Enhanced Landfill Mining Toolkit: Extractive Waste Facilities
Enhanced Landfill Mining Toolkit

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Introduction

Resource security is now a priority for governments of developed countries. This priority is partly due to considerable concern over the security of the supply of the so called 'critical' raw materials (CRM). Their supply is essential to the maintenance and development of the EU economy, as its industries rely on a steady supply of Raw Materials (RM). Over the centuries, the need for RM continued to expand, as did the number of RM utilised in industry, involving also metals and elements not known or used in the past (Figure 0.1). Most of CRM are exploited from countries outside of the EU, causing high economic dependence on non-EU countries (China above all).

RM and CRM can be exploited from ore deposits, but are also present in landfills and waste streams. Over last few decades, there has been increased interest and emphasis on environmental protection, shaping waste management policies towards an environmental focus and integrated waste management. The European Commission (EC) in a 2012 communication stated even that more needs to be done to help reduce the landfilling of materials throughout their life cycle (European Commission 2009). It is thus clear that existing and future policy will support a comprehensive approach to waste management, including policy about waste prevention, waste exploitation (RM, SRM, CRM) and contemporary environmental protection.

Figure 0.1: Evolution of metal and element use along time in industry (Bellefant et al. 2013)
The mining sector has always been a primary sector for human development; mining activities have produced, and still produce, huge amounts of waste (rock waste, operating residues and tailings) which were, and still are, disposed of in extractive waste (EW) facilities. EW is often mono-waste material, represented by similar minerals and elements present in the original ore deposit that are not completed exploited. It is predicted that 5.9 billion tonnes of EW waste is stored within the EU (BRGM, 2001).

Mining activity (mining and quarrying) involves materials that must be removed to gain access to the mineral resources (such as topsoil, overburden and waste rocks), and materials remaining after selection/processing/treatment (operating residues, as well as tailings) see Figure 0.2; indeed the desired mineral may be present in the ore in minute amount (less than 1%).

**Figure 0.2**: scheme of the different exploitation phases and related waste materials,

Source: [http://www.groundtruthtrekking.org/Issues/MetalsMining/MineTailings.html](http://www.groundtruthtrekking.org/Issues/MetalsMining/MineTailings.html)
The different waste categories resulting from mine exploitation are:

**Overburden:**
This is the material that lies above an area characterised by economical interest for exploitation, such as the rock, soil, and ecosystem that lies above the ore body.

**Waste rock:**
This is a result of stripping or gallery tracing (for underground mining) and so is an unused extraction product that is generally stored in a landfill site, often located in the immediate vicinity of the main mining centre (for economic reasons associated with transport costs). Waste rock (Figure 0.3) is also the non-ore rock, which miners discard as they dig to access the ore. The quantity of mining waste that can be stored at a mining centre varies considerably and mainly depends on the selectivity of the mining method. The main type of waste rock is generated by surface stripping to expose the shallow ore. This rock is weathered to varying degrees, although increasingly fresh with depth and showing the geological characteristics of the local surrounding material. Its composition is similar to the rocks of the sector. In underground mines, these barren rocks are generated by the passages (shafts, crosscuts).

**Operating residues:**
These come from sorting during excavation of the rich and poor ore (where the recovery of the minerals will be economically unfavourable). The poor ore is usually stored on site awaiting possible treatment if the metal prices were to rise. In old mines, it was set apart or rejected in the same way as other residues. Such residues may contain metal contents and accompanying elements equivalent to the ore.
Tailings:

These are typically a mud-like material as a result of dressing and treatment activities. The storage and handling of tailings is a major environmental issue. Many tailings are toxic and must be kept perpetually isolated from the environment. Tailings containment facilities are regarded as the world’s largest man-made objects. Mine tailings’ size and composition depend on the mining and dressing methods. For hard rock metal mines, tailings are usually a very fine mud or powder, which is left over after ore is crushed and milled and valuable minerals are extracted from it. Tailings may also contain chemicals used for mineral extraction that could be critical for the environment (Figure 0.4).

Tailing may produce various subtypes of waste, which can include:

- aqueous solutions from cyanidation,
- slurries of finely ground particles that have undergone one or more types of physical or chemical treatment, and which frequently contain one or more industrial additives that have participated in the conversion process (xanthates, miscellaneous salts, starch, etc.). These tailings are normally dumped in a sort of lagoon or settling basin.

Consequently, EW facilities represent a vast, untapped resource for valuable materials. Finite resources, including secondary raw materials (SRMs), raw materials (RMs) and associated critical raw materials (CRMs) such as rare earth metals (REEs) and platinum group elements (PGEs) are buried amongst waste in mining facilities. These resources are currently sourced from outside of the EU, are under high demand and are becoming increasingly scarce. Thus, EW facilities can be considered as “new ore-bodies”.

Figure 0.4: tailings (multiple active spigot discharge; © Jon Engels), source: http://www.tailings.info/basics/tailings.htm
Enhanced Landfill mining (ELFM) offers an opportunity to tap into this pool of resources. By excavating EW facilities, recovering these resources and selling them back into the market, we can reintroduce old “waste” into material cycles in line with the circular economy. At the same time, land space is liberated to be used for other scopes, including recreational and outdoor activities, land for urbanisation in the face of rapid population growth, areas for new landfills and new opportunities to access the original ore body. ELFM typifies sustainable waste management by reducing the pool of waste and transforming it into products through recovery, recycling and reuse.

This Toolkit aims to give an overview of the information needed to best exploit this opportunity. We provide an overview of: the ELFM concept and its drivers for EW (Sheet 1 and Sheet 2); the process and technologies involved (Sheet 3); initial steps to begin exploring and planning (Sheet 4 and Sheet 5); financial assessments, environmental assessments and decision support tools (Sheet 6 and Sheet 7); and case studies of projects from across the EU (Sheet 8).
1. Enhanced Landfill Mining Concept

The ELFM concept was first introduced in Israel in 1953 as a method to obtain fertilisers for orchards. However, the concept was not reported of again until the 1990s, where significant interest in the topic arose as a result of stricter environmental legislation and the need for land space. Interest in the concept has rapidly increased in recent years as a result of diminishing finite resources. New technologies have permitted mixed wastes to be effectively separated and treated to produce high quality, marketable materials and green energy.

The overall aim is for disposed resources to be recovered and re-introduced into material cycles as secondary raw materials (SRMs), acting as a source of materials for primary production in the face of finite resources. The extraction of deposited materials may also be integrated with remediation and aftercare measures to handle the environmental consequences of landfilling. Meanwhile, ELFM can also facilitate energy recovery and the recovery of land space for urban development. Future waste and waste fractions that cannot yet be effectively transformed are stored in a systematic way for future valorisation when technological and economic feasibility permits.

**Figure 1.1** provides an overview of the LFM and ELFM processes for EW.

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**Landfill Mining (LFM)** can be defined as “a process for extracting minerals or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground”. It describes the emerging field of exploring and extracting disposed material.

**Enhanced Landfill Mining (ELFM)** can be defined as “the safe conditioning, excavation and integrated valorisation of (historic 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.”
Broadly, waste is extracted from EW facilities, sorted and dressed. Some of this waste can be directly reused (e.g. reuse of rock waste for land rehabilitation or as filler material), replacing primary resources.

Other wastes must be processed before they become marketable.
2. Opportunities and Challenges

There are a number of policy, market and social drivers in favour of ELFM. The concept is congruent with achieving the policy goals of relevant EU Directives, including moving up the waste hierarchy towards more sustainable practices and creating a more circular economy. The key EU concepts, alongside other drivers for ELFM, will be outlined in this section.

2.1. Policy Drivers

2.1.1. EU Extractive Waste Management Directives

Waste management policy has evolved rapidly over recent time: a comprehensive framework for the safe management of waste at EU level is now in place, comprising:

- **Directive 2006/21/EC** on the management of waste from the extractive industries (the mining waste directive): the Directive provides measures, procedures and guidance to prevent or reduce possible adverse effects on the environment (in particular water, air, soil, fauna and flora, landscape), and any resultant risk to human health, brought about as a result of the management of mine waste;

- **Amendment of the Seveso II Directive** to include in its scope mineral processing of ores and, in particular, tailings ponds or dams used in connection with such mineral processing.

