Enhanced Landfill Mining Toolkit for Municipal Solid Waste streams
Introduction

For decades, landfills were seen as a way of dumping waste at minimum cost. This has resulted in an estimated 150,000 to 500,000 historic and active landfill sites across the European Union. An estimated 90% of these sites are “non-sanitary” landfills, which pre-date the 1999 EU Landfill Directive. These sites often lack environmental protection and so require extensive remediation to avoid environmental and health problems. They tend to be filled with municipal solid waste and include wastes which are now recycled (for example, aluminium and plastics) rather than landfilled under new legislation.

Consequently, landfill sites, and particularly “non-sanitary” landfills, represent a vast, untapped resource for valuable materials. Finite resources, including secondary raw materials (SRMs), critical raw materials (CRMs) and rare earth metals (REEs) are buried amongst waste in our landfill. For example, it is estimated that the amount of copper buried in landfills globally is equal in size to the current stocks available. These resources are currently sourced from outside of the EU, are under high demand and are becoming increasingly scarce.

Enhanced landfill mining (ELFM) offers an opportunity to tap into this pool of resources. By excavating landfills, 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 urbanisation in the face of rapid population growth. 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 (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 a conceptual overview of the LFM and ELFM processes.
Broadly, waste is excavated from landfill and separated into waste fractions. Some of this waste can be directly reused or recycled into materials (WtM) and sold onto the market for manufacturing, replacing primary resources. Other wastes must be processed before they become marketable. Combustible wastes are thermally converted into green energy (WtE). Wastes than cannot yet be valorised can be re-landfilled systematically for future use.
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 Waste Management Directives

Waste management policy has evolved rapidly over recent time, as shown in Figure 2.1. There are two key EU Directives that have greatly influenced waste management practices, the Landfill Directive (EU 1999) and later the Waste Framework Directive (2008/98/EC). Both have a strong focus on reducing the negative impacts of landfill activities on both human health and the environment. They advocate a transition away from disposal of waste and towards more sustainable waste and material management.

This shift in focus propels waste management practices towards identifying new opportunities to recover materials, while remediating the land space to reverse environmental impacts, both of which are achieved through ELFM.

![Figure 2.1: Regulation timeline](image-url)
2.1.2. Waste Hierarchy

Disposing of waste in landfill sites 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 2.2) 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 programmes and waste sorting. ELFM corresponds with this concept by converting waste into product, moving materials up the hierarchy.

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. 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.

In order to achieve a circular economy within waste management practices, life cycle thinking must occur (Figure 2.4). This can be achieved by eliminating the production of waste and promoting reuse and recycling.

Figure 2.3: Linear economy versus Circular economy
Figure 2.4: Circular economy—an industrial system (from www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram)
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.

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. The EU relies on countries from outside the EU for the vast majority of their critical raw materials (CRM) supply, putting manufacturing and industrial activities within the EU at risk.

All of 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 2.5). 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 development.

![Figure 2.5: Population Growth in the EU 1960-2016 (at 1st January, million persons) (Eurostat, 2016)](image)
2.4. Potential Barriers

Despite the above drivers for ELFM, there are a few barriers to consider:

1. There is often some social resistance to ELFM due to excavation activities
2. ELFM can initially cause local pollution despite wider environmental gains
3. At present, economic feasibility for the site operator/owner is not often realised and so wider social, environmental and economic gains need to be internalised and translated to profit for the operator through policy
4. Current policy views landfilling as a final disposal destination; this is contradictory to the ELFM view of landfills as temporary waste storage for future valorisation. This acts as a bottleneck for ELFM, as any waste that is re-filled back into landfill is taxed. Therefore, the same waste is taxed twice under current policy.

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.
Over the past few decades, new technologies have come available that allow valorisation of heterogeneous wastes through mixed waste separation and the treatment of different waste streams. Waste is processed to produce materials (Waste-to-Material, WtM) or energy (Waste-to-Energy, WtE). This section aims to give an overview of the ELFM process, the technologies available and the valorisation routes for excavated wastes.

3.1. ELFM Process Overview

Landfill mining is generally a six-step process: (1) exploration, (2) aerobic stabilization (not always included), (3) mining and transport, (4) conditioning, (5) specific treatment of material, (6) recycling resources/residue disposal.

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

**Figure 3.1**: Overview of ELFM process
The top soil and vegetation must be first removed and the site **excavated** using an excavator or a front-end loader.

**Pre-separation** can include basic approaches, such as trommel screening, to separate fines and larger fractions for further processing. Often, a coarse trommel followed by a fine rotating trommel is appropriate. Following this, windshifters/air separators can be used to remove film plastics, paper and other light fractions and electromagnets/eddy current separators can be used to extract ferrous and non-ferrous metals respectively.

More **advanced separation and processing techniques** include near-infrared [NIR] sorters for identifying and dividing plastics into polymer types. This will also include any treatment needed to produce the desired output fractions, such as the chemical removal of metals from the soil/fines fraction.

This produces **waste fractions** which can be valorised along the most feasible and effective route. The waste fractions are used to produce materials (**WtM** route) or energy (**WtE** route). This may include direct reuse of waste materials or intensive treatment technologies in order to increase the value of the end product.

The valorisation potential and the most feasible valorisation routes are dependent on the waste composition of the site, the characteristics of the waste and the age of the site. 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.

