe (REDMUD, RemovAL)**

Freshly produced flows and stocks of landfilled industrial residues such as mine tailings, non-ferrous slag, and bauxite residue (BR) can provide remarkable amounts of critical metals and, concurrently, minerals for low-carbon building materials. The European Training Network for Zero-Waste Valorisation of Bauxite Residue (REDMUD) is an H2020 project targeting the vast streams of new and stockpiled bauxite residue in the EU-28.

REDMUD has trained 15 early stage researchers in the science and technology of bauxite residue valorisation. The project investigates innovative, eco-friendly, and integrated methods of metal recovery while valorising the residues into building materials.

Bauxite residues are produced as a red slurry (hence the common term "red mud") and contain significant amounts of iron, aluminium, silicon, and titanium oxides as well as smaller concentrations of critical and/or industrially important elements such as vanadium, chromium, gallium, rare earths elements (mainly cerium, lanthanum, yttrium, neodymium), and scandium. It is estimated that 0.9-1.5 tonnes of solid residue are generated for each tonne of alumina produced, depending on the initial bauxite-ore grade and the efficiency of alumina extraction. Given the increasing demand for aluminium, the management, and storage of bauxite residue is an important issue in both economic and environmental terms as well as for land use competition. Since 1964 more than 700 patents have been issued on technologies for the utilization of bauxite residue. A number of processes have been proposed for the simultaneous recovery of the major metals from bauxite residue but never implemented. The techno-economic viability and legislative aspects have been among the main barriers preventing the deployment of these technologies.

The ongoing H2020 project RemovAl combines, optimises, and scales-up to TRL 7 developed processing technologies for extracting base and critical metals from industrial residues and valorising the remaining residues for use in the construction sector.

In term of technological aspects, RemovAl deals with several by-products from the aluminium sector and from other metallurgical sectors in Europe (SiO_2 by-products, SPL, fly ash, and others). The various waste streams are combined to allow for optimal and viable processing in different technological pilot nodes. The technologies and pilots in most cases have already been developed in previous or ongoing projects and they will be pooled together by RemovAl into a European industrial symbiosis network.

In term of societal or non-technological aspects, RemovAl deals with key sectors like the non-ferrous metal and cement sectors in order to secure true industrial symbiosis through a top-down approach which also considers legislation and standardisation at European level in order to facilitate the implementation of the most promising technical solutions.

Technological highlights and challenges

Despite more than 50 years of research and ample publications and patents (734 patents since 1964 as mentioned above), several barriers have prevented major high-added value use of bauxite residue from being obtained.

It is therefore necessary to combine more than one technology in order to achieve viable and meaningful bauxite residue utilization. Pooling them together and optimizing them in an integrated manner is the only way to render bauxite residue reuse viable from an economic point of view and obtain acceptable by the industry.

Achieving a near-zero waste and a near break-even flowsheet is the key challenge to be addressed.

- **SMART GROUND database and protocols for data collection**

Valuable raw materials disposed in landfills are mainly lost due to inefficient waste management practices. Existing knowledge, reporting standards, and inventory on SRM seem to be inefficient. This is the context in which the SMART GROUND project set out to foster resource recovery in landfills by improving the availability and accessibility of data and information on SRM in the EU while creating synergies between the different stakeholders involved in the SRM value chain.

The project was funded under the H2020 scheme, with an EC contribution of around 2.5 Million Euros and with the involvement of 20 partners from five countries (Italy, Spain, Finland, Hungary, and the UK).

The specific objectives of SMART GROUND are now summarised as follows:

- Collecting quantitative and structural knowledge from existing SRM resources, identifying critical points and bottlenecks that hinder their effective use and identify the most promising markets for recovery of SRMs.
- Reviewing existing standards for RM and waste inventory and providing a benchmark of available best practices.
- Evaluating and analysing the environmental, economic, and social impacts and benefits triggered by SRM recovery from anthropogenic deposits.
- Undertaking a series of pilot studies on SRM recovery potential from anthropogenic deposits and translating the knowledge and understanding gained into scientific recommendations for best practices taking the broader sustainable development and circular economy context into account.
- Developing an online databank platform to facilitate access for end-users to information on available SRMs.
- Raising awareness among policy makers and the wider public of the societal benefits of SRM recovery from landfill and extractive mining sites.

- **Raw Material National Survey in Hungary: Assessment of CRMs potential of coal power plant fly ashes (CRITICEL)**

Even though share of coal in Hungarian electric power production has declined, around two million tonnes of fly ash is produced every year. Globally around one third of electricity is still generated from coal. Accumulation of rare elements in fly ash has been well-known since the 1960s and investigated in terms of resource recovery potential. The CRMs potential of Hungary was assessed for both primary and secondary resources by the CriticEl project in the period between 2012 and 2014. The project covered all CRMs as defined by the EU Criticality Report of 2011 (14 items). One of the key topics in the project was the assessment and utilization of rare element technologies connected to coal fly ash from various Hungarian power plants.

Analysis of archive data from 1960-2005 found that fly ashes of Hungarian coals were rich of various critical elements. Samples of fly ash storages from three power plants were analysed for rare element content within the framework of the CriticEl project. The most promising results were from the Pécs power plant, where anomalous average concentrations of beryllium, cobalt, gallium, niobium, tantalum, zirconium, and rare earths were detected and exceeded 3-10 times the upper continental crust average values.

Since its completion, the CriticEl project has served as a unified database of geological, geochemical, and technical information as well as of treatment methods for CRM-bearing primary and secondary resources including data on relevant and remarkable waste streams and facilities. In coordination with the Hungarian Geological Survey, results of the CriticEl project on CRMs in coals and fly ashes were used in a recently completed project assessing how the Hungarian coal reserves may be used in the future.

7 Existing practices for recovery of critical raw materials and other raw materials

7.1 Recovery of Tantalum and Niobium from tailings of the old Penouta mine

Verónica Mateos Aquilino, Teresa Llorens González, and Francisco García Polonio
STRATEGIC MINERALS SPAIN (SMS)

Context

The Penouta Sn-Ta-Nb deposit is located in the Central Iberian Zone, in the innermost part of the Iberian Variscan Belt in Galicia in northwest Spain where two main formations crop out: the Viana do Bolo Series (high-grade metamorphic rocks) and the Ollo de Sapo Formation, characterized by a volcanogenic sequence which mainly consists of augen gneisses (Montero et al., 2009; Díez Montes et al., 2010).

The deposit is largely a sheet-like albitised-greisenised granitic cupola elongated in a SW-NE direction with a maximum length of about 1100 m and maximum EW width of 700 m, and extending more than 200 m in depth. Mineralization consists of cassiterite (containing Sn) and columbite-group minerals (containing Ta and Nb) which are finely disseminated throughout the granite, increasing contents and size towards the apical area, where intense kaolinization of the granite occurs (López Moro et al., 2017; Llorens et al., 2017).

Occasionally, banded pegmatitic-aplitic dikes can be found in the apical zone of the granitic cupola, which also contains Sn-Ta-Nb minerals. The cupola system culminates with the development of a stockwork of quartz veins up to 2 m thick containing coarse-grained cassiterite. Crystallization of these quartz veins occurred simultaneously with strong greisenisation of the hosting augen gneiss and the granitic cupola, causing the development of an irregularly distributed greisen body throughout the eastern area of the deposit.

The Penouta Mine was one of the most important tin mines in Spain. Historically, mining in the Penouta area has been carried out since Roman times using small underground tunnels which followed the cassiterite mineralized quartz veins hosted by the albite leucogranite. Mining in the Penouta deposit has been documented since 1906, but it was not extensively exploited until the 1970s when it was mainly worked to obtain cassiterite from the granitic cupola and the swarm of related hydrothermal quartz veins, while Ta was obtained as a by-product. Mining during this period was carried out by open pit methods, specifically targeting the kaolinised leucogranite and those portions of the country rock which had been muscovitised and were soft enough to be extracted using free dig methods. These materials were not milled and only fragments up to 2 mm in size were treated in the gravity plant so that a large amount of Sn and Ta-Nb minerals was not liberated from the hosting rock and was progressively accumulated in the tailing ponds, which have not been rehabilitated at all. As a consequence, sands from tailings reach similar grades as those of the original granite.

Several exploration projects together with feasibility studies and drilling campaigns were carried out in the Penouta granite from 1961 to 1985, including the study of both cassiterite and Ta-Nb-bearing minerals. These comprise mineral estimation projects and evaluation of mud pits, together with several drill-hole campaigns to investigate resources and viability of the mining project, considering 13 Mt of reserves with average grades of 750 ppm Sn and 90 ppm Ta (ADARO, 1982, 1985). However, the drop in metal prices led to the definitive closure of the mine in 1985 (**Figure 12**) after being acquired by different owners.

Figure 12 Open pit at the moment of closure in 1985

As a consequence of such inefficient separation processes, these mining wastes still contain significant amounts of metals such as tin, tantalum, and niobium as well as significant quantities of industrial minerals (quartz, mica, feldspar, and kaolin). The revival of mining in recent years has encouraged Strategic Minerals Spain (SMS) to develop new exploration on the resources of the Penouta deposit, which has permitted the estimation of mineral resources both in the remaining original deposit (95.5 Mt of Measured and Indicated Mineral Resources with average grades of 77 ppm Ta and 443 ppm Sn) and in the old tailing waste-rock heaps where the company has started operations (12 Mt of resources with average grades of 35 ppm Ta and 428 ppm Sn) (**Figure 13**).

Figure 13 Images of tailing ponds and waste-rock heaps in 2017

The following areas may be differentiated among the old tailings of the Penouta Mine (**Figure 14**):

- Tailings Pond 1 ("Roldan"): 4.8 Mt, average grades of 387 ppm Sn and 48 ppm Ta (Indicated resources)
- Tailings Pond 2 ("Abeja"): 0.2 Mt, average grades of 421 ppm Sn and 26 ppm Ta (Inferred resources)
- Waste-rock heaps: 6.8 Mt, average grades of 428 ppm Sn and 27 ppm Ta (Inferred resources)

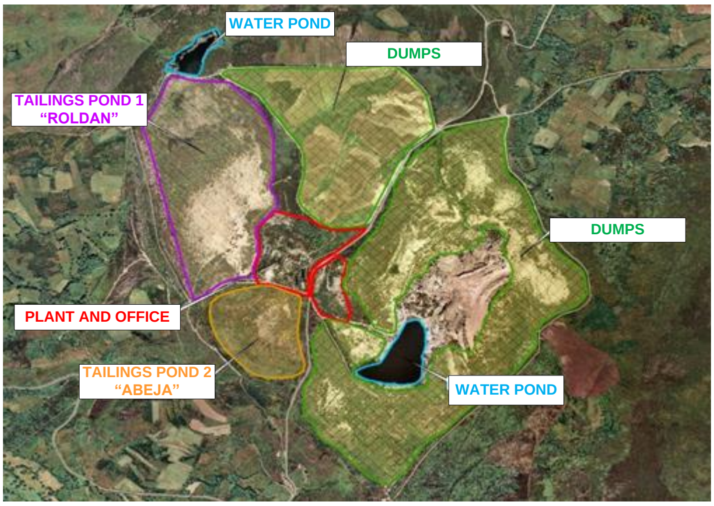


Figure 14 Areas of Penouta Mine

SMS has also carried out studies to draw up the exploitation plan and detailed engineering, which designed an optimum, effective and efficient gravimetric process, allowing the maximum use and valorisation of these residues.

The Penouta Mine Project "Exploitation of the Resources of Section B Penouta" has been authorized by the Ministry of Industry of Spain, and regulated by the requirements of the Spanish Mining Act (22/1973) in 2013.

In order to obtain this authorization, an exploitation project was developed which endorses:

- Technical feasibility: completion of geological studies, surveys, sample analysis, and exploitation simulations.
- Economic viability: includes short- and medium-term cost/benefit studies.
- Environmental viability: environmental impact study and preliminary reports
- Social viability: study of the degree of social acceptance as well as the positive impacts on the socio-economic environment.

The result of all these studies derived in the construction of a gravimetric separation plant for the processing of these wastes, which started operating in early 2018.

Description

The processing of tailings from waste-rock heaps and ponds of the old Penouta mine leads to the obtaining of tantalum and niobium minerals. These two metals are listed by the EU as being critical raw materials due to the high supply risk and high economic importance (European Commission, 2017). It should be noted that Ta and Nb are known as rare metals because of their scarcity in nature, so that, for example, one tonne of the earth's crust contains between 1 and 2 grams of Ta (1-2 ppm). Thanks to their exceptional properties, they are elements that today have important applications in new technologies, medicine, and science.

The largest tantalum reserves in the world are in South America (40%) and Australia (21%), only 1% being found in Europe. The main producers of tantalum in recent years have been Rwanda and the DRC, which accounted for more than 50% of world production in 2015 (Roskill, 2016). With the exception of small quantities of tantalite that are obtained as a by-product from the exploitation of kaolin in France, there is currently no production of primary origin in the EU. There are only a few processors in the EU, that is, in Estonia (imported primary materials), Austria, Germany, and UK (mainly secondary materials).

Niobium is widespread throughout the world but it is rarely accumulated in large enough concentrations for economic mining. Brazil has around 93% of world production, while

Canada, China, and Nigeria supply the remaining 7% (Roskill, 2016). In the USA more than 150,000 tonnes of niobium resources have been identified and in Europe there are known deposits of niobium and tantalum in Finland and Norway, but they cannot be economically exploited using conventional processes (Pohl, 2011). There are some deposits of niobium and tantalum in Spain that could be exploited in satisfactory economic conditions.

The similar electronic structures of niobium and tantalum means that they are almost always found together in nature and require similar processes for extraction and purification, and can substitute each other in certain applications. Niobium and tantalum are components in approximately 100 different minerals, mainly consisting of complex salts of niobium and tantalum together with varying proportions of titanium, zirconium, tin, REE, thorium, uranium, and alkaline earth metals (Zelikman et al., 1966).

Tantalite and columbite are respectively the main sources of tantalum and niobium in the Penouta mine. Thanks to the development of new technologies and the evolution of old mineral separation techniques, it is now possible to recover the metals of interest contained in these tailings and waste-rock heaps of the former Penouta mine. That is why SMS has invested a great deal of effort in the construction of a processing plant for these materials, applying the best available techniques.

During the processing of tailings from waste-rock heaps and ponds of the old Penouta mine, around 1% of tin, tantalum, and niobium concentrate is obtained, which is sold to international companies that process the raw material to generate intermediate compounds that serve to produce highly specific components. In this process 99% of mining tailings are generated, which are mainly composed of silicate minerals that can be reprocessed, obtaining around 70% of industrial minerals, namely quartz, mica, feldspar, and kaolin. The aim of the overall process is to achieve approximately 80% revalorization of mining wastes. The final residue will be used as material for environmental rehabilitation.

Designed to handle 1 million tonnes per year of feed material from the old tailings, the technology used to extract Sn, Nb, and Ta employs a gravimetric process (**Figure 15**) without any chemical products or waste that is harmful to the environment.

Figure 15 Image of the gravimetric plant

The main stages of the gravimetric process are:

- Milling: the rock is milled at this stage in order to reduce the mineral size so that it can be liberated for the next concentration stage.
- Gravimetric concentration: the metallic minerals of interest have a high specific gravity so they are concentrated using a combination of:
- Spirals: This is the first part of the gravity-based concentration, and consists of various stages of successive spirals that remove the less dense waste material and concentrate the minerals of interest.

- Shaking tables: This is the second phase of concentration, and consists of various stages of successive shaking tables, where the minerals of interest are classified by relative density (Figure 14).
- Low-intensity magnetic separation: The minerals are separated based on their different magnetic and paramagnetic properties. This stage serves to remove both mineralogical iron and iron from milling element erosion.
- Drying of the final product for storage and sale.

Figure 16 Mineral concentrate (black) on shaking tables

The design of such a modern processing plant uses energy and water resources efficiently. The water supply for the exploitation plant is obtained by capturing surface water in old water ponds and at the old pit face, which is currently flooded. The processing plant has a closed circuit water system so that water recovery reaches 70%, which is then recirculated to the circuit.

Chemical substances do not participate in the process, as it is an exclusively gravimetric process. Therefore, there are no chemicals in the wastes generated. These wastes are chemically similar to the feed material because only low amounts of metallic minerals (mainly tantalum-niobium oxides and tin oxides) and kaolin are obtained during the processing.

The chemical analyses carried out during exploration have shown that the contents of sulphide minerals (pyrite, marcasite, pyrrothite, galena, etc.) are very low in both the parental rock and in the tailings to be exploited so acid waters will not be formed from the weathering of these wastes.

Due to the characteristics of the project, no type of new final waste disposal facility will be necessary. The wastes generated will be directly used in the rehabilitation work, either in the filling of the exploited waste ponds or in the filling of the hole in the old exploitation front and the tailings. The current sterile ponds in which the extractive waste of the process will be deposited are considered to be a non-A extractive waste facility.

The industrial minerals obtained have an equal or better quality than products that are already on the market so it is easy to gain a foothold in this sector although the SMS is gambling on boosting investment in R&D for the development of new technologies and new applications of products, both metallic and industrial, that will result in the opening of new national and international markets.

It should be noted that the mine is located in a social, economic, and environmentally degraded area of Galicia on the west-central border of Ourense province. The economy of the rural environment declined progressively after the closure of the mine in 1985 so that the population survives on a subsistence economy. Therefore, the opening of the new processing plant in Penouta could trigger a progressive improvement in a degraded rural economy during the project's 12-year life.

Additionally, the mine is adjacent to a protected natural area called Red Natura "Peña Trevinca". When this natural area was declared as Red Natura 2000, the zone occupied by the abandoned Penouta mine was excluded due to its poor ecological quality. The future rehabilitation of these abandoned mining wastes will result in an area with better ecological quality. Therefore, a great challenge for the project consists of reaching a degree of quality that allows the area to be included in this protected space.

Furthermore, the Penouta Mine Project expects to be a reference for sustainable mining in which abandoned wastes are valued to generate economic, environmental, and social benefits in the framework of a Circular Economy.

Drivers

Recovery of an environmentally degraded area

The Penouta Mine was closed in 1985. It was exploited by open pit methods in a poorly selective way. Mineral wastes were deposited in waste-rock heaps and tailing ponds, which have not been rehabilitated at all.

For this reason, the mining area has low ecological quality, lacks of top soil, and has steep slopes, which are some of the reasons that have made natural rehabilitation impossible.

To meet the objective of reducing and eliminating the environmental impact, on its own initiative Strategic Minerals Spain developed a detailed Pre-Operational Study in the Penouta Mine and surrounding areas (Strategic Minerals Spain, 2016) in order to use this information as the starting point to apply improvements. This work was needed to diagnose the situation of the Penouta Mine from an environmental point of view and included:

- Climate study through data collected from weather at the mine site and other stations in the surroundings.
- Surface water and groundwater study by 50 sampling points (Figure 15), data collection of daily flows and levels of mine dams, internal and external analysis of physical and chemical water parameters, hydromorphological and biological studies, bathymetry of the mine dams, and vertical profiles.
- Vegetation study using a sampling grid in the mine and in the surroundings, inventory, and distribution of vegetal species as well as preparation of a herbarium.
- Wildlife study through birdwatching, identification of animal footprints, traces, and excrements, detection of insects, amphibians, and reptiles.
- Soil study by developing edaphic profiles, study of existing slopes, and distribution mapping of soil types.
- Study of air quality in the mine and the environment by noise simulations and placement of dust and particles sensors.

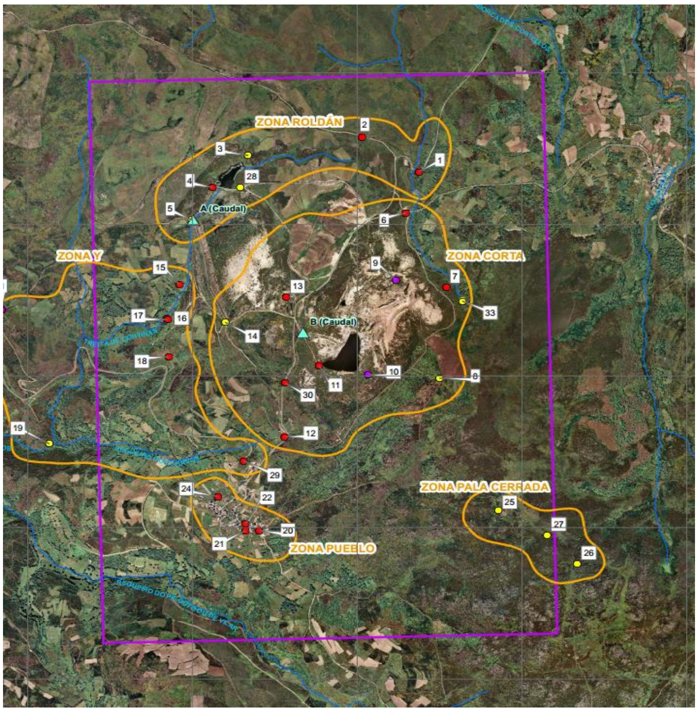


Figure 17 Environmental review points

This environmental information is currently used to carry out operational control and rehabilitation work.

As the exploitation progresses, the excavation voids will be filled in with the tailings. Then the techniques of landscaping and geomorphic reclamation, spreading of topsoil, and sowing will be applied.

In this context, control plots have recently been designed for the study of the mixture of soils, tailings, and vegetal species as well as follow up in order to apply the best technique resulting for rehabilitation.

The collection and conservation of seeds is being carried out from the beginning of the exploitation, and a nursery will be created with the goal of obtaining information in advance so as to develop future restoration work correctly.

Boosting the economy in a rural environment

The Penouta mine is located in the Penouta village, a small rural town that belongs to the district of Viana do Bolo, in the province of Orense (Spain). The economy is based on traditional agriculture, livestock, and forestry. The industrial sector is marginal.

The population over 60 years old in this area is the most represented age class and the number of young people is low. The depopulation and economic decline of the area has been constant in recent years, both in the village of Penouta and the district of Viana do Bolo, since the 1980s when definitive closure of the Penouta Mine occurred.

The Penouta Project is creating direct and indirect employment in this rural area which is suffering the continuous economy and population decline. It is expected that the Penouta mine project will improve the economy of the place in the short to medium term. Currently, more than 70 direct jobs have been created, being 80% of those in areas close by.

In addition, around 30 people work in the mine for subcontracted companies doing such things as earthmoving, analysis for the chemical laboratory, dining service, surveillance system, and cleaning services. Generally speaking, each direct job in mining projects generates three indirect jobs.

SMS understands that in being a specific sector and prioritizing local hiring, training of all workers is essential, also as a fundamental support to making the influence of the economic improvement of the Penouta Mine project visible even after the closure of the mine. Therefore, the Penouta mine project is continuously improving the training of the workers in the area by means of a training plan previous hiring to carry out the work. These training plans include safety and environmental issues which are fundamental to complying with the company's general CSR objectives.

Emerging global demands

As previously indicated, more than half of the tantalum production comes from the Central Africa, mainly from the Great Lakes region, which includes the DRC, Rwanda, and Burundi. However, a progressive slowdown has been noted in the supply from this area since the implementation of conflict-free policies, a decrease that is expected to continue in the forecasts until 2020 (Roskill, 2016). This decrease is complemented by the increase in the supply of tantalum from mines from South America, such as Pitinga (which also supplies Nb), or from Australia due to the resurgence of lithium mining, where tantalum is obtained as a by-product.

With the exception of small quantities of tantalite that are obtained as a by-product from exploitation of kaolin in France, there is currently no production of primary origin in the EU. Indeed, the EU does not import large quantities of Ta concentrates, the importation of chemicals (oxides, salts, and alloys) and processed final products being more important.

The exceptional properties of both Ta and Nb have led to a high demand for these metals for highly specialized applications (**Figure 18**) so that it is expected that there will be a growth of demand of 4-5% per year over the forecast period (Roskill, 2016). Capacitors are, and are expected to remain, the largest single market but the increasing functionality of smartphones, and ongoing reductions in capacitor size, are the main limitations on growth because the Ta content required for manufacturing is decreasing.

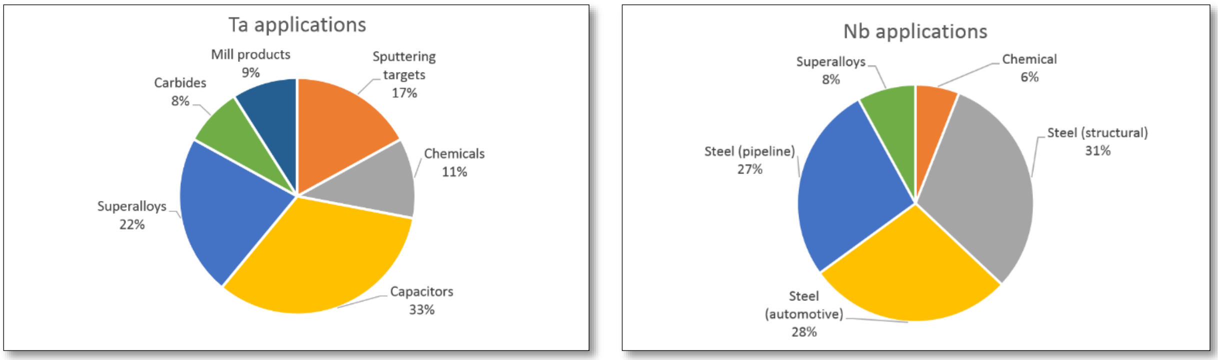


Figure 18 Main applications of Ta (left) and Nb (right) (Roskill, 2016 and EC, 2017).

