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Mining the European Anthroposphere (MINEA)
Working Group 2: Resource potential of waste from landfills

Deliverable 2.1
Recovery technologies for materials in landfills

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Acronyms

EIR – Extractive industry residues
UL – Urban Landfills

1 INTRODUCTION

Europe hosts more than 500,000 landfills of which 90% are non-sanitary and around 80% essentially contain Urban Solid Waste (https://www.eurelco.org/infographic). Urban landfills (UL) and extractive (mining and metallurgical) industry residues (EIR) are potential sources of materials that, if recovered, can contribute to the circularity of economy. Among other factors, technology plays one essential role in the viability of landfill mining projects (Krook, et al, 2012). The methods for mapping landfills, sampling and characterizing waste, the readiness of technologies, the optimization of technologies and their combination in treatment and recovery schemes, their applicability, costs and environmental impacts effect the valorization of waste from landfills.

This report addresses Deliverable 1.1 “Recovery technologies for materials in landfills” developed by Working Group 2 of COST Action “Mining the European Anthroposphere” (MINEA). MINEA aims to quantify and assess the material resources and reserves in the Anthroposphere and consolidate existing knowledge related to the exploration, evaluation, classification and recovery of materials in anthropogenic deposits and waste flows.

This report integrates the activities of the MINEA WG2 in the 1st Grant Period (May 2016 to April 2017). The following documents were developed: (1) Literature Review Report on practices and technologies for waste valorization from landfills (Calvo, 2016) and (2) MINEA WG2 Workshop on technologies in the landfill-mining sector, which resulted in an overview on landfill mining projects and on state-of-the-art as well as enhanced recovery technologies (Workshop on “Technologies for material recovery from landfills and mining residues”, Book of abstracts, 2016). This report also profits from the non published report on “Science and technology in enhanced landfill mining” (EURELCO, 2016), which has been developed by the Working Group II of the European Enhanced Landfill Mining Consortium (EURELCO).

Both activities examine current practices, knowledge transfer and recovery technologies across European countries, research fields and disciplines. This information is essential to assess the availability of secondary material from landfills and the viability of landfill mining projects in the context of circular economy.

2 PRACTICES AND TECHNOLOGIES FOR WASTE VALORIZATION FROM LANDFILLS: LITERATURE REVIEW

The Literature Review Report addresses (1) the current best practices on the landfill mining and mining residues, (2) innovative concepts and technologies to survey, excavate, separate and upcycle waste from landfills and mining residues into products, and (3) advantages and disadvantages of these technologies (Calvo, 2016).

The report is divided in the 4 sections below. It covers the state-of-the-art technologies used in the recovery and valorisation of mining wastes subdivided in function of their purpose, as well as the applications in laboratory or in industrial scale. The main advantages and disadvantages of these technologies, referred by the authors, are also listed.

1. In-Situ extraction technologies
2. Ex-Situ extraction technologies
3. Separation and beneficiation technologies
4. Valorisation of landfill mining product technologies

The In-Situ Technologies cover the pre-treatment for decontamination/stabilisation and for direct resource recovery (Enhancement of methane generation and Leaching). The control of preferential flow was addressed in several papers that cover hydraulic flow control of solute leaching, permeation grouting, bioclogging and electrokinetic methods.

In what concerns the Ex-Situ extraction technologies, the report covers several papers that focused the excavation, drying, screening and several separation technologies (density and magnetic separation) and improved automation and sensor based separation.

A comprehensive list of valorisation of landfill mining product technologies was made based on 20 references. Those include plasma gasification and vitrification, kilning and thermal treatment methods.

3 TECHNOLOGIES FOR MATERIAL RECOVERY FROM LANDFILLS AND MINING RESIDUES WORKSHOP

The MINEA Workshop was locally organized at University of Novi Sad, Serbia on 22/23 September 2016. The Workshop aim was to provide a comprehensive overview of innovative recovery and recycling technologies for materials in landfills and mining residues across Europe and to discuss and evaluate the current challenges and opportunities as well as future trends.

The workshop programme included keynote presentations, specialised sessions and oral presentations. Representatives from universities, research centres, industrial organisations, public institutions and organisations, local governments and legislators presented papers at the workshop and shared best practices on the recovery and recycling strategies and technologies related to landfills and mining residues.