- **The fines fraction** is often the most mixed in terms of composition and therefore the most difficult to process.
- **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 such materials that pose a threat to environmental safety. This fraction also often contains **high metal content**, which can be separated and treated to produce metals of resale quality.
- **Metals, ceramics glass and stones** can be utilised through the **WtM** route to produce material for resale. This requires substantial separation and treatment.
- **Paper, cardboard, wood, textiles and plastics** (combustibles) can be valorised through the **WtE** route using thermal treatment. Thermal treatment technologies can vary from basic waste incineration to new technologies, such as plasma gasification.
This is summarised in Table 3.1.

**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>Combustibles - organic material and plastics</td>
<td>WtE</td>
<td>thermal treatment to produce electricity; residues for construction materials</td>
</tr>
<tr>
<td>Soil</td>
<td>WtM (reuse)</td>
<td>fertilisers, compost, top soil</td>
</tr>
<tr>
<td>Stones, glass, ceramics and metals</td>
<td>WtM</td>
<td>metals and construction materials 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. Analyses of the fines fraction is particularly necessary, as rare earth elements (REE), critical raw materials (CRMs) and metals are often contained in this fraction.

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**.

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.
4. Site Investigation

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 landfill sites through physical sampling.

4.1. Preliminary Information

- Operation history: is the landfill filled by layers or by creating new landfill area;
- The depth of the landfill bodies;
- Geotechnical stability (occupational safety);
- Degradation stage of the landfill, i.e. is methane being generated (occupational safety);
- Possible hazardous waste placed in the landfill (occupational safety)

**Figure 4.1: Site investigation overview**
4.2. Sampling Strategy and Techniques

There is no definitive rule for the number of samples per landfill area, or for the waste volume that should be taken to be representative of the landfill's composition. Instead, it is governed by the sampling resources available. No matter how many samples are taken from a landfill site, huge uncertainties remain in evaluating the total number of materials, the waste composition and their properties for a given site.

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 landfill, including cover materials, are discarded.
2. A **vertical shaft** is made into the landfill 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.
3. Depending on the operating history of the landfill (filled by layers or by creating new landfill area), 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. 600 litres) is transferred to a large bag or a similarly suitable container for **manual sorting**. The sub-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. A 600 litre sample has been shown to be manually sortable in the field in approximately 1 to 2 working days (2 persons).
Drilling

Drilling with a hydraulic piling rig operated in auger mode is a common and proven technology for the installation of landfill gas collection wells (Figure 4.3). This technology is also a feasible sampling technique for evaluating waste composition. This technology produces samples of a relatively large size (typical size 200 litres with auger of 0.9 metres in diameter and 1 metre in height) with a known depth. It can sample landfill at depths of 30 metres as a minimum and allows you to divide the landfill into different depth profiles. However, a clear disadvantage of this technology is high investment costs, high transportation costs and lack of competition among operators.

Drilling can affect the properties of the samples obtained, thus producing samples with differing properties in comparison to excavating and the use of a cactus grab canes; for example, drilling may reduce the particle size of the coarsest objects.

Excavating

Using an excavator is often the easiest way to sample landfill. 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.

Cactus grab cane

A cactus grab crane can be used to collect waste samples to the maximum depth of the landfill (Figure 4.4). A shaft of about 1 metre$^2$ in area and up to 15 metres deep is excavated at each location.
4.3. Sample Sorting

The purpose of the manual sorting of waste sampled from landfill is to be able to plan the best valorisation routes for the different particle size categories and waste fractions. The goal is to mimic the possible full-scale treatment options for recovery.

4.3.1. Manual Sieving

The first stage in full-scale mechanical treatment of waste is sieving to produce different particle size categories. Sieves for manual sieving can be quite easily built from usual hardware shop materials (Figure 4.5).

Sieves with openings of less than 20 mm are challenging to operate manually for municipal solid waste (MSW) sampled from landfills because the waste is often moist. 20 mm is practical for cutting off the fine fraction. Sieves with 100 and 40 mm mesh size are selected to represent the openings of typical drum screens in full-scale mechanical equipment.

Therefore, manual sieving can be used to separate waste into the following fractions: >100 mm, 40-100 mm, 20-40 mm and >20 mm. All particle size categories are then to be weighed.

Figure 4.5: Manual sieving
4.3.2. Sorting to Waste Fractions

Each particle size category, with the exception of the fines fraction (<20 mm) can be manually sorted into waste fractions. Sorting of each of the coarser particle size categories (20-40, 40-100 and >100 mm) to waste fractions has been shown to be feasible in a reasonable time frame and produces enough necessary data for processing and valorisation considerations.

Possible waste fractions:

1. Metals – ferrous and non-ferrous
2. Paper and cardboard
3. Plastics – film and dense
4. Textiles
5. Wood
6. Inert fraction (including bricks and stones)
7. Organic fraction (including soil)
8. Fines fraction
9. Glass and ceramics
10. WEEE
11. Miscellaneous combustibles (including rubber, foam)

The metals fraction can be split into ferrous and non-ferrous metals through the use of a magnet.

The exact fractions used depend on the composition of the landfill: for example, if little plastic is present, it may be advisable to separate all plastics into a single fraction; or if there is low quantity of one fraction present, it may be advisable to group it with another fraction of similar properties, e.g. wood and textiles.

