From mineral processing to waste management and recycling: common challenges and needs for innovation in France

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COMMENT

From mineral processing to waste management and recycling: common challenges and needs for innovation in France

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The world's population is constantly growing, the global standard of living is increasing, urbanisation is developing on all continents and both the digital transformation and the necessary energy transition are underway. These different "societal phenomena" have in common that they exponentially increase the need for raw materials (metals and other minerals).

For example, the demand for certain strategic metals for manufacturing batteries required for electric mobility and the energy transition is expected to explode. According to the recent raw material score board (2021) from the European commission, the lithium demand will increase by a factor of 20 in 2030; an increase by 5 is expected for cobalt. Projections for copper use show that consumption in the next 25 years will be higher than the total cumulative consumption since the Copper Age (during the Neolithic).

To meet these supply challenges whilst respecting the major sustainable development goals adopted by the United Nations, it is necessary to improve the resource efficiency, meaning using the Earth's limited resources in a sustainable manner whilst minimising impacts on the environment: delivering greater value with less input. In other words, R&D action must help to improve the environmental and societal efficiency of extractive activities, to optimise the use of metals and materials throughout their life cycle by reducing losses, and finally to set up recycling processes as part of a circular economy. The shift from a linear to a circular economy is imperative to ensure that the economic growth is not only based on the use of natural resources.

In Europe, the "circular economy package" (http://data.europa.eu/eli/dir/2018/851/oj) and, in France, the "circular economy roadmap" (FREC) (https://www.ecologique-solidaire.gouv.fr/feuille-route-economie-circulaire-frec) support this transition. In order to reduce the pressure on natural resources, and in particular the production of metals and materials from primary deposits (mines and quarries), many secondary resources or resources derived from recycling have been identified and integrated into supply chains (mining waste or tailing, waste and scraps from the industry and in particular the metallurgy industry, end-of-life products). However, it will be impossible to answer the needs from this secondary supply because of the demand growth, the inevitable losses of materials at all stages of their life cycle and the length of time they remain locked in the anthroposphere (Labbé 2016).

From a technical and scientific point of view, there are many commonalities in the issues related to the valorisation of these different mineral raw materials. Whether primary (mine), secondary (tailing and industrial waste and scraps) or end of life products (urban mines), these resources are all complex, multi-element solids requiring a reduction in particle size (powdering), separation to concentrate the recoverable fractions and finally extractive metallurgy (for metals) to ensure their recovery and reuse. Correctly characterising complex polymetallic objects, limiting energy and water consumption and inputs, minimising the production of secondary waste (liquid effluents or solid residues), adding economic value to by-products and reducing emissions into the environment are major common challenges to overcome in order to ensure an efficient treatment of all these different mineral resources, throughout their life cycle.

The objective of this paper is not only to show the common challenges faced by ore and waste treatment technologies but also to highlight some specific innovation needs associated with each resources depending of their origin (primary secondary end of life).

Primary, secondary and recycled raw materials: from resource to deposit

When the first debates on the risks to metal supplies in Europe started a long time ago, some imagined that we could substitute the production of metals from primary

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resources (ores) with recycled metals. However, it is clear that the potential resources represented by the millions of tonnes of waste generated by human activities are not necessarily exploitable under current technical and economic conditions. In mining, the distinction between "resource" and "reserve" is fundamental. If these millions of tonnes of waste can be considered as a resource, they are far to be considered as reserves. A reserve is an identified mineral concentration (a deposit, if it has been located) that is economically, socially and environmentally exploitable. Therefore, great caution should be exercised when comparing a metal demand with the potential amount of such a metal in urban mines. By analogy with the mine, the first requirement is a perfect knowledge of the waste deposits. Then viable recycling processes will have to be developed, taking into account the specificity of their geographical dispersion and the evolving composition of the objects to be recycled. The implementation of sustainable long-term and profitable waste management and reuse solutions is therefore based on (i) the ability to properly sample and characterise the potential waste deposits (in quantity and quality) (ii) and the ability to collect high volume of waste over a long enough period to justify the Capex and Opex of a recycling plant.

In spite of numerous works of the producer responsibility organisations and other actors of the recycling sector involved in the recycling of waste electrical and electronic equipment (WEEE) (ADEME 2018), sampling and characterisation of urban mine deposits are still problematic. The theory of Pierre Gy (1992), widely used for the sampling of fragmented materials (ores, etc.), does not directly apply to post-consumer waste. Some work is necessary to develop specific "material model" dedicated to the object category studied.