During the Workshop, academics and professionals from17 countries introduced and discussed current practices, case studies and state-of-the-art as well as advanced technologies in the landfill mining sector. The research findings were discussed with 25 attendees from the fields of Waste Management and Recycling, Chemistry, Environment, Geology, Geoenvironment and Geotechnics, Water Protection and Management, Business.

3.1 Programme

22. September 2016

N°	Time	Duration	Topic	Facilitator / Presenter
	09:00	00:15	Workshop opening	U. Kral T. Carvalho N. Stanisavljevic
1	**Systems Analysis for Evaluation of Landfill Mining**			
	09:15	00:25	Evaluating and classifying resources from old landfills - A new methodology	A. Winterstetter
	10:40	00:25	Life cycle assessment on mining of an old Danish landfill	O. Udodi
	10:05	***00:30***	***Coffee break***	
2	**Surveying and Exploration of Landfills**			
	10:35	00:25	Flemish approach on mapping and prioritization of landfill site management in relation to mining potential	L. Umans
	11:00	00:25	Enhanced Landfill Mining in the UK: Resources or fuel?	S. Wagland
	11:25	00:25	Characterization of a landfill by boreholing	T. Carvalho
	11:50	***00:10***	***Short break***	
3	**Experiences from real-life projects**			
	12:00	00:25	Landfill Mining in practice: Dismantling and removal of a former dumpsite	M. Steiner
	12:35	00:25	Experiences from LFM projects in Denmark	R. Rosendal
	13:00	***1:30***	***Lunch***	

	Technologies for material separation, recovery and upgrading			
4	14:30	00:25	Development, optimisation and modelling of a separation process for ELFM materials	A. Maul
	14:55	00:25	Technology for manufacturing high grade products from excavated landfill plastic	M. Kriipsalu
	15:20	00:25	Review on sustainable innovative separation techniques for ELFM	L. Umans
	15:45	***0:30***	***Coffee break***	
	16:15	00:25	Technological and environmental indicators for rinsing of materials recovered from landfills	A. Bucinskas
	16:40	00:25	In-situ resource recovery from waste repositories	P. Cleall
	17:05	00:25	SMART GROUND: SMART data collection and inteGRation platform to enhance availability and accessibility of data and infOrmation in the EU territory on SecoNDary Raw Materials	S. Wagland
	17:30	00:25	The database; a key tool to redefine wastes to resource	P. Gundersen
	18:00		**End**	

23. September 2016

N°	Time	Duration	Topic	Facilitator / Presenter
1	09:00	09:10	Reflections and main conclusions from the 1st day of presentations	T. Carvalho
	09:10	00:30	Plenary discussion: How to proceed with the “T1–Technology” track of the WG? Which are the next steps and which actors would like to contribute in this work?	T. Carvalho
	09:40	***00:05***	***Short break***	
2	**Strategic discussions and planning of the WG´s activities**			
	09:45	00:15	Introduction	J. Krook
	10:00	01:00	Discussions in smaller groups regarding the WG´s incl. Coffee/refreshments: - mid- and long-term objectives/deliverables (what should be the main focus areas?) - opportunities and needs for collaboration with already existing networks/initiatives - internal organisation, working structures and suitable networking tools	all
	11:00	11:20	Short Power-Point presentations of the group work	tbd
	11:20	00:55	Selection and implementation of WG´s activities and networking tools to achieve the objectives with special emphasis on the coming year	tbd
	12:15		***End of official meeting***	
	12:30	01:30	Lunch	

3.2 Book of Abstract

The Workshop Book of Abstracts includes the abstracts for oral presentations and the biographies of the presenters. In the following pages selected text from the abstracts is presented.

Life cycle assessment on mining of an old Danish landfill

Obianuju Udodi, TU Denmark

The life cycle inventory data is based on a real landfill mining project implemented at AV Miljø and additional experimental data were collected from scientific papers. Three scenarios were set up; S1 - Do nothing scenario S2 – recovery of only ferrous metal and combustibles and S3 – recovery of metals, plastics and combustibles. All residues are re-landfilled. Within the assumptions made the results show that the recovery of recyclables (metals and plastics) and combustible material – S3 delivers net environmental benefits as opposed to the baseline scenario. Contribution analysis revealed that WtE, excavation and sorting process and leachate treatment at waste water treatment plant are the main contributor to the impacts considered.