All waste fractions in all particle size categories are weighed after sorting. After weighing, and within one sampling shaft, all the metal fractions in different particle size categories (20-40, 40-100 and >100 mm) are combined to reduce the amount of samples to be sent to laboratories. The same goes for soil and “other” fractions. For the combustible fractions (paper and cardboard, plastics, textiles, wood, miscellaneous), composite samples of 50 litres are formed from the different particle size categories (20-40 mm, 40-100 mm and >100 mm) based on the mass distribution in the sorted fractions, to represent the combustible fractions of each sampling shaft.
5. Analytical Methods

The samples collected from MSW landfills need to be characterised to ascertain their value for the landfill mining operation. Samples are generally sent to an external laboratory for such analyses with the aim to determine the calorific value of the combustible fractions and to gain insight into the characteristics of the fine fraction. All analytical methods follow The International Organisation for Standardisation Association protocols, which can be found at:

https://www.iso.org/standards.html

An overview of reference methods is given in Appendix 2.

5.1. Combustiles

The combustible fractions include:

- Paper and cardboard
- Plastics
- Textiles
- Wood
- Miscellaneous combustibles (i.e. rubber, foam)

These fractions are tested within their particle sizes for their gross and net calorific value to ascertain the potential for thermal treatment of these fractions. Semi-quantitative X-ray fluorescence analysis (XRF) is used to assess the elemental composition of these fractions including the presence of contaminants (such as chlorine). Biological methane potential (BMP) is also used to assess the energy potential of the organic materials contained.
5.2. Fines Fraction
This fraction is likely to be highly heterogeneous and so is the hardest fraction to utilise presently. This fraction contains the highly valued SRMs, CRMs and REEs. Further analyses on this fraction, therefore, are necessary in order to determine the best valorisation route.

According to the Landfill Directive, composition and leaching behaviour of wastes must be known. Therefore, leaching potential is determined in line with the methods defined by this legislation. This analysis will also provide information on the content on certain metals. XRF is also applied to determine the elemental composition. The concentration of a number of elements, including CRMs, REE and metals, can be determined in this way.

Other analytical methods can be applied to ascertain the presence of other critical raw materials, rare earth elements and metals. A full list of elements identified by these methods can be found in Appendix 2. The total organic carbon (TOC) tests are also performed to ascertain the organic content of this fraction. BMP is also used to assess the energy potential of the organic materials contained.

Once these properties of this fraction is determined, the best treatment process(es) can be determined. Depending on the elements present and their concentrations, this may involve:

- Separation and processing to obtain such elements for resale
- Thermal treatment with filtration processes
- Storage of this fraction until future technologies/economic feasibility allow processing of this fraction
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:

\[
FNPV(C) = \sum_{t=0}^{\infty} \frac{S_t}{(1+i)^t} = \frac{S_0}{(1+i)} + \frac{S_1}{(1+i)^2} + \ldots + \frac{S_n}{(1+i)^n}
\]

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:

\[ 0 = \sum S_t \left( \frac{1}{1 + FRR} \right)^t \]

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.
7. Decision Support Tool

SMART GROUND also offers a **Decision Support Tool** 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.

The tool provides stakeholders with five waste composition mix options and the option to input their own from their sampling procedures. Nine processing scenarios are evaluated for each waste composition mix. Using multi-criteria analysis, the best process approach from a sustainability point of view is identified.

A full introductory video for the SMART GROUND Decision Support Tool can be found by clicking on the **image below**:

The Decision Support Tool therefore aids stakeholders in deciding:

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

For help with using the tool, click on the **image below** to view our user guide video:
For an ELFM project to be initiated, the project must be economically viable. It needs to be profitable for the site operator/private investor purely in monetary terms, and therefore an economic assessment of any potential site is necessary. However, landfill mining has strong environmental and social implications and these broader impacts need to also be considered in decision-making. A full socioeconomic analysis accounts for these broader impacts within an economic framework so that all considerations are accounted for and computed into a single value. In this section, economic, social and socioeconomic case studies from across Europe are presented in order to give an overview of landfill mining viability.
The “Pohlsche Heide” landfill in Hille, North-West Germany is an active landfill and has been operational since 1988. The landfill is around 270,000 m² and in a rural location. It contains roughly 3,000,000 m³ of municipal solid waste (MSW) which was deposited until 2005. After 2005, the site has been used to landfill mineral waste and residual fractions from a mechanical biological treatment plant.

**Background:**

Three 2600 m³ trenches have been excavated for analysis, each containing a different time period as follows:

- 1988-1991,
- 1991-1997
- 1992-1995

Excavated waste was separated two fractions:

- <20 mm
- >20 mm

The fraction >20 mm was manually sorted and the average percentage composition across all three trenches was calculated (Table 8.1).

**Economic Analysis:**

An economic, material-flow based assessment of ELFM versus landfill aftercare upon site closure has been undertaken for this site from the perspective of the landfill operator, i.e. only accounting for direct economic impacts. Six processes are analysed, varying in technology and processing effort. Details of the processes can be found in Table 8.2.

The Net Present Value (NPV) was calculated for all processes, using a discount rate of 6% per annum and an inflation rate of 2% per annum. This was compared to a landfill closure (10 years) and aftercare (30 years) scenario. A land value of €10/m² and an airspace value of €15/m³ were used for this site.