The extraordinary resistance of Ta and Nb to high temperatures and corrosion make them suitable for use in a series of applications for alloys, a sector which is likely to have an above-average rate of growth mainly due to a healthy outlook for the commercial aerospace sector.

In steel, niobium is used as ferroniobium, mainly in the production of high-strength, low-alloy (HSLA) steels for the construction, automotive, and pipeline industries (Jordens et al, 2013), which predicts an annual increase of 8% (European Commission, 2017). It is also used in certain types of stainless and heat-resistant steels, which significantly increases strength and reduces cost substantially. This forms the basis for an increase in the niobium intensity of use, consequently providing an area of potential growth in niobium demand.

Sputtering targets, tantalum, and niobium chemicals and mill products have a wide range of final applications. Therefore, demand in these segments is also expected to display above average growth.

On the contrary, the use of tantalum in carbides, which are used almost exclusively in carbide cements for cutting tools, is forecast to decline slowly by 1% per year through the coming years.

Attempts have been made to replace the use of Ta in capacitors using Nb, but the size of these is greater, or by ceramic capacitors, but the resistance of the latter is lower. As the prices of other refractory metals that can be used instead of Ta are similar it is not worth using Ta in cutting tools. As for alloys, tantalum plays an important role at a relatively low cost so it is considered to be irreplaceable. In addition, this scenario also favours the growing demand of this metal during the coming years as well as the maintenance of market prices.

Tantalum has historically been susceptible to rapid changes in market balance with volatile price movements, specifically related to mining and inventory supply. On the contrary, niobium prices are historically very stable and seem to continue steadily increasing.

Considering this scenario of increasing demand and more or less stable or rising prices of metals, the reopening of the Penouta mine to reprocess the mining wastes there will be the only exploitation of these strategic metals throughout Europe. Although this mine does not meet all of the European demand, the Spanish product does have a significant market share.

Growing niche in the R&D field

A mixed concentrate of Sn-Ta-Nb is now being obtained in the Penouta mine's process plant and sold to international smelters and refineries, which perform the separation of the metallic Sn from the Ta and Nb. This process has not only been tested and studied in detail by the company staff but also in collaboration with the European consortium in charge of the OptimOre H2020 project, of which SMS was part of the advisory board. One of the main aims of Strategic Minerals Spain is to develop innovative technologies for the recovery of these metals through a combination of electrostatic and high intensity magnetic separation together with pyro and hydrometallurgical techniques (López et al., 2018), thereby obtaining a product with higher added value. Obtaining these products within the EU by revalorization of abandoned mining waste, is of high scientific-technical as well as economic and environmental interest, maximizing the economic benefit obtained from these complex materials.

The combination of electrostatic and high intensity magnetic separation techniques could lead to the separation of cassiterite concentrate and columbo-tantalite concentrate. SMS is currently researching the best way to implement these technologies in the processing plant in order to obtain better final products to be sold either as separate concentrates or to be smelted.

Pyrometallurgical processes have been almost completely replaced by hydrometallurgical ones in recent years. The most common way to extract Ta and Nb from mineral concentrates is by using solvents, where these concentrates are attacked by a mixture of hydrofluoric and sulphuric acid at high temperatures, dissolving Ta and Nb to form fluorinated complexes (Kumar et al., 2013), which involves high energy consumption for solvent extraction only (Nuss and Eckelman, 2010, Koltun and Tharumarajah, 2014).

The current lines of research in this field are focused on the substitution of the current fluxes in the pyrometallurgical process by others that produce much more soluble Nb and Ta salts. This would allow the replacement of HF by organic acids, which are less hazardous and more friendly from an environmental point of view, and perhaps much more effective (Sánchez-Segado et al., 2017). Therefore, the goal is to implement new solutions that will make the hydrometallurgical process of recovery of Nb and Ta a more innovative and competitive one (**Figure 19**).

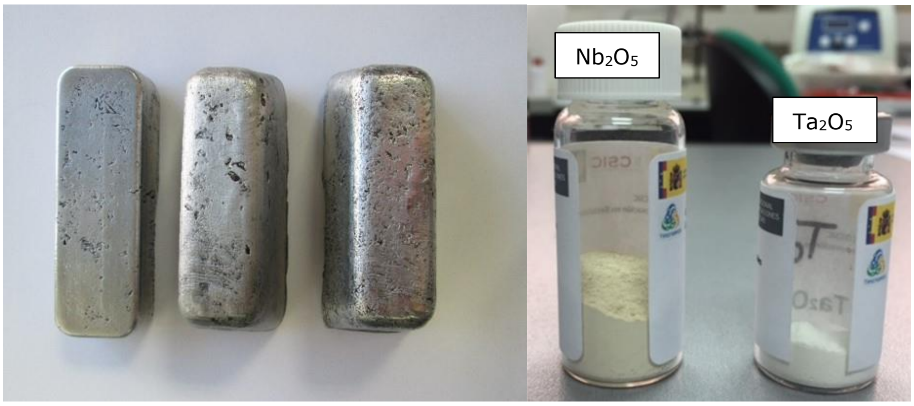


Figure 19 Products resulting from the R&D projects: tin ingots (left) and Nb and Ta oxides (right)

The R&D investment in this field would respond to an important social demand and is of great interest mainly from the socio-economic and scientific-technical points of view, allowing the development of the technology necessary to recover Ta, Nb, and Sn from complex minerals, which meets the demands of European industry and technology for these materials in different industrial sectors. Therefore, the production of these strategic metals in a conflict-free region would also have an important impact on the Spanish and European markets.

Environmental and social acceptance as a driver of regulatory authorization

The fact that the Penouta mine has been a degraded area since its closure where no process of environmental rehabilitation has taken place in the last 30 years has facilitated the environmental impact study since many of the impacts were already present in the area before the implementation of any industrial activity. The positive environmental impacts are greater than in other mine opening projects in natural areas since once the industrial process has been completed, the rehabilitation will improve the ecological quality compared to the situation that existed before. These issues have facilitated the administrative processing of the legal authorization of the project.

The existence of old facilities such as mining pools, water connections, and the old pit face, now flooded, have facilitated the authorization of both water catchment and discharge.

In general, the Penouta Project has had a good environmental and social acceptance for its authorization and start-up. The previously existing mining jobs favoured the acceptance of the local environment for the reopening of the mine as local terrains are now without any productive use and are being revalorized for mining, which generates wealth as well as jobs for the village of Penouta (Figure 19), and improves the economy of the area. These are positive impacts that remain in the memory of the inhabitants from when the mine was working decades ago, and it has now become a positive point for the authorization of local licenses.

Figure 20 Image of the village of Penouta

Innovation

Taking into account the scarcity of primary deposits with tantalum and niobium in Spain and Europe, an alternative source especially in Spain where there is a long tradition of tin mining, is the recovery of old waste-rock heaps where Nb and Ta are associated in the form of columbo-tantalite, together with the accessory of tin oxide (cassiterite). The existence of these secondary sources of Nb and Ta, unique in the world, make them both attractive and challenging at the same time from both a technological and economic point of view. However, it is impossible to achieve efficiency and competitiveness in Spanish and European industry without considering and optimising multiple aspects of the supply of raw materials in Europe.

Within such a complex and inter-linked framework, the Penouta Mine project features highly innovative aspects that are promoted and supported by the European Commission through the Horizon 2020 Work Programme 2018-2020, specifically in Societal Challenge 5 on *"Climate action, environment, resource efficiency, and raw materials"*, in particular:

1. Increasing efficiency in the use of raw materials.
2. Developing primary and secondary technologies for processing.
3. Improving the efficiency of its processing, recycling, or the products that contain it.

The Penouta Project can be considered a good practice in the raw materials field on the basis of the following strong points:

- The valorisation of mining waste from the Penouta Mine, with subsequent reduction of the presence of waste in waste-rock heaps and tailings ponds where no rehabilitation process was carried out after closure.
- The recovery of strategic and critical metals like tin, tantalum, and niobium as well as industrial minerals, which together bring a reduction of wastes up to 80%.
- Mining exploitation in a previous environmentally degraded area. After mining by SMS, techniques of environmental rehabilitation will be applied. The ecological quality will improve on the current state and will offer uses non-existent today. A great challenge for the project consists of reaching a degree of quality that allows the area to be included in the protected space (Natura 2000).
- Obtaining conflict-free metals from mining wastes.
- The design and development of a modern mining plant that allows the efficient use of energy and water resources. The use of chemical substances is avoided because it is an exclusively gravimetric process (environmentally-friendly technology).
- Generation of direct and indirect employment in a rural area after decades of economic decline and depopulation.
- The ambition of the Penouta Mine Project is to be a reference for sustainable mining in which abandoned wastes are valued to generate economic, environmental, and social benefits in the framework of a Circular Economy.
- It is expected that the Penouta mine project will improve the economy of the area. Currently, more than 70 direct jobs have been created who compose 80% of the hired people resident in the nearby environment.
- It is expected that the Penouta mine project will improve the training of workers in the area.
- The influence of the economic improvement of the Penouta Mine project should be visible even after its closure.
- Incorporation and achievement of R&D projects to improve the efficiency and effectiveness of the process, the quality of the products, sales, environmental control, and rehabilitation activity.

Bottlenecks

Technological development is one of the main bottlenecks as it requires a large investment in R&D to develop new technologies that carry out more effective separation in line with a new mining model of the 21st Century and Circular Economy practices. Since they are materials that were previously processed, these types of deposits are low grade, which makes beneficiation even more difficult. Fortunately, today's mining companies are aware of this fact and are investing great financial and human resources in this direction as this can make the difference between success and failure for mining works.

Historical **information** is another big bottleneck, as there is barely any accessible historical information about the existing mining resources in abandoned tailing ponds and waste-rock heaps. Spain hosts a large number of mining indicators and old closed or abandoned mines due to the prices of the metals falling in the 1970s and 1980s. However, information about these deposits is mostly private, there are usually no records that can be reviewed, or if there are, the information is incomplete since the data and the original samples have not been preserved. This fact greatly hinders the knowledge of its existence and the development of future mining investigations. To solve this problem, various research groups have developed several projects at European level in recent years that try to develop a database of this type of resources (i.e. SMARTGROUND, Minerals4EU) so that the information is more easily accessible to companies potentially interested in its benefits.

From the **regulatory** point of view, the administrative times to resolve any type of consultation or request as well as licences and permits are currently extremely lengthy and uncertain. This is also influenced by political changes. It should be a much simpler and faster process given that success strongly depends on the price of the raw materials. This point is decisive in most of cases when starting a project since the project may be profitable at a time of rising prices, so immediate opening is necessary so that the periods of low profitability can be supported. Measures have been proposed by national and regional governments to speed up these procedures and to promote the development of mining in certain strategic sectors. However, in practice, the results have not been seen yet.

This links directly to another possible bottleneck of the **market scenario.** There are times of high international demand for CRMs, as is the current situation, which makes the opening of projects such as the Penouta mine possible. However, the same market has constant fluctuations. There are periods in which the situation becomes unsustainable in a climate of excessively high prices, and it is at this time when the intermediate processors go to the reservoirs of the metals of interest. That creates an excess of supply that translates into a price drop, which leads to greater difficulty placing the mine product. This means that only certain types of products reach the market, which particularly favours the most processed product because it has greater added value. In addition, a company’s technological development once more plays an important role in placing the company in a strategic position.

The issue of **financing** is a link to all of the above-mentioned bottlenecks. In order to develop innovative technologies that generate products with high added value, a significant financial investment is required. To get access to historical information, if any, finance is generally needed to buy it, or again significant funding is required for all mining research. From the regulatory point of view, the administration usually needs to prove the viability of the project through long and expensive mining research, which must prove sufficiently sustainable mining for the administration to grant the appropriate permits for its exploitation. All this entails a great deal of investment, not only in the research itself but also in maintaining the entire business network while the permits arrive to be able to start producing and reach the market, thereby benefitting. In particular, this last issue is a limitation that means that a mining project is developed over an extremely long period of time in which there is only investment, which leads to these kind of projects having great difficulty in obtaining financial resources since they are high-risk investments and stockholders want to recover their financial resources as soon as possible. This fact can weigh on a mining project so that it does not start.

Recommendations

The Penouta mine scheme could also be applied to other similar mining deposits not only in Spain but also in Europe (from the Moldanubian zone of the Czech Republic, through the Armorican Massif and French Massif Central and finally the Iberian Massif), which contain Sn associated with various CRMs such as Ta, Nb, and/or W. There are numerous ore deposits here that have been previously exploited and, as occurred in Spain, were mostly abandoned after the fall in metal prices during the seventies and eighties. Therefore, there are many abandoned waste-rock heaps and ponds with a certain degree of mineralization that should benefit from this example.

The minerals composed of these elements respond to separation by density in a similar way, which is the principle on which the gravimetric separation implemented in Penouta is based. This fact can be an advantage in replicating this model of utility in other mining wastes, but is also an obstacle at the same time since each deposit has its own characteristics, exclusive mineral associations, and certain grades. The market situation can also determine whether or not a low grade mining waste is profitable or not at a given moment in time, in addition to the regional distribution (there are serious energy supply limitations in some mining areas), and the political and regulatory conditions in each region. Additionally, there may be environmental protection measures that also limit the use of such waste.

In this context, several projects within the H2020 program have contributed to increasing knowledge of this type of resources in Europe, as previously mentioned. Moreover, a project has been funded with the objective of mapping best practices and boosting opportunities for cooperation in relation to the entire raw materials value chain (INTRAW) by developing an International Observatory for Raw Materials.

In order for these projects to become a reality and to promote cooperation to develop and strengthen the mining model in Europe, first it is necessary to reflect and examine the causes of success in the raw materials sector in other regions, to understand what the European Community can improve in leveraging its mineral resources in an efficient and sustainable way. This assumes the development of a strong education and R&D culture which helps to develop a highly industrialised economy, based on the manufacturing of knowledge-intensive and high-quality, high value added products.

In this context, Australia could be taken as an excellent development model for both mining and associated industries. In this region, mining companies have great support based on mining equipment, technology, and service companies grouped in a mining cluster that supports the mining industry (Bonito et al., 2016) as they cover the entire value chain, thus providing technologically advanced products and services for mining companies worldwide. This is also possible in Europe where there are the raw materials, the mining companies, and a wide network of technological and support services, and even end-users with sufficient capacity to give maximum value to the product.

References

ADARO (1982): Proyecto de Investigación de la Mina de Penouta. Cálculo de reservas para leyes de corte de 800 y 600 g/t. Internal Report, Madrid.69 pp. (Unpubl.).

ADARO (1985): Investigación Minera del Yacimiento de Penouta. 9 volumes. Internal Report, Madrid (Unpubl.).

Bonito, N., Cristo, N., Peres, M. and Peças, T. (2016): Analysis on Industry and Trade. Operational Report. INTRAW EU Horizon 2020 Project.

Díez Montes, A. (2006): La Geología del Dominio "Ollo de Sapo" en las comarcas de Sanabria y Terra do Bolo. Universidad de Salamanca e Instituto Geológico y Minero de España, PhD, 496 pp. (Unpubl).

European Commission (2017): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU (Online). Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0490

Jordens, A., Cheng, Y. and Waters, K. (2013): A review of the beneficiation of rare earth element bearing minerals. *Minerals Engineering*, 41, 97-114. https://doi.org/10.1016/j.mineng.2012.10.017.

Koltun, P. and Tharumarajah, A. (2014): Life Cycle Impact of Rare Earth Elements. ISRN Metallurgy, 2014, 10 pp. http://dx.doi.org/10.1155/2014/907536.

Kumar, T.S., Kumar, S.R., Rao, M.L. and Prakash, T.L. (2013): Preparation of niobium metal powder by two stage magnesium vapor reduction of niobium pentoxide. Journal of Metallurgy, 2013, 6 pp. http://dx.doi.org/10.1155/2013/629341.

López, F.A., García-Díaz, I., Rodríguez Largo, O., García Polonio, F. and Llorens, T. (2018): Recovery and purification of tin from tailings from the Penouta Sn-Ta-Nb deposit. Minerals, 8(1), 20. https://doi.org/10.3390/min8010020.

López-Moro, F.J., García Polonio, F., Llorens González, T., Sanz Contreras, J.L., Fernández Fernández, A. and Moro Benito, M.C. (2017): Ta and Sn concentration by muscovite fractionation and degassing in a lens-like granite body: The case study of the Penouta rare-metal albite granite (NW Spain). Ore Geol. Rev. 82, 10–30. https://doi.org/10.1016/j.oregeorev.2016.11.027.

Llorens González, T., García Polonio, F., López Moro, F.J., Fernández Fernández, A., Sanz Contreras, J.L. and Moro Benito, M.C. (2017): Tin-tantalum-niobium mineralization in the Penouta deposit (NW Spain): Textural features and mineral chemistry to unravel the genesis and evolution of cassiterite and columbite group minerals in a peraluminous system. Ore Geol. Rev., 81, 79–95. https://doi.org/10.1016/j.oregeorev.2016.10.034.

Montero, P., Talavera, C., Bea, F., Lodeiro, F.G. and Whitehouse, M.J. (2009): Zircon geochronology of the Ollo de Sapo Formation and the age of the Cambro–Ordovician rifting in Iberia. J. Geol. 117, 174–191. http://dx.doi.org/10.1086/595017.

Nuss, P. and Eckelman, M.J. (2014): Life Cycle Assessment of Metals: A Scientific Synthesis. PLoS ONE 9(7), e101-298. https://doi.org/10.1371/journal.pone.0101298.

Pohl, W.L. (2011): Economic geology: Principles and Practice. Chichester, West Sussex: Wiley Blackwell. ISBN: 978-1-444-33663-4, 678 pp.

Roskill (2016): Tantalum: Global Industry, Markets & Outlook to 2020. Twelfth Edition. Roskill Information Services Ltd. ISBN 978 1 910922 12 5. 148 pp.

Sanchez-Segado, S., Monti, T., Katrib, J., Kingman, S., Dodds, C. and Jha, A. (2017): Towards sustainable processing of columbite group minerals: Elucidating the relation between dielectric properties and physico-chemical transformations in the mineral phase. Scientific Reports, 7 (1). https://dx.doi.org/10.1038/s41598-017-18272-3.

Strategic Minerals Spain (2016): Pre-operational environmental study of the "Cero State" of the Penouta Mine (internal report).

Zelikman, A., Kreĭn, O. and Samsonov, G. (1966): Metallurgy of rare metals. Jerusalem: Israel Program for Scientific Translations (Available from the U.S. Dept. of Commerce, Clearinghouse for Federal Scientific and Technical Information, Springfield, Va.).

7.2 Recovery of CRMs and valuable metals from inorganic industrial waste streams

Liesbeth Horckmans
VITO
CHROMIC consortium

Context

Europe is heavily dependent on imports to sustain its supply of raw materials. At the same time, significant concentrations of critical and valuable metals (CRMs and VMs) are locked in industrial wastes and by-products that are currently still landfilled or used in applications where the metal value is not (fully) utilized. In addition, the presence of these industrial wastes and by-products often creates environmental concerns as well as health and safety issues for society, thereby imposing constraints on the valorisation.

Recovery of CRMs and VMs from industrial waste and by-product materials will not only unlock previously untapped resources for the EU, but will also simultaneously improve the residual matrix material (often >95% of the bulk material) for further valorisation. Processing of waste streams to recover metals is neither economic nor sustainable without solving the issue of the bulk streams. As such, the traditional approach of maximising metal yield with little or no regard for the waste streams generated is no longer an option. Instead, **valorisation of the residual matrix is the key to feasible metal recovery from these low-grade streams** leading to a more sustainable circular economy model.

This requires innovative, highly selective recovery technologies that **capture the metal without impairing the properties of the residual matrix material for valorisation**. Given the typical low concentrations of metals in these streams, a radical new approach is needed with smart combinations of innovative technologies throughout the whole value chain.

As an example of this approach, this chapter presents the H2020 project CHROMIC (GA 730471) which aims to recover Cr, Mo, V, and Nb from stainless and regular steel slags as well as ferrochrome slags. However, a similar strategy is adopted in other ongoing H2020 projects, which target a variety of elements and industrial residues, such as PLATIRUS (GA 730224, PGM recovery from batteries and catalysts), METGROW+ (GA 690088, In/Ga/Ge/Zn/Pb/Ni/Cr recovery from slags and sludges), CROCODILE (GA 776473, recovery of Co from batteries and catalysts) and NEMO (GA 776846, Ni, Cu, Zn, REE recovery from sulphidic mine tailings).

Universities and research institutes work together with industry in these research projects to develop processes that are scalable and economically viable. The CHROMIC consortium consists of 11 partners:

- Research institutes: VITO (coordinator), HZDR, BFI, FEhS, BRGM
- Universities: TUKE
- Industry: Orbix, MEAM, EWW, ARCHE, Formicablu

More information on the project and its partners can be found on the project website www.chromic.eu.

Description

CHROMIC aims to recover valuable and critical raw materials (VMs and CRMs) from three model streams, namely:

- **Stainless steel slags (1.8 Mt/y EU production)**

- Carbon steel EAF slags (20 Mt/y EU production, of which an estimated 10% is enriched in Cr)
- Ferrochrome slags (0.6 Mt/y EU production)

These slags contain appreciable amounts (1-10 wt.-%) of chromium (Cr, 2014 CRMs list), as well as lower amounts (100 – 500 mg/kg) of vanadium (V, 2017 CRMs list), niobium (Nb, 2014 and 2017 CRMs list), and molybdenum (Mo, VM). More details about the potential for recovery and import dependency reduction are given in **Table 5**. It is important to note that annual production only shows part of the potential since historic stocks and landfills of several million tonnes have been built up across Europe. In some cases, historic stocks can be even more enriched in metals due to less efficient processing methods being used in the past.

Table 5: Target metals in CHROMIC

Metal	*EU metal import (t/y)*[1]	*EU import dependency*	*CHROMIC recovery potential (t/y)*	*Import dependency reduction*	*Market value (M€/y)*
Cr	720,000	75%	92,340	12%	92
V	9124	84%	632	7%	5
Mo	40,290	100%	211	0.5%	1
Nb	13,300	100%	810	6%	25

1 Data for EU metal imports and import dependency according to CRMs report 2017 (Deloitte Sustainability 2017a, 2017b, 2017c).

From a technological point of view, CHROMIC aims to improve both mineral processing and (hydro) metallurgical technologies applied to low-grade secondary resources to increase the energy-, material- and cost-efficiency of the overall metal recovery process (**Figure 21**).

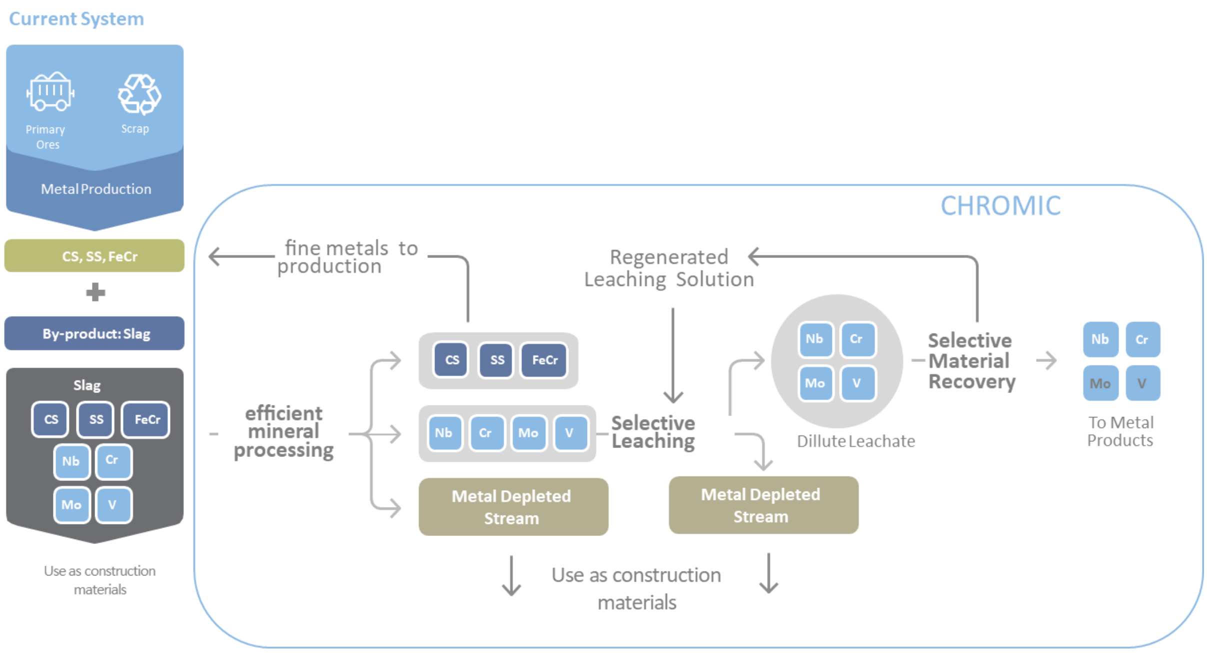


Figure 21: Overview of CHROMIC

To a large extent mineral phases such as Fe, Ca, and Mg oxides and silicates that make up the bulk (matrix) of many mineral waste streams from the ferrous and non-ferrous metal industry typically dissolve in acidic environments, which are generally used in many traditional hydrometallurgical processes. However, these materials are fairly insoluble in alkaline environments whereas Mo, V, Cr, and Nb can dissolve in oxidative alkaline conditions because of the formation of soluble oxyanions. This opens up the path towards new recovery technologies for these metals based on selective leaching in alkaline environments. Concurrently, novel enrichment and purification techniques must be developed for selective extraction of these oxyanions from complex alkaline solutions. Importantly, suitable pre-treatment mineral processing schemes has been devised to decrease the overall energy demand and increase efficiency making the process economically viable (i.e. "more with less" energy, material, costs). Finally, as stated above, **the metal recovery of low-grade (secondary) resources is only viable if a (commercial) solution is provided for the large bulk (residual matrix) of the material**.