The sensitivity analysis showed that increase in electricity and heat recovery, bio-cover efficiency, fuel consumption during the excavation, causes a significant change in the result, revealing these as key parameters in the system.

The scenario analysis showed that with change in the marginal electricity been used and substituted for, the observed savings were reduced and much smaller. This scenario analysis goes further to explain that with changes in the marginal electricity in the future, the S1 presents a better result for global warming and terrestrial acidification potential than S2 and 3 whereas for all other impact category, S3 still remains favorable. Scenario analysis also showed that the environmental cost of setting up a new landfill is much smaller than expected but there is also critical socioeconomic implication e.g. not in my backyard and the financial cost.

Flemish approach on mapping and prioritization of landfill site management in relation to mining potential

Luk Umans, OVAM, Tom Behets, OVAM

The OVAM developed a three step approach towards ELFM: mapping (inventory of the number of landfill sites on level of the Flemish Region, with indication of specific characteristics of the area), exploring of individual landfill sites (identification of the specific landfill body, identification of the composition of the landfilled waste, identification of the geo-physical and -chemical characteristics of specific surroundings of the landfill site), mining of a specific landfill site (digging up of the waste, (pre-)treatment of the waste to make it suitable for material reuse or valorisation).

In the mining phase of the three step approach moreover 2000 sites were located in Flanders. Mining or even investigating all those 2000 sites in a short period was unrealistic, therefore a methodology for prioritization of potential for Landfill Mining based on a multicriteria-analysis calculation tool (FLAMINCO) was developed. The criteria were based on the content of the landfill site, the period of landfilling of the stored waste, the volume of the landfill body, the actual or future use of the location, the accessibility, the proximity to neighboring landfill sites and the need to remediate the location.

Enhanced Landfill Mining in the UK: Resources or fuel?

Stuart Wagland, Cranfield University.

The work has involved sampling 9 landfill sites to assess the presence of critical and valuable metals and understand the chemistry of their mobilisation. Further to this the economic feasibility of landfill mining in the UK for resource recovery and the potential of processing extracted materials into refuse-derived fuels were assessed. The typical proportion of fines and inert material of the waste samples were ≤70%. This presents a challenge in processing extracted materials and significantly affects recovery of recyclable material. However, high quantities of metals are observed in the fines fraction, thus enhancing the overall economics; i.e. aluminium and copper content ranged from 12,000-17,500 mg/kg and 1,000-2,500 mg/kg, respectively. The sorted recyclable materials present included plastics (8-25% w/w) and paper/card (5-10%), however these materials are contaminated and would require further processing before being sold. With a calorific value of the sorted waste on average 12.9±3.8 MJ/kg (gross, as received) and 11±3.9 MJ/kg (net, as received). These materials could yield RDF. While the capital investments are relatively high in all cases which make the mining of small landfills unprofitable, these can be offset through profits from higher tonnage in medium and large sites.

Characterization of a landfill by boreholing

M. Teresa Carvalho, Bruno Guedes, CERENA, Instituto Superior Técnico, Lisbon University, Graça Brito, GeoBiotec, FCT, Universidade Nova de Lisboa.

It is addressed the characterization by means of boreholing that allows the information acquisition at larger depths than other direct methods of sampling. The difficulties in obtaining a precise characterization are addressed.

A case study is presented in the characterization of an urban Portuguese landfill showing the limited potential for materials recovery. Six boreholes were characterized in terms of particle size (-6.3, 6.3-10.0; 10-22.4; +22.4 mm) and materials. The global composition of the boreholes is mainly soil, construction and demolition residues and organic materials (including plastics). It was observed that the global metals content is approximately 5%, varying from 0 to 20% in a few layers.

Landfill Mining in practice: Dismantling and removal of a former dumpsite

Martin Steiner, TBU Environmental Engineering Consultants.

The case study intended to be presented contains in its first part a hands-on assessment of the content of a former landfill which was operated between 1920 and 1985 and accepted all municipal waste streams generated in a predominantly rural environment with tourism as a main economic factor. The assessment was performed – according to the principle "let´s replace assumptions by knowledge" – prior to the complete removal of the landfill content.

The second part gives an overview on the excavation and separation works itself which have been triggered by flood events in summer 2013 (Kössen, a small town located on a river emptying into Chiemsee in Bavaria was the municipality mostly affected by this flood in Western Austria).