Beside the challenge on urban mining, it is also important to note that to date, mining and mineral processing wastes, especially historical wastes, have been poorly sampled, with little or no characterisation. Although their location and associated risks (metals in effluents, acidic drainage) are well covered by the European directive on waste from the extractive industries (Directive 2006/21/EC), the potential for treatment as a by-product remains poorly studied. For the last 10 years, several European projects (FP7-Promine (http://promine.gtk.fi/), Era-Min ENVIREE (http://www.enviree.eu/home/), H2020-Prosum (http://www.urbanmineplatform.eu), H2020 NEMO (https://h2020-nemo.eu/), etc.) have been carried out to assess the metal content of these wastes and to propose some technical solutions. However, to date, industrial actions to treat produce value from those wastes remain opportunistic and are still mainly focused on processing mining waste containing gold.

Some examples targeting other metals such as copper or cobalt are describe in a recent publication from the JRC (Blengini et al. 2019). The recovery of zinc and lead ores from post-flotation waste in Poland is currently on going in ZGH Bolesław, Poland.

The issue of wastes from the manufacturing industry (scraps and production wastes) is somewhat different: whilst there may be strong similarities between these wastes, the ability to pool them to achieve the volume necessary for the development of treatment processes that would be profitable is still an issue. The main reason for that is that the confidentiality associated with the industrial operations that generate them.

With regard to objects that have reached their end of life, sampling and characterisation methodologies (chemical and structural) are being developed to take their complexity into account. Whilst complex polymetallic ores (that are increasingly mined) may contain six to ten different metals, WEEE often contains more than forty. The concept of metals that are associated with the base metals, the main value carriers, is well known and partly exploited by the mining world. In the field of recycling, this is still a characterisation issue when it comes to metals, often strategic, found in low concentrations in complex matrices. The collection of data on the presence and quantification of these strategic metals in three main streams of the Urban Mine (end-of-life vehicles, WEEE and batteries) has been undertaken within the framework of the European H2020 Prosum project (http://www.urbanmineplatform.eu). However, the obstacles regarding the long-term access to detailed information from product content remain to be overcome as most of the data are difficult to collect and often confidential.

Mineral processing/metallurgy and recycling: common challenges and specificities

Beyond the notions of resource and reserve, the traditional extractive industry (mines and quarries) and the world of waste treatment and recycling implement similar processing technologies.

Some mineral processing and metallurgical concepts associated with ore processing can be transferred to the exploitation of mining, metallurgical and manufacturing waste and also to the treatment of post-consumer waste. These processes face common constraints and challenges such as (i) increasing complexity of solid matrix; (ii) recovering more substances such as the associated metals present in small to very small quantities; (iii) limiting inputs (energy, reagents, water) and impacts on humans and the environment and (iv) limiting the production of fine (< 20 μm) to very fine particles that are difficult to manage in the recovery and recycling circuits.

However, in view of the growing complexity of these materials and the complexity (and costs) of the processes to produce pure materials aligned with the market organisation, the need for specific innovations (particularly disruptive innovations) is becoming increasingly important. These innovations can be on the process technologies themselves, on the organisation of the plant (small, modular, mobile, agile) or on the value chain itself by adapting the processes to produce a material taking into account the final use of the recycled metals in terms of purity and expected chemical form. Some recycling processes should be better adapted to the final use of the recycled materials and not necessary target pure metal production.

During the size reduction (or "comminution" by crushing and then grinding) of ores and concentration (by physical or chemical sorting), the challenge is to achieve the mineral release grind size of the recoverable substances and to set up the different and separate operations needed to concentrate the value. Comminution is particularly critical in the energy balance of mineral processing (more than 50% of the energy needed to produce a metal is spent at this stage with an efficiency of barely 5%). In addition to energy efficiency, the challenge of ensuring material efficiency and the reduction of final waste is now emerging. Various European initiatives such as Horizon 2020 Nemo and Iterams (http://www.iterams.eu/) have been working in this direction.

Mineral processing tails have the advantage of having already undergone a significant reduction in particle size. The energy required for its recovery is therefore greatly reduced, although the lower metal concentrations and their dispersion in the matrix can strongly affect and reduce this benefit.