**Table 8.1: Percentage composition of waste fractions**

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Percentage composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20mm fine grain</td>
<td>46%</td>
</tr>
<tr>
<td>wood</td>
<td>10%</td>
</tr>
<tr>
<td>soil</td>
<td>10%</td>
</tr>
<tr>
<td>plastics</td>
<td>9%</td>
</tr>
<tr>
<td>stones</td>
<td>8%</td>
</tr>
<tr>
<td>paper</td>
<td>5%</td>
</tr>
<tr>
<td>sorting residues</td>
<td>4%</td>
</tr>
<tr>
<td>textiles</td>
<td>3%</td>
</tr>
<tr>
<td>metals</td>
<td>3%</td>
</tr>
<tr>
<td>glass</td>
<td>2%</td>
</tr>
<tr>
<td>composite material</td>
<td>1%</td>
</tr>
</tbody>
</table>

Back to Topic Overview
For both land recovery and airspace recovery, the NPVs of all landfill mining processes are lower than that for landfill closure and aftercare.

Between landfill processes, process 1a has the best NPV and so the higher investment of more complex processing cannot be offset by the extra revenues created due to product value.

**Table 8.2: ELFM Processes**

<table>
<thead>
<tr>
<th>ELFM Process</th>
<th>Processing effort</th>
<th>Technology</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Low</td>
<td>Basic</td>
<td>Excavation and pre-conditioning with mobile devices. Production of a coarse fraction &gt;60 mm sent to a waste incineration plant and bottom ash treated for metal recovery. a fine fraction &lt;60 mm directly landfilled if non-hazardous and a ferrous fraction directly sold depending on quality.</td>
</tr>
<tr>
<td>1b</td>
<td>Low</td>
<td>Basic</td>
<td>As above except fine fraction is hazardous and must be treated before landfilling.</td>
</tr>
<tr>
<td>2a</td>
<td>Medium</td>
<td>Intermediate</td>
<td>As above + extensive treatment of fine fraction with wet mechanical sorting by density. This results in a high calorific fraction which can be used in RDF incineration plants, a glass fraction, a ferrous metal scrap fraction, a residue fraction, recycling sand and gravel.</td>
</tr>
<tr>
<td>2b</td>
<td>Medium</td>
<td>Intermediate</td>
<td>As above with greater pre-conditioning allowing for greater metal recovery. This produces high quality non-ferrous metal and a ferrous metal fraction.</td>
</tr>
<tr>
<td>3a</td>
<td>High</td>
<td>Advanced</td>
<td>Extensive pre-conditioning Plastic fraction can be processed to plastic granulate. Generation of high quality metals</td>
</tr>
<tr>
<td>3b</td>
<td>High</td>
<td>Advanced</td>
<td>Pre-conditioning similar to 2b Focuses on production of high quality RDF for co-incineration. Generation of high quality metals</td>
</tr>
</tbody>
</table>

**Scenarios:**

**ELFM processes (1a-3b, Table 8.2) versus closure and aftercare**
Enhanced Landfill Mining Toolkit
Case Studies

Feasibility Conditions:

Due to the high uncertainties in airspace value, land value and prices of intermediate products, sensitivity analysis was carried out.

This identified the conditions needed for mining processes to be economically feasible, by identifying the values of key parameters at a break-even point (where the NPV of a mining process exceeds that of the closure and aftercare scenario).

- Land value of €360/m² (for process 1a) to €450/m² (for process 3b) is necessary, which is plausible in urban areas.

- An airspace value of >€45/m³ is needed for all processes to be feasible, which is dependent on the need for landfill space specific to that region.

In order to identify the effect of material price on economic feasibility, the break-even values for four products were compared to reasonable values for those products, while varying land value (€0/m² to €200/m²) and airspace value €0/m³ to €20/m³). The results are shown in Table 8.3.

Table 8.3: Feasibility analysis outcomes for different parameters

<table>
<thead>
<tr>
<th></th>
<th>Price for handing high calorific fractions to waste incineration plants</th>
<th>Price of handing RDF to RDF incineration plants (processes 2a, 2b, 3a, 3b only)</th>
<th>Price for non-ferrous fractions (processes 2b and 3a only)</th>
<th>Price for ferrous fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values Needed</td>
<td>€40/t cost to €83/t income</td>
<td>16/t to €116/t income</td>
<td>€14,000/t to €435,000/t income</td>
<td>€840/t to €1600/t income for best process (2b)</td>
</tr>
<tr>
<td>Realistic Values</td>
<td>€70/t to €50/t cost</td>
<td>€60/t to €35/t cost</td>
<td>€1000/t income</td>
<td>€170/t income</td>
</tr>
<tr>
<td>Outcome</td>
<td>ELFM can be profitable given land or airspace of some value</td>
<td>Unlikely to be feasible in the near future</td>
<td>Unlikely to be feasible in the near future</td>
<td>Unlikely to be feasible in the near future</td>
</tr>
</tbody>
</table>
Conclusion:

- None of the 6 mining processes investigated are feasible compared to landfill closure and aftercare for the Pohlsche Heide site.

- Altering the parameters away from those of this case study gives an indication under what conditions ELFM may be profitable.

- ELFM can be profitable at higher airspace and land value, both of which are feasible at present. Higher metal prices and higher prices for combustible fractions are also important drivers of profitability, however are seldom feasible at present.

- Generally, more simplistic mining processes are more profitable at present, suggesting a need to offset costs through financial incentives if extensive resource recovery is preferred.