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1The European Commission published decisions and reports in order to explain in a deeper way the requirements of the Directive:

- **Commission Decision 2009/337/EC** on the criteria for the classification of waste facilities in accordance with Annex III of the Directive;
- **Commission Decision 2009/335/EC** on the technical guidelines for the establishment of the financial guarantee;
- **Commission Decision 2009/360/EC** completing the technical requirements for waste characterization contained in annex II;
- **Commission Decision 2009/359/EC** on the definition of inert waste;
- **Commission Decision 2009/358/EC** on the harmonisation and regular transmission of the information which have to be transmitted.
2.1.2. Waste Hierarchy

Disposing of EW waste results in an enormous lack of efficiency in material use while impacting both human health and the environment. As a result, a key priority for the EU is to move away from landfilling and waste disposal towards more sustainable practices. The waste hierarchy (shown in Figure 2.1) places emphasis on the reducing waste and maintaining materials as products in order to increase sustainability.

The most sustainable option must be preferred. Avoidance of waste, followed by reuse, recycling and then recovery are recommended. Disposal, as the least sustainable practice, must occur as a last resort only.

This concept has become a legal requirement for all Member States as the basis of their waste policy. The outcome is a reduction in waste production and a movement towards recycling programs and waste sorting.

Figure 2.1: Waste hierarchy
Thus, it is vital to think about “waste” as “future resources” and “EW facilities” as “new ore bodies”. An approach such as this corresponds with this concept by converting waste into product, moving materials up the hierarchy. Substituting the word “waste” with “reserve” transforms the 4R hierarchy into a 5R hierarchy (Figure 2.2).

2.1.3. Circular Economy
The so-called circular economy has become the key conceptual basis for a number of EU policies. In the past, production has followed a largely linear economy model of take, make and dispose (Figure 2.3). However, this has resulted in an abundance of waste and the depletion of finite, raw resources including critical raw materials (CRMs) and secondary raw materials (SRMs), putting manufacturing and industrial activities across the EU at risk.

The circular economy replaces this model with one in which resources circulate within the economy at a high value. It is the basis for a re-planning of the industrial processes that minimises the exploitation of natural resources and reuses/recycles/converts potential waste into resources (for the same or other productive cycles). The constant recovery of waste (which can be considered as by-products) from processing activities is the tendency for the future. Products, into which raw materials and energy have been invested, are recycled and reused. This reduces both the production of and the need for finite, raw resources.

Figure 2.2: Passage from a 4R to 5R waste hierarchy
In order to achieve a circular economy within waste management practices, life cycle thinking must occur. This can be achieved by eliminating the production of waste and promoting reuse and recycling. ELFM offers the added benefit of reintroducing previously disposed-of materials back into the loop, so-called closing the loop. This reduces the effects of a previous linear economy and further reduces the need to use of finite resources, by providing a source of finite materials which can then continue to recirculate within the economy.

Figure 2.3: Linear economy versus Circular economy
2.2. Market Drivers

2.2.1. Price/Market Share of Critical and Secondary Raw Materials

Globalisation, growth in consumption levels and the emerging economies (such as China and India) has led to increasing concerns about the availability of certain raw resources. Resources are finite and rapidly depleting; in the meantime, demand is ever increasing. The result is an overall trend of increasing raw material value and dramatic price spikes and fluctuations. Therefore, resource security is now a priority for governments of developed countries.

The security of supply of the so-called ‘critical’ raw materials (CRM), with rare earths (REE) has attracted the greatest attention in the press.

The “criticality” concept is based on the combination of economic importance and supply risk for the RM. The EU recognises 20 CRM in 2014 (Blengini et al., 2017); the latter is shown in Figure 2.4. A third revised list, based on a revised criticality methodology, is expected by the end of 2017 (Blengini et al., 2017).

The EU relies on countries from outside the EU for the vast majority of their critical raw materials (CRM) supply (Table 2.1; Figure 2.5), putting manufacturing and industrial activities within the EU at risk and causing high economic dependence on non-EU countries.

![Figure 2.4: Economic importance and supply risk of Raw Materials (EU Commission, 2014)](image-url)
### Table 2.1: World production of Strategic Raw Materials and Industrial Minerals.

a Tantalum and Niobium (or Columbium) concentrates; b Rare Earth concentrates. In 2014 China REE production, though increased as absolute value, was decreased to ca. 84% of the World production (USGS 2014); c Platinum Group Metals, here given as Pt+Pd+Rh, in kg. d gross weight. Source of production data: World Mining Data 2013, apart from feldspar (USGS 2013). Import data (referred to 2006-2009, depending on the material) are from EC 2010 - Report of the Ad-hoc Working Group on defining critical raw materials. Apart from feldspar, all minerals in the Table belong to the CRM as defined by mentioned EC 2010 Report.

<table>
<thead>
<tr>
<th>Minerals/Elements</th>
<th>World production 2011 (t)</th>
<th>Change (%) 2011-2007</th>
<th>Main producers - world (%)</th>
<th>EU production – world (%)</th>
<th>Main EU producers</th>
<th>Import to EU (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>113386</td>
<td>76.56</td>
<td>Congo 66.15</td>
<td>140</td>
<td>0.12</td>
<td>Finland 26500³</td>
</tr>
<tr>
<td>To-Nb a</td>
<td>176648</td>
<td>29.74</td>
<td>Brazil 95.93</td>
<td>-</td>
<td>-</td>
<td>Ta: 131 Nb: 19700</td>
</tr>
<tr>
<td>Tungsten</td>
<td>82278</td>
<td>48.31</td>
<td>China 84.96</td>
<td>1862</td>
<td>Portugal</td>
<td>5329</td>
</tr>
<tr>
<td>Gallium</td>
<td>85</td>
<td>14.86</td>
<td>China 50.59</td>
<td>5</td>
<td>5.88</td>
<td>Hungary Not given</td>
</tr>
<tr>
<td>Germanium</td>
<td>66</td>
<td>22.22</td>
<td>China -</td>
<td>-</td>
<td>-</td>
<td>31.1</td>
</tr>
<tr>
<td>REE b</td>
<td>100261</td>
<td>-20.05</td>
<td>China 96.65</td>
<td>-</td>
<td>-</td>
<td>17600</td>
</tr>
<tr>
<td>PGM c</td>
<td>428336</td>
<td>-5.1</td>
<td>RSA 58.50</td>
<td>1536</td>
<td>0.36</td>
<td>Finland Not given</td>
</tr>
<tr>
<td>Graphite</td>
<td>1166197</td>
<td>1.50</td>
<td>China 68.60</td>
<td>7000</td>
<td>6.9</td>
<td>Romania 122000</td>
</tr>
<tr>
<td>Fluorspar</td>
<td>7015439</td>
<td>22.50</td>
<td>China 59.87</td>
<td>174903</td>
<td>2.49</td>
<td>Spain 715000</td>
</tr>
<tr>
<td>Feldspar</td>
<td>2120000</td>
<td>-0.05</td>
<td>Turkey 28.30</td>
<td>7353000</td>
<td>34.68</td>
<td>Italy 3947</td>
</tr>
</tbody>
</table>
These factors drive:

1. A need for new sources of raw materials; and
2. A need for the EU to reduce its reliance on global imports of such materials and to become more independent.

ELFM can play an enormous role in achieving these aims. Materials recovered from ELFM provide a new source of raw materials from within the EU.

### 2.3. Social Drivers

#### 2.3.1. Land Space

As a result of rapid population growth, demand for land space has risen dramatically, particularly for urban development (Figure 2.6). This has resulted in a rapid increase in land value. Whilst site remediation reuses the land space, ELFM recovers the land space to a higher land value which can be used for much needed urban or environmental (land) development.

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**Figure 2.5: Production of Critical Raw Materials in the world ("Growth - European Commission." Critical Raw Materials. [http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm])**
2.5. Future Outlook

Despite the barriers described above, the EU has recently voted to include ELFM in the EU Landfill Directive:

*The Commission shall further examine the feasibility of proposing a regulatory framework for enhanced landfill mining so as to permit the retrieval of secondary raw materials that are present in existing landfills. By 31 December 2025 Member States shall map existing landfills and indicate their potential for enhanced landfill mining and share information.*

Therefore, barriers and bottlenecks relating to current EU policy are being addressed and will be amended in the very near future. It is also possible that further policy elements will be added that promote ELFM, including providing economic incentives for such activities.