Experiences from LFM projects in Denmark - Skaarup Landfill

René Rosendal, Danish Waste Solutions

The LFM project aims at excavating roughly 8.000 tons of waste that was landfilled in the 1979-81s at Renosyd's site in Skårup, Skanderborg, Denmark. The landfill…. The basic idea is to demonstrate different sorting techniques and try non-invasive geoelectric methods to investigate the surface of the landfill before excavation in order to see if this works landfills.

An integral part of the project is also to assess the potential of reducing the landfills footprint, thereby minimizing both the cost of handling leachate and the aftercare of the landfill. All this data will subsequently be utilized to develop a business model which hopefully will allow large scale LFM operations to become (more) feasible in the future.

Development, optimisation and modelling of a separation process for ELFM materials

Anja Maul, VITO

To study, design and optimise an industrial separation process for a landfill site in Belgium, VITO evaluated different pre-treatment techniques, as well as dry and wet density separations at pilot or industrial scale and developed WasteSim, a process simulation program for waste treatment.

Materials recovered from trial excavations at the landfill were used to conduct large scale separation tests at different companies on pilot or industrial scale as well as in the lab at VITO to evaluate the efficiencies of different separation units and combinations thereof. Evaluation of these separation units has led to the development of an efficient process flow model for separation of all excavated waste and a concept for a demonstrator plant. Furthermore, the necessity to better understand and optimise the separation processes led to the development of WasteSim.

In this talk, the most prominent results regarding material separation on an enhanced landfill mining project, gained by both experiment and simulation will be discussed. This includes a comparison with conventional waste separation process planning methods, mass balances, output fraction purity, and a specific case regarding unit optimisation.

Technology for manufacturing high grade products from excavated landfill plastic

Mait Kriipsalu, Estonian University of Life Sciences

Elegro Technology has developed a technology for recycling mixed plastic waste into high grade construction material. This study describes how mixed excavated landfill plastic was processed.

This study demonstrates that construction materials and products like decking boards, noise barriers, garden furniture etc. could be produced also from landfilled plastic waste. Taking into account vast number of landfills that contain plastic waste, application of this technology saves resources and broadens the market value of previously landfilled materials.

Review on sustainable innovative separation techniques for ELFM

Luk Umans, OVAM, Katrien Van de Wiele, OVAM

This review, based on a study by OVAM, investigates if current waste separation techniques are sustainable and efficient to use. In this study two landfills have been partially excavated and waste samples have been delivered to different contractors. The study shows that (1) not all landfills can be used to reclaim materials and/or secondary energy sources (i.e. fuels) and (2) this poses a problem for contractors that need to anticipate the quality of the landfill. Furthermore it is verified that landfills are heavily polluted thus exceeding current norms for re-use in soil applications. It is also stated that more innovative studies could prove beneficial in the field of landfill detection and estimating landfill compositions and energy potentials.

Technological and environmental indicators for rinsing of materials recovered from landfill

Algimantas Bucinskas, TU Kaunas

Investigations were carried out in Alytus regional landfill, using waste samples taken from the landfill. Samples were taken from different depths of borehole, made in the landfill. After analysis of recovered materials quantities and composition two waste fractions were selected for an experimental study: textiles and plastics. These fractions were washed with distilled and tap water. Ash content and volatile substance in textile and plastic waste were determined before and after washing. Permanganate oxidation (ChDS(Mn)) and heavy metal analysis of filtrate from the landfill was performed. According to this analysis it is evident, that washing improves energetic properties of materials (if it is used for energy generation), recovered from landfills, and contributes to the reduction of environmental pollution.

In-situ resource recovery from waste repositories

Peter Cleall, Cardiff University

This presentation presents a synthesis of concepts concerning in situ technologies developed from mining and contaminated land remediation industries that have enormous potential for application to technospheric mining. Furthermore potential target waste streams, their mineralogy and character are presented along with a discussion concerning lixiviant systems and metal capture that could be applied. Issues of preferential flow (critical to the success of in situ techniques) and how to control it with engineering measures are discussed. This presentation, via reporting the progress of a large national research programme, aims to provide an overview of in situ resource recovery within a conceptual framework that seeks to: (i) Explain why in situ resource recovery technologies are appropriate to waste repositories; (ii) Identify existing technologies that can be transferred to this new area; (iii) Highlight key waste/ waste repositories that could targeted; (iv) Explain how the waste mineralogy will be critical in devising lixviant systems; (v) Discuss the issue of preferential flow and how to control it with engineering measures; (vi) Identify metal capture technologies; (vii) explore current technology development level and international applicability.