For further information:

CASE STUDY 2: Socioeconomic Assessment of ELFM in Greece

Background:
The EU funded LIFE reclaim project used the Polygyros landfill site in Chalkidiki, Greece, as a pilot site to study the feasibility of ELFM. As part of this project, socioeconomic analysis was performed on this site, accounting for both financial and socio-economic benefits. The Polygyros landfill site contains around 39,000 t of MSW and is municipality-owned, active landfill site in a rural location in Greece.

Scenarios:

- **Scenario 1:** Polygyros site
- **Scenario 2:** “typical” Greek landfill site
  (20-30 years old and close to an urban centre using the technical and financial assumptions of the Polygyros site)
- **Scenario 3:** “typical” Greek landfill site with WEEE also excavated

Economic:
Financial benefit was measured through Net Present Value (NPV) and Internal Rate of Return (IRR) estimators using a discounted cash flow equity valuation approach.

Financial Costs include:

- Pre-activity research and inventory costs
- Permits
- Consultancy and design costs
- Site preparation
- Purchasing/rental costs of excavation, hauling, screening and sorting equipment
- Installation costs (e.g. incineration facilities)
- Labour costs
- Administrative costs
- Maintenance costs
- Fuel/energy costs
- Water
- Other operating costs
Financial Revenues considered are as follows:

- Revenues from recyclable and reusable materials (including ferrous metals, non-ferrous metals, glass, plastics, combustible waste, stones and construction waste, waste of electrical and electronic equipment (WEEE) and reclaimed soil as landfill cover material)
- Value of airspace recovered
- Value of land recovered
- Avoided costs of post-closure care
- Avoided future liability for remediation

Social Costs considered are as follows:

- Harmful effects of excavation and processing (e.g. particulate matter emissions, methane emissions, odour release, leachate escape, increased dispersal of unwanted substances such as heavy metals etc.)
- Harmful effects associated with energy and heat recovery from combustible waste
- Harmful effects of waste disposal

Socioeconomic:

The socioeconomic analysis used a Cost benefit Analysis (CBA) approach, where the financial cash flows are adjusted to reflect the social costs and benefits to estimate a social NPV and IRR.

Social Benefits include:

- Direct employment
- Minimisation of potential contamination source
- Reduction of “stigma” from environmental damage caused by landfill on surrounding residential property values
- Production of green energy from combustible waste
- Land reclamation from social purposes
Socioeconomic Assumptions:

In order to assess social support for the Polygyros ELFM project, Contingent Valuation Analysis (CVA) was used. This estimates the Willingness to Pay (WTP) of the local community for the project through the use of surveys.

In total, 286 surveys were completed (response rate of around 70%).

- 24% of the respondents were willing to pay on average €46.70/year per household and a median of €50/year per household in increased taxes.

- However, 76% of respondents were not willing to pay.

- This gives an overall mean WTP for the sample of €12.5/year per household and a median value of €0/year per household.

This can be attributed to the fact that 70% of respondents said that the most important problem they face is unemployment and 51% of those refusing to pay reasoning unaffordability due to low income.

Although 95% of respondents felt that there should be an ELFM project, only 18.2% said they feel some responsibility in paying for it (77.3% felt that it is not their responsibility).

The population area of interest to the case study consists of 8,156 households.

For the “typical” and “advanced” Greek landfill scenarios, a national CVA was used, mean value of €50 pa per household.

Waste Composition:

For the Polygyros site (Scenario 1), waste excavation for sampling purposes used surface (open-pit) mining from the top level of the landfill (+620 m). The trenches measured 5 m in depth, 3-4 m in width and around 30 m in length. Based on this sampling, the waste compositions are assumed for the purpose of this analysis are shown in Table 8.4.

Table 8.4: Percentage composition by waste fraction at the Polygyros site

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Percentage composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>organics and other</td>
<td>71.6%</td>
</tr>
<tr>
<td>landfill cover materials</td>
<td>17.8%</td>
</tr>
<tr>
<td>soft plastics</td>
<td>5.6%</td>
</tr>
<tr>
<td>plastics</td>
<td>2.4%</td>
</tr>
<tr>
<td>ferrous metals</td>
<td>1.1%</td>
</tr>
<tr>
<td>glass</td>
<td>0.3%</td>
</tr>
<tr>
<td>non-ferrous metals</td>
<td>0.3%</td>
</tr>
<tr>
<td>WEEE</td>
<td>none</td>
</tr>
</tbody>
</table>

The waste composition for the “typical” Greek landfill scenario (Scenario 2) is taken from data relating to historical waste composition in the Greek National Report from the United Nations Commission on Sustainable Development (UN-CSD 2011) for 1990-2007 and literature containing waste compositions of other European case studies.

A recovery rate of 85-90% is assumed. This gives the assumed waste composition for this scenario as in Table 8.5.
Table 8.5: Percentage composition by waste fraction for a “typical” Greek site

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Percentage composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>fines and soil</td>
<td>45.0%</td>
</tr>
<tr>
<td>residuals</td>
<td>10.0%</td>
</tr>
<tr>
<td>gravel and stones</td>
<td>4.5%</td>
</tr>
<tr>
<td>ferrous metals</td>
<td>3.6%</td>
</tr>
<tr>
<td>plastics</td>
<td>3.4%</td>
</tr>
<tr>
<td>glass</td>
<td>3.0%</td>
</tr>
<tr>
<td>non-ferrous metals</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

For the “advanced” Greek landfill scenario (Scenario 3), recovered WEEE is also accounted for as 1.35% of the waste composition. This reduces the proportion of residuals from 40% to 39%, while all other waste compositions remain as in the previous scenario.