In the field of recycling, an issue often neglected in R&D programmes is the development of separate physical and physico-chemical treatment operations prior to the extractive metallurgy stages. One of the major issue is to find the good balance in between the manual dismantling operations which are often accompanied by a depollution action such as removing cryogenic greenhouse gases or toxic metal vapour or layers (mercury), specific to the treatment of end-of-life objects and the mechanical treatment operations (shredding/grinding) to reduce the particle size of the wastes. These mechanical treatment operations are generally followed by several physical sorting stages (by optical sorting, magnetic separation, eddy currents or flotation). In France, a lot of studies (ADEME 2017) have investigated the recycling of components of WEEE (electronic cards, capacitors, magnets, LEDs, battery electrodes) but the methods for recovering these components by shredding and selective sorting have been too rarely studied despite their importance. Nowadays, many research teams are developing solutions for recycling of Li-ion batteries from various equipment; most of them will focus on the separation and purification of the elements of interest once concentrated in the black mass but less on the mechanical dismantling operations needed upstream.

After the processing of ores or wastes, two main refining technologies (extractive metallurgy) are used to recover value: pyrometallurgy and hydrometallurgy.

Pyrometallurgy exploits the chemical reactions that take place between minerals in solid state or melted and gases during processing in a high-temperature furnace. This approach is extremely efficient but requires large quantities of materials to be processed and high concentrations of recoverable metals in order to be viable. It is carried out in very large facilities and requires major investments and extremely complex treatment of the gases produced. This treatment is accompanied by the loss of any metals with a strong affinity for oxygen in the slag.

Hydrometallurgy is based on converting metals into aqueous species (in ionic form) by dissolving the carrier minerals. This leaching stage (chemical, biologically catalysed, sometimes under pressure, in acid or basic conditions, oxidising or reductive) is followed by various liquid-phase refining stages (precipitation, solvent extraction, electrolysis) of varying complexity depending on the composition complexity of the so-called Pregnant Leach Solution and on the metals to be recovered. Some metals such as gold or silver are sometimes concentrated in the residual solid fraction and have to be extracted in a second step. Hydrometallurgical techniques are generally more flexible, applicable on site and suitable for polymetallic matrices. Compared to pyrometallurgy, hydrometallurgy often significantly reduces the indirect environmental impacts associated with energy demand or gaseous emissions. However, it consumes significant quantities of chemicals and may have impacts on water resources (in terms of quantity and quality) and can generate quantities of metallic sludge.

In Europe, the recycling of metals (base metals, precious metals or technology metals), whether from industrial waste or urban mining, is mostly carried out by large groups such as Umicore, Aurubis or Boliden using pyrometallurgical processes that were initially developed to treat metal ore concentrates.

In 2018, in France, a study conducted by the Comité aux MEtaux Stratégiques (COMES) (http://www.mineralinfo.fr/actualites/recommandations-comite-metaux-strategiques-comes-developpement-competences-industrielles) showed that many innovative companies are trying to enter in the recycling market (WEEE, batteries, etc.).

The viability of these solutions is highly dependent on the ability to manage the heterogeneity and dispersion of potential waste deposits associated with the complexity of the objects and ongoing technological developments. Furthermore, the dispersion of "metals of interest" in end-of-life products creates a thermodynamic barrier, which makes them very difficult to recycle. Appropriate recycling strategies circumvent this issue by not necessarily reverting to completely purified metals. Thus, the recovery of mixed metals opens up opportunities for use in the market for steels, alloys, metal powders or additive manufacturing. The "short loop" recycling of metal fractions or complex alloys is a potential solution specific to urban mine waste recycling and could help to overcome some entropic limitations.

Towards efficient and sustainable treatment of primary, secondary and recycled raw materials

Many scientific and technological barriers remain to be overcome to ensure efficient exploitation of mineral resources throughout their life cycle.

For ores or mine tailings, it is essential to improve the performance of the mineral processing treatment stages of increasingly complex materials, which often require a significant reduction in particle size, leading to increased energy consumption and requiring the management of fine or even ultrafine particles. With respect to comminution, the R&D challenges are currently focused on methods of embrittling the material (embrittlement by electro-fragmentation or by microwave pre-weakening) in order to better liberate the valuable minerals and to reduce energy requirements for particle size reduction. Concerning the physical and physico-chemical concentration/sorting stages (such as flotation), efforts should focus in particular on the treatment of fine particles, the dry separation of particles with similar physico-chemical properties and the optimisation of water cycle in the process (including some efficient process water recycling loops).