2.6. Conclusions

Overall, ELFM has the potential to alleviate many large issues associated with the economy, the environment and resource sustainability. It is driven by current EU Directives, encompasses their overarching aims and will be further promoted by future Directive amendments.
By applying and adapting the technologies known for RM processing, it is possible to think about specific treatments of different facility typologies and waste streams. Waste is processed to produce materials (Waste-to-Material, WtM): RM, CRM and SRM. This section aims to give an overview of the ELFM process regarding EW facilities, the technologies available and the valorisation routes for excavated wastes.

3.1. ELFM Process Overview

Enhanced Landfill mining for EW facilities can be summarised in a four-step process: (1) exploration (including site and waste characterisation), (2) mining and transport, (3) processing, (4) recycling resources/residue disposal.

An overview of the ELFM process is illustrated in Figure 3.1.

**Figure 3.1:** Overview of ELFM Process for EW
The valorisation potential and the most feasible valorisation routes are dependent on:

- the characteristics of the site
- the ore-deposits typology: depending on that and on ore-assemblage, it is possible to associate the main exploited minerals/elements to other minerals/elements (e.g., in Zn-Pb mine it is possible to find Cd, In, Ge, Ga; in Ni sulphides mine it is possible to find PGE, Cu, Co)
- the characteristics of the waste

Therefore, the valorisation potential is site specific. The most suitable valorisation options will depend on the technologies available, economic and environmental feasibility and the characteristics of each fraction.

- **Top soil and fines** can also be valorised through direct reuse for fertilisers and construction materials, though this is unlikely due to high levels of contamination with heavy metals and other pollutants that pose a threat to environmental safety. This fraction also often contains **high metal content**, which may be separated and treated to produce a metal enriched product (to be used, potentially, for other applications). After the metal separation, the fine fraction can be treated (e.g., adding organic matters) to obtain new soil to use for land remediation (Dino et al. 2014).

- **The fines fraction** is often the most poor in terms of RM and therefore most difficult to process. Tailings represent the waste coming from dressing activities, thus it is assumed that RM have been separated; but in some cases they can be enriched in not exploited RM; for example, tailings coming from the treatment from Zn-Pb minerals, for which only the separation of Zn have been set, can be enriched in Pb. Furthermore, such waste can be rich in CRM not known or not exploited (because not needed) at the processing time.

- **The coarse fraction** can be utilised through the WtM route to produce RM/CRM and products for resale. This requires substantial separation and treatment.

This is summarised in Table 3.1.
As the ELFM process and recovery routes are site-dependent, site prospecting and analysis is necessary before the exact processes can be defined. The waste composition of the site must be determined through sampling and separation. An analysis of the fines fraction is also needed. Methodology for this is described in Sheet 4 and Sheet 5 respectively. Valorisation routes are also determined by economic and environmental feasibility, as different levels of separation and processing will affect the economic costs and the revenues of the project. Economic and environmental analysis is described in Sheet 6.

### Table 3.1: Valorisation routes for different waste fractions

<table>
<thead>
<tr>
<th>Waste Fraction</th>
<th>Valorisation Route</th>
<th>End Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>WtM (reuse)</td>
<td>Soil amendment, top soil</td>
</tr>
<tr>
<td>Fines Fraction</td>
<td>WtM</td>
<td>New artificial soil or RM/CRM (if sent to advanced processing)</td>
</tr>
<tr>
<td>Coarse Fraction</td>
<td>WtM</td>
<td>Aggregates and/or RM/CRM for resale</td>
</tr>
</tbody>
</table>

3.2. Next Steps

As the ELFM process and recovery routes are site-dependent, site prospecting and analysis is necessary before the exact processes can be defined. The waste composition of the site must be determined through sampling and separation. An analysis of the fines fraction is also needed. Once this investigative stage has occurred, a flow map for the whole project can be established, determining the level of separation and processing needed, the technologies involved, the valorisation routes for each fraction and the expected outputs.
In order to assess the valorisation potential of a site, site investigation is necessary. This will determine the waste composition of the site, the characteristics of the waste fractions and the valorisation routes to be considered. This section outlines the full site investigation process as the first step towards establishing an ELFM project.

Figure 4.1 summarises the approach taken to assess facility sites through physical sampling.

**Figure 4.1** Site Investigation Overview

- **Waste Rock**
  - Excavating and/or Sampling Activity using hand shovel or chips selection
  - Sampling to produce sub-samples for each sampled area
  - Quartering and manual sieving of each sample
  - < 2 mm
  - > 2 mm
  - Fines Fraction
    - Characterisation for environmental impacts and for RM/CRM/SRM content

- **Operating Residues**
  - Core drilling or excavating (consolidated tailings)
  - Sampling to produce sub-samples for each sampled area
  - Characterisation for RM/CRM/SRM content

- **Tailings**
  - Sampling to produce sub-samples for each sampled area
  - Characterisation for environmental impacts and for RM/CRM/SRM content
4.1. Preliminary Information

When planning a field survey, it is fundamental to collect the information below in order to obtain representative samples:

- Operation history: is the facility filled by layers or is constituted by different waste typologies, etc.;
- The depth and extension of the facility bodies;
- The typology of EW material (rock waste, operating residues, tailings, or mix);
- Geotechnical stability (occupational safety);
- Possible hazardous waste placed in the landfill (occupational safety).

4.2. Sampling Strategy and Techniques

There is no definitive rule for the number of samples per area, or for the waste volume that should be taken to be representative of the facility's composition. Consideration that EW facilities are mainly constituted by mono-waste materials must be taken; thus, the numbers of samples, the localisation within the facility and the mass of each sample have to be adequate to guarantee that sampling activity is representative.

4.2.1. Sampling Strategy

Sampling activity using a net scheme: this protocol is appropriate when the size and shape of the landfill are suitable for the organisation of a net scheme. In this case, it is possible to sample the material at the net intersection (a) or in the centre of each net area (b), and locate the sampled areas on a map (see Figure 4.2).

Random sampling activity: when it is not possible to arrange a net scheme, it is best to sample the material using a random protocol. In this case, it is necessary to adopt a random scheme (not selectively sample specific areas) and to locate the sampled areas on a map.
4.2.2. Sampling Protocol

The landfill site can be sampled as follows:

1. **Top layers** of the facility, including cover materials and soil, are discarded.

2. Where possible, a **vertical shaft** is made into the facility body, the area and depth of which depends on the chosen sampling technique. When creating the shaft, the excavated/drilled material is deposited in skips located on the side of the shaft. If possible, the skips are weighed empty and again with the sampled material in to produce the mass of each sample. If no shaft is possible (e.g. for rock waste dumps) the sampling techniques employed is: mechanical or hand shovel, quartering and sampling; or chips sampling (collecting random chips from the area in the nearby of the sampling point.

3. Depending on the operating history of the facility (e.g. several areas linked to the same EW facility), different **depth profiles** can be created by recording the depth from which the waste is sampled. Then, the samples taken from different depths can be deposited in separate skips.

4. By using a clamshell bucket or a small-scale excavator, the contents of each skip is mixed thoroughly and a **sub-sample** representing each skip (e.g. 0.5 m$^3$) is quartered to produce samples to be treated and analysed at laboratory scale (each sample is weighed).

**NOTE:** The selected sample size for manual sorting is always a compromise between the sample representativeness and the time required to manually sort the sample.

4.2.3. Sampling Techniques

**Core Drilling**

A possible method to collect representative samples from mining landfill is by means of core drilling/borehole (**Figure 4.3**): a borehole is a narrow shaft bored in the ground, either vertically or horizontally. Drilling activities are useful to collect rocks, soil and also water samples during a field survey.

Samples collected from boreholes can be tested to determine their physical, petrographic and mineralogical properties, or to assess levels of various chemical constituents and/or contaminants. Two main core drilling techniques can be recognised:
This technology allows the division of the landfill into different depth profiles. On the other hand, high operating costs are a clear disadvantage of this technology. Furthermore such a kind of techniques is not the most appropriate one if we have not consolidated material or hard rocks.

Excavating

Using an excavator is another way to sample mining waste. It is most useful for not consolidated material (Figure 4.4). It is possible to use excavators (also little-excavator) associated with trenching and pitting. Excavation is accomplished by digging up the waste using construction equipment. The waste can be transported elsewhere for separation and/or further treatment. A sampling shaft of around 10 metres can be excavated depending on the size of the excavator. Drawbacks in comparison to drilling are mostly related to dealing with hard, non-penetrable objects.