SMART GROUND: SMART data collection and inteGRation platform to enhance availability and accessibility of data and infOrmation in the EU territory on SecoNDary Raw Materials

Marco de la Feld, ENCO

SMART GROUND aims to facilitate the availability and accessibility of data and information on SRM in the EU, as well as creating synergy and collaboration between the different stakeholders involved in the SRM value chain. In order to do so, the SMART GROUND consortium is carrying out a set of activities to integrate in a single EU database all the data from existing sources and new information retrieving pilot landfills as progress is made. Such database will also enable the exchange of contacts and information among the relevant stakeholders, interested in providing or obtaining SRM. The project will further spin out the SRM economy and employment by: delivering targeted training on the feasibility of SRM recovery from landfill and establishing a dedicated network of stakeholders committed to cost-effective research, technology transfer and training.

The database; a key tool to redefine wastes to resource

Pål Gundersen, Geological Survey of Norway

The author will therefore go through some of the projects that already exist and that MINEA and especially the mining waste part of WG2 would need to relate to. Focus will be on how to collect and facilitate the relevant waste stock and flow data for the end users.

The author will also present his personal view on what internal philosophy WG2 should adapt to achieve progress and results. Key words that will be discussed are: Keeping the targets clear and condensed. Keeping the language simple, short and without the buzzwords. Technical issues on how to cooperate. The common language and tools we need to master before we start

4 RECOVERY TECHNOLOGIES

The technologies used in landfill mining are commonly classified as (1) in-situ such as pre-treatment and direct recovery technologies and (2) ex-situ such as screening, density separation, magnetic separation, eddy current separation and sensor based separation.

4.1 In-Situ technologies

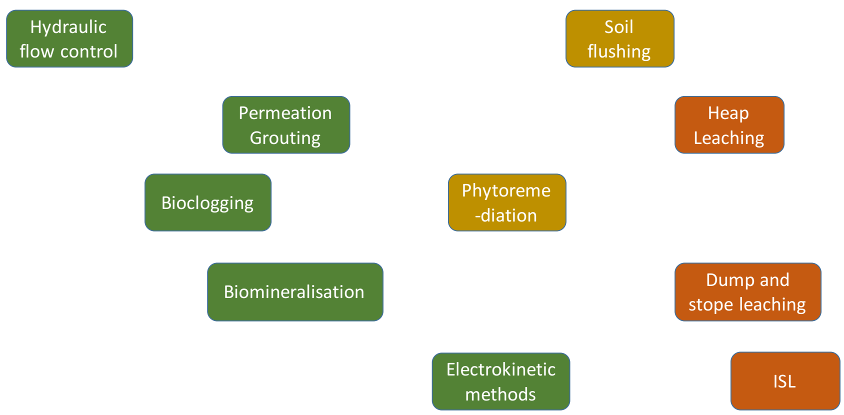
In-situ technologies can be sub-divided in pre-treatment technologies and direct recovery. The former are used in UL for the decontamination or stabilisation of the landfilled material to allow or facilitate subsequent ex-situ mining rather than for direct materials recovery.
The direct recovery is used to recover metals in EIR (including mine wastes, red mud, metallurgical dusts and slags (direct recovery of metals of value and indirect recovery/stabilisation). Calvo (2016) made a comprehensive review of technologies used in in-situ extraction technologies in IER. Leaching is the technique used in real applications although “low intensity” systems for metals removal using for instance phytoremediation, microbiological or geochemical approaches have been investigated.
In-situ leaching is not used in UL as the leachates do not contain economically recoverable amounts of metals (less than 0.02 %, according to Kjeldsen et al., 2002, or 0.9% observed by Rosenthal, 2016).

Figure 1. In-situ leaching (Cleall, 2016)

In leaching, the industrial or mining wastes are flushed by an extractant (fig. 1), introduced at the top that passes down through the material. The metals are then extracted from the pregnant liquor by methods such as ion exchange or solvent extraction before electrowinning. The method is well established for Cu recovery (Shippers et al. (2010), Panda et al. (2014)) but leaching of gold/silver and some non-sulphide Cu ores is accomplished with a cyanide lixiviant with significant negative aspects. The efficiency of leaching is affected by preferential flow. Several methods have been proposed to control it but most of the listed methods (Calvo, 2016) were used in soil applications or only at a laboratory level.