Therefore, **an important boundary condition for the treatment is the quality of the residual matrix, which must be recyclable**. Indeed, if the leached slags can no longer be used but must be discarded as waste, then the process is not sustainable. Potential applications considered in CHROMIC are both the traditional use as aggregates and fillers in the construction industry (where most slags are used today), and more high-value options such as novel binders. For the first option, the applications will need to be adapted to the changed properties of the slags after metal recovery (e.g. size reduction, loss of hydraulic properties due to contact with water). Granulation or pelletisation will be studied to increase the particle size. For the novel binders route, CHROMIC will particularly focus on the use of cleaned slag for the production of carbstone blocks, an innovative technology producing building materials from slags and CO_2 using a process of carbonation which was developed by VITO and Orbix (Quaghebeur et al.,2015, 2010).

Specifically, CHROMIC focuses on:

- Material-specific comminution techniques (electro fragmentation, microwave-induced liberation) to obtain a high degree of metal and mineral liberation and avoid over milling.
- Tailored physical separation schemes to divide the input streams into metal concentrates on the one hand and metal-depleted residue matrix materials on the other. The separation techniques applied are magnetic separation, density separation, electrostatic separation, and flotation, each of which needs to be adapted for use on fine-grained materials (i.e. < 2mm).
- Innovative leaching technologies based on selective dissolution of transition metal oxyanions in alkaline media without dissolution of the matrix, and with great efficiency (> 90%) due to the introduction of dielectric or ultrasonic energy as well as oxidation by roasting or using strong oxidants
- Highly selective metal recovery techniques that recover individual major and by-product metals from complex alkaline solutions even at low concentrations by a combination of selective precipitation, adsorption, and solvent extraction.

The viability of the processes developed will be iteratively assessed by a multi-criteria assessment including techno-economic, environmental, and risk analysis. The framework for this assessment was first developed within the METGROW+ project, and will be further refined in CHROMIC. The goal is to steer technology development from the start towards optimized economic and environmental sustainability.

An important aspect of CHROMIC is community involvement. Treatment of large amounts of waste materials often raises public concerns, and so proactive interaction with the general public is needed from the start to ensure societal trust. CHROMIC tackles this challenge through a series of participative events. A first series of focus groups with lay people revealed the need to communicate more clearly about the role and the importance of metals and their recycling as this knowledge is often incomplete. More insights are expected from the recently completed series of workshops to which stakeholders from various backgrounds (industry, research, NGO's) were invited to discuss the potential impacts of CHROMIC. A third event will reach out to both the general public and (professional) stakeholders.

CHROMIC runs from 2016-2020 with a budget of 4.9 M€ and partners from 5 countries (Belgium, Germany, France, Italy, and Slovakia).

Drivers

The main driver for the recovery of critical and other raw materials from industrial residues is the need for Europe to sustain its supply of these economically important materials (example for CHROMIC in **Table 5**) and diversify the input streams. From a sustainable materials management and circular economy point of view, as much raw materials as possible must be recovered.

The recovery of metals and minerals from secondary resources is not only beneficial for Europe's dependency on imports, but also reduces the need for extraction of primary resources and (often long-distance) transport of these primary resources to Europe. This creates an additional environmental benefit.

Residues that require landfilling may leach heavy metals (e.g. bauxite residue from Al production, goethite sludge from Zn production, pickling sludges from steel refining/finishing, etc.) so removal of metals can lower their environmental impact and enable the reuse of the matrix material. At the moment, most countries base the classification of residues on leaching tests because it is considered that these evaluate the actual danger of release into the environment. Residues that comply with the leaching criteria (as well as technical requirements) can be recycled, e.g., in the construction industry. For residues were recycling is currently not allowed due to exceeding the leaching criteria, removal of metals can help to reduce the environmental impact and enable recycling.

It must be stated that this does not apply to the majority of slags considered in CHROMIC because Cr is tightly bound in these materials as Cr (III) in stable oxide phases and so does not leach out. As stated elsewhere, these materials are already used today, mostly in road construction (~50%) and metallurgical applications (15%) (2016 Euroslag statistics). However, this may be an additional benefit for the limited fraction of steel slags that is currently landfilled (14% according to 2016 Euroslag statistics).

By lowering the environmental risk of the residues, and making sure that the cleaned up fraction can be reused as a mineral resource, landfilling can be avoided. This is an economic benefit for the companies involved since the associated costs (landfill tax, gate fees) are avoided, and it is also an environmental and social gain due to the recovery of valuable land for other uses. Landfill bans are likely to be imposed in the near future, which will further stimulate recycling of industrial residues. Additional economic gains are obtained from the value of the recovered metal itself as well as the higher value of the treated (cleaned) slag (**Table 5**).

Finally, society's view on landfilling and waste management is also changing with the need for a more sustainable materials management becoming clear to all. In the long run, the social driver may become the most important of all, that is, to safeguard future generations from raw material shortage and the burden of historic waste generation.

Innovation

Slags are often used as aggregates in the construction industry where their technical properties are much appreciated. However, in such applications, the metals present in the slags do not serve a purpose, and their value is lost. Moreover, the presence of metals even limits the reuse options in some cases. As mentioned in the previous paragraph, the recovery of metals from secondary resources has several advantages, such as:

- Avoidance of primary extraction, and the associated costs and impacts
- Extending the resource base for Europe
- Avoidance of landfilling, freeing up land for other uses
- Low(er) cost raw materials

The model streams in CHROMIC (stainless steel slags, carbon steel slags, ferrochrome slags) already have the potential to contribute significantly to reducing Europe's import dependency: for example, it could reduce Europe's import dependency for Cr by 12%, for Nb by 6 % and for V by 7 %. However, replication in other metals and streams is expected after the project has been completed. An internal assessment at VITO showed that the potential metal value in industrial streams can be as high as 2,500 Euro/tonne, with an average value of 400 Euro/tonne. This value in some streams comes almost completely from the content of critical raw materials whereas the value of other streams is dominated by other primary and by-product metals.

The use and replication of the new recovery process developed by CHROMIC boosts the supply of critical and valuable by-product metals for Europe since it triggers the cost-effective exploitation of previously untapped secondary resources. Concurrently, vast amounts of hitherto cumbersome waste streams will be transformed into raw materials, thereby improving the competitiveness of European industry, unlocking land currently occupied by landfills and alleviating the burden for future generations.

Bottlenecks

It is clear from the previous paragraphs that recovery of metals from industrial residues has significant potential. However, there are also a number of bottlenecks to reach these goals, as described below.

Technological

In the CHROMIC materials, Cr is present in both fine metallic (stainless steel, steel, or ferrochrome) particles (remnants of the production), and in Cr-enriched spinel phases. While these phases are well separated, they are closely entangled with other mineral phases and are very fine (10-100 µm range) (**Figure 22**). Therefore, physical separation is very challenging. CHROMIC tackles this in two steps:

- Firstly, comminution of the slags to the desired particle size is an energy- and time-consuming process. CHROMIC has developed microwave-assisted comminution (VITO, MEAM) and electro fragmentation (BRGM) to make this process more efficient, with better liberation of the target phases.
- Secondly, beneficiation and upgrading is needed to separate the solids into metallic particles (suitable for reintroduction into the metal production process), a metal-enriched fraction to undergo further leaching, and a metal-depleted fraction that may be directly used in construction applications. CHROMIC has investigated several techniques to accomplish this, namely magnetic separation (VITO, BRGM, BFI), density separation (VITO, BRGM), electrostatic separation, and flotation (BRGM)

Moreover, spinels are very stable minerals (which is why Cr does not normally leach out) and so selective attack is difficult. CHROMIC has selected alkaline leaching as the best option to ensure metal liberation with minimal matrix dissolution. The efficiency of the leaching step has been improved by using a combination of existing and novel technologies, such as dielectric heating (MEAM, VITO, TUKE), traditional and microwave roasting (BFI, FEhS, VITO, MEAM), heap leaching (VITO, Orbix), ozonation leaching (TUKE), and ultrasound assisted leaching (BFI, FEhS).

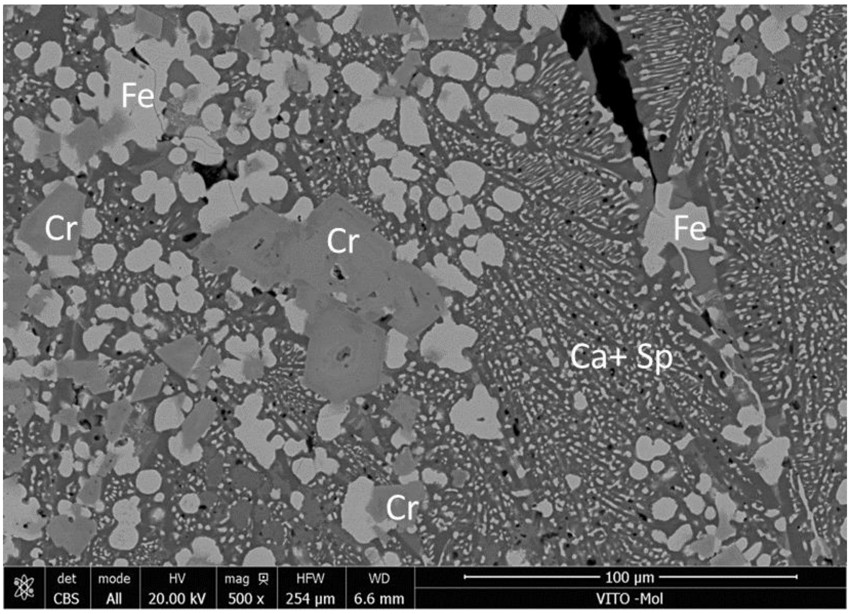


Figure 22: Morphological aspects of carbon steel EAF slags. Fe = Fe-oxides, Cr = Cr-rich spinel minerals, Ca = Ca-silicates, Sp = Cr-poor spinel minerals

Finally, in the metal recovery step, CHROMIC faces the challenge of selectively extracting elements with very similar chemical behaviour (chromate, vanadate, molybdate, niobate). CHROMIC has developed techniques for this such as selective precipitation (BFI, FEhS), novel LDH-based sorbents (VITO), solvent extraction (HZDR) and electrochemistry (TUKE).

Preliminary laboratory scale testing has demonstrated the technical feasibility to physically separate a pure metallic phase (24 wt.-% of a 97% pure Fe fraction from carbon steel slag), and to achieve 60-80% Cr recovery in the leachates. Further optimisation of the aforementioned process steps and development of selective metal recovery from solution is ongoing.

Once the CHROMIC process is demonstrated at lab scale, upscaling to industrial application will be the next challenge. In CHROMIC, tests of the optimised process at slightly larger scale will provide data for upscaling calculations.

Economic

Clearly, the treatment processes described above come at a cost. To increase leaching efficiency, slags have to be milled to a smaller size than usual (< 1 mm) which increases the energy requirement. Furthermore, the leaching step requires investment in equipment and reagents.

In addition, secondary resources are often (very) low grade compared to primary ore. As an example, Cr content in the CHROMIC materials ranges between 1 and 10%, while primary chromite contains 35-68% Cr_2O_3. Concentrations of the other metals (Nb, Mo, V) are even lower, ranging from 100 to 1000 ppm. Based on the market prices of the pure metal compounds, the value contained within the slags can be roughly calculated as 50-250 €/t Cr, 10-50 €/t Nb and only 1-5 €/t Mo and V. As mentioned above, current results show 60-80% metal recovery and the output of the CHROMIC processes will result in intermediate raw materials rather than pure metallic compounds. Therefore, the actual value obtained by sale of the recovered metal may be far lower.

Depending on the complexity of the required treatment process, the metal value may not cover the treatment costs. Metal prices are fixed on a worldwide market, and so cannot be changed to incorporate the higher production costs. On the contrary, a larger supply of metals may even reduce the market price. Moreover, it is clear that the value of V and Mo does not warrant an additional processing step but form (limited) additional profit if they can be captured through the same treatment steps.

Similar conclusions have been reached by other projects. For example, it became apparent in METGROW+ that the business case for low grade secondary CRMs ores relies heavily on the extraction of base metals such as Zn and Pb, often present at higher concentrations, with minor added benefits being obtained from the critical raw materials concerned. Economic recovery of metals from low grade ores needs all metals to be released during the same process so an extraction process recovering the minor elements alone is only viable for very high value metals such as PGMs. CHROMIC deals with this by developing a leaching process that can simultaneously extract Cr, V, Nb, and Mo based on their similar solubility in alkaline environments. Subsequently, selective recovery of each metal from the leachate will be achieved by specialized sorbents or selective precipitation, which is technically challenging due to the similar chemical behaviour of the oxyanionic species of the four metals in solution.

It is clear from these considerations that the economics of CRMs recovery from industrial residues is highly challenging.

One way to improve the economics of the overall recycling process is to maximize the revenue to be gained from the cleaned matrix, which means that high value applications must be selected. Novel binders may have a market value of 40-60 €/t compared to only 0-5 €/t for aggregates. One such valorisation route is the carbstone process, where building materials are produced by carbonation of slags with CO_2 gas (https://www.carbstoneinnovation.be/en/) (**Figure 23**).

Figure 23: Production of carbstone bricks in the Orbix pilot facility in Belgium

For landfilled streams, the avoided cost of landfilling (gate fees, landfill tax, etc.) may count as an additional revenue. However, this is highly dependent on local landfill policy. If landfilling taxes are high or landfilling is not possible due to lack of space or an outright ban, the economic benefits created by avoiding landfill are much higher than in situations where landfilling is cheap and available space is limitless. This can tip the balance of a treatment process' economic viability.

Other ways in which CHROMIC aims to optimize the economics of the recovery process are:

- Reducing milling costs due to the use of novel disintegration and particle liberation techniques based on electrical fragmentation and selective mineral heating
- Reducing reagent costs by: (i) upgrading the material streams into metal concentrates and metal-depleted reusable fractions, based on smart combinations of physical separation techniques specifically tailored to fine grained residues, and (ii) the application of efficient leaching processes with lower reagent consumption compared to state-of-the-art processes and recirculation of leaching solutions

- Selective recovery of the released metals in line with market demand and regenerability of the recovery agents

To ensure that the processes developed are economically viable, an integrated assessment will be performed in an iterative way to take into account boundary conditions set by the market. Since the data obtained by laboratory scale experiments are insufficient to form the basis of reliable estimates, upscaling experiments will be performed at a relevant scale to validate the feasibility of the approach and improve the assessment. Even then, some assumptions will need to be made.

Regulatory

One of the main regulatory bottlenecks is the heterogeneity of standards and requirements for recycling, reuse, and transport of waste materials within the EU. No uniform European regulation for specific slag utilisation exists. Slag quality is determined on the basis of regulations in the (European) country or even region where the slag is produced or used. The environmental behaviour of the slag may be evaluated differently by different regions: different leaching procedures, different limiting values, and different elements/parameters that need to be investigated. For example, in Belgium criteria for recycling of waste materials in the construction sector in the Flemish region are based on leaching limits that differ from those applied in Wallonia or Brussels. In Germany, leaching criteria and potential applications are linked to the origin of the slags (e.g. BOF, EAF) and practices differ between federal states. Combined with the stringent administration to transport waste materials across EU internal borders, this situation makes it very difficult to develop sufficient market share as market introduction must be repeated region by region. Of course, the policy adopted determines the potential value to be gained from matrix valorisation as well: if de facto certain applications are not allowed even if the technical specs are met, this clearly affects market potential.

Because of the differences in legal requirements, transport distances of slags are limited. Moreover, the environmental benefit of recovering the metals and matrix materials would be reduced if this required long distance transport. Therefore, recovery of metals from slags ideally takes place close to the location where the residue matrix is to be reused.

Another bottleneck is the difficulty of getting new materials into standards. Standards for binders, for example, are very much OPC-centric (ordinary Portland cement) and the process of introducing new materials is difficult and time-consuming. An alternative route is to directly produce building materials and bring these on the market, but this significantly limits the market potential.

Business model

CHROMIC believes that the economic viability of the treatment process not only depends on the recovered metal value, but also on the value generated by increasing the matrix quality. However, incorporation of the benefits associated with the reuse of the recovered metals and the matrix material requires close interaction between different stakeholders in the value chain. Indeed, the process will require industrial symbiosis between the metal production, chemical, and construction industry to share materials and profits along the value chain. This implies the creation of a new business model involving many stakeholders. Experience has shown that this is not easy to accomplish, especially within a research project at low TRL. Nevertheless, it is important to have all the stakeholders involved in the project from the start, to initiate discussions. Therefore, CHROMIC involves industrial partners in the consortium and in the advisory board to get feedback on the relevance of the solutions developed towards current market situation. Discussions on business plan development may be initiated at the third stage of community interaction, but further follow-up and professional support will be needed.

Social

Treatment of waste materials is often perceived negatively by society on the basis of risk perceptions that may not always be substantiated. The CHROMIC consortium is aware that this is all the more the case for metals such as chromium, which are set in the collective memory as highly dangerous, based on real and perceived risks (Cr(VI) is carcinogenic, but in slags Cr is present in its non-toxic forms, e.g., like in cutlery). Therefore, care is taken from the start to list all associated risks within the overarching assessment, overcome them, and communicate this to all parties involved. Specific events are organised to involve local society in a process of co-creation and co-design through focus groups. Initial results of these activities have shown that it is important to tailor the communication to the level of knowledge of the audience, which may be different from what has been assumed. Nevertheless, people have an overall positive attitude towards the processes, and the potential gains for society are recognized.

On a global scale, recovery of metals from secondary resources reduces the overall environmental impact by the avoiding primary extraction. However, at a local scale impacts may increase due to the new treatment process that is implemented, or old landfills that are reopened. This impact shift between local and global communities, or between current and future generations, can create tension and requires a leading role by policy makers.

Recommendations

The technical feasibility of the processes are currently being tested within the CHROMIC project, and the multi-criteria assessment will find the economic and environmental viability. However, the latter will be based on laboratory and limited upscaling trials. Further research towards pilot scale will be needed before industrial deployment.

The upscaling trials in CHROMIC will be carried out on selected flowsheets tailored to the model streams under investigation (stainless steel slags, steel slags, ferrochrome slags). The process, if successful, will be initially implemented by the industrial partners involved in the project that produces these specific materials. However, the technologies developed have potential for replication to other streams and industries, such as:

- Slags and other waste streams from non-ferrous metallurgy
- Mine tailings
- Low grade primary ores

Other recommendations enabling deployment of CRMs recovery from industrial residues are:

- Homogenization of regulations across Europe to facilitate market introduction and replication of technologies
- Performance-based regulations, taking into account actual risks or technical requirements. The potential use of slags should be based on their composition as well as environmental and technical performance instead of focusing on the origin of the materials (type of slag)
- Support in business plan development/discussions across value chain.
- Policy support to improve the economics of the treatment process and promote resource efficiency

References

- Deloitte Sustainability, et al., 2017a. Study on the review of the list of Critical Raw Materials - Criticality Assessment. Report prepared for the European Commission.
- Deloitte Sustainability, et al., 2017b. Study on the review of the list of Critical Raw Materials - Criticality Assessment. *Critical Raw Materials Factsheets*. Report prepared for the European Commission.

- Deloitte Sustainability, et al., 2017c. Study on the review of the list of Critical Raw Materials - Criticality Assessment. *Non-critical Raw Materials Factsheets*. Report prepared for the European Commission. p. 476.
- Quaghebeur, M., et al. (2015), Accelerated Carbonation of Steel Slag Compacts: Development of High-Strength Construction Materials. Frontiers in Energy Research.. 3(52): 12p.
- Quaghebeur, M., et al.(2010), Carbstone: sustainable valorisation technology for fine grained steel slags and CO2. Refractories worldforum. 2(2): p. 75-79.

7.3 Biohydrometallurgy for treatment of low grade resources: the Kasese site, Uganda

By Patrick D'Hugues, Chris Bryan, Anne Gwenaelle Guezennec, and Dominique Morin
BRGM (BUREAU DE RECHERCHES GÉOLOGIQUES ET MINIÈRES, FRANCE)

Context

Bio-hydrometallurgy is an industrial reality providing a complementary technique or an alternative for the treatment of certain mineral resources for the recovery of metals such as copper, gold, nickel, and cobalt in favourable conditions.

Biohydrometallurgy is well established in the treatment of certain sulphide minerals for the leaching of low grade copper ores (bioleaching) and the pre-treatment of pyritic gold ores and concentrates (biooxidation).

Biomining is mostly carried out either using continuous stirred tank reactors or heap reactors. Continuous stirred tank reactors (CSTR) are used for both bioleaching and bio-oxidation processes, collectively termed as biomining.

Figure 24 Picture of the tank leaching processes implemented at the Kasese Cobalt Company site in Uganda.

In particular, biomining was used in the re-processing of a sulphidic mine wastes at the Kasese Cobalt Company site in Uganda where cobalt was produced from old copper mining waste tailings using stirred tank bioleaching technology (See ***Figure 24***). By contributing to the stabilisation of these wastes, this biohydrometallurgical operation has also drastically decreased the Acid Mine Drainage (AMD) discharge into the environment.

Tailings and mining waste containing residual sulphides and metals, often responsible for AMD issues, are potentially a very good target for biomining activities.

Description

Bioleaching uses the oxidation ability of natural bacteria to dissolve metal sulphides and facilitate the extraction and recovery of precious and base metals from primary ores and concentrates. The microbial consortia involved are mainly composed of acidophilic autotrophic iron- and/or sulphur-oxidizing bacteria. These micro-organisms get their energy from the oxidation of iron and/or reduced inorganic sulphur compounds, producing sulphuric acid and ferric iron. Ferric iron (Fe^{3+}) is a primary oxidizing agent, attacking sulphide minerals (MS), as seen in Equation 1, and the role of the organisms is the regeneration of Fe^{3+} from Fe^{2+} and the oxidation of sulphur compounds to produce sulphuric acid (Equations 2 and 3).

$$MS + 2Fe^{3+} \rightarrow M^{2+} + 2Fe^{2+} + S^0 \quad [1]$$

$$2Fe^{2+} + 0.5O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O \quad [2]$$

$$S^0 + 1.5O_2 + H_2O \rightarrow 2H^+ + SO_4^{2-} \quad [3]$$

Many biomining microorganisms occurring naturally on mineral ores are known (Rawlings and Johnson, 2007). Autotrophic species of the iron- and sulphur-oxidizing *Acidithiobacillus* genus and the iron-oxidizing *Leptospirillum* genus are significant contributors to commercial systems. Mixotrophic or heterotrophic acidophilic microorganisms such as *Sulfobacillus* spp., *Acidimicrobium* spp. and *Ferroplasma* spp. are also important not only for their contribution to mineral dissolution via iron and/or sulphur oxidation, but also because they breakdown organic materials acutely toxic to the primary bioleaching organisms.

The main bioleaching pathways and the associated microorganisms involved are described on **Figure 25**.

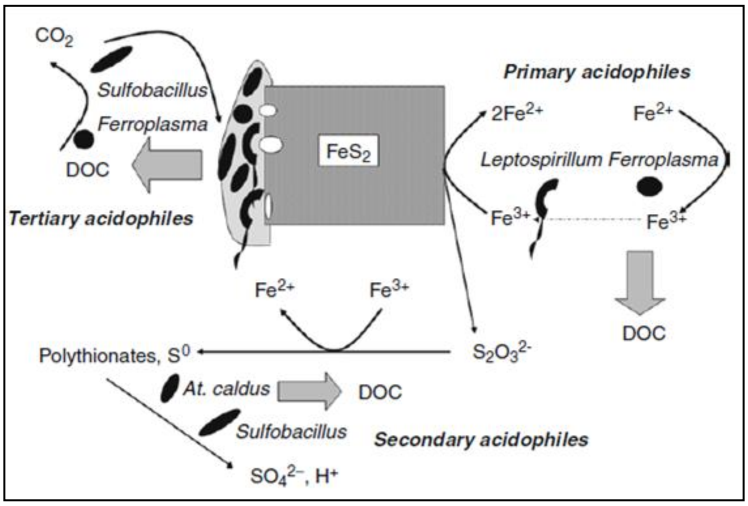


Figure 25 Schematic diagram of the metal sulphide bioleaching pathways (from Johnson and Hallberg, 2008).