Sampling activity using hand shovel or chips selection

When it is not possible to use neither core drilling nor excavating, mostly because of the high costs, it is possible to sample mining waste, using hand shovel (and hammer). It is useful for not consolidated material and for rocks (using a hammer) connected to the ore deposit or to the border rocks (Figure 4.5). Hand shovel can be used to sample specific area/point, but it is not appropriate if we need to sample in depth.
The purpose of the sorting of waste sampled from facilities is to be able to plan the best valorisation routes for the different particle size categories and waste fractions. The goal is to have enough representative data to design and test, at first, the prototype of a possible treatment plant for recovery RM/CRM/SRM from EW facility (if the prototype will give positive results, the interested company will be able to pass from a prototype to a full-scale treatment plant).

The samples collected from EW facilities need to be characterised to ascertain their value for the landfill mining operation. Samples are generally sent to a laboratory (often external) for such analyses with the aim to determine the characteristics of the materials. Figure 5.1 shows an overview of the analytical procedure.

**Figure 5.1:** Analytical procedure overview
5.1. Physical Characterisation

Physical characterisation includes:

- Humidity
- Bulk density (EN 1097-3; EN 1097-4)
- Size distribution (EN 933-1; EN 933-2)

Where the interest to obtain material for construction industry is strong, other analysis have to be set, for example:

- Flat index (EN 933-3)
- Shape index (EN 933-4)
- Los Angeles test (EN 1097-2 (5°))
- Microdeval test (EN 1097-1)
- Freeze-thaw test (EN1367-1)
- Fine particles content (EN 933-8; EN 933-9)
- Atterberg limits (ASTM D4318-84; ASTM D4943-89)

For all these test specific EN regulation have been set.

5.2. Petrographic Characterisation

In order to determine the composition and properties of the waste fractions, optical microscopy under transmitted and/or reflected polarized light of thin/polished (usually ∼30μm thick) sections is required.

Quantitative volume % determinations (i.e., modal analyses) can also be required in some cases. Depending on the specific target, they can be performed by point counting or image analysis of composition maps (e.g., XRF or SEM-EDS element maps) of thin/polished sections.

5.3. Mineralogical Characterisation

Main techniques: optical microscopy under transmitted and/or reflected polarized light of thin/polished (usually ~30μm thick) sections, and/or (depending on the material); XRD (X-ray diffraction) analyses on pulverized material, and/or electron microprobe techniques (SEM-EDS/WDS). Other types of spectroscopic analyses (e.g., micro-Raman spectroscopy) may be required under certain circumstances.
5.3. Geochemical Characterisation

For the geochemical characterisation, a small (40-100g), representative and homogeneous sub-sample from the material.

For rocks and inorganic material, typical procedure is:

- Crushing;
- Pulverising (generally ≥85% passing 75 μm);
- Quartering and selection of pulp for analysis (excess pulps are stored).

Finely pulverised material (i.e., pulp) requires further treatment (lithium borate fusion; aqua regia/four acid digestion methods...) for analysis, which strongly depend on the analytical methodology adopted (which also depends, of course, on the elements of interest: see below). There are two main types of geochemical characterisation: whole rock and single phase analyses.

Whole rock geochemistry:
Main techniques: XRF (X-ray fluorescence spectrometry), particularly for major elements, and/or several types of spectroscopic techniques (AAS, ICP-AES, ICP-MS etc.), particularly for minor and trace elements.

Single phase analyses (i.e., mineral chemistry):
Main technique: electron microscopy (SEM-EDS/WDS) on polished and metallised sections/samples.
6. Cost Benefit Analysis

In order to decide whether to undergo an ELFM project, as with all investments, a cost-benefit analysis from an economic perspective is necessary in order to see if the venture would be profitable. As ELFM also has many environmental and social outcomes, it is also important to include these effects in an overall analysis in order to ascertain as to whether it is beneficial from a wider viewpoint.

This section provides an overview of the method in order to perform these analyses. A detailed guidance document for Cost-Benefit Analysis can be found at:


6.1. Selecting the Time Horizon

The first step for this method is to select a time horizon for the investment. This will depend on the quantity of the input material compared to the capacity of the technology. In optimal cases, this should be equal to the useful life of the machinery purchased for ELFM, but can be shorter or longer depending on the circumstances. A maximum of 30 years operation period should be calculated for the investment, as a result of future technology innovation.

6.2. Assessing the Costs and Revenues

The next step is to determine the costs and revenues of the investments, which can be categorised as shown in Table 6.1.
The most common financial indicators of an investment are the financial net present value (FNPV) and the financial rate of return (FRR) of the cash-flows of costs and incomes.

To calculate this indicator, a discount rate should be selected so that the future cash-flows can be converted to a present value. Usually, this rate is connected to the interest rate on the market; however using a constant 4% rate is generally acceptable.

FNPV can be calculated without taking the capital investment cost into account (i.e. FNPV (C)) or taking it into account (FNPV (K)). The equation for its calculation is as follows:

$$FNPV(C) = \sum_{t=0}^{n} a_t S_t = \frac{S_0}{(1+i)^0} + \frac{S_1}{(1+i)^1} + \ldots + \frac{S_n}{(1+i)^n}$$

where: $S_t$ is the balance of cash flow at time $t$; $a_t$ is the financial discount factor chosen for discounting at time $t$; and $i$ is the financial discount rate.
6.3.2. FRR

This indicator shows at which financial discount rate the net present value of the investment equals zero. FRR can also be calculated without taking the capital investment cost into account (i.e. FRR (C)) or taking it into account (FRR (K)). The equation for its calculation is as follows:

$$0 = \sum \frac{S_t}{(1 + FRR)^t}$$

where: $S_t$ is the balance of cash flow at time $t$.

6.4. Calculating the Environmental Factors

Environmental indicators are calculated similarly to financial indicators. There are only two modifications needed in the financial cash-flow in order to calculate environmental indicators.

6.4.1. Adding External Benefits and Costs

In the financial analysis, the market prices of employment and purchasing goods and services are calculated. However, these prices also contain elements (e.g.: taxes, subsidies, social benefits, transaction costs, etc.) which are not connected directly to the landfill mining investment, but are cash-flow transfers to finance other services of the modern society. Therefore, in cases where prices are higher because of the lack of a competitive market, or because of included social transfers, prices should be adjusted. This is usually done by using correction factors for the market prices (e.g. calculating shadow wages for non-skilled employment, or reducing the prices of goods and services where natural monopolies distort the competition).

6.4.1. Shift from Market to Shadow Prices

Beyond its own framework, a landfill mining investment may have positive or negative effect on its environment. Recyclables can eliminate the negative environmental effects of producing primary raw material and combustible outputs can substitute carbon based fuels. By quantifying these effects and adding a suitable pricing, they can be added as external cash-flow to the whole project cash-flow calculated at shadow prices.

6.4.3. Environmental Indicators

The calculated environmental indicators are the Environmental Net Present Value (ENPV) and the Environmental Rate of Return (ERR). The equations for these indicators are identical to those for the financial indicators; only they are calculated from the environmental corrected cash-flow of the project which also contains the external costs and benefits. In the case of ENPV calculation, a 5% discount rate is generally acceptable.
6.5. Interpreting the Indicator Calculation Results

There are several possible scenarios for the indicators which may influence the decision regarding the landfill mining investment (Table 6.2).

<table>
<thead>
<tr>
<th>FNPV (C) value</th>
<th>FNPV (K) value</th>
<th>ENPV value</th>
<th>Explanation</th>
<th>Decision Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNPV (C) &gt;0</td>
<td>FNPV (K) &gt;0</td>
<td>ENPV &gt;0</td>
<td>The ELFM project can be financed from the market using private capital and is also considered desirable for the society</td>
<td>These landfill mining investments should be implemented</td>
</tr>
<tr>
<td>FNPV (C) &gt;0</td>
<td>FNPV (K) &gt;0</td>
<td>ENPV &lt;0</td>
<td>The ELFM project can be financed from the market using private capital but has an overall negative impact for society</td>
<td>The relevant environmental authorities should forbid private investors to continue with the project</td>
</tr>
<tr>
<td>FNPV (C) &lt;0</td>
<td>FNPV (K) &gt;0</td>
<td>ENPV &gt;0</td>
<td>The ELFM project cannot be financed from the market but is desirable for society</td>
<td>A subsidy should be given to the project. Usually, this scenario is the pre-condition for any EU investment subsidy</td>
</tr>
<tr>
<td>FNPV (C) &lt;0</td>
<td>FNPV (K) &lt;0</td>
<td>ENPV &gt;0</td>
<td>Although the project may be desirable from a social viewpoint, there is no suitable financing scheme which makes the operation sustainable, even with investment subsidy</td>
<td>The two options are either to cancel the project, or to identify additional incomes to make it financially sustainable</td>
</tr>
<tr>
<td>FNPV (C) &lt;0</td>
<td>FNPV (K) &lt;0</td>
<td>ENPV &lt;0</td>
<td>In this case the project implementation is not desirable from an environmental point of view or an economic perspective</td>
<td>The competent environmental authority should forbid the implementation. But, since it is not profitable, there will be no investor willing the finance the project</td>
</tr>
</tbody>
</table>

Table 6.2: ELFM scenarios
6.6. Sustainability Analysis of the Project

A project should also generate enough cash-flow to finance the everyday operation; having positive indicators alone is not sufficient. If the accumulated cash-flow of a project is positive for every year of the operation, it shows that the landfill mining investment is sustainable. If the accumulated cash-flow is negative for only some years (for example when the replacement of assets take place), this can be counter-balanced by taking a credit. On the other hand, if the accumulated cash-flow is negative for longer periods or at the end of the project, the financial sustainability of the landfill mining operation is questionable.