Sapsford et al (2016) presented a review of in-situ resource recovery techniques from waste repositories. In particular they explored the potential for mobilization and capture of metals from so called anthropogenic ores. They noted the rationale for resource recovery is often multi-faceted and needs to consider both the economics of recovery (including consideration of the energy required and exergy costs) and other drivers such as remediation of impact to the environment and human health, this is also conclude by Crane et al (2016). They proposed a taxonomy for in-situ techniques applied for resource recovery; subdividing techniques in to those that offer direct recovery and those that provide a route to in-direct recovery by facilitating or allowing subsequent exploitation. These indirect techniques were further classified as either i) indirect material recovery through decontamination; ii) indirect material recovery through changing the physicochemical nature of the waste and iii) indirect land recovery. In-situ techniques can also be considered in terms of their area of original application.

As noted above many techniques have been developed as part of extractive mining industries, such as in-situ leaching, dump leaching and heap leaching. An alternative area of development has been in relation to contaminated land remediation technologies, Sapsford et al (2016) offer a review of many of these approaches and assess their limitations and constraints and technology status (as shown in figure 3). One method of interest is the application of electrokinetic techniques as they have particular applicability to the fine grained materials often found in EIR. Peppicelli et al (2018) have recently published results of an experimental study of the changes in metal speciation and mobility during electrokinetic treatment of industrial wastes. They also consider the implications of this approach in terms of remediation and resource recovery noting that this type of approach has the potential to convert waste materials into asset by transforming them into viable ore deposits.



TRL	1	2	3	4	5	6	7	8	9
Technology Readiness level	Basic principles observed	Technology concept formulated	Experimen tal proof of concept	Technology validated in lab	Tech valid in relevant environment	Tech demo in relevant environment	System prototype demo.	System complete & qualified	Actual system proven

Figure 2. Assessment of the TRL of technologies' applications to in situ recovery of resources from waste repositories (after Sapsford et al 2018)

4.2 Ex-Situ Technologies

In EIR, a large set of methods used in the mineral processing can be used ex-situ to recover materials (e. g. Wang et al, 2016). As they are comprehensively described in the literature (see, for instance, Wills, 2016), in this chapter, only available technologies for urban landfills mining are considered.

The processes, processing diagrams and equipment selection are strongly dependent on the characteristics of the material. Particle size, contents in the different materials, relative composition, moisture content, etc., as referred by Quagheubeur (2013), may vary significantly. The desired quality of the separation products and the value of these may be determinant to the project. In UL, the materials/products to be valorized are mainly the metals but also light materials, such as plastics and paper, can be recovered for energy recovery. The inert fraction is mainly valorized in the construction field.

In UL, large objects have to be separated, so, dry technologies that avoid the wastewater treatment and disposal are used. Nevertheless, the efficiency of dry processes reduces drastically with the increase in moisture content, so, when this is too high, the wet separation or the material drying, before separation, have to be considered. The larger the particles, the easier is to physically separate them. Nevertheless, when material is entangled, chopping or shredding are mandatory to allow the separation of materials.
The main properties used to separate materials are the particle size, density, magnetic susceptibility and electrical conductivity. The following technologies are used:

4.2.1 Screening

Screening has two main objectives: 1) to produce a uniform product within the final desired particle size interval; 2) to prepare the material to feed downstream processes. This is needed because a) the separation processes and equipment are efficient only in a certain range of particle size; b) the removal of large objects (e. g. with a wheel loader) is needed for protection of subsequent machinery and processes; 3) the fine fraction (minus about 50-60 mm) has to be removed before further sorting processes.

There are screens of different types, like shaking, vibrating, trommel and disc/star screens. The selection of these depends mainly on the particle size distribution and composition of the screen feed and moisture content.

Figure 3. Different possible screens (Steiner, 2016)

"Banana screening decks feature multiple slopes with the deck angles progressively declining from feed to discharge. At the feed end of the screen deck angles start at 30 to 35 degrees, progressing to 5 to 10 degrees at the discharge end. The change of deck angles reportedly provides better distribution and stratification of material over the decks. According to various manufactures this means that this type of screens can process dry material with high fines contents (exceeding 30 %) faster and more effectively than conventional screens." (EURELCO, 2016).