This natural ability of microbes to degrade minerals was already used for copper recovery in Roman times but without being aware of the role of micro-organisms. In contrast, extensive research has been carried out on biomining processes in the last 35 years. As a consequence, and where circumstances are favourable, biohydrometallurgy has emerged as an industrial reality and an alternative treatment of some minerals (mainly sulphides) and the recovery of metals such as copper, gold, nickel, and cobalt.

Stirred tank bioleaching has been applied at an industrial scale for more than 20 years. Most of the current stirred-tank bioleaching operations are applied to refractory gold arsenopyrite-pyrite flotation concentrates where the gold trapped in the sulphides is liberated by bio-oxidation of the host minerals and then recovered by conventional cyanide treatment. Without pre-treatment, less than 50% of the gold is usually recovered. After bioleaching, more than 95% of the gold is extracted depending on the mineral composition of the ore and extent of pre-treatment (Olson et al., 2003). Mineral bioleaching at moderate temperatures (40°C-45°C) to treat refractory gold concentrates is usually carried out using the BIOX® Process.

In 1989, BRGM developed an application of stirred-tank bioleaching technology to extract cobalt from a pyritic concentrate, which was the waste from the previous treatment of a copper ore. About 900,000 tonnes of the pyritic material was stockpiled in the district of Kasese (Uganda). Leaching of the stockpile by heavy rainfalls leads to the production of

sulphuric acid and heavy metal solubilisation. This phenomenon was a serious environmental problem for the area and caused severe damage in the Queen Elizabeth National Park downstream from the deposit.
Bioleaching of this cobaltiferrous pyrite was studied in batch tests at laboratory scale and in continuous operations with agitated tank reactors at laboratory (80 litres), pilot (4m3), and semi-industrial (65 m3) scales. These tests all demonstrated that bioleaching was a technically, economically, and environmentally attractive way of valorising the cobaltiferrous pyrite of Kasese. It was demonstrated that the mineral oxidation rate was at least 30% faster in continuous mode than in batch conditions, showing the importance of running continuous bioleaching tests when the objective is to evaluate performances with a view to application.
The following operating conditions were investigated in detail:
- Solid concentrations;
- Residence time;
- Oxygen and carbon dioxide: gas–liquid transfers; consumption and limiting concentrations in solution;
- Nutrient concentrations.

At pilot scale (**Figure 26**), approximately 90% of the cobalt was solubilised in 6 days residence time, 20% solids concentration, and 42°C. Results of the bioleaching step at industrial scale were as good if not better in terms of final recovery and leaching kinetics.

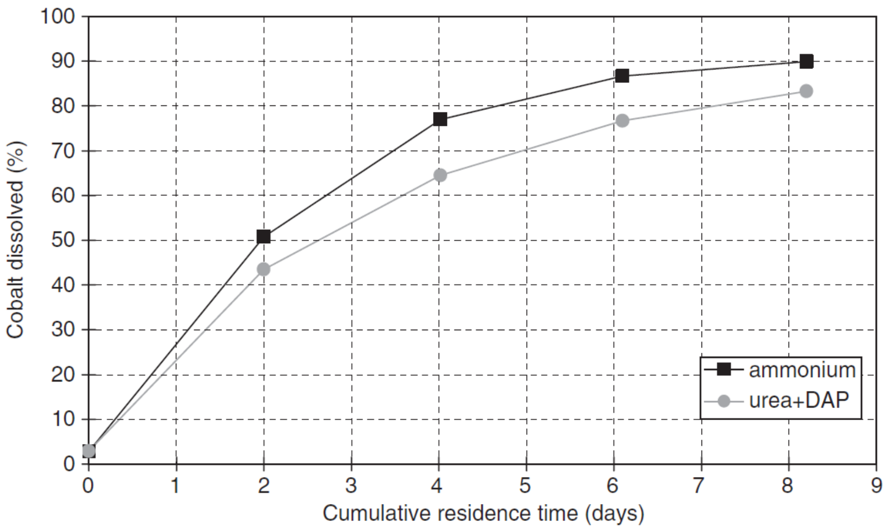


Figure 26: Bioleaching kinetics - Influence of the nitrogen source on the kinetics of cobalt dissolution in continuous laboratory scale bioleaching unit (100 L) (d'Hugues et al, 1997)

Consequently, an industrial mining project of cobalt recovery by applying biohydrometallurgy was set up by the Kasese Cobalt Company. The recovery of a base metal by a process including a biooxidation plant at the Kasese Cobalt operation was a world first.

Drivers

The treatment of sulphide tailings and residues by bio-hydrometallurgy in Uganda was not only enhanced by the technological development led by BRGM: there was also strong political motivation to eradicate the environmental black spot represented by the stockpile at the border of a natural reserve (Queen Elizabeth National Park) that contaminated several square kilometres of land and a lake (Lake George).

From a practical and technical point of view, several parameters were essential before the bioleaching treatment could be turned into a reasonable option in Uganda. For example, the applicability of bioleaching to recover cobalt from the cobaltiferrous pyrite concentrate passed all the required feasibility studies because a large number of positive features appeared to give the project a real chance of succeeding, including:

- The pyrite concentrate did not require any mining investment;
- Water was potentially abundant at the Kasese site;
- Limestone (necessary for pH control and CO_2 supply) was abundant as it is a major component of the subsurface of the Rift Valley near the site;
- The region is served by reasonable infrastructure, including an electricity supply;
- The site topology below the stockpile is characterized by a gentle slope, appropriate for the hydraulic transport of the slurries and solutions;
- There was virtually no activity on the land around the site;
- Natural biodegradation of the pyrite could be observed on site, and was confirmed by initial laboratory tests.

Innovation

Compared to pyrometallurgy, hydrometallurgical processes offer relatively low capital cost and are particularly suitable for small-scale installations targeting waste treatment. Bioleaching represents an attractive alternative to conventional techniques because it offers several advantages: operational simplicity, lower capital and operating costs, environment friendliness, and suitability for treating complex and low-grade ores.

This technological innovation first implemented at the Kasese Cobalt Company site in Uganda could be replicated closer to home in Europe. Europe hosts large reserves of mine waste related to past and present mining and metallurgical activities. Much of this was deposited at a time when little thought was given to long term environmental impacts. As a result, at least 5000 Km of Europe's rivers are contaminated with acidic, ferric iron-rich run off known as acid mine drainage (AMD) which is formed by microbiological weathering of sulphide-rich materials. Often the value of the metals within these wastes, while significant, is insufficient to cover the costs of reprocessing them directly, so there is little or no effort to do so.

Mining activities have left a legacy of severe environmental damage, largely imparted through the formation and uncontrolled release of AMD. This is caused by microbially-mediated decomposition of exposed sulphide minerals in mine wastes and voids: the same biogeochemical processes harnessed in biomining. In most European countries, the technology currently applied to prevent deleterious environmental impacts of mine wastes from the processing of sulphidic ores consists of covering them with appropriate materials in order to prevent moisture ingress, thereby preventing AMD formation. This solution is costly and does not address the issue of AMD generating potential, the capping materials have a limited lifetime, and constant monitoring is required.

Until a few decades ago, and in some cases even now, only a single or, at best, a couple of metals were extracted from any given mine. The other elements were either not detected by contemporary analytical methodology or considered as mineralogical "exotica". As demonstrated by the European research project ProMine, these types of wastes not only contain rare and precious metals but also appreciable amounts of base metals. This implies that these old mine wastes are a potential resource in many European regions for several sought-after metals and semi-metals, including those increasingly used in modern high-tech applications ("e-tech" elements).

Treating mining wastes for their metal content is also a way of reducing very detrimental environmental impacts associated with the phenomena of AMD.

Of course, for practical and reasonable implementation of the bioleaching treatment at European sites, some key parameters (such as the ones described in section "Drivers" above) will need to be met.

Recommendations

(Bio)Hydrometallurgy offers a diversity of technologies that can be implemented as a way of exploiting difficult-to-treat (complex, non-ferrous, low grade) resources or as a complement to current processing routes. Biohydrometallurgical processes have become an industrial reality in the main mining areas of the world because it exploits these resources, sometime at a lower cost, and has a smaller environmental footprint.

The potential perspectives for the development of bioleaching operations will depend on the ability to address various economic, technical, and scientific limitations.

The bioleaching operation must fit the available resources that are lower grade, more complex, poly-mineral, and poly-metallic. The potential of bioleaching for the treatment of secondary resources (mining wastes and post consumption wastes) needs to be investigated further[85]. For economic and environmental reasons there is not only a need to optimise bioleaching for all of these applications in order to recover base metals (Cu, Ni) and precious metals (gold, silver) but also those associated with them (Co, Va, PGM, …). It is also very important to integrate the bioleaching treatment into a more global site remediation approach.

The current limitations/constraints of running an industrial plant with continuous stirred-tank reactor model (CSTR) and heap leaching are quite well documented. In CSTR increase of solid load and optimization of gas/mass transfer (oxygen and carbon dioxide) are key parameters in improving the technology. Work on "designed heap" to improve the bioheap operations is on-going. Beside R&D on CSTR and heap bioleaching, there is a clear need to develop research and innovation in order to find new types of bioreactors that will fill the gap in between heap/dump leaching (100% solid concentration) and CSTR (25% solids concentration). The aim is to find a type of reactor whose key operating parameters can be controlled, but do not need the same level of CAPEX/OPEX as a CSTR (Guezennec et al., 2017).

From a scientific point of view, bioleaching technology is facing two major challenges: (i) as one of the main Cu carriers, chalcopyrite remains a challenge for bio-applications. A lot of work is still required to improve management of the leaching of this mineral and overcome the passivation phenomena, (ii) in term of microbiology, one of the most important challenges is probably optimizing the use of thermophilic organisms at industrial scale.

References

Rawlings D.E., Johnson D.B. (2007) The microbiology of biomining: development and optimization of mineral-oxidizing microbial consortia. Microbiology. 2007 Feb; 153(Pt 2):315-24.

Morin, D., d'Hugues, P. (2007). Bioleaching of a cobalt-containing pyrite in stirred reactors: a case study from laboratory scale to industrial application. In: Rawlings, D.E., Johnson, D.B. (Eds), Biomining, Springer-Verlag, Berlin, pp. 35 - 55.

d'Hugues P, Cézac P, Cabral T, Battaglia F, Truong-Meyer XM, Morin D (1997) Bioleaching of a cobaltiferrous pyrite: a continuous laboratory-scale study at high solids concentration. Miner Eng 10:507–527

Johnson and Hallberg (2008) *Carbon, Iron and Sulfur Metabolism in Acidophilic Micro-Organisms.* Advances in Microbial Physiology Volume 54, 2008, Pages 201-255

[85] See http://ceres.biohydromet.net/

Olson G.J., et al, 2003 Progress in bioleaching: applications of microbial processes by the minerals industries, Appl. Microbiol. Biotechnol. 63 (3): 249–257

Anne-Gwénaëlle Guezennec, C. Joulian, J. Jacob, A. Archane, D. Ibarra, R. Gregory, F. Bodénan, P. d'Hugues (2017) Influence of dissolved oxygen on the bioleaching efficiency under oxygen enriched atmosphere Minerals Engineering Volume 106, 15 May 2017, Pages 64-70

7.4 Bauxite Residue as a resource in Europe

By Efthymios Balomenos, Mytilineos S.A., Metallurgy Business Unit/NTUA Laboratory of Metallurgy

Context

Bauxite residue (BR) is produced in the form of a red slurry (hence the common term "*red mud*") and contains iron minerals and other non-alumina bearing bauxite minerals as well as liquor desilication products (calcium and sodium alumino-silicate precipitates) from the Bayer process cycle. It is estimated that 0.9- 1.5 tonnes of solid residue is generated for each tonne of alumina produced depending on the initial bauxite ore grade and alumina extraction efficiency (Power et al. 2011). As the global demand for aluminium metal increases, so does BR production, currently in excess of 150 million tonnes per year (worldwide). This is generated at some 60 active Bayer plants. In addition, there are at least another 50 closed legacy sites so the combined stockpile of bauxite residue at active and legacy sites is estimated to be between three and four thousand million tonnes.

The large volume of waste produced during the Bayer process has been of concern to alumina producers since the early days of its adoption**.** In cases where land availability is becoming limited, the ever-growing demand for BR disposal space ultimately threatens the longevity of established alumina refineries**.** BR disposal in the alumina refinery in Greece takes up 1 km^2 of land for an annual 0.75 Mt BR deposit. At the Auginish plant in Ireland, the management of the 1.2 Mt of BR produced annually results in the current land use of 1.83 km^2. Stopping BR disposal or gradually reclaiming the legacy BR disposal sites is vital for both industry and society.

The European (EU28+EFTA) alumina – primary aluminium industry in 2016 utilized about 12 million tonnes of bauxite to produce about 7 million tonnes of alumina (out of the 115 million tonnes worldwide), and imported an additional 4 million tonnes of alumina to produce about 4 million tonnes of primary aluminium (out of the 59 million tonnes worldwide). The alumina and primary aluminium sector in Europe employs directly about 16,000 people. The alumina and primary aluminium sector in Europe are at the basis of the whole European aluminium industry, which employs directly and indirectly more than 1,000,000 persons in more than 600 plants and generates about 40 billion Euros in annual turnover (source European Aluminium Association).

Figure 27 Typical Bauxite residue slurry storage (left) and filtercake storage at Mytilineos (right)

Description

In Europe, alumina refineries operate in Bosnia Herzegovina, France, Hungary, Germany, Greece, Ireland, Romania, Spain, and the Ukraine, while significant BR deposits from refineries that have stopped their operations (legacy sites) exist in Italy, France, Germany, Hungary, and other countries. The current BR production in the EU is 6.8 Mt/y while the cumulative stockpiled level is a staggering >250 Mt (dry matter)**.** The catastrophic red mud dam failure of the Hungarian Ajka refinery in 2010 is indicative of the magnitude of the residue disposal challenge and its high environmental and economic impact.

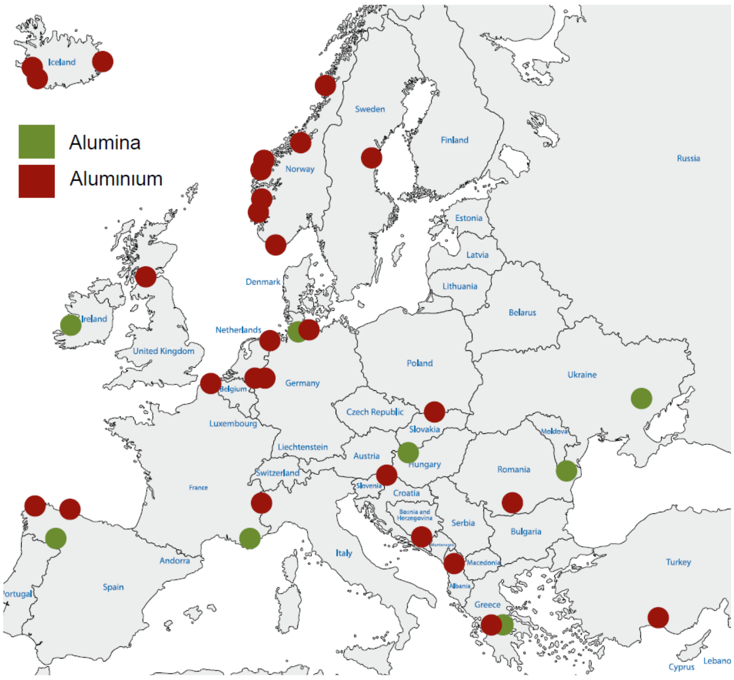


Figure 28 Map of the European alumina (green) and aluminium (red) production sites (source: REDMUD project)

Table 6. European Alumina and BR production

Country	Location	Total Alumina Annual Capacity (kt) (source EA)	Estimated BR (kt)
Ireland (AAL-RUSAL)	Aughinish	1,990	1,800
Spain (ALCOA)	San Ciprian	1,500	1,350
Germany (AOS)	Stade	1,050	950
Greece (Mytilineos)	Viotia	850	750
France (ALTEO)	Gardanne	635	570
Bosnia Herzegovina (Alumina Zvornic)	Birac	600	540
Romania (ALUM)	Tulcea	500	450
Turkey (Eti)	Seydisehir	490	440
	TOTAL	7,615	6,850

Bauxite Residue and especially European BR (originating from European bauxites) contains significant amounts of iron, aluminium, silicon, and titanium oxides as well as smaller concentrations of critical and/or industrially important elements such as V, Cr, Ga, REEs (mainly Ce, La, Y, Nd), and Sc. The Greek BR (mainly originating from Greek bauxites) contains ~1 kg REEs/tonne and this concentration is fairly constant, with a variation of only 8% in examinations over a period of 15 years.

Many plants now use high pressure filtration (the most efficient method of alkali recovery) as a final step of slurry treatment in which the bauxite residue is pressed to remove the maximum remaining liquor and produce a compact filtercake with a relative humidity of 25-30%. The filtration method of mechanical compression is the Best Available Technique (BAT) for red mud dewatering, according to the "BREF for Non-Ferrous Metal Industries" and to the (EU)2016/1032 Decision of 13 June 2016 establishing BAT conclusions. In particular, BAT 57 states that in order to reduce the quantities of waste sent for disposal and to improve the disposal of bauxite residues from alumina production, one or both of the following techniques should be applied:

- Reduce the volume of bauxite residue by compacting it in order to minimize the moisture content, e.g., using vacuum or high-pressure filters to form a semi-dry cake.
- Reduce/minimise the alkalinity remaining in the bauxite residues to allow disposal of these residues in a landfill.

After high pressure filtration of the bauxite residue slurry, the resulting filtercake, called "Filtered Bauxite Residue" (or ferroalumina), has a solid content of about 75%wt constituting a moist material, which can be trucked or put on a conveyor belt. The liquid filtrate from the filter-press, which contains a small amount of caustic soda, is recycled to the washing lines, effectively re-entering the Bayer circle.
Some of the most significant differences between bauxite residue as slurry and bauxite residue as a filtercake apparently refer to water and soda content in the final residue for disposal (**Figure 27**). The characteristics of filtered bauxite residue (75-77% wt. solids, 1-3% wt. Na2O) in contrast to bauxite residue slurry (30-50% wt. solids, 4-6% wt. Na2O) are appropriate for drastically enhancing its properties and its transportation either for disposal or for use (e.g. in the cement or iron industry).

Drivers

In Europe the total amount of bauxite residue produced from the alumina industry is stockpiled on a dry basis at a rate of 7 Million tonnes per year. Therefore, the first driver is to find adequate and sustainable solutions for these huge flows of residues.

- On the other hand, given the volume and chemical composition, there is also a potential mineral resource for reuse, as the 7 Million tonnes overall mean that:
- With an average iron oxide content of 40 wt%, it can be considered to be the equivalent of 3.4 Mt of iron ore available in Europe. This translates into a 4% decrease in iron ore imports and an 18% increase in European iron ore production.
- With an average alumina content of 20 wt% and an inherent clay-like behaviour, BR is a valuable raw material for various building applications. Recycling the alumina and soda (2-4 wt%) of the BR back to the alumina refinery will practically lead to an alumina from bauxite ore extraction efficiency of 100%.
- BR is a considerable resource for REE/Sc. Extracting the REE from Mytilineos - Aluminium of Greece's annual BR production can meet approximately 10% of the European REE demand.
- Gallium is found in bauxite ores at levels of 30-80 g/t and is dissipated in the alumina and BR streams. Extracting gallium from both the BR and Bayer liquor from a single European alumina refinery would amount to global levels of gallium production (annual world production 284 t in 2012).

Innovation

The list of areas where bauxite residue could be used covers almost all areas of inorganic material science with special emphasis on the recovery of elements present in the bauxite residue. Even Bayer himself in his 1892 patent describing the Bayer Process proposed the potential for iron recovery.

Seeking effective solutions has attracted many researchers from industry, universities, institutes, and entrepreneurs to develop applications including construction of cement, bricks, roads, soil remediation as well as base metals and CRMs metallurgical extraction. This vast amount of research and studies on BR utilisation is justified by more than 734 patents since 1964 (Klauber et al. 2011). Possible applications can broadly be broken down into the following categories:

- recovery of specific elements present in the bauxite residue, e.g. iron, titanium, aluminium, and rare-earth elements (i.e. lanthanides, yttrium, and scandium);
- use as a major component in the manufacture of another product, e.g. cement;
- use of the bauxite residue as a constituent in a building or construction material, e.g. road building, dyke construction, concrete, tiles, bricks, and mineral wool insulation;
- use of some specific property which might include conversion of the bauxite residue to a useful material by modifying the compounds present, e.g. catalysis, phosphate trapping, soil amelioration, landfill capping, and acid mine drainage treatment.

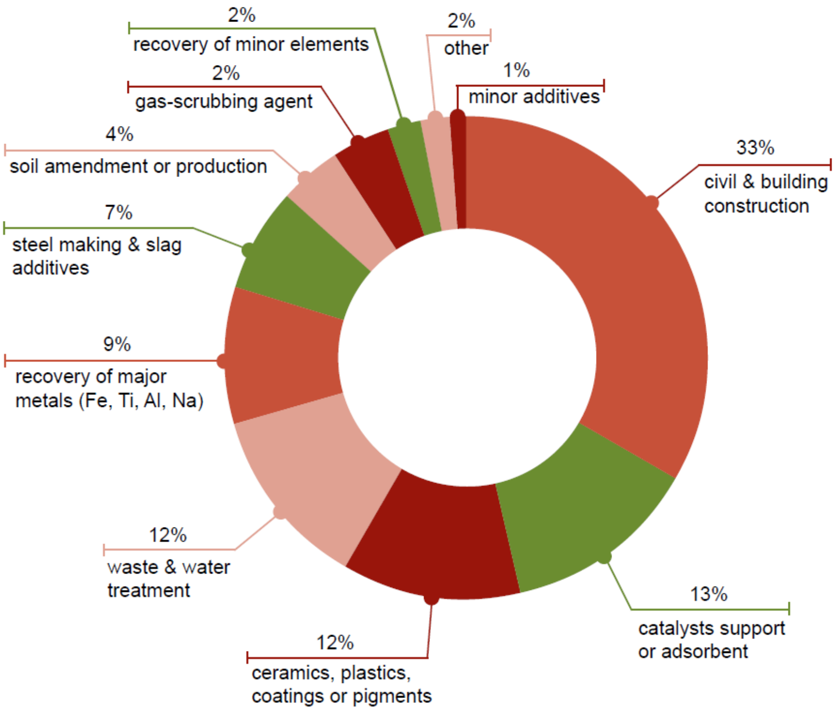


Figure 29 Patents on BR processing divided into areas of intended usage

A number of processes for the simultaneous recovery of the major metals from bauxite residue (towards "zero waste" objective) have been proposed but never implemented. With regard to cost and risk, a detailed cost/benefit analysis of one or more specific process proposals is not only needed to establish economic viability but also to deal with the entire volume of the residue produced. Despite the lab-scale success of much of the work so far, the industrial success of BR utilization is estimated at 2-4 million tonnes accounting for less than 2.5% of annual BR production, with the main applications being in the construction sector and iron-steel production.

The combination of an easily transportable dry matter with low soda content enables bauxite residue to be accepted as an alternative raw material in nearby cement plants.

In fact, the Mytilineos refinery which has adopted filter pressing for its entire red mud output since 2012, and in 2018 had reached a level of nearly 9% (85,000 t) reuse of its annual BR in 2 Greek and 1 Cyprian cement plants. The BR is used in these plants as a clinker raw meal substitute in levels between 1.5-3.0 %wt for OPC production.

Internationally, BR is similarly reused in China, India, and Brazil, where BR has been used as both raw meal substitute in OPC production and as supplementary cementitious materials in blended cement production. In addition, use of BR as raw material in blast furnace pig-iron production have been reported in China and India.

Bottlenecks

Despite more than 50 years of research and ample publications and patents, there has been no major, high-added value use of BR. This is due to several barriers that hamper its effective exploitation such as:

- Volume: Applications that consume large quantities of residue are required.
- Performance: The performance of residue in any application must be competitive with the alternatives in relation to quality, cost, and risk.
- Costs: No strong economic case has been established yet. Technical propositions need to come with a justifiable economic analysis that demonstrates viability.
- Risk: It must be proved to the industry that the associated risk in any application is less than the risk associated with continued storage.

Technologically BR reuse solutions are found in the literature as stand-alone , but pooling them together and optimizing them in an integrated manner is the only way to render bauxite residue reuse viable from an economical point of view and acceptable to the industry.

Therefore, more than one technology needs to be combined to achieve viable and meaningful BR utilization [REMOVAL project objective[86]].