6.7. Sensitivity of the Calculation Results

During the calculation of the financial and environmental indicators, it is assumed that we know precisely the costs and incomes of a future operation. This, in reality, is not the case. Sensitivity calculation shows how the indicators are affected if the elements of the project (e.g. investment, operation costs, incomes etc.) are altered or differ from those assumed. At each calculation, change in only of one project element is analysed, assuming that all other assumptions remain unchanged. A project element is considered sensitive if a 1% change in the value of the element results in more than a 1% change in the financial or environmental indicator(s).

6.8. Risk Assessment of the Calculations

Knowing the sensitivity of the project elements and by adding the probability that they will change and between which intervals this change is possible, we can generate several artificial scenarios. These together produce the probability distribution of the financial and environmental indicators of the project. The method for this calculation is called Monte Carlo Analysis (receiving its name from its development for casinos). Random values are generated between the probability intervals of the project elements and, through several thousand iterations, the probability distribution is calculated. From this distribution, we can discern the real probability that the value of FNPV or ENPV being higher than zero. If it is close to 100%, the risk is relatively low; but, if it is closer to 0%, the calculations may need to be revised, as would decisions regarding different scenarios.
SMART GROUND also offers a Decision Support Tool for Extractive Wastes, in order to evaluate the feasibility of an ELFM project. The tool incorporates social, environmental and economic factors and uses a step-wise approach to evaluate the performance of each of these factors. Using multi-criteria analysis, the best process approach from a sustainability point of view is identified.

The Decision Support Tool therefore aids stakeholders in deciding:

- The best process and valorisation routes of waste
- The feasibility of the project, from economic, social and environmental perspectives

The Decision Support Tool can be found on our website.
The SMART GROUND project has performed in-depth characterisation of a number of EU extractive mining sites. The objective is to identify and characterise more accurately the specific secondary raw materials (SRMs) with a market value for its further utilization as raw materials (RMs) or energy. Here, we outline the methods and findings of three pilot sites based in Italy.

CASE STUDY 1: CAMPELLO MONTI, PIEDMONT, ITALY
CASE STUDY 2: GORNÖ, LOMBARDY, ITALY
CASE STUDY 3: MONTORFANO, PIEDMONT, ITALY
The Campello Monti mining area is located in Strona Valley (Piedmont, Western Italian Alps), ca. 20 km from the Swiss border. Mine waste deposits in this area are related to a nickel mine which operated intermittently from the second half of the 19th century to 1945. This exploited Fe-Ni-Cu-(Co) magmatic sulphide deposits (nickel average grade: from 1-2 to 0.5 wt. % Ni in the last years of activity) with an estimated production which probably of around 50 short tons per year. The treatment activities in the area were intensive during World War II and included a first phase of manual sorting, followed by mechanical (grinding, milling) and chemical (flotation) treatment. Over the last decades, localized PGE enrichments were documented in some mineralisations.

Background:
The Campello Monti mining area is located in Strona Valley (Piedmont, Western Italian Alps), ca. 20 km from the Swiss border. Mine waste deposits in this area are related to a nickel mine which operated intermittently from the second half of the 19th century to 1945. This exploited Fe-Ni-Cu-(Co) magmatic sulphide deposits (nickel average grade: from 1-2 to 0.5 wt. % Ni in the last years of activity) with an estimated production which probably of around 50 short tons per year. The treatment activities in the area were intensive during World War II and included a first phase of manual sorting, followed by mechanical (grinding, milling) and chemical (flotation) treatment. Over the last decades, localized PGE enrichments were documented in some mineralisations.

Field Surveys:
Preliminary field surveys identified two types of mineral waste in the area:

Waste rock – the most common type of waste material occurring in dumps, over an area of ca. 30,000 square metres.

Operating residues – these occur in two areas: close to the dressing plant (deposit named “area 1”) and on the opposite side of the valley (area 8). The two deposits are strongly different: the deposit of area 1, close to the dressing plant, is fine grained, red/orange to brown in colour, and represents “waste” related to a first phase of the treatment; the deposit of area 8 represents instead sorted ore material likely coming from a nearby license area (that was connected to the dressing plant by funicular.)
Based on the preliminary surveys, 8 waste areas were selected for the project: six rock waste dumps (areas 2 to 7) and two deposits of operating residues (areas 1 and 8). For each waste facility, sampling was performed by adopting a net scheme (or grid method). Each sample was collected in an area of 1.5 square metres; after cleaning the sampling point from organic residues (leaves and branches), the sample was collected using hand shovel and, where necessary, hammer to reduce the grain size of the rock.

41 samples of rock waste and 12 of operating residues were collected for mineralogical, petrographic and geochemical characterisation.

**Figure 8.3: Sampling areas**

**Geochemical Characterisation:**

The main geochemical features of all samples are typical of ultramafic rocks affected by processes of exsolution and accumulation of sulphide liquid, as typical of Ni-sulphide magmatic mineralisations worldwide. Concerning the metals content, the samples show:

- variable, but generally high to very high Ni, Co, Cu values
- relatively high Cr and Mn
- low rare earth element (REE) content
- strongly localized PGE enrichments

The SRM potential of waste materials connected with Ni-sulphide mining is represented by metals as Ni, Cu, Co and (possibly) PGE. The geochemical data allow the recognition of four groups of samples:

- “Group I” (area 1): very strong Ni (>10000 ppm), Cu (≥5000 ppm) and Co (>600 ppm) values
- “Group II” (areas 3, 4, 8): strong Ni (2000-10000 ppm), Cu (600-1500 ppm) and Co (100-300 ppm) values
- “Group III” (areas 2, 6): moderate Ni (700-1600 ppm), Cu (200-600 ppm) and Co (100-200 ppm) values
- “Group IV” (areas 5, 7): relatively low Ni (100-700 ppm), Cu (50-200 ppm) and Co (50-100 ppm) values.
A positive correlation is generally observed between Ni, Co and Cu. Concerning the critical PGE and Au, the geochemical data show that PGE content is highly variable (Pd+Pd: 5.8 to 821 ppb) and the main PGE are represented by Pd and Pt. The Au content is highly variable, from 3 to 190 ppb; Au is a broadly correlated with the PGE content.

Mineralogical and Petrographic Characterisation:

Coarse-grained waste materials (dump rock waste and sorted material of area 8):

In thin-polished sections under the microscope, these materials are composed of mafic silicates associated with a variable amount of metal sulphides. The mineralization is made of sulphides consisting of pyrrhotite (Fe$_{1-x}$S), pentlandite ((Fe,Ni)$_{9}$S$_{8}$), chalcopyrite (CuFeS$_{2}$) and minor cubanite (CuFe$_{2}$S$_{3}$). Pentlandite, the main ore mineral, generally occurs as subhedral to euhedral crystals (ca. 0.1-2 mm across) enclosed by anhedral pyrrhotite (∓ chalcopyrite).

The electron microprobe study shows that:

- The very fine-grained (<1–100 µm across) material is composed of: iron oxides/hydroxides and sulphate; Mg-rich silicates; partially oxidized pyrrhotite, pentlandite and chalcopyrite; covellite (CuS); native sulphur.
- Ni occurs in partially oxidized pentlandite (23.2 to 36.0 wt. % Ni, up to 1.8 wt. % Co), while Cu may occur both in chalcopyrite and in chalcocite (Cu$_{2}$S, ca. 80 wt. % Cu).