Scenario Outcomes:
Scenario outcomes are displayed in Table 8.6.

Table 8.6: Scenario outcomes

<table>
<thead>
<tr>
<th>Economic</th>
<th>Socioeconomic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td></td>
</tr>
<tr>
<td>NPV of the project = €-804,100</td>
<td>Social NPV = €-210,000,</td>
</tr>
<tr>
<td>NPV most affected by the price of plastics.</td>
<td></td>
</tr>
<tr>
<td>Therefore, this project is not justified from a social viewpoint. In order to achieve a zero social NPV, a Willingness to Pay = €26/year per household is needed.</td>
<td></td>
</tr>
</tbody>
</table>

Excavation and processing done by contractors:

<table>
<thead>
<tr>
<th>Economic</th>
<th>Socioeconomic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2</td>
<td></td>
</tr>
<tr>
<td>Excavation and processing done in house:</td>
<td></td>
</tr>
<tr>
<td>Low productivity scenario:</td>
<td></td>
</tr>
<tr>
<td>NPV = €-1,520,000,</td>
<td>Social NPV = €32,000,000,</td>
</tr>
<tr>
<td>b) High productivity scenario:</td>
<td></td>
</tr>
<tr>
<td>NPV= €2,020,000,</td>
<td></td>
</tr>
<tr>
<td>net benefit of €5/t of waste</td>
<td></td>
</tr>
<tr>
<td>Therefore, ELFM is totally justified from a social viewpoint. The social value of the project is again almost entirely affected by the society’s WTP.</td>
<td></td>
</tr>
</tbody>
</table>

Scenario 3

NPV varies from €66,500 (separation and no processing), €72,000 (separation and processing) and €91,000 (no separation or processing).

Therefore, the project is totally justified from an economic and social viewpoint. As before, the NPV is almost entirely affected by the society’s WTP for ELFM.
Conclusion:

- For the Polygyros case study site, ELFM is not justified from a financial or socioeconomic perspective.

- Extrapolation across Greece shows that ELFM can be financially beneficial depending on the level of productivity, use of own resources where possible and the extraction of WEEE devices.

- The price of plastics plays a dominant role on expected revenues. ELFM is also feasible form a socioeconomic perspective in all cases when extrapolated across Greece.

- The value of the socioeconomic feasibility is almost entirely affected by WTP values and so it can be concluded that local public engagement is crucial, as is the size of the population affected by the project.

- However, it is important to note that this study does not include a number of significant environmental benefits, including energy recovery, land redevelopment and reduction in waste management costs.

For further information:


CASE STUDY 3: Remo Landfill Site, Belgium

Background:
The Closing the Circle (CtC) project is the first to apply enhanced landfill mining (ELFM) in practice.

The Remo landfill site, Houthalen-Helchteren, Flanders, Belgium is used as a pilot site, an active landfill that has been operating since the 1970s.

Key facts:
- Area = 130 ha
- Rural location in the direct vicinity of a number of villages, an old coal mine slag heap, a military training area and a large nature reserve.
- 8 million metric tonnes of waste, comprising of 11.8 tonnes of MSW and comparable industrial waste and 6.3 million tonnes of industrial waste
- 1.5 million tonnes of sand used as intermediate cover.

Waste Composition:
Based on log book data, over 5 million metric tonnes of the dry mass consists of industrial waste (consisting of >40 wt % shredder material and ~20 wt % sludge).

Over 7.5 million metric tonnes is MSW (with construction and demolition waste comprising ~25 wt % and plastics comprising ~20 wt %).

Six trial excavations from different locations (4 MSW zones, 2 industrial waste zones) were carried out to better characterise the site’s composition. A cactus grab cane was used to a maximum depth of 18 m and samples were analysed through manual sorting for fractions >10 mm and classified into 8 different fractions. The weight of the <10 mm fraction was recorded. The resultant waste composition for MSW is given in Table 8.7.

<table>
<thead>
<tr>
<th>dry mass (wt%)</th>
<th>MSW from log book</th>
<th>MSW from excavation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper/cardboard</td>
<td>11.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Textile</td>
<td>0.6</td>
<td>6.8</td>
</tr>
<tr>
<td>Plastics</td>
<td>20.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Metals</td>
<td>2.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Glass/ceramics</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Aggregates</td>
<td>34.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Wood</td>
<td>2.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Fines</td>
<td>12.0</td>
<td>44.0</td>
</tr>
<tr>
<td>Organic Fraction</td>
<td>7.5</td>
<td>-</td>
</tr>
<tr>
<td>Unidentified</td>
<td>8.4</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 8.7: Waste composition
An assessment on the likely effects of the ELFM project on the environment was conducted at:
- Local scale
- Regional scale
- Global scale

Local environmental costs:
- ELFM of this site is likely to disturb local animal populations and result in the partial loss of ecosystems temporarily until ecosystem restoration.
- The proposed WtE plant is also likely to cause some eutrophication due to nitrogen and sulphur.

However, there will also be a number of local environmental benefits.