The financial viability of this approach has been shown conceptually on the basis of the RTD experience[87]. A scenario combing EAF processing for iron production, hydrometallurgical leaching for REE/Sc, and slag valorisation for cement, inorganic polymers, and mineral wool is examined. End-product value in each case is strongly dependent on integrated processing and innovation, i.e., the difference between producing Fe-Si instead of pig-iron or a pure Sc_2O_3 concentrate instead of mixed REE/Sc concentrate [SCALE project objective][88]. The scenario developed assumes the processing of the entire annual BR production of Mytilineos refinery and presents the total low and high revenue to be achieved against an averaged and simplified OPEX. The study suggested that such a flowsheet could be profitable with additional RTD in producing higher added value products such as pure Sc_2O_3 of Fe-Si alloys. Other groups have published similar techno-economic assessment for holistic BR treatment flow sheet (Balomenos et al., 2016; Borra et al. 2016).

Recommendations

The main barriers to deploying any solution for the valorisation of BR identified by the alumina industry is not only the techno-economic viability but also the legislative environment. According to the industry, the simplest BR recycling option of utilization in cement clinker raw meal is hindered by European waste legislation that requires the cement company receiving BR to have the appropriate licence for it to utilize/process wastes in its operations. Furthermore, if the company is located in a different country from the alumina refinery, a specialized transfer procedure is needed. Moreover, while most cement plants can obtain licences to process waste materials, the same is not true for other sectors (iron industry, building materials, etc.) which could implement innovative BR reuse solutions.

- When sending BR to another industry for valorisation today, an EU alumina refinery faces:
- costs for licensing the transfer and the cost of the transfer itself
- potential gate fee costs at the end-user industry, a practice that is very common effectively negating the premise of circular economy.

---

[86] https://www.removal-project.com/
[87] E.Balomenos et al, J. Sustain. Metall. doi:10.1007/s40831-016-0110-4 [2016]
[88] http://scale-project.eu/

Conversely, to landfill the BR is often not only the more economical solution, but is also far less complicated one.
Two main actions areas have been identified to remove such barriers:

A. Simplify the waste de-characterization process or establish an end-of-waste process for BR which is delivered as material with less than 30% moisture (processed in accordance with the relevant BATs). This would greatly simplify both the transport and the reuse of BR in other industries, driving down costs and time. The legislative framework for this already exists in many countries because non-hazardous waste can be de-characterised if appropriate conditions exist such as a use for the waste in another process, or there is no threat to human health and others from using the waste. However, such de-characterisation decisions are very difficult for national governments to make independently because they are very sensitive about these issues. A framework on waste de-characterization or end-of-waste for BR harmonized across the EU would be welcome.

According to directive 2008/98/EC article 6, BR is awarded end-of-waste status_because it complies with the following criteria:

- the substance is commonly used for specific purposes as can be seen in the cases of the Greek and Cyprian cement industries
- a market or demand exists for such a substance. The market demand for use of BR in cement plants not only exists in the example of Greek BR but is also increasing year by year: in the last four years the amount has increased by a factor of 10.
- the substance fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products. This has been studied and extensively proven in the case of cement clinker production.
- the use of the substance or object will not lead to overall adverse environmental or human health impacts. BR has been classified as a non-hazardous waste, following detailed characterization and testing and according to Regulation (EU) 1357/2014. Furthermore, reusing BR will reduce environmental impacts by reducing the amounts of BR in landfill and reducing other virgin raw material mining such as iron and clay minerals.
- The proven utilization of bauxite residue as an alternative raw material in the cement and steel industry designates bauxite residue as a non-waste by-product for which specific end-of-waste regulations could be applied.

B. Provide incentives so that industries prioritize the use of industrial by-products over virgin raw materials. Currently industries that could utilize BR as iron and alumina sources in their process have no incentive to do so as virgin raw material are cheap and their use is less complicated (both technologically and legislatively). Therefore, most companies will only use BR if it comes at a lower price or even at negative price (gate fees). Economic and social incentives should be provided to industries that promote circular economy practices, otherwise by-products like BR will only be used where and when virgin raw materials are scarce or depleted. Incentives might take the form of tax reductions, CO_2 emission allowances, green product labels, and others.

References

- Power, G. et al. (2011), Hydrometallurgy, 108 (1-2), 33-45;
- Klauber, C., Gräfe, M., Power. G. (2011) Bauxite residue issues: II. Options for residue utilization. Hydrometallurgy 108, 11–32
- E.Balomenos et al, (2016) J. Sustain. Metall. doi:10.1007/s40831-016-0110-4
- C.R. Borra et al., (2016) JOM 68, vol 11,pp 2958-2962

7.5 Smart Ground database and protocols for data collection

Giovanna Antonella Dino (University of Torino, Italy); Piergiorgio Rossetti (University of Torino, Italy); and Marco de la Feld (ENCO CONSULTING, Italy)

Context

Very little knowledge is currently available concerning the potential of secondary raw materials (SRM) in mining waste, municipal solid waste, and industrial waste. Although Eurostat collects and reports relevant data, for example, on volumes of extractive wastes and on statistics about the flows of municipal solid waste disposed in landfills, there is no systematic and consistent collection of data relevant to (critical) raw materials contained in these wastes flows (Mathieux et al., 2017).

This chapter introduces the main results of the Smart Ground H2020 project (2015-2018, Grant n. 641988) . The project was funded under the H2020 scheme, with an EC contribution of around 2.5 Million Euros and with an involvement of 14 partners from five countries (Italy, Spain, Finland, Hungary, and UK). ENCO and UNITO, both from Italy, were respectively coordinator and scientific coordinator. The main activities were developed by: ATOS (Spain), Cranfield University (UK), Bayzoltan (Hungary), and Mikkeli University (Finland); those partners were the WP leaders. The other partners involved in the project were: GTK, VTT, and Metsäsairilia (Finland), University of Pecs and MKM consulting (Hungary), Imageo and Regione Piemonte (Italy), and Bioazul (Spain)[89].

The main objectives of the Smart Ground project are summarized as follows:

- To obtain quantitative and structural data from both existing and not known RM/CRM/SRM resources that could be profitably recovered at local and EU scale;
- To review existing standards for RM and waste inventory and implement new methodologies (**two different research plans** for collecting info at field and lab scale have been implemented), validated through selected pilot sites;
- To identify the most promising markets for recovered CRM/SRMs. As quality and quantity of CRM/SRM is crucial, characterisation activities and impact analysis must be carried out (together with the two cited research plans, another **3 shared protocols for environmental impacts on soil, water, and air** have been produced);
- To integrate and harmonize data collected in a single EU database, the **Smart Ground platform**[90] facilitates access for end-users to information on available SRMs.

All datasets from the pilot studies and information collected from previously published studies by the partners as well as from other sources has allowed the Smart Ground consortium to identify the most important characteristics of SRMs in support of waste management decision making at EU level. This platform is publicly accessible through a web portal that facilitates searches for SRM-related information. Furthermore, the use of the platform facilitates the registration and collection of new information from other landfills and EW facilities.

Description

The main waste streams targeted by Smart Ground are Extractive Waste (EW) and Municipal Solid Waste (MSW) (including industrial waste - IW). Knowledge of the quality and quantity of such wastes is fundamental in evaluating the potential SRMs exploitable from landfills and from the different waste streams. In order to collect relevant information on waste characteristics and volumes of SRMs, a total of 10 sites (6 EW facilities and 4 MSW and IW landfills) were investigated as pilots (see **Table 7**). Another 6 pilots were also selected for Spain and the UK (not included in **Table 7**).

[89] http://www.smart-ground.eu/ [accessed on 18/02/2019]
[90] http://smartground.atosresearch.eu/home [accessed on 18/02/2019]

Table 7 Pilot sites for Data Collection plan validation (Dino et al., 2018.a)

Waste types	Name and location	Pilot description	Status
Waste from extraction and processing of mineral resources	Montorfano mining area, Italy	Feldspar production from granite waste facilities exploitation	Active site
	Gorno mining area, Italy	EW facility characterized by a high content of metals such as Zn, Pb and possible CRMs such as Ge, Te, In, Cd etc.	Closed site
	Campello Monti mining area, Italy	EW facility characterized by high Ni, Cu, Co content and possible CRMs such as PGM	Closed site
	Aijala mining area, Finland	EW facilities in Southwest Finland. Tailings from mining containing Cu, Zn, S, Ag, and Au	Closed site
	Rudabánya, Hungary	EW facilities containing tailings from sulphide exploitation	Closed site
	Pátka, Hungary	EW facilities containing tailings of fluorite dressing plant	Closed site
Municipal Solid Waste (MSW) including Industrial Waste (IW)	Metsäsairila landfill, Finland	MSW landfill	Both active and closed parts
	Kuusakoski Oy landfill, Finland	Private industry landfill; waste from vehicle and aluminium industry	Active site
	Debrecen, Hungary	MSW landfill	Active site
	CAVIT, La Loggia, Italy	C&D waste treatment plant for the production of recycled aggregate	Active site

The following sections describe the main outcomes of the project including: two data collection plans developed and implemented for both municipal solid waste and extractive waste; the Smart Ground platform, i.e. the database that gathers together relevant data and information on waste deposits; and the development of training materials.

Data collection plan for the characterization of waste in MSW deposits

The data collection plan for MSW landfills including the following activities:

- Collection of preliminary information such as operational history, depth of the landfill cell, degradation stage (for occupational safety), presence of hazardous waste (occupational safety), and geophysical characterization;
- Sampling activity: various sampling techniques were used for MSW sampling including drilling, excavating, and cactus grab crane. Sample were sorted either manually or mechanically in order to separate the different waste fractions. The physical-chemical properties of the fractions was then characterised (**Figure 30**);
- Sampling preparation to obtain representative samples for analysis (**Figure 30**).

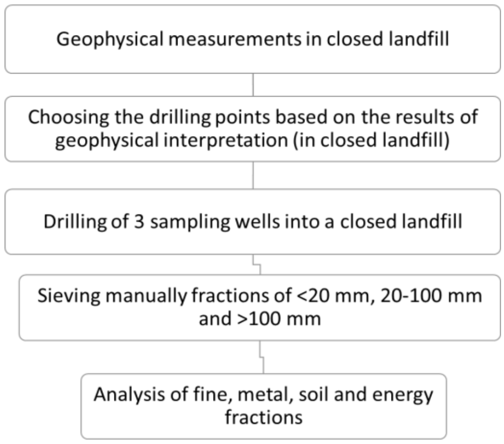


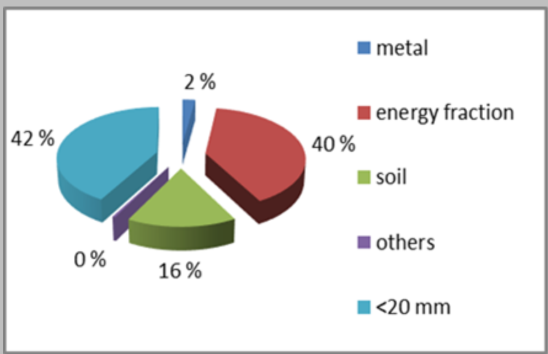
Figure 30 Suggested investigation process in MSW landfill (Metsäsairila; Dino et al. 2017).

MSW pilot site characterization: the example of Metsäsairila landfill

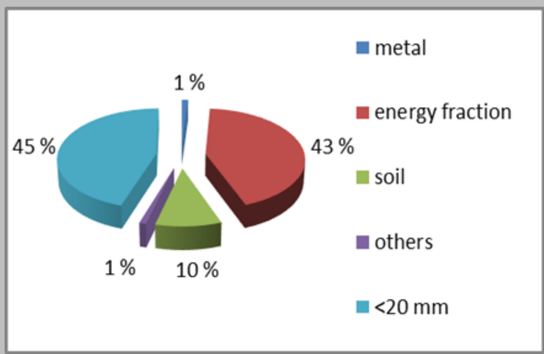
The Metsäsairila landfill is located in the City of Mikkeli in South-Eastern part of Finland around 200 km from Helsinki. It has been operating since the beginning of 1970s but the old part of the landfill was closed in 2007 and the new part opened in the same year. The surface area of the old landfill is around 8 ha and the currently active area is around 3 ha. Waste in old and new areas mainly consists of MSW but also some industrial, C&DW, and hospital waste have been deposited in the landfill area.

After removal of top layers of the landfill including cover materials, sample collection wells were drilled using a hydraulic piling rig from 5m down to 17m depth depending on the sampling well. Aggregate waste samples from each well were taken to a sorting point where they were manually sorted by sieves into different particle size categories (>100 mm, 20–100 mm and <20mm) and waste fractions. Waste fraction separation was carried out to fraction sizes of 20-100 mm and >100 mm and transferred to separate big plastic bags. Material size of <20 mm was packed in buckets. After the weighing procedure, all aggregate samples were transferred to the laboratory for detailed analysis. Samples were analysed for elements, total organic carbon (TOC), dissolved organic carbon (DOC), chloride, and fluoride in an external laboratory (ALS Finland Oy). X-ray fluorescence (XRF) analysis for metals and calorimetric values for energy fraction were measured at Mikkeli University of Applied Sciences (XAMK).

Percentage distribution of two different waste fractions is shown in **Figure 31** (a) and (b). The waste fraction distribution is quite similar in the closed and currently active areas. However, the active area has more energy and fine material fractions (<20 mm). Detailed results on the characterization of Metsäsairila MSW landfill are presented in the XAMK annual research publication (Soininen et al., 2016).



(a)



(b)

Figure 31 Percentage distribution of sorted waste fractions from sampling wells drilled at the Metsäsairila landfill in (a) the closed landfill area; and (b) in the currently active landfill area (Dino et al. 2017).

Data collection plan for the characterization of waste in extractive waste deposits

To estimate the CRM/SRM remaining in the EW facility, several investigation steps must be followed, as shown in **Figure 32**.

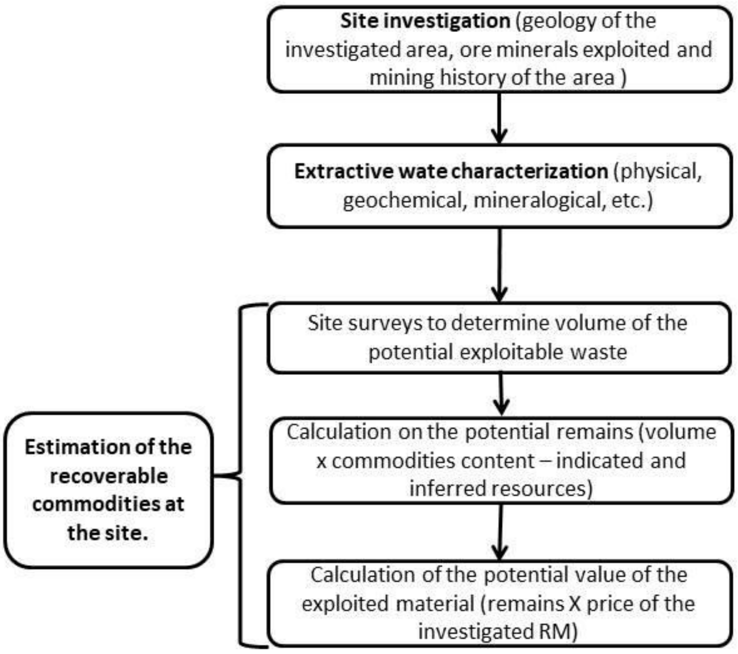


Figure 32 Flow chart to summarise the protocol adopted to estimate RM/CRM remains (Dino et al. 2018.b)

Site investigation (**Figure 33**) includes the collection of information on geology, ore minerals exploited, and mining history of the area (mining and dressing activity), together with the characterisation of the EW facility. The data connected to waste quantity are often estimated, together with the localization of the old waste-rock heaps, and this is a big concern because the reliability of the data is poor. Therefore, to determine the characteristics of the area investigated such as morphology, extension, thickness, characteristics of the original rocks, evaluation of the volume to exploit, and evaluation of the yield of CRM/SRM present in the EW facilities, it is fundamental to apply the right protocol for site investigation, to use photogrammetry, a laser scanner, and geophysics techniques to evaluate the volume to be exploited, and to have information about geochemistry and mineralogy to calculate the potential yield of CRM/SRM to exploit (Dino et al, 2018.a).

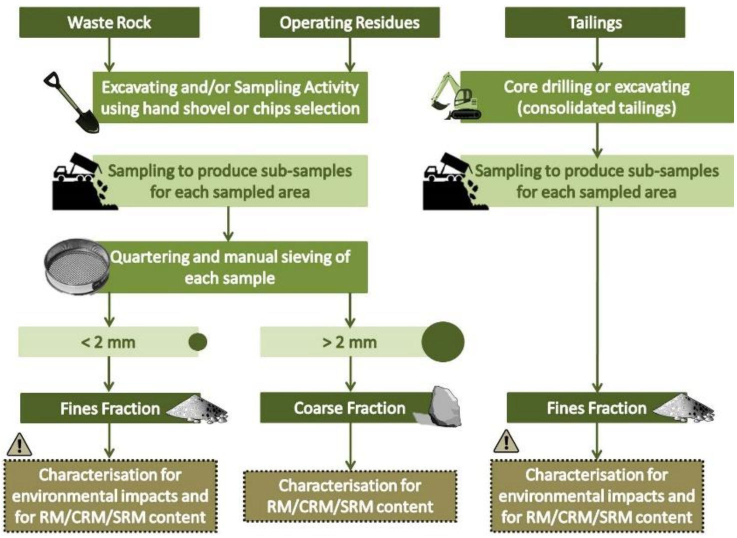


Figure 33 Overview of site investigation steps (Dino et al. 2018.a)

The overview of the extractive waste sample characterisation (concerning waste rocks (WR), operating resides (OR), and tailings) is shown in **Figure 34**. All of the samples need to be processed in order to obtain representative sub-samples for subsequent analyses.

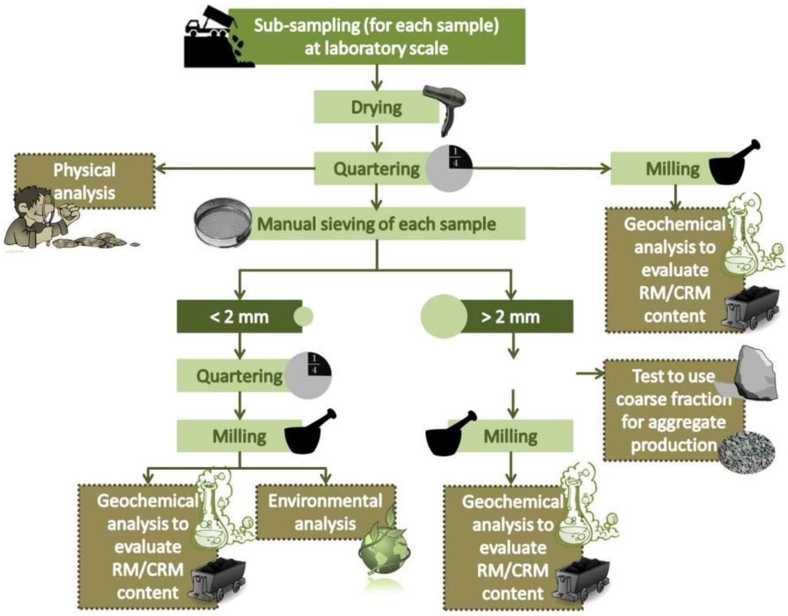


Figure 34 Overview of laboratory sample characterisation procedures (Dino et al. 2018.a)

- A complete characterisation is needed to evaluate RM/CRM/SRM content and includes:
- Physical analysis: grain size distribution, bulk density, tests for aggregate characterisation, etc…;
- Whole-rock geochemical analysis, which can be performed with different analytical techniques (mostly spectroscopic), depending on the elements of interest and on the required detection limit. Main techniques for whole rock geochemistry are XRF (X-ray fluorescence spectrometry, especially for major elements), and/or several types of spectroscopic techniques (AAS, ICP-AES, ICP-MS etc. especially for minor and trace elements);
- Mineralogical characterisation: important because the possibility of extracting a metal from a rock is strongly dependent on its mineralogical form. This study can be performed by optical transmitted/reflected Polarized Light Microscopy (PLM) on thin/polished sections (usually ~30μm thick), and/or Electron Microscopy (EM), and/or X-ray powder diffraction (XRPD) techniques. Other types of spectroscopic analyses (e.g., micro-Raman spectroscopy) may be required under certain circumstances;
- Petrographic characterisation of the material is needed because mineral recovery strongly depends on grain size and microstructure. Such characterisation can be carried out by optical transmitted/reflected Polarized Light Microscopy (PLM) and/or Electron Microscopy (EM) on thin-polished sections (usually ~30μm thick). Quantitative volume % determinations (i.e., modal analyses) may also be required in some cases. Depending on the specific target, they can be performed by point counting or image analysis of composition maps of thin/polished sections (e.g., XRF or SEM-EDS element maps);
- Single phase analyses (i.e., mineral chemistry): may be needed for characterisation of ore minerals when they are extremely fine-grained (e.g. in tailings), or show a variable composition. The main technique is electron microscopy (SEM EDS/WDS) on polished and metallised sections/samples.

The estimation of the recoverable commodities at the site is based on the evaluation of the volume and value of the CRM/SRM to be exploited, and a market analysis of the commodities to be exploited is fundamental as is the yield of RM/SRM present in the EW facilities in estimating the recoverable commodities.

This phase includes the site survey and GIS data collection to calculate volume and area (Dino et al. 2018.a), together with estimation of the residual amounts of recoverable and valuable commodities. The amount of metal commodities in waste is theoretical due to the fact that only those occurring within ore minerals may represent exploitable RM/CRM.

To determine the residual amounts of materials (as indicated and inferred resource[91]) of a selected commodity (X) formulas (1) and (2) have been applied.

$$(1) \mathrm{Ri}\ (\mathrm{X}) = \mathrm{Vi} \times \rho \times \mathrm{G}$$

$$(2) \mathrm{Rii}\ (\mathrm{X}) = \mathrm{Vii} \times \rho \times \mathrm{G}$$

Where: Ri (X) = Indicated resource of commodity X; Rii (X) = Inferred resource of commodity X; Vi = volume of the EW as "indicated resource"; Vii = volume of the EW, as "inferred resources"; ρ = average bulk density of the EW; G = average grade of commodity X arising from geochemical analysis.

To determine the theoretical economic value of the remains (indicated and inferred resource), formulas (3) and (4) have been applied.

$$(3) \mathrm{Ci}\ (\mathrm{X}) = \mathrm{Ri} \times €(\mathrm{X})$$

$$(43) \mathrm{Cii}\ (\mathrm{X}) = \mathrm{Rii} \times €(\mathrm{X})$$

where: Ci (X) = economic value of indicated resource; Cii (X) = economic value for inferred resource; Ri (X) = Indicated resource connected to commodity X; Rii (X) = Inferred resource connected to commodity X; €(X) = market value for commodity X.

EW pilot site characterization: the example of Campello Monti mining area

The mine in Campello Monti was exploited from 1850 to 1945 mainly for its Fe-Ni-Cu-(Co) sulphide deposits, occurring as lens-shaped, sulphide-rich, subvertical bodies in ultramafic layers/dykes of the Mafic Complex in the Ivrea Verbano Zone, a tectonic unit which runs NE-SW for about 120 km from Locarno to Ivrea (Fig. 32). It consists of three main Formations: Mantle Tectonites, Mafic Complex, and Kinzigite Formation (Garuti et al., 1980; Rivalenti et al., 1984; Sinigoi et al., 1994). The average grade of the ore was approx. 1-2 wt. % Ni (0.5 wt. % in the final years of activity). Nickel was extracted from pentlandite, occurring as both coarse-grained intergrowths and very fine-grained exsolutions in pyrrhotite. A concentrate of 5-6 wt. % Ni was recovered by enrichment using a flotation process (Rossetti et al. 2017).

There is no previous data available on the SRM potential for Campello Monti. Consequently, a preliminary survey was conducted to investigate the mining history, waste typologies, and geological information. After that, sampling campaigns were carried out to collect representative samples (May - October 2016). The types of waste sampled were WR and OR: each facility was sampled following a grid method. Each sample was collected in an area of 1.5 square meters: after cleaning the sampling point of organic residues, samples of 8-10 kg were collected. For each sample point all relevant information (operator, date, UTM WGS84 coordinates, type of material, photos etc.) were registered. 41 WR samples and 12 OR samples were collected (***Figure 35***).

[91] "Indicated resources" are calculated based on waste deposits sampled in detail during the characterisation study; "Inferred resources" are calculated by also including waste deposits whose characteristics were observed in the field, but that were not sampled and analysed. Resource estimates (always conservative) of these were made based on metal contents of the nearest sampled dump and geological considerations.