In the extractive metallurgy stages, the wider development of (bio)hydrometallurgical methods (better suited to complex, low-grade deposits with smaller sizes) should be pursued. In order to reduce the final waste and residues, the (mineral) matrix associated with the metals/minerals of interest will also need to be treated and recycled to ensure the environmental sustainability of the proposed solutions.

For industrial waste or end-of-life objects that have reached extreme degrees of complexity, the main challenges are characterising deposits whose composition varies rapidly over time, automating the dismantling and selective sorting of elements, and implementing breakthrough innovations that are sometimes independent of conventional metallurgical knowledge. For the time being, recycling rates for metals remain low. This can be the result of low performance of the collection system, poor efficiency of the dismantling/mechanical sorting steps and low efficiencies of metallurgical steps (dissolution and recovery of metallic substances).

The consumption of raw materials remains closely linked to economic growth and in all growing economies, the consumption of raw materials is increasing (this is the case for all the so-called critical metals, for which world demand doubles on average every 5 years). Only a small part of this consumption can be met by recycling due to the lifespan of products in use, with the rest coming from the mining industry. One of the current limitations to the sustainable development of metal recycling solutions is the highly heterogeneous and rapidly changing composition of end-of-life objects in our urban mines. Strategies that aim to substitute certain metallic substances sometimes conflict with the development of recycling solutions. Other strategies aiming at lowering the use of metals of economic importance in products (for instance in permanent magnets) may prevent from developing economically viable business recycling schemes. Ecodesign for disassembly is a prerequisite to facilitate the implementation of such solutions but so far, material scientists and recyclers do not speak to each other to develop eco-friendly and economically sound strategies for the design of new products. Bridges between sectors must be identified in order to avoid having to refine metals and to find direct industrial outlets for mixed metals from recycling (metals from printed circuit boards could be used as alloys for petrochemical catalysts for example). This reduces energy, reagent and water consumption. The question of dilution of metals (geographical dispersion of waste and dilution of metals in complex matrices/EOL products) arises. The higher the dilution, the higher the amount of energy you need to concentrate and purify metals. And at this stage, the question of quality arises also. Recycling processes and schemes should avoid downcycling for a quite simple reason: it can be implemented just once. And as such, it can not be considered as a recycling route serving circular economy schemes but only "linear recycling".

In conclusion, the diversification of target metal production requires the development of innovative solutions leading to robust and flexible treatment or recycling plants. These new plants will have to be based on technological building blocks that can be assembled, possibly mobile depending on the collection "basins" or the size of the deposits (old mining waste—some of them having a higher grade than currently processed primary ores, small high-grade deposit) in order to adapt to the products to be treated. The development of geo-metallurgical approaches (for mining) and combined approaches (co-processing of secondary materials and wastes, as in the Ceres project (http://ceres.biohydromet.net/) must be intensified to meet these challenges. In addition, work on mathematical modelling/numerical simulation of separate operations and processes must be strengthened by coupling them with life cycle analysis approaches, thus enabling environmental externalities to be taken into account in the criteria for choosing a technology and developing new sourcing chains..

Finally, the maximum benefit will be attained if these developments can be integrated into a sector strategy with resources that are not exported but contribute to the development of a European manufacturing industry that creates jobs. This is, for example, one of the ambitions of the European Battery Alliance. This approach should also help to ensure traceable, sustainable and responsible sourcing for European industry.

References

Labbé J-F (2016) Les limites physiques de la contribution du recyclage à l'approvisionnement en métaux Responsabilité et environnement ° 82 - Avril 2016 - Les métaux stratégiques, un enjeu mondial?

Rapport Annuel du registre des déchets d'équipements électriques et électroniques. ADEME, Erwann FANGEAT, Deloitte Développement Durable, Alice DEPROUW, Marion JOVER, Sarah CHOUVENC, Alexandra PENSEC. 2018.

Gy PM (1992) Sampling of heterogeneous and dynamic material systems, theories of heterogeneity, sampling and homogeneizing. Elsevier, Amsterdam, p 653p

Blengini GA, Mathieux F, Mancini L, Nyberg M, Viegas HM (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 978–92–76–03391–2. https://doi.org/10.2760/494020, JRC116131

ADEME, Deloitte Développement Durable, Monier V, Planchon M, Lemeillet A, SAÏDI N, Taylla SCAPIM-YAMAGUCHI – 2017 - Définition d'orientations prioritaires de recherche-développement de compétences françaises de recyclage des métaux critiques – Rapport – 204 pages

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