These data show that the waste material of area 1 is the partially oxidised equivalent of the coarser-grained material of the other areas, after milling and some mineral dressing operation.
Conclusions for SRM exploitation:

The data obtained suggests that Ni, Cu, Co (± PGE) represent potential SRM in the mineral waste; not only these metals always occur well above the “clarke rock value”, but – above all – within minerals (metal sulfides) suitable for metals recovery.

The in depth geochemical screening shows that the metals distribution is not homogeneous, with strong differences occurring among the different waste deposits. Even if some variability of metal concentration occurs also at the single area scale, each area shows a relatively homogeneous “geochemical signature”, which allows at least a broad estimate of the metals content. The geochemical data allow the distinction of four main groups of samples, corresponding to specific areas.

The average values of Ni, Cu and Co of the areas (as well as the minimum/maximum values and standard deviation) are given in Table 8.1.

Such a picture clearly emphasizes the complexity of the SRM estimation in waste deposits connected with the mining activity: different waste facilities can, in fact, represent completely different “products” of mining.

Table 8.1: Average values of Ni, Cu and Co for the investigated areas

<table>
<thead>
<tr>
<th>Group</th>
<th>Area</th>
<th>Ni</th>
<th>min</th>
<th>max</th>
<th>σ</th>
<th>Cu</th>
<th>min</th>
<th>max</th>
<th>σ</th>
<th>Co</th>
<th>min</th>
<th>max</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>24467</td>
<td>13700</td>
<td>39390</td>
<td>7534.6</td>
<td>9050</td>
<td>4900</td>
<td>11400</td>
<td>2434.5</td>
<td>995</td>
<td>620</td>
<td>1300</td>
<td>268.1</td>
</tr>
<tr>
<td>II</td>
<td>3</td>
<td>2485</td>
<td>1090</td>
<td>3360</td>
<td>781.5</td>
<td>719</td>
<td>278</td>
<td>1010</td>
<td>246.9</td>
<td>122</td>
<td>91</td>
<td>136</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5476</td>
<td>2820</td>
<td>9020</td>
<td>2536.4</td>
<td>921</td>
<td>666</td>
<td>1360</td>
<td>236.9</td>
<td>197</td>
<td>141</td>
<td>256</td>
<td>50.8</td>
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<tr>
<td></td>
<td>8</td>
<td>3114</td>
<td>2480</td>
<td>4250</td>
<td>611.9</td>
<td>909</td>
<td>670</td>
<td>1180</td>
<td>176.0</td>
<td>163</td>
<td>139</td>
<td>202</td>
<td>18.3</td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>1080</td>
<td>766</td>
<td>1250</td>
<td>298.1</td>
<td>311</td>
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<td>358</td>
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<td>143</td>
<td>122</td>
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<td>246.6</td>
<td>366</td>
<td>247</td>
<td>547</td>
<td>140.4</td>
<td>104</td>
<td>76.6</td>
<td>137</td>
<td>21.6</td>
</tr>
<tr>
<td>IV</td>
<td>5</td>
<td>364</td>
<td>281</td>
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<td>72.0</td>
<td>143</td>
<td>105</td>
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<td>74</td>
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<td>84.8</td>
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<td>231</td>
<td>50.4</td>
<td>64</td>
<td>31.3</td>
<td>79.5</td>
<td>13.4</td>
</tr>
</tbody>
</table>
The Gorno mining district is located in the Seriana, Riso and Brembana valleys (Lombardy, Northern Italy). The District lies in the “Lombard Basin” of the Italian Southern Alps. The Gorno Zn-Pb (±Ag, fluorite and barite) district belongs to the Alpine Type Zinc-Lead-Silver stratabound ore deposits. The dominant distribution trend of the orebodies is approximately N-S, as tabular “columns” up to over 2 kilometres long, with a width ranging from 50 to 400 meters and thickness between 3 and 20 metres. The primary mineralization is mainly composed of sphalerite (ZnS) and galena (PbS) (average Zn/Pb ratio= 5:1), ± pyrite (FeS2), marcasite (FeS2), chalcopyrite (CuFeS2) and argentite (Ag2S). A secondary mineralisation is composed of oxidation products of sphalerite, i.e., Zn-carbonate and silicate. The dominant gangue minerals are calcite, dolomite and quartz (± ankerite).

Background:
The Gorno mining district is located in the Seriana, Riso and Brembana valleys (Lombardy, Northern Italy). The District lies in the “Lombard Basin” of the Italian Southern Alps. The Gorno Zn-Pb (±Ag, fluorite and barite) district belongs to the Alpine Type Zinc-Lead-Silver stratabound ore deposits. The dominant distribution trend of the orebodies is approximately N-S, as tabular “columns” up to over 2 kilometres long, with a width ranging from 50 to 400 meters and thickness between 3 and 20 metres. The primary mineralization is mainly composed of sphalerite (ZnS) and galena (PbS) (average Zn/Pb ratio= 5:1), ± pyrite (FeS2), marcasite (FeS2), chalcopyrite (CuFeS2) and argentite (Ag2S). A secondary mineralisation is composed of oxidation products of sphalerite, i.e., Zn-carbonate and silicate. The dominant gangue minerals are calcite, dolomite and quartz (± ankerite).

Field Survey:
A preliminary field survey focused on two areas:

1. Arera mining area (extractive waste facilities):

The waste sampling activity in Arera area was focused on 6 extractive waste facilities (rock waste dumps), in an area of approximately 0.5 km at the exit of main mine tunnels. The rock waste material has been sampled using hand shovel, while a hammer was used where necessary. Each sampling spot covers an area of approximately of 4m$^2$. Two main rock types occur in the dumps: grey limestone and beige to brown dolomitic rock. The preliminary dumps survey showed that in the higher altitude areas the mineralisation, mainly composed of coarse-grained sphalerite, is selectively concentrated in the dolomite, while the grey limestone is barren. Therefore, a random sampling would have the effect to dilute the grade; dilution can be easily avoided by selecting the brownish material. For this reason, the following sampling procedure was adopted for these areas:

- Assessment of the relative proportions of the two rock fractions in the waste dump (by random sampling and fragments counting);
- Sampling of the dolomite material for analysis.

Figure 8.4: Location of Gorno
2. Gorno mine tailings deposits:

Tailing sampling was focused on one of the tailings deposit in the District, close to the Riso river. 4 sampling points have been identified within deposit: three (DH1, DH2 and DH3) at a distance of 37 meters each other, the fourth one (DH4) in the easternmost part of the deposit, at a distance of 80 meters from DH3, to check the lateral continuity and the thickness of the top soil. Sampling was performed by hand drilling, removing first the top soil covering the tailing pond; samples of the tailing deposit were taken at different depth.

Figure 8.5: Tailing deposits sampling points

Geochemical Characterisation:

The SRM potential of waste materials connected with alpine-type Zn-Pb deposits mining is represented by metals Zn, Pb, Ag, Cd, Ge, Ga, In and industrial minerals (e.g. fluorite and barite). The key points of the geochemical screening, regarding the potential SRM, are:

A strong difference is observed between the rock waste samples (areas 2÷7) and tailings (area 1), especially for some metals. In particular, tailings are strongly depleted of Zn, but also Cd and Ga; they are instead enriched in Pb. Ag appears slightly depleted, but the small difference (coupled with the low concentration) is less significant.

The waste rock is characterised by:

- Strong to very strong Zn concentration (8.07 to 29.4 wt.% Zn);
- Relatively high Cd content (69.2 - 830 ppm), and low to moderate Ga values (6.0 – 88.6 ppm);
- Very low Ge and In content (mostly <1 ppm);
- Low Pb and Ag content.
Zn can occur as sulfide or oxide ore in the Gorno district. Historically the oxide ore has been preferred. Two types of mineralisations occur in the rock waste: primary (i.e., sulphide) ore, and secondary (i.e., oxide) ore.

**Primary (sulphide) ore:**
In thin-polished section, under the microscope the waste rocks (mostly dolomitized limestones) are composed of carbonate (dolomite and calcite) and very minor quartz and mica. The zinc mineralization is mainly composed of sphalerite, as coarse-grained crystals (up to 1 cm across) occurring along hydrothermal veins crosscutting the carbonate rocks. Sphalerite is generally the only sulphide, or is locally associated with very minor pyrite and/or galena. Scanty grains fluorite and barite may also occur. The geochemical (ICP) analysis of a sphalerite separate shows that sphalerite is almost devoid of iron, but shows a significant Cd content (1970 ppm).