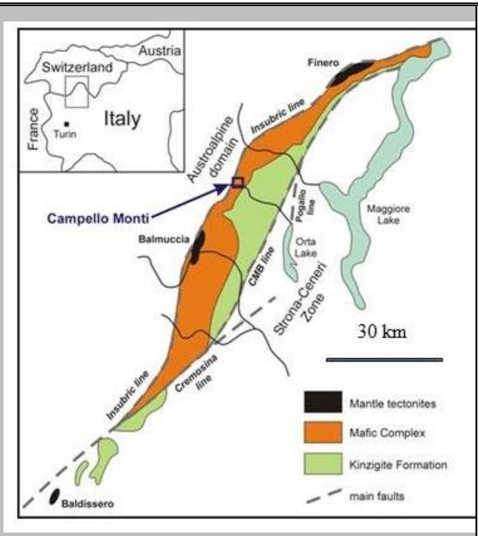


Figure 35 Campello Monti geological sketch map

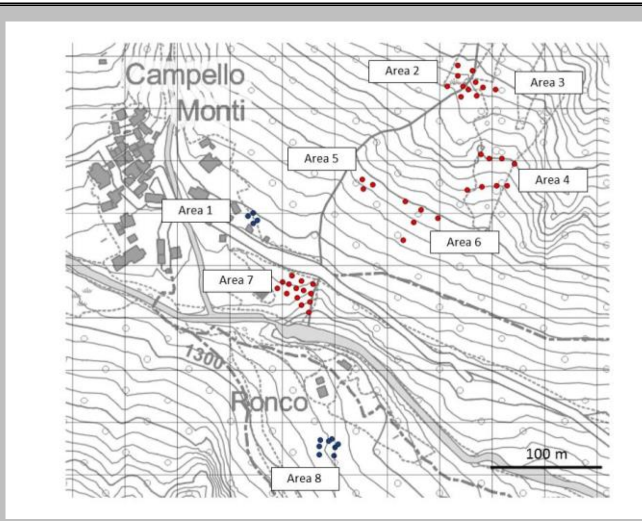


Figure 36 Location of the areas investigated in Campello Monti, including sampling points (waste rock in red and operating residues in blue). (Rossetti et al. 2017)

All the samples were processed at the Mineral Dressing and Samples Laboratory (Earth Sciences Dept. – University of Torino) and analysed at ACTLABS (Canada). The results arising from the characterization phase are reported below.

The results of geochemical characterisation show relatively high to very high Ni, Cu, and Co content (Ni>Cu>Co). However, the extent of metals enrichment can be very different. Four groups can be recognized (Dino et al. 2018.a):

- "Group I" (area 1): very high values of Ni (>10000 mg/kg), Cu (≥5000 mg/kg), and Co (>600 mg/kg). Furthermore, the OR present in area 1 show very high Palladium Group Metals (PGM) enrichments: Pd (404 to 556), Pt (282 to 362 µg/kg), Ru (106-133 µg/kg), Os (61-73 µg/kg), Ir (46-84 µg/kg), and Rh (38-66 µg/kg).The Au content is also relatively high (170-241 µg/kg). Total PGM concentration was 1213 µg/kg.
- "Group II" (areas 3, 4, 8): high values of Ni (2000-10000 mg/kg), Cu (600-1500 mg/kg) and Co (100-300 mg/kg). WR present in area 3 shows moderate PGM enrichments: Pd+Pt concentration range between 50 and 164 µg/kg. Au content varies greatly (3 to 190 µg/kg).
- "Group III" (areas 2, 6): moderate values of Ni (700-1600 mg/kg), Cu (200-600 mg/kg) and Co (100-200 mg/kg).
- "Group IV" (areas 5, 7): relatively low values of Ni (100-700 mg/kg), Cu (50-200 mg/kg) and Co (50-100 mg/kg).

The mineralogical characterisation of samples shows that Ni occurs in pentlandite, $(Fe,Ni)_9S_8$ (32.5-33.6 wt.% Ni, up to 1.4 wt.% Co), Cu in chalcopyrite, $CuFeS_2$ (ca. 34.5 wt.% Cu) and in cubanite, $CuFe_2S_3$ (ca. 23.4 wt. % Cu). These ore minerals are generally relatively coarse-grained, suitable for mineral dressing. The OR in area 1 are very fine-grained (particle size: <1–100 µm across) and consist of partially oxidized enriched ore.

Table 8 Data used to evaluate the quantity of commodities at Campello Monti (Rossetti et al. 2017)

	Campello Monti	
Waste typology	*Waste Rocks*	*Operating Residues*
Commodity average content in geochemical analysis	Ni, Cu, Co for areas 2-7	Ni, Cu, Co for areas 1 and 8
Bulk density	2,235 kg/m^3	1,783 kg/m^3
Total estimated volume for indicated resources	31.484 m^3	
Total estimated volume for indicated resources	52.512 m^3	

Furthermore, it has to be highlighted that the PGM content of the waste deposits has not been reported because the available geochemical analyses show that PGM are only (relatively) abundant within the small area no.1, and therefore their overall abundance across the Campello Monti pilot site is likely to be very low.

Table 9 Content of commodities from Campello Monti EW (WR and OR)

Resource Type		**Commodity**	**Commodity mass [kg]**	**Commodity in-situ value [€]***
Indicated resources	*Campello Monti (WR and OR)*	Ni	161.576	1.502.344
		Cu	40.498	218.485
		Co	8.817	460.954
Inferred resources	*Campello Monti (WR and OR)*	Ni	281.478	2.617.200
		Cu	69.407	374.443
		Co	14.924	780.244

* based on values published on 18th October 2016 from www.snl.com

Presentation of relevant data and information of waste deposits on the Smart Ground Platform

The Smart Ground Database (see **Figure 37**) contains information connected to both a) Extractive Waste (EW) facilities, and to b) Municipal Solid Waste (MSW) and Industrial Waste (IW). The structure of the Database was conceptualised and developed by involving domain experts and software developers. It contains information retrieved from existing databases at local and national scale, complemented with specific information gathered (following a shared methodology) on selected pilot sites (see previous sections).

The main feature of the Smart Ground platform is the design of a data model to store the relevant information of waste deposits which facilitates registration, search, and access to relevant information (materials, processing activities, samples, etc.) for the waste materials community (waste operators, public administrations, voluntary activists) at European scale. This complex data can be screened out by the platform using a range of search filters that suit the needs of different stakeholders. End-users can use the Smart Ground platform to identify and match the supply and demand for SRM by interrogating the data and identifying suitable urban waste landfill sites and/or EW facilities for SRM recovery and other valuable materials. The platform is intended to provide a reliable and transparent source of harmonised and validated information on SRM estimates from anthropogenic deposits available across Europe. Consequently, the database provides guidance to the users on the validity of a potential landfill mining project.

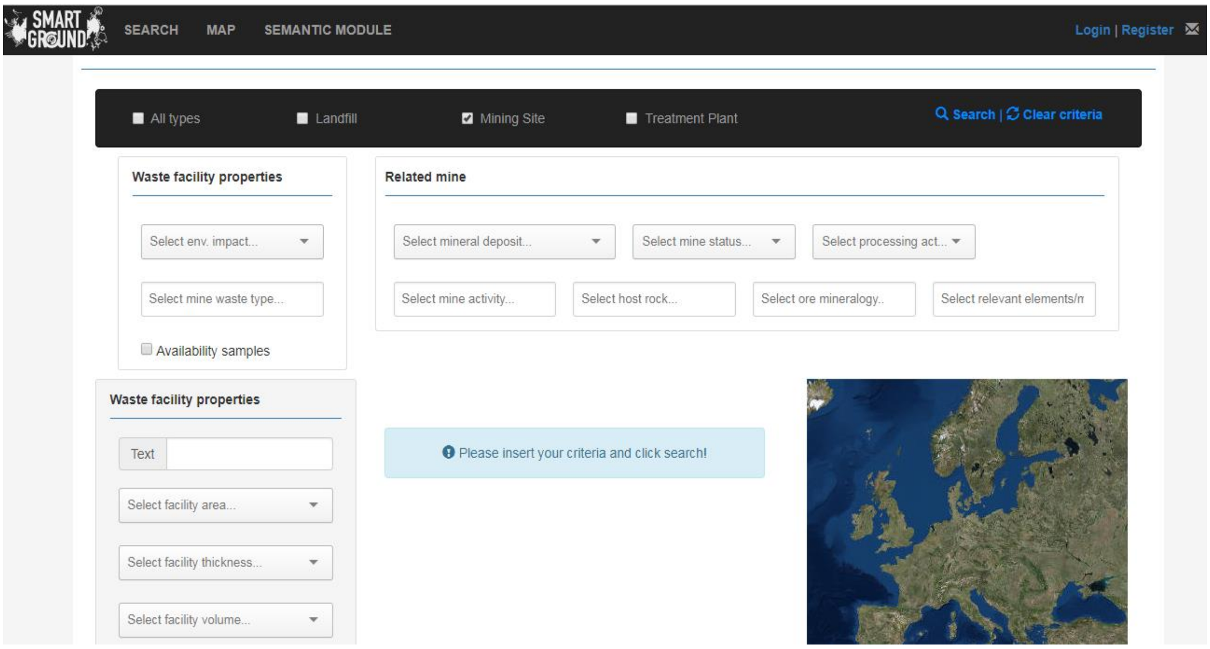


Figure 37 Screen copy of the Smart Ground platform where waste deposit sites can be searched using various filters

Training materials

Original training materials were developed and they consist of[92]:

(1) landfill mining toolkits for MSW and EW;

(2) a range of decision support tools (DST) to predict quickly whether or not a landfill/facility represents a potential new ore body for RM/CRM/SRM exploitation; and

(3) an E-book.

The landfill mining (MSW and EW) toolkits have been designed to give stakeholders information about what is needed to initiate CRM/SRM recovery from landfill sites or EW facilities, and state the potential viability of reuse of CRM/SRM in their specific circumstances. However, the toolkits cannot be used to provide a full engineering study of any project or a complete and detailed business case but they will give the users the understanding and basic data to allow them to progress onto more detailed analysis with potential suppliers and technical advisors to build a technical and business case for the project.

The second set of training materials developed are the decision support tools associated with the Smart Ground platform which are based on the waste age in a landfill, site life, and other economic factors such as revenue of the additional space, value of the recovered soil, and the costs avoided.

[92] http://www.smart-ground.eu/training-toolkits.php [accessed on 18/02/2019]

Finally, the third and final material is the E- Book. The E- Book is an interactive pdf file available on the Smart Ground website. It is a stand-alone knowledge transfer output including online tools, decision support tool, and a toolkit.

Drivers

EW facilities represent a vast, untapped resource for valuable materials which presents a unique opportunity for landfill mining (LFM) activities (Dino et al. 2016). By excavating deposits from EW facilities and recovering CRMs and SRM, we can reintroduce old "anthropogenic waste deposits" back into material cycles (**Figure 38**). Accessing SRM is often not the only driver: land space can indeed be liberated and can be reused for new purposes and services such as recreational and outdoor activities, industrial or urban redevelopment including commercial activities, areas for new landfills, or new opportunities to access the original ore body.

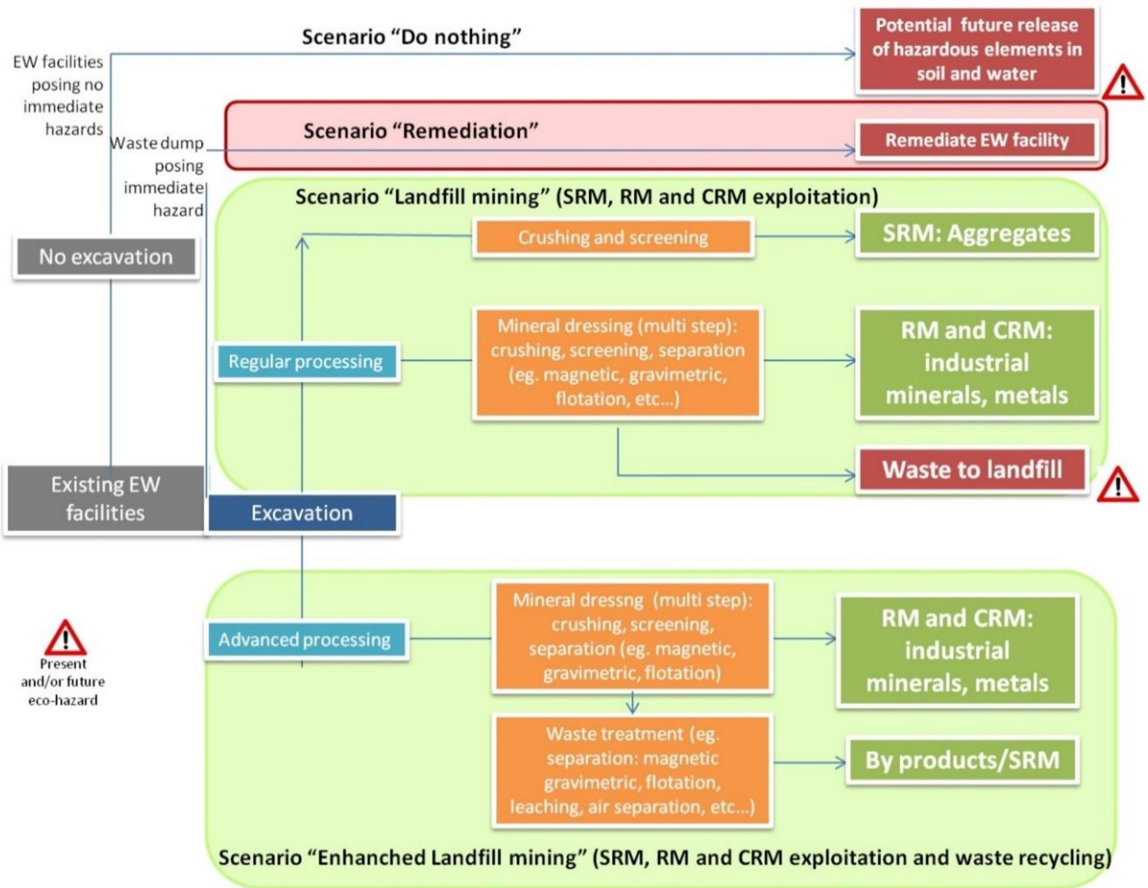


Figure 38 Overview of (Enhanced) LFM Concept applied at EW (Dino et al. 2018.a)

In general, a multidisciplinary analysis that considers **economic, social, and environmental impacts** must be followed for waste management. This considers both the risks associated with actual waste production (challenges), alongside the potentialities to recover CRMs and SRM from waste exploitation (opportunities).

The **environment** can be an important driver of LFM. There are numerous negative effects which LFM may cause. In general, it may lead to release of dust, liquids, and leachate, landfill gases (LFG), and odours (especially for MSW), all of which are a risk to human health. Hazardous waste is often uncovered, especially in older landfills where waste disposal practices and acceptance criteria were not very strict. Excavation of a landfill area could undermine the integrity of adjoining cells, which could lead to subsidence or collapse of landfill but may also attract various types of vermin. Landfill mining would certainly create noise and lead to additional traffic flow on the local road network (Ford et al., 2013).

Life Cycle Assessment (LCA) is suitable for identifying environmental impacts of different LFM or EW exploitation scenarios. Documented research has investigated the difference in impacts between leaving the landfill to naturally degrade against the impact of a possible LFM project. In this case, the benefits of using recovered materials as a substitute (e.g. refuse-derived fuel (RDF) extracted from landfill compared to the use of traditional fossil fuels) needs to be balanced with environmental impacts (Fisher, 2013). Three protocols for environmental impacts on different matrixes (soil, water, air) have been produced in support of this by Smart Ground.

Economic performances obviously need to be carefully examined for any decision making in LFM project. According to a study from Scotland (Warren and Read, 2014), LFM is rarely self-sufficient. Economically viable cases usually include LFM operations involving onsite energy recovery at non-hazardous landfills: excavation, shredding, screening, and removal of ferrous metal, with sale of metals in addition to recovery of soil for use as daily cover. Besides, compaction of waste based on the recovery of void space may be economically viable.

LFM with resource and off-site energy recovery might be feasible where wastes are excavated anyway, assuming that the alternative is to pay for landfill elsewhere. In cases where industrial wastes are also landfilled, more valuable materials can be recovered, thereby resulting in economically feasible solutions (Ford et al., 2013). There are still examples of profitable RM and SRM recovery from EW facilities, mainly as for waste from recovery of dimension stone waste (e.g. granite waste: Bozzola et al., 2010).

Consequently, waste composition, historic operating conditions, extent of waste degradation, and market prices for recovered materials also need to be considered in LFM feasibility decisions.

Finally, **social aspects** need to be addressed. LFM operations can have significant social impacts on local residents. LFM could lead to road congestion based on the intensive process activities near the landfill. At the same time there could be considerable concern over health, comfort, and nuisance impact due to the LFM process. Besides, property values close to landfill during the period of LFM can also fall (Ford et al., 2013).

However, after the removal of landfilled waste, the value of those properties can increase. Excavation of landfill, as a process that reduces or eliminates on-going risks and impacts on health and the environment, also implies new jobs not just for experts but also for low-skilled workers as well. Therefore, communicating with the local residents is always crucial in LFM strategies (Ford et al., 2013; Garamvölgyi, 2016).

Innovation

The Data Collection Plans developed during the project include field sampling, sample preparation, and analysis protocols. The methodologies and protocols for field survey, sampling, and characterization phases have been developed and validated by in-depth characterization studies of ten selected pilot landfills with very different characters. The validation phase suggests that this methodology can be adopted to estimate SRM potential in landfill and facilities.

Furthermore, data gathering about specific waste streams, the technologies to recover SRMs/CRMs, and the potential impacts (environmental, economic, social) associated with various scenarios, is fundamental to evaluating economic and environmental performance in specific case studies. Modelling and decision support tools were implemented for these purposes. They aim to discover the distribution of SRM available across EU landfills so that the SRM recovery market can be targeted.

The main achievement of the Smart Ground platform is the design of a data model to store relevant information about waste sites which allows the recording of, searches through, and access to relevant information (materials, processing activities, samples, etc.) for the waste materials community (waste operators, public administrations, voluntary activists) at European scale. The platform is intended to provide a reliable and transparent source of harmonised and validated information on SRM estimates from anthropogenic deposits available across Europe, and it should be seen as a decision support tool. The development of added-value information and services on top of the baseline information is important in the adoption of the platform and establishing a viable business model.

Smart Ground findings and best practices can be transferred to different stakeholders in order to maximize its impact and to establish new approaches in the waste management sector.

Bottlenecks

Two main bottlenecks were identified during the Smart Ground project. The first concerns information availability: the collection of information is key to the platform being adopted. However, it is not possible to implement a data harvesting system that automatically collects information from other public national platforms given the heterogeneous models, concepts, and languages of each database. In order to integrate information from external database, the consortium had to deal with them on a case by case basis. Indeed, the collection of data mainly relies on the engagement of different actors who upload the information to the platform.

The second bottleneck concerns the economic aspect. In fact, obtaining information about the SRM in waste deposits needs to be supported financially, but the return on investment is not always guaranteed.

Recommendations

Cooperation with other EU initiatives and valorisation of the existing databases on SRM could certainly support the creation of the necessary knowledge base to boost the recovery of secondary raw material at EU level. On the other hand, Smart Ground has found that most of the quantitative and qualitative information needed was never collected or is currently unavailable, consequently suggesting that systematic and appropriately funded campaigns for field sampling and data collection might be a necessary and highly recommended step.

References

Bozzola G., Dino G.A., Fornaro M., Lorenzi A., 2010. Technological innovations and secondary raw materials obtained from a virtuous management of wastes connected to mining activities: The examples of Gruppo Minerali Maffei S.p.A. Rendiconti on line della Società Geologica Italiana. pp. 519-520. ISSN**:** 20358008

Dino, G.A., Rossetti, P., Perotti, P., Alberto, W., Sarkka, H., Coulon, F., Wagland, S., Griffiths, Z., Rodeghiero, F., 2018.a. Landfill mining from extractive waste facilities: The importance of a correct site characterisation and evaluation of the potentialities. A case study from Italy. Resources Policy, https://doi.org/10.1016/j.resourpol.2018.04.012. p 1-12. (In Press)

Dino, G.A., Mehta N., Rossetti, P., Ajmone-Marsan, F., De Luca, D.A., 2018.b. Sustainable approach towards extractive waste management: Two case studies from Italy. Resources Policy (2018). https://doi.org/10.1016/j.resourpol.2018.07.009. (in press)

Dino, G.A., Rossetti, P., Biglia, G., Sapino, M.L., Di Mauro, F., Särkkä, H., Coulon, F., Gomes, D., Parejo-Bravo, L., Aranda, P.Z., Lopez, A.L., Lopez, J., Garamvolgy, E., Stojanovic, S., Pizza, A., de la Feld, M., 2017. Smart ground project: A new approach to data accessibility and collection for raw materials and secondary raw materials in Europe. Environmental Engineering and Management Journal Volume 16, Issue 8, 1 August 2017, Pages 1673-1684.

Dino, G.A., Rossetti, P., Biglia, G., Coulon, F., Gomes, D., Wagland, S., Luste, S., Särkkä, H., Ver, C., Delafeld, M., Pizza, A., 2016. SMART GROUND Project: SMART Data Collection and Integration Platform to Enhance Availability and Accessibility of Data and Information in the EU Territory on Secondary Raw Materials. Energy Procedia Volume 97, 2016, Pages 15-22

Edraki, M., Huynh, T., Baumgartl, T., Huang, L., Andrusiewicz, M., Tungpalan, K., Tayebi-Khorami, M., Wightman, E., Palaniandy, S., Manlapig, E., Evans, C., Farrokhpay, S., Bradshaw, D., Vink, S., 2013. Designing mine tailings through collaborative research. In: Winchester, S., Valenzuela, F., Mulligan, D. (Eds.), Enviromine 2013: Third International Seminar on Environmental Issues in Mining, Santiago, Chile, 4-6 December, 2013. 231-239.

Fisher, R., 2013. Landfill Mining - ISWA Key Issue Paper, http://www.iswa.org/home/news/news-detail/browse/22/article/new-publication-landfill-mining-iswa-key-issue-paper/109/: ISWA.

Ford, S. et al., 2013. Feasibility and Viability of Landfill Mining and Reclamation in Scotland, Scotland: Zero Waste Scotland, Frändegård P., Krook J., Svensson N., Eklund M., 2013. A novel approach for environmental evaluation of landfill mining. J. Cleaner Production. 55: 24-34.

Garamvölgyi, E., 2016. Overview of landfill mining impacts. Bergamo, Italy: SUM 2016, 3rd Symposium on Urban Mining and Circular Economy.

Garuti G., Rivalenti G., Rossi A., Siena F., and Sinigoi S., 1980. The Ivrea–Verbano mafic ultramafic complex of the Italian western Alps: discussion of some petrologic problems and a summary. Rend. Soc. Ital. Min. Pet., 36, 717–749.

Han Onn, A., Woodley, A., 2014. A discourse analysis on how the sustainability agenda is defined within the mining industry. J. Clean. Prod. 84, 116-127

Lodhia, S., Hess, N., 2014. Sustainability accounting and reporting in the mining industry: current literature and directions for future research. J. Clean. Pro. 84, 43-50.

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. and Solar, S., Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-74282-8 doi:10.2760/378123 JRC108710.

Rivalenti G., Rossi A. Siena F., Sinigoi S., 1984. The layered series of the Ivrea-Verbano igneous complex, Western Alps, Italy. Tschermaks Mineral. Petrogr. Mitt., vol. 33, 77–99.

Rossetti P., Dino G.A., Biglia G., Costa E., 2017. Characterization of secondary raw materials from mine waste: a case study from the Campello Monti Ni±Cu±Co±PGM mining site (Western Alps, Italy). Sardinia 2017 / Sixteenth International Waste Management and Landfill Symposium / 2 - 6 October 2017.. S. Margherita di Pula, Cagliari, Italy / © 2017 by CISA Publisher, Italy. ISSN 2282-0027. pp. 13. (Proceedings)

Sinigoi S., Quick J.E., Clemens-Knott D., Mayer A., Demarchi G., Mazzucchello M., Negrini L., Rivalenti G., 1994. Chemical evolution of the large mafic intrusion in the lower crust, Ivrea-Verbano Zone, northern Italy. Journal of Geophysical Research, 99, 21575–21590.

Soininen, H., Dufva, K., Kontinen, K., 2016. Materiaalit ja ympäristöturvallisuus: Soveltavaa tutkimusta ja tuotekehitystä; Vuosijulkaisu 2016. Free-form publications. Mikkeli University of Applied Sciences, Mikkeli, Finland.
Warren, K., Read, A., 2014. Landfill Mining: Goldmine or Minefield?. [Online] Available at: https://waste-management-world.com/a/landfill-mining-goldmine-or-minefield [Accessed 21 November 2016].

7.6 CriticEL - Raw Material National Survey in Hungary

by Ferenc Mádai, János Földessy, Gábor Mucsi, Imre Gombkötő
University of Miskolc, Faculty of Earth Science and Engineering
H-3515 Miskolc-Egyetemváros, Hungary

Context

Like most EU Member States, Hungary is a net importer of critical raw materials, some of which with a significant dependence from distant sources. Moreover, the country is significantly behind on research into energy and other mineral sources and with the development of exploitation and production technologies. Nevertheless, since 2011 political resolutions have been published according to which the national mineral resources have important roles in the planning of the national economy's strategic directions (Ministry of National Development, 2011; Mineral resource utilization and reserve management action plan 2013, amended for energy minerals in 2018).