- Heat generated from the WtE plant will be used in local horticulture to heat greenhouses and fertilise plants. This will reduce fossil fuel usage.
- The recovery of SRMs will also influence land-use elsewhere.
- Inert aggregates can be used as local gravel substitute, reducing local gravel extraction.
- The overall reduction in the use of fossil fuels and the use of SRMs and WtE will improve net carbon balance.
- Comparing this ELFM project to a “do-nothing” scenario, where the energy and products produced by the ELFM project are instead produced on the market, gives a net CO₂(eq) advantage of 1 million metric tonnes over 20 years.

Environmental Impact Assessment (EIA):
An assessment on the likely effects of the ELFM project on the environment was conducted at:
- Local scale
- Regional scale
- Global scale

Scenarios:
- Remo ELFM versus “do-nothing” scenario
- Flanders region potential

Full Economic and Socioeconomic Assessment:
A full site assessment method has been devised, taking into account site selection on a regional scale, simulation tools for private benefits (NPV and IRR) and costs and analysis on the societal benefits and costs (CBA).
A full site assessment method has been devised, taking into account site selection on a regional scale, simulation tools for private benefits (NPV and IRR) and costs and analysis on the societal benefits and costs (CBA).

**Economic:**
In terms of IRR for the Remo site, variations in WtE (including WtE efficiency, electricity price, CO₂ price, WtE investment and operational costs) and ELFM support have a large impact.

At a regional scale, Flanders has a considerable economic potential for ELFM. WtE constitutes 60% of the economic costs and 70% of the economic benefits. Governmental incentives for renewable energy also comprise a large proportion of the benefits, with land reclamation a relatively low benefit.

**Socioeconomic:**
From a societal viewpoint, a monetary value is attached to many of the factors discussed in the EIA.

- The monetary value of CO₂ emissions is estimated at €20-40/t.
- WTF for national parks in the Flanders region is estimated at €26 million (based on transferring a military domain to 160 ha of forested area), or €3-27 million for parks 1-163 ha.
- Restoration for residential building space is estimated at €155/m²

Therefore benefits to society for land reclamation are most likely to be higher than market prices for land. Social valuation of soil pollution for local neighbourhoods in the Flanders region is estimated at €1-22 million.

Recovery of SRM resulting in a lowered vulnerability to price shocks for raw materials is estimated to be 5-15% of the market value of energy. Certificates for green energy are exchanged at €108 per MWh and combined heat and power certificates are exchanged at €39 per MWh energy savings. Further subsidies are available for forest plantation in the region. Therefore, it is concluded that there are considerable extra societal benefits to ELFM projects in the Flanders area.

A full Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have since been applied to the Remo site, comparing ELFM for waste valorisation to a “do-nothing” scenario.

Valorisation of MSW and industrial waste (IW) has a large positive normalised environmental impact on natural land transformation, metal depletion and fossil depletion; however, this also negatively impacts climate change for both human health and ecosystems. (Figure 8.1).
The net environmental impact of ELFM versus a “do-nothing” scenario is greater for all impact categories. The key negative impacts of a “do-nothing” scenario fall on climate change on both human health and ecosystems. However, this impact is greater for ELFM. ELFM also has a negative impact on ozone depletion, but has great positive impacts on freshwater eutrophication, human toxicity, particulate matter formation, ionising radiation, natural land transformation, metal depletion and fossil depletion.

However, as before, the climate change effects of ELFM will be reduced by the use of by-products for horticulture. Overall, there are greater environmental benefits to ELFM versus a “do-nothing” scenario.
The economic assessment also showed that the **thermal treatment process** contributes greatest to the positive effects on fossil depletion, but also greatest on the negative effects on climate change; however, these negative impacts can be reduced by using the CO\(_2\) and heat for horticulture.

- The **separation process** contributes most to the positive effects on metal depletion;
- **Land reclamation** contributes almost entirely to the positive effects on natural land transformation.

This system maps anthropogenic resources across three axes: socioeconomic viability (E), knowledge and geological composition (G) and field project status and technical feasibility (F).

Four **scenarios** were investigated:

- Gas-plasma Technology
- Incineration
- Private Perspective
- Public Perspective
- Versus
- “Do-nothing” Scenario

In both WtE scenarios, **thermal treatment** of RDF contributes the most to emissions. ELFM gives a net increase in CO\(_2\) emissions versus a “do-nothing” scenario. The DCF shows that the costs are greater than the revenues (negative NPV) for all 4 scenarios. In terms of revenues, **electricity production** and **metal sales** are of high importance, while land reclamation is of minor importance (at a mean price of €40/m\(^2\)). The cost of emissions is important for public perspective scenarios as the tax is not discounted.
Conclusion:

- WtE (the thermal treatment process) is a key indicator of economic and socioeconomic viability.

- ELFM in this case is profitable from a societal viewpoint.

- However, profitability from an environmental perspective seems to depend on methods used for assessment, factors considered and assumptions made. This suggests a need for a universal framework for environmental assessment and assumptions.

- The importance of land reclamation both socially and economically depends on how it is measured; as direct present value or as value after reclamation as housing or as a nature reserve.

- Overall, this case study suggests a great potential for ELFM in the Flanders area, both economically and socioeconomically.

For further information:


Lessons Learnt

The conclusions from each case study are summarised in Figure 8.2. Overall, the case studies tend to suggest a lack of economic viability from a purely private perspective; however they do indicate the potential for economic viability. There is contrasting opinion on the importance of airspace and land space value, however general agreement that the thermal treatment process is a key parameter. From a social perspective, ELFM is justifiable when WTP is high enough, and so this is a key indicator of social feasibility, suggesting a need for public engagement in ELFM projects. Environmentally, ELFM has both positive and negative effects, which can be reduced by utilising the heat and CO₂ outputs locally. All models are subject to great complication, sensitivity and variability making predictive models difficult and investments high risk.