**Secondary (oxide) ore:**
The secondary ore (“calamine”) is typically composed of very fine-grained intergrowths of Zn-carbonate (smithsonite, ZnCO₃, and/or hydrozincite) and hemimorphite, Zn₄(Si₂O₇)(OH)₂·H₂O. The oxidized ore can be locally seen in the waste dumps as whitish to orange very fine grained crusts.

The primary ore is the dominant ore type in the dumps, but oxide ore may also occur. A rough estimate of the relative proportions of sphalerite and oxide can be calculated from the geochemical analyses, considering that sphalerite is virtually the only sulphide phase.

**Mineralogical and Petrographic Characterisation:**
Zn can occur as sulfide or oxide ore in the Gorno district. Historically the oxide ore has been preferred. Two types of mineralisations occur in the rock waste: primary (i.e., sulphide) ore, and secondary (i.e., oxide) ore.

The tailings show instead:
- Much lower Zn (190 – 8950 ppm), Cd 1.1 – 39.1 ppm) and Ga (<0.1 – 7.0 ppm) contents;
- A Pb content much higher than the waste rocks, but rather low as absolute values (38.7 – 2170 ppm);
- Fluorine content is moderately high (0.01 – 0.12 wt.%) and no fractionation between rock waste and tailings is observed;
- Barium content is low in the rock waste (4 – 101 ppm) and strongly enriched in the tailings (138 – 2850 ppm)
- The Zn content is positively correlated with Cd and Ga, which clearly occur as minor elements in sphalerite.
The calculations suggest that in the rock waste most of the zinc is contained in sphalerite even if some zinc “oxides” also occur and are dominant in few samples.

A different picture is instead shown by the tailings. Due to the fine grain size, this material is not suitable for optical microscopy, so it was observed and analysed with electron microprobe microscopy (SEM-EDS) technique.

The electron microscopy study shows that:

- The waste material is very fine-grained, and single grains size ranges from <1µm to ca. 50µm;
- The material is composed of chemically strongly different component (minerals)
- The chemical analyses allow the recognition of the following minerals: calcite, dolomite, micaceous/clay material, quartz, barite, Fe sulphate, Zn-silicate (hemimorphite), Zn-carbonate (smithsonite and/or hydrozincite) and rare Cu-As-Sb±Pb sulphosalt(s) (these latters too fine grained for an even semi-quantitative analysis).

Concerning the possible SRM:

- Metallic phases are quite rare. Zn mostly occurs as very fine-grained “oxide” minerals, both as silicate (hemimorphite, $\text{Zn}_6\text{Si}_2\text{O}_7\text{(OH)}_2\cdot(\text{H}_2\text{O})$, containing ca. 67 wt.% ZnO) and carbonate (smithsonite, $\text{ZnCO}_3$, and/or hydrozincite, $\text{Zn}_5\text{(CO}_3\text{)}_2\text{(OH)}_6$, containing ca. 65 and 74 wt.% ZnO, respectively);
- Extremely fine grained barite ($\text{BaSO}_4$) has often been detected.
Conclusions for SRM exploitation:

- The data presented suggest that Zn and Cd (± Ga) represent potential SRM in the mineral waste. These metals, in fact, occur well above the “clarke rock value”, and also within minerals (mainly sphalerite) suitable for metals recovery.

- Other metals which may be present in sphalerite, like Ge and In, are instead in extremely low concentration.

- The metals distribution is not homogeneous, but strong differences occur between rock waste and tailings.

- In spite of the obvious variability, all the analysed rock waste dumps are enriched in Zn (+Cd±Ga), while the tailings are strongly depleted in the same metals.
CASE STUDY 3: MONTORFANO, PIEDMONT, ITALY

Background:
The extractive waste facilities are located on the southern slope of the Montorfano granite Massif within Montorfano and Verbania territories (Verbano-Cusio-Ossola – VCO – district; NE Piedmont Region, Italy). It is located at the end of the Ossola Valley, where dimension stone quarrying activities take are still active.

In particular, the Rosa Baveno granite shows a medium-fine homogeneous grain size, a massive texture, and the mineralogical composition is given by plagioclase, quartz, perthitic K-feldspar and biotite, with small amounts of hornblende. Typical accessory minerals are zircon, apatite, allanite and traces of sulphides. The Bianco Montorfano granite shows the same mineralogical composition, but K-feldspar is white, and it contains occasionally mafic microgranular enclaves and sulphides (especially arsenopyrite) that harm the quality of the stone.

The huge volumes of rock waste is a clear example of the problems connected to mining activities: the exploitation works in this territory have caused and are causing an evident hazard for the population, as well as significant environmental and landscape impacts on this rather touristic area.

The investigated area is part of a wider extractive waste area, interesting for the exploitation of granites. Montorfano granite, together with Baveno pink granite and Mergozzo green granite, represents one of the most important dimension stone, exploited in VCO area. The two most famous granite varieties are the pink and the white ones.

Figure 8.6: Location of Montorfano

Figure 8.7: Southern side of Montorfano Massif
Minerali Industriali Group decided, in 1995, to invest in a dedicated dressing plant, in order to exploit and convert the granite rock waste from "extractive waste facilities" into a new “deposit” for feldspar and quartz exploitation, producing, at the same time, several commercial by-products. In particular, ECOMIN s.r.l. dressing plant treats the materials exploited in three granite quarry waste disposal sites:

1. Sengio area (Montorfano)
2. Ciana-Tane-Pilastretto area (Montorfano)
3. Braghini area (Baveno-Mottarone)

At present, they are looking for new extractive waste facilities to exploit, and the field survey and the characterization activity here presented are parts of the activities useful to ask for the new mineral concession.

Mining and Treatment Activities:
In order to guarantee the highest level of safety, the material present in the extractive waste facilities is exploited from the top to the bottom of the whole volume: the quarried material is then loaded into dumpers and transported to the treatment plant. The feeding material is treated by crushers (jaw crushers) and mills (conic and hummer mills) in order to obtain 1.25 mm as the maximum grain size dimension.

Sieving activity is fundamental to obtain different grain size materials and to separate the powder granite from the other products. Finally, this material passes through electromagnetic separators, which select the ferromagnetic minerals from the final product, characterized by appropriate physical-chemical properties.

The main product is commercially known as F60P (quartz feldspar mixture: 60% of feldspar, mostly K-feldspar), whose production is about 80,000 t/year. Different by-products, obtained after the enrichment of produced “waste” (mainly powder granite and fractions enriched in ferromagnetic minerals), have to be added to the F60P production: they are commercially known as SNS-sand (premix for building uses), NGA-coarse black sand (used for industrial sandblasting), SF-wet feldspar (for the ceramic industry), and SF100 and SF200 (used as fillers in cement industries). The total amount of by-products is about 120,000 t/year.
Field Survey:
A study by UNITO in 2009 investigated the volume and the characteristics of the extractive waste present in the yet exploited extractive waste facilities, in order to evaluate the quality of the ore body to mine and to estimate the period to recover and treat the dumped material.

78 samples were taken in total:

- 26 samples from the Sengio quarry dumps
- 30 from the Ciana Tane- Pilastretto area
- 22 from the Braghini area.

The sampling net was 30-50 metres per side, on average. The material was sampled with a minimum size of about 30 mm (up to 150mm). During summer 2016 another sampling campaign, leaded by UNITO, was set; it interested Montorfano pilot site (new extractive waste facilities NE from Ciana-Tane-Pilasteretto and Sengio mining areas, object of SMART GROUND investigation. In total 8 samples were collected. The samples were collected using hammer and chisel. Each sampling spot covers an area of approximately of 10m².

Another 8 samples from treatment plant (ECOMIN) were collected, in order to characterise the feeding material (from Sengio, Ciana-Tane Pilasteretto and Braghini areas), the product and the by-products, and appreciate if and where enrichment in critical raw materials (CRM) is present (such as rare earth elements (REE)).
Results:
The rock wastes present in the Montorfano pilot site seem to be very similar to the ones present in the yet investigated waste facilities. Referring to the results of the past study, the exploited granite waste facilities are composed of > 30 mm material (70 – 75%), < 30 mm (20 %) and metric rocks (5 to 10 %) (granitic gravel sand, with a small percentage of silt and the absence of clay). The mineralogy of the samples generally reflects the characteristics of the original rock (Montofano white granite, as for the investigated pilot site).