Within this context, structured research programmes were initiated in 2012 – as one of the earliest of its kind in European countries - including R&D modules - determining the strategic potential of national mineral resources, and conduct successful fundamental and applied research. The TÁMOP 4.2.2.A-11/1/KONV-2012-0005 program "Fundamental research into the exploitation of the economic development potentials of critical raw materials in international co-operation – CriticEl", with a total funding of 1,600,000 EUR started on the 1st of November, 2012 and was carried out during the following 2 years. The project aimed to identify the potential of CRMs in Hungary from both primary and secondary sources using archive data mining and exploration methods while not only investigating the occurrence and amount but in parallel determining applicable processing and recovery methods for the sources identified and also promoting its business availability.

The CriticEL project confirmed the scientific potential of the University of Miskolc as well as facilitating long-term research cooperation relationships. The fundamental research programmes were supervised and coordinated by Prof. Dr. János Földessy as scientific coordinator of the project, and directly coordinated by Prof. Dr. Barnabás Csőke and Dr. Norbert Zajzon.

As an important secondary resource, coal fly ash (CFA) storage facilities were also evaluated for their rare element potential as well as for their use in high added-value construction materials.

Description

The CriticEL survey on primary and secondary raw materials potential collected existing information about several aspects of critical raw materials. Neither the timeframe of the project nor the budget has been sufficient to carry out a fully comprehensive program. Instead, the research focused on the previously known/indicated occurrences and enrichments of critical elements. Most of the archive research reports were written in pre-computer times, so the materials needed archiving and digitalizing.

Systematic data collection and evaluation of the group of primary raw materials was possible thanks to the state archive documentation and publications being well-organized. Approximately 150 different geological reports were found to contain meaningful assay data about the CRMs searched. These were widely different in the time of sampling, the assay methods, the sensitivity of assays etc. None of these reports were detailed and reliable enough to make quantitative estimates, although in some cases the magnitude of the added-value provided by the accumulation of minor elements were assessed. This preliminary evaluation has been published in a 2-volume monograph (Less 2013a, 2013b), where archive data is presented element by element.

The diverse origins of and the usually undocumented material properties (among other of mine wastes) did not make this systematic approach fully applicable to the case of potential secondary raw materials. Instead, some important, high volume types were selected (coal-based fly ash, fluorite flotation tailing, e-waste, quartz-sand processing waste) for the survey to focus on these materials.

An important group of landfill waste materials – fly ash from thermal power plants – has been fully mapped. Apart from discussing the material properties, several possible applications and uses – such as concrete additive, asphalt component, geopolymers, minor element source – were discussed and tested. A monograph volume contains the results of the investigations (Mucsi, 2014).

Creating a think tank from archive and new data

Within the framework of the CriticEl project, about 1400 new chip samples were taken from various accessible sites in the field as well as from archived samples taken by companies and in museum and university collections. These were assayed for a standard set of minor elements, which included all of the searched critical elements but not indium, which was in the standards used for assaying. The laboratories used were the geochemical laboratory of the MFGI (Hungarian Geological and Geophysical Institute) and the ALS Global laboratory. The new results were collected and organized in a MySQL database. The database is still operational and serves as a basis for several follow-up research projects. The data evaluation has been published in a REE monograph (Szakáll 2014) and a summary volume (Földessy 2014).

The Institute of Bay-Logi coordinated the task of collecting data about the raw material resources from different secondary materials (Bodnárné Sándor, 2014). Landfills and mine-wastes as well as smelter and power-plant wastes were not included since other state research projects simultaneously aimed at collecting these data. In this volume data about car catalysators, PV solar cells, batteries, and e-wastes were collected and integrated into a database. A separate section of waste logistics were also created.

The sampling, testing, and processing of different types of E-Wastes were targeted in a separate subproject. Different parts and equipment such as LCDs, Plasma TVs, and spent batteries were studied. Initial processing tests were carried out, the resulting products were assayed, and extraction techniques of different microelements were tested using physical and chemical methods. The proceedings are discussed in a separate volume. Several innovative techniques such as peeling of LCDs were developed (Csőke, 2014).

Monograph on CFA (Mucsi, 2014) provided a complex approach to using this landfill waste. It gives an overview of Hungarian coal fuel materials from different coal basins, the results of geochemical research on selected CFA storage materials, a review of the literature on technologies recovering rare elements from CFAs as well as the theoretical background and experimental results on using the bulk material as geopolymers or other value-added construction materials.

A national project reassessing the Hungarian coal reserves and their utilization with clean carbon technologies was completed in May 2018 (Püspöki, 2018). It was coordinated by the Hungarian Mining and Geological Survey. One of this project’s work packages was dedicated to detailed assessment of the CRMs potential of different Hungarian coal basins and formations (Földessy et al., 2018).

Drivers

Several waste types were assessed in the framework of the CriticEL project for their recovery potential. These included bauxite residue (monograph No. 5. Szakáll 2014.), WEE (monograph No. 7. Csőke, 2014), REE-bearing heavy mineral residue of pure quartz silica (monograph No. 5. Szakáll, 2014), fluorite-bearing waste from waste-rock heaps (monograph No. 3. Molnár, 2014), and combustion fly ashes (monograph No. 6. Mucsi, 2014). Complex utilization, i.e., recovery of its CRMs content as well as using the bulk material as a value-added product, was only assessed for fly ash residues.

Environmental drivers

Coal combustion power plants (CCPPs) was the predominant type of electric power generation in Hungary until 1982,when the Paks nuclear plant was commissioned. Most of the thermal plants were run on sub-bituminous coal of Eocene-Miocene age, one (Visonta) on Late-Miocene lignite, and one (Pécs) on the Jurassic bituminous coal of the East-Mecsek Mountains (**Figure 39**).

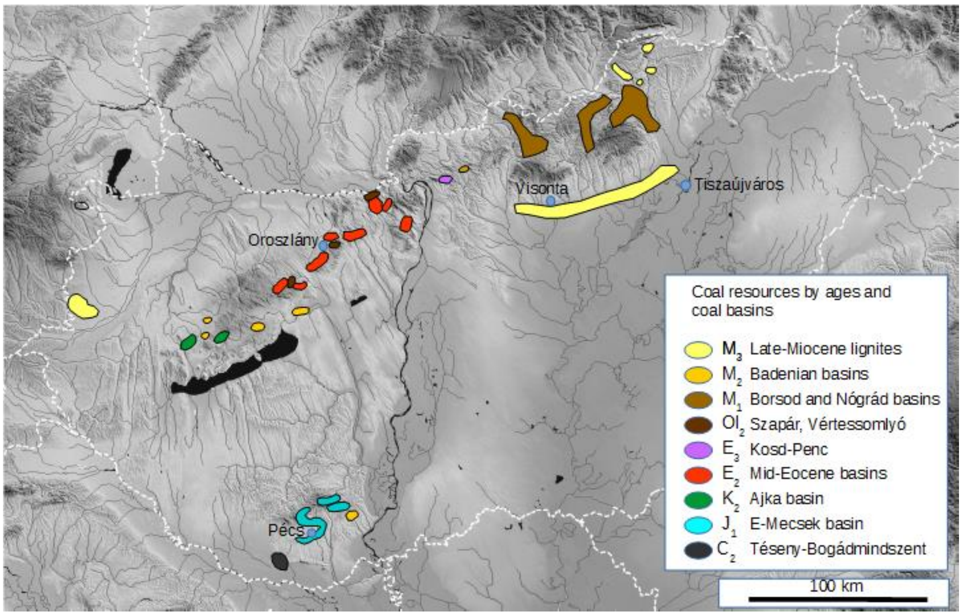


Figure 39 Coal basins of Hungary and the location of the four power plants and CFA storage facilities referred in this study

From the 1980s most of the coal-based PPs underwent a refit to combined – coal plus oil and/or gas, or biomass – and later some of them totally to oil, gas, or biomass fuel. **Table 10** summarizes the relevant CCPPs, the accompanying fly ash storages, fly ash waste volumes, and their current status as extractive waste facilities.

Table 10 Technical data on Hungarian CCPPs operating in the last 50 years and associated fly ash storage (sources: Gáspár, 2005; ENFO-MOKKA database - www.mokkka.hu)

power plant	current status	fuel material used	area of storage facility [ha]*	volume of storage facility [Mm³]*	current storage facility status
Ajka	active	bituminous coal, later predominantly biomass	88	20.7	partly closed/active
Berente	closed	sub-bituminous coal, later biomass	15	19.1	rehabilitated
Várpalota (Inota)	closed	sub-bituminous coal	180	27	rehabilitated
Visonta	active	lignite (until 2008), later lignite + biomass	51	7.6	active
Oroszlány (Vértes PP)	active	sub-bituminous coal, biomass since 2015	105	21	under closure/active
Pécs	active	bituminous coal (until 2004), later gas, then biomass	233.3	39.2	closed, under rehabilitation
Komló	closed	sub-bituminous coal, later gas + biomass	4	1.1	rehabilitated

Tatabánya (Bánhida)	closed	sub-bituminous coal	25	4.6	under rehabilitation
Dorog	closed	sub-bituminous coal. later gas + biomass/coal	25	1.2	rehabilitated
Tatabánya	active	sub-bituminous coal, gas and oil since 2004	27	28	rehabilitated
Tiszapalkonya	closed	sub-bituminous coal, biomass and coal since 2002	255	14.1	rehabilitated
In total* (Gáspár, 2005)			**1009.5**	**184.2**	

The only active fly ash tailings facility where coal combustion residue is currently deposited is at the Mátra power plant (near Visonta). Other active storage facilities receive biomass or combined residue and many of the facilities have been completely rehabilitated.

Active and still not rehabilitated tailings facilities currently only have a small impact on the environmental while containing relatively high concentrations of various rare elements, including CRMs. Elevated concentration of radioactive elements is only known at the Pécs fly ash storage facility, where The concentration in the bulk samples reached 40-48 ppm and U concentration 16-20 ppm.

Hungarian fly ash storage facilities were also thoroughly inspected during the specific inspection campaign completed just after the Ajka red mud accident in October 2010. The Environmental, Nature Conservation, and Water Inspectorate concluded that there is no geotechnical risk connected to active or not rehabilitated CFA tailings management facilities.

According to **Table 10**, total land area of the CFA is more than 1000 ha, which is not utilized. However, beyond recovering the land and further limiting the environmental impact, the most important environmental and social driver is the recovery of resources, including for the production of construction materials.

Economic drivers

Complex utilization of CFA is currently a global issue. Despite it being well-known that CFA is enriched in several rare elements, its recovery can only be economic and/or socially acceptable if the bulk material also has a use. Rare elements are only likely to be recovered as by-products if the cost of the rather complex treatment is covered by other revenues.

The bulk of the CFA is used as pozzolanic material in the cement industry. Another emerging solution is its use as geopolymer composites, which can be directly used in the construction industry as heat or sound insulating panels, pavement panels etc. (Csőke et al., 2007, Mucsi et al., 2015, Mucsi et al., 2017). There is still great potential in coal combustion by-product utilization: 80% of the global utilization comes from 3 countries: China (335 Mt/year), USA (118 Mt/year), and India (105 Mt/year) (Mucsi & Csőke 2014). The highest rate of use is reached in Japan (96.4%) while the lowest rates are in Africa and the Middle-East (10.5%). Just over 50% of US coal fly ashes are reused beneficially (Kolker et al, 2017).

Utilization of CFA as the bulk component for geopolymers is based on its high aluminium-silicate content. Compared to utilization of the CFA as a pozzolanic material in the cement industry, an important benefit is that the geopolymerisation process takes place at much lower temperatures and CO_2 release is only 10-20% of that of cement production (Davidovits, 2011). Due to the flexible production technology, geopolymer-based final products are bricks and insulation panels (fire, heat, sound), pavement blocks, water insulation layers, and roofing composites. Due to their fast binding property and fine-grained structure, geopolymer-based materials may be used for 3D printing construction technologies (e.g. Xia and Sanjayan, 2016).

Research on CFA as a cement additive or geopolymer material showed that its pozzolanic activity primarily relates to the volcanic glass content of the fly ash (Opoczky, 2001). X-ray powder diffraction analyses – shape of the amorphous hump – show that around 70-80% of the SiO_2 and Al_2O_3 content of Hungarian fly ashes comprises the pozzolanic part (Opoczky, 2001). However, pozzolanic activity of the raw CFAs is 1.5-2 times lower compared to trass and 4-5 times lower compared to diatomite. This weaker activity is due to the more heterogeneous particle size distribution. Therefore, the CFA needs to be ground before achieving high specific surface area and appropriate reactivity.

Furthermore, the recovery of rare elements from CFA is now a hot topic. While technologies for recovery of some rare elements such as Ge and/or Ga were known long ago (e.g. Jandova et al, 2002; Lisowij et al., 1987), in-depth research on recovery of REE from CFA has only started in recent years. Recently (last few years) published articles on REE recovery have mainly come from USA and Japan researchers. However, none of the proposals are likely to be viable on a commercial scale.

Complex valorisation of CFA, recovering its rare elements as well as the second step using the bulk material for added-value products such as geopolymers or zeolites is a leading topic for innovation (e.g. Carlson, 2017). It could turn rare element recovery into an economically viable process.

Innovation

A major outcome of the CriticEl database, which can be replicated at a larger scale, was that data on major and rare elements was made available for four CCPP fly ashes: bulk samples from the Vértes (Oroszlány), Tiszapalkonya and Pécs PP fly ash storage facilities and two fresh fly ash samples from the Visonta PP.

Table 11 summarizes some physical and chemical properties which are important in complex use.

Table 11 Physical and technical properties of the CFA samples investigated. Sources: Kovács (2001) (Visonta), Mucsi & Csőke (2014), Gáspár (2005), Lachner et al., (2002)

	Vértes PP Oroszlány (CFA storage)	**Pécs (CFA storage)**	**Visonta (fresh CFA)**	**Tiszapalkonya CFA storage**
Average ash content of the coal fuel used (%)	40	55 – 60	15 – 25	40 - 43
Average grain density of CFA (cm^3/g)	2.22	2.08	1.93	1.59
Compacted bulk density (cm^3/g)	0.95	1.08	0.72	0.86
BET specific surface (cm^2/g)	19000 - 29000	35000 - 60000	30000 - 40000	25000 - 30000
Blaine specific surface (cm^2/g)	2800 - 4410	4050 - 4100	3600 - 7800	3000 - 3400
Residue not dissolvable in cold HCl (%)	70.2 – 73.5	80.0 – 85.4	64.0 – 67.6	NA

Major component chemistry of the samples reveals the pozzolanic type of the fly ash materials. Fresh CFA from Visonta (lignite) shows relative abundance of CaO (alkaline-type fly ash), while the Vértes, Pécs, and Tiszapalkonya fly ashes are depleted in CaO (acidic-type fly ash). Extended experiments on the Tiszapalkonya fly ash have demonstrated its very good potential for geopolymer-based utilization (Mucsi et al. 2015).

Table 12 Major element chemical composition of the Hungarian CFAs investigated. Source: CriticEl project, Mucsi et al. (2014)

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	LOI	SO3
Vértes (CFA storage)	42.80	0.83	23.10	7.57	0.03	1.30	6.37	0.57	1.05	8.43	2.92
Pécs (CFA storage)	53.60	0.98	20.30	8.67	0.18	1.35	2.17	<0.03	3.09	3.91	<0.15
Visonta-1 (fresh CFA)	43.10	0.50	15.20	12.70	0.17	3.02	13.40	0.45	1.21	2.26	4.39
Visonta-2 (fresh CFA)	44.40	0.52	15.20	12.20	0.18	3.13	12.80	0.54	1.31	2.17	3.50
Tiszapalkonya (CFA storage, d<63 µm)	57.00	0.47	23.90	4.26	0.02	0.85	1.40	1.05	1.22	1.84	<0.15
Tiszapalkonya (CFA storage, d=63-106 µm)	62.70	0.54	25.20	4.94	0.02	0.96	1.68	1.06	1.54	0.96	<0.15
Tiszapalkonya (CFA storage bulk sample)	61.90	0.48	26.30	4.26	0.02	0.90	1.53	0.99	1.42	1.80	<0.15

Rare element contents of the above listed CFA samples are summarized in the following table (source: CriticEl database).

Table 13 Rare element composition of the Hungarian CFAs investigated. Source: CriticEl project, Mucsi et al. (2014)

rare elements (ppm)	Vértes (CFA storage, bulk sample)	Pécs (CFA storage, bulk sample)	Visonta-1	Visonta-2	Tiszapalkonya (CFA storage)		
			(fresh CFA, bulk sample)		(d<63 µm)	(d=63-106 µm)	(bulk sample)
Be	5.53	12.90	4.16	3.80	4.40	0.42	0.43
Sc	29.40	9.17	9.50	16.60	12.90	11.60	11.60
V	242.0	124.0	118.0	123.0	66.70	79.00	58.50
Co	34.00	195.00	21.00	8.67	79.20	27.50	20.20
Ga	22.30	30.40	18.10	17.10	16.30	1.85	1.23
Y	55.40	69.60	26.80	25.50	27.90	2.91	2.61
Zr	137.0	743.0	102.0	105.0	150.0	17.60	13.80
Nb	14.10	146.00	10.80	11.00	21.80	2.41	1.87
Σ REE	357.76	891.04	148.59	144.81	323.31	19.36	18.56
Ta	1.22	9.58	0.95	1.00	2.01	<0.25	<0.25
Th	19.90	41.50	14.40	13.30	28.40	2.95	2.93
U	17.90	16.80	7.46	6.77	7.74	0.83	0.76

An abundance of various rare elements compared to the CFA global average values (Ketris & Yudovich 2009) was only found for the samples from the Pécs CFA storage. Results here show the increased abundance of REE (especially La and Ce), Zr (3.5X), Nb (7.3X), Ta (5.5X), and Co (6.1X). Total REE content form the Pécs samples was 891 ppm, which is 2.5 times higher than the global CFA average.

Rare element concentrations of the sample from the Vértes CFA storage equals or is very slightly greater than the global average values for Sc, V, Co, Y, La, Ce, Er, and U. Rare element values from the Visonta CFA samples are generally 0.4-0.6 times the global CFA average, while the Tiszapalkonya sample for lighter rare elements (Sc, V, Co) is half the global average, but is far below (10-20 times) that for other rare elements.

The fuel used in Tiszapalkonya was a mixture of different brown coals from NE Hungary and imported coals from Russia what may be the reason for the very low rare element concentrations.

Expressing the same concentration results compared to the upper continental crust average values (Rudnick & Gao 2003), CFA of the Pécs PP shows significant potential in Co (11X), Nb (12X), Ta (32X), and LREEs (5-9.5 X) while U concentration is up to 6-times abundant. With the exception Ta (4X) and U (6.6X), rare element concentration of the Vértes PP's CFA only exceeds the continental crust average by 2-2.5 times for most of these elements.

Bottlenecks

Although the CriticEl project itself is considered to be a success in terms of original goals for the available resources, the project team has identified several bottlenecks or barriers which are inhibiting use of these mineral resources in Hungary. In terms of the structure and diversity of the resource industry in Hungary, these barriers are mostly legislative and economic.

At that time and now too there was no metal production from primary mineral resources at all in Hungary – not including the limited steel production in Dunaújváros and Ózd – which means that the upstream part of the primary raw material value chain is technically missing in Hungary. There are no active, large scale exploration projects and potential investors have problems with the complex legislation and tender policy in combination with conflicting land use priorities. Data for supporting investment decisions for large scale exploration projects are available but they are from the era of the 1960's and the 1980's and so are outdated in terms of the complexity required to make serious financial decisions.

As a consequence of the missing non-ferrous metal smelters, high metal content waste streams (WEEE, ELV,…) are to some extent processed in other EU countries, where copper, aluminium, lead, or zinc smelters are operating. The amount of these waste streams collected in Hungary is not sufficient to financially sustain investments and operations of non-ferrous smelter plants. Unfortunately, if there were a sufficient amount of metallic wastes, the recovery of most of the existing metals in these waste streams would require an expensive and complex combined mechanical and metallurgical process that would anyway question financial feasibility. The waste scene is further complicated by the ownership of different waste streams and stocks (tailings and waste rock).

As mentioned in the introduction, in using coal fly ashes, with the exception of two power plants – Visonta and the Vértes PP in Oroszlány – all of the others were refitted to alternative fuels or shut down 18-20 years ago. Therefore, most of the CFA storage facilities are closed and rehabilitated (details in Table 9). The infrastructure and ownership rights around them have changed during this period, and present obstacles to reopening and using these facilities.

Observations and sampling of CFA from old (20+ years) facilities show some alteration in the material, but this does not affect its applicability to geopolymer-type utilization strongly. However, alteration may affect the mobilization of easily soluble rare elements (Ge, Ga).

With the most promising rare element potential being connected to the Pécs PP's CFA storage, the elevated radioactive element of this material must be managed which may bring additional costs from using the technology.

Recommendations

Based on the available geochemical data, storage volume and bulk density, the potential resources for rare elements in the Pécs and Vértes CFA storage facilities comprise several tens to thousands of metric tonnes (**Figure 40**). CFA of the Pécs PP storage exceeds the world CFA average values for Co (6X), Zr (3.5X), Nb (7.3X), Ta (5.6X), and LREE (2 – 4.6 X).

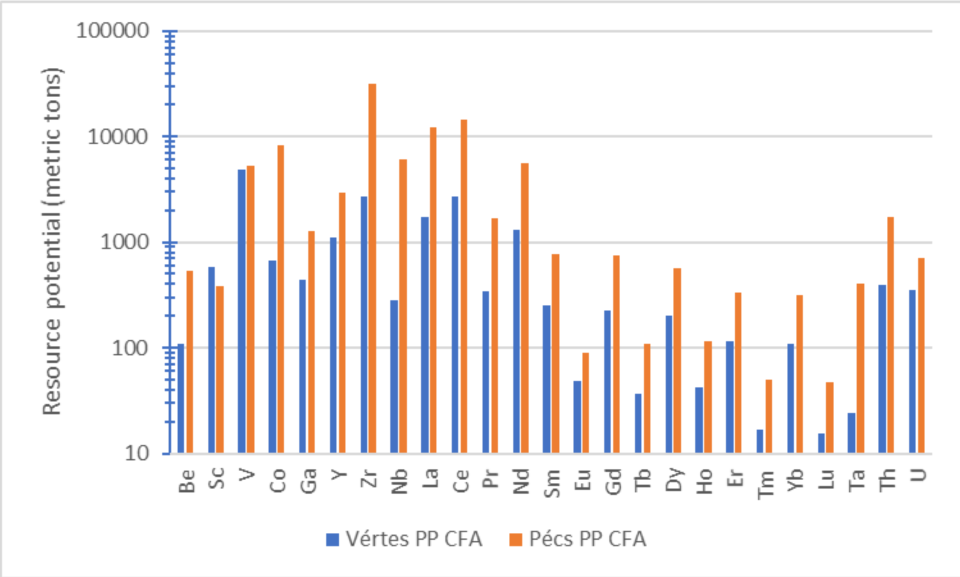


Figure 40 Estimated resource potential of rare elements from the Vértes and Pécs PP's CFA storage. Data based on the CriticEl database.

The CriticEl database contributed to filling in some gaps in the data and improving the knowledge base necessary so that a comprehensive utilization scheme for CFA storage materials can be developed such as for those generated at the Pécs and Vértes PPs. This experience can be improved on and replicated at a larger scale by focusing on the following issues:

- Systematic sampling in full profile to check whether vertical migration of rare elements has taken place within the facility after the deposition.
- Systematic sampling to characterize the lateral and vertical heterogeneity of the CFA material. As in many other Hungarian landfill or mine waste facilities, that materials from other waste streams have also been deposited at this site cannot be excluded.
- Detailed research using state of the art analytical methods (e.g. FIB-SEM, computerised tomography) for speciation of CRMs of fly ashes is recommended, in order to support the appropriate recovery technologies.
- Development of the appropriate recovery technology based on the latest research results (mechanical activation, selective leaching, combined grind-leaching process, etc…).
- Investigation of synergetic use of FA with other silicate or alumino-silicate waste streams in order to improve geopolymer properties by developing composite materials (i.e. fibre-reinforced geopolymer).
- Economic feasibility of CRMs recovery may only be realistic if the bulk material is also used. Therefore, R+D is necessary to obtain value-added products from the residue: synthetic zeolites and/or utilization of this as geopolymer construction blocks. The latter was an important topic in the CriticEl project.

References

Arroyo Torralvo F., Fernández-Pereira C. 2011: Recovery of germanium from real fly ash leachates by ion-exchange extraction, Minerals Engineering 24 35–41

Bodnárné Sándor R. (ed.) 2014: Strategic elements in secondary raw materials (in Hungarian). CriticEl monograph series No. 9. http://kritikuselemek.uni-miskolc.hu/files/files/monografia_9.pdf

Bokányi Lj. & Rácz Á. 2014: Extraction of critical elements from power plant fly ash (in Hungarian). CriticEl monograph series No. 6. pp. 89-104.