There is a general agreement for the need of governmental incentives to privatise the social and environmental gains, making ELFM profitable for the site operator. Currently, the EU is reviewing policy and regulation around landfill mining in order to embed it within their circular economy framework. For any ELFM project, there is a great need for synergy among actors. It can be concluded that both the economic and social viability of any potential ELFM project is case-dependent. There is a need for a universally agreed best-practice site identification model, full socioeconomic assessment model and assumptions.

Figure 8.2: Summary of case study conclusions
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 the 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 A1.1: Gy formula

\[
\frac{\sigma'(A_{g\lambda})}{A_{g\lambda}^2} = \left[ \frac{1}{M} - \frac{1}{M_0} \right] f \mu \left[ \frac{1}{A_{\lambda}} - 2 \right] + gd^3
\]

where:

- \( \sigma' \) = fundamental error;
- \( M \) = weight of the batch/parcel to be sampled (g);
- \( M_0 \) = weight of the sample (g);
- \( A_{\lambda} \) = proportion of the size fraction \( \lambda \) within the batch/parcel (% expressed in decimals: e.g. 10% = 0.1);
- \( A_{g\lambda} \) = proportion of the size fraction \( \lambda \) within the sample (% expressed in decimals: e.g. 10% = 0.1);
- \( A_{g\lambda} \) = average of \( A_{g\lambda} \) distribution (% expressed in decimals: e.g. 10% = 0.1);
- \( f \) = parameter connected to the shape of the grains;
- \( \mu \) = density of the sampled material (g/cm\(^3\));
- \( d_{\lambda} \) = average of the dimension of the grains present in the “gran class” \( \lambda \) (cm);
- \( g \) = parameter connected to size distribution;
- \( d \) = dimension of the bigger grain present in the batch-parcel to be sampled (cm).
## 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>
A1.2 Fractioned Shoveling
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 A1.1: Coning and Quartering
Figure A1.2: Scheme of Jones Tool
Figure A1.3: Scheme connected to quartering methods using Jones Tool: each time we change the box chosen to be “the sample”
### Appendix 2: Sample Characterisation

#### Table A2.1: Analyses by waste fraction

<table>
<thead>
<tr>
<th>Waste fraction</th>
<th>Analyses</th>
<th>Possible Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine fraction &lt;20 mm</td>
<td>TOC</td>
<td>ISO 8245:1999 (R10)</td>
</tr>
<tr>
<td></td>
<td>Elemental composition (XRF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Contaminant leaching potential</td>
<td>CEN batch leaching tests EN 12457-3</td>
</tr>
<tr>
<td></td>
<td>Critical raw materials (other than above)</td>
<td>ISO/TS 21258-2:2007 ED 1 (R11)</td>
</tr>
<tr>
<td></td>
<td>Biogas potential</td>
<td>APHA 1998</td>
</tr>
<tr>
<td>Metal fractions</td>
<td>Visual inspection: Share of non-metal parts attached to metals (degree of liberation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Division to magnetic and non-magnetic metals (Cu + Al) and stainless steel</td>
<td></td>
</tr>
<tr>
<td>Soil fractions</td>
<td>Visual inspection (most likely mainly stones + bricks)</td>
<td></td>
</tr>
<tr>
<td>Energy fractions</td>
<td>Drying (to enable shredding and homogenization for representative determination of calorific values)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Visual inspection + weighing of the fines that detach from the combustibles when dried</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calorific value</td>
<td>ISO 1716:2010</td>
</tr>
<tr>
<td></td>
<td>Elemental composition (XRF): CRM, REE, PGM</td>
<td></td>
</tr>
</tbody>
</table>

#### Table A2.2: Elements identified by analyses

<table>
<thead>
<tr>
<th>Contaminant Leaching Potential</th>
<th>Elemental Composition (XRF)</th>
<th>Other Critical Raw Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>Cu</td>
<td>Sc</td>
</tr>
<tr>
<td>Ba</td>
<td>Al</td>
<td>Y</td>
</tr>
<tr>
<td>Cd</td>
<td>Sb</td>
<td>La</td>
</tr>
<tr>
<td>Cr</td>
<td>Li</td>
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<td>Co</td>
<td>Pr</td>
</tr>
<tr>
<td>Hg</td>
<td>Cr</td>
<td>Nd</td>
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<tr>
<td>Mo</td>
<td>Mg</td>
<td>Sm</td>
</tr>
<tr>
<td>Ni</td>
<td>Cu</td>
<td>Eu</td>
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<tr>
<td>Pb</td>
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<td>Gd</td>
</tr>
<tr>
<td>Sb</td>
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<td>Dy</td>
</tr>
<tr>
<td>Zn</td>
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<td>Ho</td>
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<tr>
<td>Cl</td>
<td></td>
<td>Er</td>
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<tr>
<td>F</td>
<td></td>
<td>Tm</td>
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<tr>
<td>Yb</td>
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<tr>
<td>Lu</td>
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<tr>
<td>Pt</td>
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<tr>
<td>Ed</td>
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<td>Ru</td>
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<tr>
<td>Au</td>
<td></td>
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</tbody>
</table>
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

Follow us on social media:
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