The geochemical analyses connected to the last sampling activity (Summer 2016) are reported:

Upgraded material: This material has been depleted of the mafic minerals by magnetic separation. As a consequence, such material is strongly depleted in iron ($Fe_2O_3$ tot down to 0.13-0.15 wt.% in samples MO_02_05 and MO_02_07) and TiO$_2$ (down to 0.012 wt.%); of course it also shows, compared to the feeding material, a general increase in SiO$_2$.

Magnetic fraction: on the contrary, the magnetic fraction is, compared to the feeding material and (of course) to the demagnetized portion, strongly enriched in iron ($Fe_2O_3$ tot up to 13.34-13.20 wt.% in samples MO_02_02 and MO_02_03), but also in MgO, MnO (and depleted in Na$_2$O).
Conclusions for SRM exploitation:

- At present, it is not yet possible to establish the landfill volume for the Montorfano Pilot site: More data about topography, satellite images and drone investigation have to be collected and elaborated (work in progress by IMAGEO).

- However a previous study based on geophysical survey of the three different waste facilities areas (Sengio, Braghini, and Ciana-Tane Pilastretto), indicates an approximate total volume of 2,500,000m$^3$ of dumped rock waste. About the 20% of these volume is not exploitable directly.

- Considering quality and percentage of not suitable material, 15 years for the production lifetime have been forecasted, starting from 2009. It is possible to think about approx 80% of the volume (to be calculated) can be treated at Ecomin treatment plant. Such feeding material will be treated to produce the main product for ceramic industry (F60P) and contemporary will produce several by-products for: premix for building uses, industrial sandblasting, ceramic industry, and as filler for cement industries.
• The discussed case studies from Italy suggest an overall suitability and feasibility of EW facilities for metal recovery through enhanced landfill mining.

• The case studies also suggest a lack of homogeneity between deposits within the same facility/site in terms of metal distribution, suggesting a need for complex site investigation prior to project initiation.

• Case Study 3 (Montorfano) suggests a potential for feedstock recovery for industry, however further investigation is necessary in order to validate this conclusion.
The material to be sampled is, in general, non-homogeneous, and therefore the sampling activity of such materials will always be a random operation. Two kinds of errors can occur during sampling activity:

- **Theoretical Errors**: most of time, negligible;
- **Operation Errors**: systematic errors, which can strongly influence sampling activities and, consequently, the results arising from analysis.

The main **Theoretical Errors** are: the "heterogeneity error" or "fundamental error" and "segregation error“.

- "Fundamental error" derives from the heterogeneity of the batch-parcel to be sampled. It is a statistical error or "variance", caused by the impossibility to completely represent a specific batch-parcel. Statistical errors cannot be eliminated; however, it is possible to keep them within certain limits by determining the weight of a representative sample. To determine the mass of the representative sample we use specific tables (see Box 5) or can apply the Gy formula (see Box 9.1).

- “Segregation error” is a result of the heterogeneity connected to the spatial distribution of the batch-parcel as a result of segregation phenomena. Such error is nearly zero only if the spatial distribution of the batch-parcel fragments or the sample is homogeneous. This presumes that the batch has been previously homogenised, or that the fragments are random selected.

Both these conditions are difficult to achieve in practice. We must consider the existence of both fundamental error and segregation error when sampling a batch-parcel; consequently we must fix the correct quantity of material sample in order to obtain a representative sample.

Despite considerations, errors cannot be eliminated. However, it is possible to reduce this by homogenising the batch to be sampled in the best way possible, or by collecting the sample by means of a greater number of samples of a small entity.
Operation Errors can be connected to:

- Same batch-parcel associated to several samples, different in weight and distribution, to obtain the “representative sample”
- The use of a wrong “sampling tool” which can drastically influence sampling activity
- The sample is altered, deteriorates, or is contaminated by external sources.

Such errors can be avoided with a correct sampling plan and the use of specific sampling tools.

As introduced, for a correct sampling activity, it is necessary to sample a representative quantity of material which depends on the size of the particles present in the batch-parcel. The representative sample from a batch-parcel must be adapted depending on the analysis to; this is strictly connected to other activities such as sieving, crushing, homogenizing, drying etc.
## Box A1.2: Sample weight for collection

<table>
<thead>
<tr>
<th>D max (mm)</th>
<th>Sample Weight (g)</th>
<th>Balance characteristics: weight max (kg)</th>
<th>Balance characteristics: Instrument sensitivity (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>100</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>10.0</td>
<td>200</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>14.0</td>
<td>500</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>20.0</td>
<td>1000</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>28.0</td>
<td>2000</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>37.5</td>
<td>6000</td>
<td>25.0</td>
<td>0.50</td>
</tr>
<tr>
<td>50.0</td>
<td>15000</td>
<td>25.0</td>
<td>0.50</td>
</tr>
<tr>
<td>63.0</td>
<td>35000</td>
<td>50.0</td>
<td>1.00</td>
</tr>
<tr>
<td>75.0</td>
<td>70000</td>
<td>100.0</td>
<td>5.00</td>
</tr>
</tbody>
</table>

### British Standards

<table>
<thead>
<tr>
<th>D max (mm)</th>
<th>Sample Weight (g)</th>
<th>Balance characteristics: weight max (kg)</th>
<th>Balance characteristics: Instrument sensitivity (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>115</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>9.5</td>
<td>500</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>19.0</td>
<td>500</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>25.4</td>
<td>1000</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>38.1</td>
<td>2000</td>
<td>0.6 - 4.0</td>
<td>0.01 - 0.10</td>
</tr>
<tr>
<td>50.1</td>
<td>6000</td>
<td>6.0</td>
<td>0.10</td>
</tr>
<tr>
<td>76.2</td>
<td>15000</td>
<td>6.0</td>
<td>0.10</td>
</tr>
</tbody>
</table>
A sample from every n-samples is collected and constitutes a representative sample. It can be used to sample materials that have dimensions up to 100 mm, but remember you cannot ensure the faithful representation of the particle size of the batch-parcel for the fraction bigger than 50 mm.

A1.3 “Coning and Quartering” Method

This technique is used to reduce the size of a large sample, making it easier to analyse. The principle of this technique is to pour the sample into a conical shape, which is then flattened and divided into quarters. Two opposite quarters (in diagonal) are sampled and the other quarters discarded. This avoids systematic bias and ensures a homogeneous sample; the two samples (A and B) will be nearly the same size and, if the two face-to-face quarters were taking, you can’t be sure that the two samples obtained will be similar.

A1.4 Quartering by Means of a Jones Tool

This tool is also used to reduce the size of very large big samples. To obtain two different samples from the original one, you simply need to put the original sample into the Jones tool and lower the lever. The sample is separated into the two boxes (one box will be the waste and the other box will be used for the sample).

This can be repeated several times to obtain the correct sample size for analysis, alternating each time the box chosen to be the “sample” versus the “waste”.

**Figure A1.2: Scheme of Jones Tool**
For further information on items discussed in this toolkit, to arrange workshops, or for further copies of this toolkit, please contact us at:

info@smart-ground.eu

Further information regarding the SMART GROUND project can be found at our website:

http://www.smart-ground.eu/

For access to our e-learning portal and to our other training materials, please visit:

http://www.smart-ground.eu/training.php

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Smart data collection and integration platform to enhance accessibility and availability of data information in the EU territory of secondary raw materials

SMART GROUND aims at improving the availability and accessibility of data and information on SRM (Secondary Raw Materials) in the EU territory, while creating collaborations and synergies among the different stakeholders involved in the SRM value chain. In order to do so, the consortium will carry out a set of activities to integrate all the data from existing sources and new information retrieved with time progress, in a single EU database. Such database will also enable the exchange of contacts and information among the relevant stakeholders (e.g. companies), which are interested in providing or obtaining SRM.

- To collect quantitative and structural knowledge from existing SRM resources and to identify critical points and bottlenecks that hinder the effective use of SRM from landfills and dumps
- To take stock of existing standards for RM (Raw Materials) and waste inventory and develop new ones for SRM, with the aim of validating them on selected pilot sites
- To Integrate and harmonize the data and information collected by gathering them in a single EU database
- To identify the most promising markets for the SRM
- To evaluate and to analyse the environmental, economic and social impacts triggered by different processes
- To analyse the existing legislation at EU and national level on waste management and diffusion of best practices
- To facilitate the access to information on available SRM for end-users
- To raise awareness among policy makers and public opinion to support the social recognisability of the positive impact of dumps exploitation to obtain SRM