Carlson G. 2017: Economical and Environmentally Benign Extraction of Rare Earth Elements from Coal & Coal Byproducts. https://www.netl.doe.gov/File%20Library/Events/2017/crosscutting/20170322-Track-C/20170322_1330C_Presentation_FE0027155_Tusaar.pdf

Csalagovits I. & Víghné F.M. 1969. Trace elements of the waste rocks and coal. (in Hungarian) Ann. Inst. Geol. Publ. Hung. 51, 518– 574

Csőke B, Mucsi G, Opoczky L, Gável V. 2007: Modifying the hydraulic activity of power station fly ash by grinding. CEMENT INTERNATIONAL 5:(6) pp. 86-93.

Csőke B. (ed.) 2014: Processing of electronic waste for recovery of strategic elements (in Hungarian). CriticEl monograph series No. 7. http://kritikuselemek.uni-miskolc.hu/files/files/monografia_7.pdf

Davidovits J. 2011: Geopolymer chemistry and application. Published by: Institut Geopolimére 16 rue Galilée F-02100 Saint-Quentin France, pp. 283-286.

Földessy J. (ed.) 2014: Basic research of the strategic raw materials in Hungary. CriticEl monograph series No. 10. http://kritikuselemek.uni-miskolc.hu/files/files/egyetem10_vegso_okt26.pdf

Földessy J., Mádai F., Mádai V., Fuchs P. 2018: Evaluation of extraction and utilization opportunities of critical elements. Review of archive data. (in Hungarian) in Püspöki Z. (ed.) The Hungarian coal resource and its possible utilization. MBFSZ, 2018. 261 p.

Gáspár L. (ed.) 2005: Secondary raw materials for road construction. (in Hungarian) IHU Kht. 246 p.

Gutiérrez B., Pazos C., Coca J. 1997: Recovery of gallium from coal fly ash by a dual reactive extraction process. Waste Management & Research, 15(4), 371-382

Hernandez-Exposito A., Chimenos J.M, Fernandez A.I, Font O., Queroi P., Cocac P., Garcia Pena F., 2006: Ion flotation of germanium from fly ash aqueous leachates, Chemical Engineering Journal 118, 69–75

Jandova, J. & Vu, H., 2001: Processing of germanium-bearing fly ash. Metallurgy, Refractories and Environment, 107–112

Kashiwakura, S., Kumagai, Y., Kubo, H., Wagatsuma, K., 2013. Dissolution of Rare Earth Elements from Coal Fly Ash Particles in a Dilute H2SO4 Solvent. Open J. Phys. Chem. 03, 69–75.

Ketris M.P. & Yudovich Y.E., 2009 Estimations of Clarkes for Carbonaceous biolithes: World averages for trace element contents in black shales and coals. International Journal of Coal Geology 78(2) pp. 135-148

Kolker, A., Scott, C., Hower, J.C., Vazquez, J.A., Lopano, C.L., Dai, S., 2017. Distribution of rare earth elements in coal combustion fly ash, determined by SHRIMP-RG ion microprobe. Int. J. Coal Geol. 184, pp. 1–10.

Kovács F., 2001: Fly ash and slag materials of brown coal power plants, their properties and utilization. (in Hungarian) Publications of the University of Miskolc, series A, Mining. 55. pp. 67-76

Lachner L. 2002: Application of soot as binder in the road building. (in Hungarian) http://internet.kozut.hu/ume/ume/e-UT_05_02_41.pdf

Less Gy (ed.) 2013a: Mineral resources of strategic importance I. (in Hungarian). CriticEl monograph series No. 1. http://kritikuselemek.uni-miskolc.hu/files/files/CriticEl_1_Monogr%C3%A1fia_k%C3%B6tet(1).pdf

Less Gy (ed.) 2013b: Mineral resources of strategic importance II. (in Hungarian). CriticEl monograph series No. 2. http://kritikuselemek.uni-miskolc.hu/files/files/CriticEl_2_Monogr%C3%A1fia_k%C3%B6tet.pdf

Lisovyj B., Hitchcock D.C., Epstein H., 1987: Process for the recovery of gallium and germanium from coal fly ash, Patent number: 4.678.647

Ministry of National Development [Hungary] 2011: National Energy Strategy 2030. http://2010-2014.kormany.hu/download/7/d7/70000/Hungarian%20Energy%20Strategy%202030.pdf

Mucsi G. (ed.) 2014: Complex utilization of power plant fly ashes (in Hungarian). CriticEl monograph series No. 6. http://kritikuselemek.uni-miskolc.hu/files/files/monografia_6(1).pdf

Molnár J. (ed.) 2014: Reassessment of fluorite and ore occurrences of the Pátka-Szűzvár mine site. CriticEl monograph series No. 3. http://kritikuselemek.uni-miskolc.hu/files/files/monografia_3.pdf

Mucsi G. & Csőke B., 2014: Physical and chemical properties of power plant fly ashes. (in Hungarian) CriticEl monograph series No. 6. pp. 67-79.

Mucsi G., Kumar S., Csőke B., Kumar R., Molnár Z., Rácz Á., Mádai F., Debreczeni Á., 2015: Control of geopolymer properties by grinding of land filled fly ash. INTERNATIONAL JOURNAL OF MINERAL PROCESSING 143: pp. 50-58.

Mucsi G., Szabó R., Nagy S., Bohács K., Gombkötő I., Debreczeni Á., 2017: Development of polystyrene -geopolymer composite for thermal insulating material and its properties with special regards to flame resistance. IOP CONFERENCE SERIES: MATERIALS SCIENCE AND ENGINEERING 251: pp. 1-8.

Opoczky L., 2001: Silicate chemistry properties of fly ashes. (in Hungarian) Publications of the University of Miskolc, series A, Mining. Vol. 55. pp. 97-106.

Püspöki Z. (ed.) 2018: The Hungarian coal resource and its utilization opportunities (in Hungarian). https://mbfsz.gov.hu/sites/default/files/file/2018/06/07/a_hazai_szenvagyon_es_hasznositasi_lehetosegei.pdf

Rudnick R.L. & Gao S. 2003: Composition of the Continental Crust. In: Rudnick, R. L. (ed): Treatise on Geochemistry, Volume 3: The Crust. Elsevier, 683 p.

Szakáll S. (ed.) 2014: Rare earth elements in Hungarian geological formations (in Hungarian). CriticEl monograph series No. 5. http://kritikuselemek.uni-miskolc.hu/files/files/egyetem5.pdf

Xia, M., Sanjayan, J., 2016. Method of formulating geopolymer for 3D printing for construction applications. Mater. Des. 110, 382–390.

8 Conclusions and outlook

This report aims to share existing practices of recovery of critical and other raw materials from these sources, consequently delivering on the Action 39 of the Circular Economy Action Plan. The present report should help Member States implement the proposed provisions on CRMs contained in the revised Waste Framework Directive, especially CRMs contained in extractive waste and landfills.

General remarks and challenges

Based on the experience gathered during the development of the current report, a first general remark is that it is practically impossible to extract only one particular critical element that is present as a minor metal (i.e. has low concentration) or in a complex mixture. It is surely more profitable to couple this with the recovery of other target metals. Therefore, the first lesson to learn is that a "*cherry-picking*" approach is neither recommended nor sustainable: if a recovery process is started, most of the resource should be valorised, e.g. base metals, minor metals, and (most) of the rock matrix as industrial minerals and/or aggregates.

Until a few decades ago, and in some cases even nowadays, only a single or, at best, a couple of metals were extracted from any given mine. The other elements were either not detected by contemporary analytical methods or were considered to be mineralogical "exotica". As demonstrated by the research project ProMine, and later by Minerals4EU and ProSUM, these types of wastes not only contain rare and precious metals but also appreciable amounts of base metals. This implies that in many European regions, those old mine wastes are a potential resource for several sought-after metals and semi-metals, including those increasingly used in modern high-tech applications ("e-tech" elements).

The challenge of full recovery of all metals in mixed matrices or solutions relies on the energy demand required for separation. It is well known in the mining industry that energy consumption increases exponentially as the concentration of the target metal falls below 1 wt%. This is already happening in many mining operations as ore grades are getting lower and more complex. This results in increased energy demand as well as an increased water footprint and greater CO_2 emissions. This also helps explain low recycling rates. Very diluted elements or which appear in a complex form (mineralogy) are difficult and expensive to recover.

As demonstrated by several projects (e.g. CHROMIC), processing of waste streams to recover metals is neither economic nor sustainable without solving the issue of the bulk streams. As such, the traditional approach of maximising metal yield with little or no regard for the waste streams generated is no longer an option. Instead, valorisation of the residual matrix is the key to feasible metal recovery from these low-grade streams leading towards a more sustainable circular economy model.

Along these lines, the Penouta project is a remarkable example of full valorisation of the resource. In this context, mining tailings mainly composed of silicate minerals are reprocessed to obtain 1% tin, tantalum, and niobium metals and around 70% industrial minerals, that is, quartz, mica, feldspar, and kaolin. The target in the overall process is to achieve approximately 80% revalorisation of mining wastes.

Drivers

Although CRMs and other RMs remain an economic target, experience teaches us that environmental and social aspects are also powerful drivers.

Indeed, land space can be liberated and can be reused for new purposes and services such as recreational and outdoor activities, industrial or urban redevelopment including commercial activities, areas for new landfills, or new opportunities to access the original orebody.

An important aspect highlighted by the CHROMIC project is community involvement. Treatment of large amounts of waste materials often raises public concerns, and so a proactive interaction with the general public to ensure societal trust is needed from the start.

For instance, the fact that the Penouta mine became a degraded area after closure, where no process of environmental rehabilitation has taken place in the last 30 years, facilitated the environmental impact study since many of the impacts were already present in the area before the implementation of any industrial activity. The positive environmental impacts are greater than in other projects opening mines in natural areas, since once the industrial process has been completed, the rehabilitation will improve the ecological quality compared to the situation beforehand. These issues have facilitated the administrative processing of the legal authorisation of the project. Additionally, the mine is adjacent to a protected natural area called Red Natura 2000, and the area occupied by the abandoned Penouta mine was excluded from this protected natural area due to its low ecological quality. The future rehabilitation of these abandoned mining wastes will result in an area with better ecological quality, so it is a challenge for the project to reach a degree of quality that means the area can be included in this protected natural space.

Innovation and potential

A remarkable innovation has been highlighted in terms of a changing approach to recovery of secondary raw materials. In the practices discussed in this report, down-cycling and/ or down-grading, are progressively replaced by more resource-efficient forms of recovery. For instance, slags once recovered are still typically used as aggregates in the construction industry where their technical properties are much appreciated. However, in such applications, the metals present in the slags do not serve a purpose, and their value is lost.

A win-win strategy is not only the recovery of valuable metals, but also the intrinsic reduction of the environmental risk associated with the residues. Subsequently, the cleaned up fraction can be reused as a mineral resource and landfilling can be avoided. This is not only a financial benefit for the companies involved since the associated costs (landfill tax, gate fees) are avoided, but also an environmental and social gain due to the recovery of valuable land for other uses. Landfill bans remain an option for the future, which might further stimulate recycling of industrial residues.

From the quantitative point of view, various assessments of the potential recovery in respect to current demand have been made available. For example, the Penouta project is able to make a substantial contribution to an important market share in Spanish production. The current production of metals such as Sn and especially Ta and Nb in Europe is very low or even nil, so the Penouta Mine is the first active exploitation of this type in Europe for many years. The fact of being a conflict-free mining operation makes the project very attractive to potential buyers.

The model streams in CHROMIC (stainless steel slags, carbon steel slags, ferrochrome slags) show that there is the potential to contribute significantly to reducing Europe's dependence on imports (for Cr (-12 %), Nb (-6%), V (-7 %)).

With an average iron oxide content of 40 wt%, bauxite residues can be considered to be the equivalent of 3.4 Mt of iron ore available in Europe. This could result in a 4% decrease in iron ore imports and an 18% increase in European iron ore production. Bauxite residues are also a considerable resource for REE/Sc. It should be noted that extracting the REE from aluminium in Greece's annual Bauxite residue production could meet the needs of approximately 10% of the European REE demand. Again, gallium is typically found in bauxite ores at levels of 30-80 g/t and is dissipated in the alumina and bauxite residue streams: extracting gallium from both the residues and Bayer liquor from a single European alumina refinery would amount to global levels of gallium production.

The potential of bioleaching for the treatment of secondary resources (mining wastes and post consumption wastes) needs further investigation. There is a need for all of these applications not only to optimise bioleaching for the recovery of base metals (Cu, Ni) and precious metals (gold, silver) but also the associated ones (Co, V, PGM, …) for economic and environmental reasons. There is a clear need to develop research and innovation in order to find new types of bioreactors that will fill the gap between Heap/dump leaching (100% solid concentration) and CSTR - Continuous stirred tank reactors (25% solid concentration). The aim is to find a type of reactor where the key operating parameters can be controlled but which does not require the same level of CAPEX/OPEX as CSTR.

Bottlenecks

A clearly identified bottleneck is the currently weak knowledge base. The general lack, or even absence, of data is posing serious limitations to effective decision making. Initiatives to improve the situation in this area have been taken and one example is the Smart Ground platform, intended to provide a reliable and transparent source of harmonised and validated information on SRM estimates from anthropogenic deposits available across Europe.

The experience gathered suggests that the metal recovery of low-grade (secondary) resources is only viable if a (commercial) solution is provided for the large bulk (residual matrix) of the material.

Depending on the complexity of the required treatment process, the metal value may not cover the treatment costs. Metal prices are fixed on a worldwide market, and so cannot be changed to incorporate the higher production costs. On the contrary, a larger supply of metals may even reduce the market price. For instance, it is clear that the value of V and of Mo do not warrant an additional processing step. Rather, they can form a (limited) additional profit if they can be captured through the same treatment steps as the main metal contained in the material.

Similar conclusions have been reached in other projects. For example, it emerged in METGROW+ that the business case for low grade secondary CRMs relies heavily on the extraction of base metals such as Zn and Pb, often present at higher concentrations, with minor added benefits from the critical raw materials concerned.

Consequently, the process will require industrial symbiosis between the metal production, chemicals, and construction industries in order to share materials and profits along the value chain.

The case of bauxite residues is particularly interesting in terms of bottlenecks. Despite more than 50 years of research and ample publications and patents, major high-added value uses have not been developed. This is due to several barriers that hamper its effective exploitation, including: firstly, volume: applications that consume large quantities of residue are required; secondly, performance: the performance of residue in any application must be competitive with the alternatives in relation to risk, cost, and quality; thirdly, costs: no strong economic case has yet been established; lastly, risk: it must be proved to the industry that the associated risk in any application is less than the risk associated with continued storage.

In summary, the alumina industry identifies not only the techno-economic viability but also the legislative environment (e.g. concerning export procedures and licencing of industrial plants) as the main barriers to deploying any solution for the valorisation of bauxite residues. Conversely, landfill is often not only the more economical, but is also the far less complicated solution.

Recommendations and outlook

The experience of the present report suggests that recovery of critical and other raw materials from extractive waste and landfills is not a widely diffused practise in the EU yet. Nevertheless, there are some notable examples which not only demonstrate the potential but also the availability of technologies and the existence of a highly innovative sector. The general lack of a knowledge base is certainly a bottleneck as well as the framework conditions that are yet to be optimised. Recovery from extractive and industrial wastes seems to be more advanced, with remarkably high potential to contribute to a sustainable and secure supply, whereas enhanced landfill mining seems to be less developed and a less promising area as far as CRMs and other raw materials are concerned.

Cooperation with other EU initiatives and valorisation of the existing databases on SRM could certainly support the creation of the necessary knowledge base to boost the recovery of secondary raw materials at EU level. On the other hand, experiences of databases development such as Smart Ground and CriticEL reveal that most of the quantitative and qualitative information needed has never been collected or is currently unavailable (or outdated). This suggests that systematic and adequately funded campaigns for field sampling and data collection might be a necessary and highly recommended step.

In conclusion, examples of good practices were identified for recovery from extractive and industrial wastes, but not in the case of enhanced landfill mining. In order for these projects to become a widely diffused reality, the EU needs to ensure the development of a strong education and R&D culture. Moreover, it should count on its assets, including its raw materials, the mining companies, and a wide network of technological and service support, and even end-users with sufficient capacity to give maximum value to the product.

List of abbreviations and definitions

AHWG	Ad hoc Working Group
AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
BAT	Best Available Technique
BFI	VDEh-Betriebsforschungsinstitute
BOF	Basic Oxygen Furnace
BR	Bauxite Residue
BRAVO	Bauxite Residue and Aluminium Valorisation Operations
BRGM	Bureau de Recherches Géologiques et Minières
CarsiFer	Innovative Recycling solution for waste containing Carbon, Silicon and Iron
CCPPs	Coal combustion power plants
CE	Circular Economy
CEN/TC	European Committee for Standardization/Technical Committee
CFA	Coal Fly Ash
CHROMIC	effiCient mineral processing and Hydrometallurgical RecOvery of byproduct Metals from low-grade metal contaIning seCondary raw materials
CRMs	Critical Raw Materials
CROCODILE	First of a kind of commercial Compact system for Efficient Recovery of Cobalt Designed with Novel Integrated LEading Technologies
CSTR	Continuous Stirred Tank Reactors
DRC	Democratic Republic of Congo
DST	Decision Support Tools
EAA	European Aluminium Association
EAF	Electric Arc Furnace
EIP	European Innovation Partnership
EIT	European Institute of Innovation and Technology
EM	Electron Microscopy
EOL-RIR	End-of-life Recycling Input Rate
ERA-MIN	Research & innovation programme on raw materials to foster the circular economy
ERDF	European Regional Development Fund
EUGeLi	European Geothermal Lithium Brines
EURARE	Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits
EURELCO	European Enhanced Landfill Mining Consortium
EURMKB	European Raw Materials Knowledge Base

EW	Extractive waste
EWD	Extractive Waste Directive
FEhS	Institut für Baustoff-Forschung
Go-4-0	From iron and manganese oxides wastes to valuable metal alloys using novel carbon source materials.
HREEs	Heavy Rare Earth Elements
HZDR	Helmholtz Institute Freiberg for Resource Technology
IW	Industrial Waste
LCA	Life Cycle Assessment
LDH	Layered double hydroxides
LFG	Landfill gases
LFM	Landfill mining
LREEs	Light Rare Earth Elements
METGROW+	Metal Recovery from Low Grade Ores and Waste
MFA	Material Flow Analysis
MFGI	Hungarian Geological and Geophysical Institute
MICA	Mineral Intelligence Capacity Analysis
Minerals4EU	Minerals Intelligence Network for Europe
Min-guide	Minerals Policy Guide
Morecovery	Modular recovery process services for hydrometallurgy and water treatment
MS	Sulphide Minerals
MSA	Material System Analysis
MSW	Municipal Solid Waste
MWEI BREF	Reference Document on Best Available Techniques for the Management of Waste from Extractive Industries
NAG	Non-Acid Generating
OPC	Ordinary Portland Cement
ORAMA	Optimising data collection for Primary and Secondary Raw Materials
PAG	Potentially Acid Generating
PGMs	Platinum Group Metals
PhosForce	Market ready technologies for P-recovery from municipal wastewater
PLATIRUS	PLATInum group metals Recovery Using Secondary raw materials
PLM	Polarized Light Microscopy
ProSUM	Prospecting Secondary raw materials in the Urban mine and Mining wastes
RDF	Refuse Derived Fuel

REDMUD	European Training Network for Zero-Waste Valorisation of Bauxite Residue
REEs	Rare Earth Elements
RemovAL	Removing the waste streams from the primary Aluminium production and other metal sectors in Europe
RESLAG	Turning waste from the steel industry into valuable low cost feedstock for energy intensive industry
RM	Raw Materials
RMC	Raw Materials Commitment
RMI	Raw Materials Initiative
RMIS	Raw Materials Information System
SCALE	Production of Scandium compounds and Scandium Aluminium alloys from European metallurgical by-products
SCRREEN	Solutions for Critical Raw materials — a European Expert Network
SIP	Strategic Implementation Plan
SlagVal	Slag valorisation for multi metal recovery and mineral resource production.
SMART GROUND	SMART data collection and inteGRation platform to enhance availability and accessibility of data and infOrmation on SecoNDary Raw Material in the EU territory
SMS	Strategic Minerals Spain
SRMs	Secondary Raw Materials
TUKE	Technickà Univerzita v Košiciach
TWG	Technical Working Group
Vivimag	A novel magnetic route for phosphorus and iron recovery from sewage sludge.
WEEE	Waste Electrical and Electronic Equipment
WtE	Waste-to-Energy
WtM	Waste-to-Material
XRPD	X-ray powder diffraction

List of figures

Figure 1: Contribution of primary global suppliers of CRMs to European demand: average from 2010-2014 9

Figure 2 EU production of primary CRMs in tonnes (and share of supply to EU in %), average 2010-2014 10

Figure 3. Current contribution of recycling to meet EU demand for CRMs: end-of-life recycling Input Rate (EOL-RIR).. 12

Figure 4 Current contribution of recycling to meet EU demand of CRMs: end-of-life recycling Input Rate (EOL-RIR).. 13

Figure 5. Overview of the generic and risk-specific BAT presented in the MWEI BREF by applying a risk-specific approach. 28

Figure 6. Scheme of the BAT for management of red muds according to the MWEI BREF. 33

Figure 7 Front page of the EC's Raw Material Information System (RMIS 2.0) 35

Figure 8 MSA framework and flows/stocks considered 38

Figure 9 Indicators and thematic clusters of the 2018 Raw Materials Scoreboard 42

Figure 10 Estimated amounts of various CRMs in the EU-28 in 'Extractive waste disposed in situ/tailings' and 'Stock in tailings'. 46

Figure 11. Estimated amounts of various CRMs as 'Annual addition to stock in landfills in the EU' and 'Stock in landfill in the EU'. 48

Figure 12 Open pit at the moment of closure in 1985 56

Figure 13 Images of tailing ponds and waste-rock heaps in 2017 56

Figure 14 Areas of Penouta Mine 57

Figure 15 Image of the gravimetric plant 58

Figure 16 Mineral concentrate (black) on shaking tables 59

Figure 17 Environmental review points 61

Figure 18 Main applications of Ta (left) and Nb (right) (Roskill, 2016 and EC, 2017) 62

Figure 19 Products resulting from the R&D projects: tin ingots (left) and Nb and Ta oxides (right) 64

Figure 20 Image of the village of Penouta 64

Figure 21: Overview of CHROMIC 70

Figure 22: Morphological aspects of carbon steel EAF slags. Fe = Fe-oxides, Cr = Cr-rich spinel minerals, Ca = Ca-silicates, Sp = Cr-poor spinel minerals 74

Figure 23: Production of carbstone bricks in the Orbix pilot facility in Belgium 75

Figure 24 Picture of the tank leaching processes implemented at the Kasese Cobalt Company site in Uganda. 79

Figure 25 Schematic diagram of the metal sulphide bioleaching pathways 80

Figure 26: Bioleaching kinetics - Influence of the nitrogen source on the kinetics of cobalt dissolution in continuous laboratory scale bioleaching unit (100 L) 81

Figure 27 Typical Bauxite residue slurry storage (left) and filtercake storage at Mytilineos (right) 85

Figure 28 Map of the European alumina (green) and aluminium (red) production sites 86

Figure 29 Patents on BR processing divided into areas of intended usage 88

Figure 30 Suggested investigation process in MSW landfill. 93
Figure 31 Percentage distribution of sorted waste fractions from sampling wells drilled at the Metsäsairila landfill in (a) the closed landfill area; and (b) in the currently active landfill area...94
Figure 32 Flow chart to summarise the protocol adopted to estimate RM/CRM remains 95
Figure 33 Overview of site investigation steps 95
Figure 34 Overview of laboratory sample characterisation procedures........................96
Figure 35 Campello Monti geological sketch map..98
Figure 36 Location of the areas investigated in Campello Monti, including sampling points (waste rock in red and operating residues in blue). 98
Figure 37 Screen copy of the Smart Ground platform where waste deposit sites can be searched using various filters 100
Figure 38 Overview of (Enhanced) LFM Concept applied at EW 101
Figure 39 Coal basins of Hungary and the location of the four power plants and CFA storage facilities referred in this study 108
Figure 40 Estimated resource potential of rare elements from the Vértes and Pécs PP's CFA storage. Data based on the CriticEl database. 113

List of tables

Table 1 The 2017 EU List of Critical Raw Materials (EC, 2017) 8

Table 2 List of relevant completed and on-going EU projects addressing CRMs from mineral-based waste and landfills. 19

Table 3 On-going EIT Raw Materials projects (completed and on-going projects addressing CRM from mineral-based waste) 24

Table 4: Guidance documents and standard on extractive waste characterisation developed by CEN/TC 292 31

Table 5: Target metals in CHROMIC 70

Table 6. European Alumina and BR production 86

Table 7 Pilot sites for Data Collection plan validation 92

Table 8 Data used to evaluate the quantity of commodities at Campello Monti 99

Table 9 Content of commodities from Campello Monti EW (WR and OR) 99

Table 10 Technical data on Hungarian CCPPs operating in the last 50 years and associated fly ash storage...108

Table 11 Physical and technical properties of the CFA samples investigated. 110

Table 12 Major element chemical composition of the Hungarian CFAs investigated. ...111

Table 13 Rare element composition of the Hungarian CFAs investigated. 111

KJ-1A-29744-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2760/600775

ISBN 978-92-76-08568-3