4.2.2 Density separation

There are several classes of processes that exploit differences in density to separate materials. Generally, the particle size plays an important role in the separation, so, the equipment feed should be previously classified in closed size intervals. The particle/object shape can also influence the separation. This property is used in ballistic separators (figure 4), commonly used in the urban waste field, to separate flat (e. g. paper or cardboard) from hollow cylindrical (like plastic bottles) items. Maul et al (2014) used this process to separate the light and heavy fractions in the TönsLM project landfill mining (Maul et al, 2016).

Figure 4. Air classifier (Stein, 2016)

Figure 5. Ballistic separator used in the TönsLM project (Maul et al, 2014)

Wind sifters (figure 5) are based on the injection of air into the mass stream which lifts the lighter particles and keeps the heavier ones unaffected. In waste treatment wind sifting is applied to separate the light fraction (e.g. plastics, paper, etc.) from the heavy fraction (e.g. stones, concrete, bricks). With the same purpose, air cyclones, that use the centrifugal force, can be applied. The main drawbacks observed by Maul (2016) in the feeding of this process with material collected in landfill were the high moisture content and the entanglement of material.

Figure 6. Wind sifter (Maul, 2016)

If wet processes are allowed, sink float separation, shaking table or jigs may be used to separate materials (Wills, 2016). The selection between the different processes is based on the particle size and materials density difference. The former, with a suspension such as Fe-Si (3.3 g/cm³), can be used to separate different materials such as magnesium, aluminium and alloys of copper, zinc (such as brass) or lead. Shaking table that consists in a slightly inclined deck, vibrated longitudinally, with an asymmetric movement, can also be used to separate materials of different density, in particle size range between some microns to some millimeters. In jigs, pulsating water current is used to produce stratification in the layer of the material to be separated. The less dense particles move upwards and denser particles downwards.

The fines fraction containing soil and different materials such as metals can be more than 60% of the excavated waste (Rosendal, 2016). These fraction was processed with wet shaking table and wet jigging to separate light and heavy materials (Breitenstein and Goldmann, 2014; Zeiner et al., 2014).

4.2.3 Magnetic separation

Magnetic separation is used in any plant where feed contains iron or steel items. Due to the very high magnetic susceptibility, even when the items have small size, it is possible to separate them efficiently by a low intensity magnetic separator, like overband separator (see figure 6) which is commonly used in waste processing.

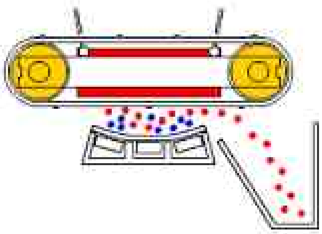


Figure 7. Schematic view of an overband separator, where the red circles are the magnetic particles (http://www.sudrecycling.com/product_overband_magnetic_separators.html).

4.2.4 Eddy current separation

Eddy current separators are used to separate different non-magnetic metals or these from non-conducting materials. A magnetic rotor (figure 7) with alternating polarity rotates rapidly inside a non-metallic drum. As the materials pass on the conveyor belt over the drum, the alternating magnetic field creates eddy currents in the metal particles. These particles are ejected away from the conveyor. The particles of non-conductive materials drop off at the end of the conveyor. such as Figure 10 illustrates an eddy current as it is applied in waste separation.

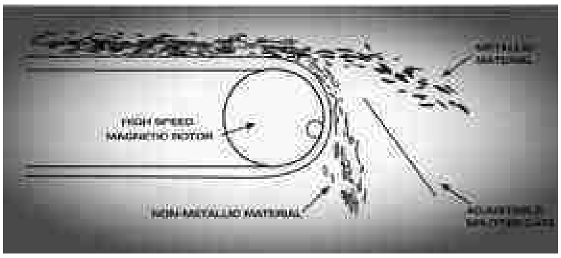


Figure 8. Eddy current separation (https://www.911metallurgist.com/equipment/eddy-current-separator/)

4.2.5 Sensor based separation

Commercially available equipment, such as TiTech, use sensors based in different principles and wavelengths depending on the application. Different technologies are used increasing the cost with the complexity incorporated in one machine. This equipment is widely used in solid waste processing plants, but not yet used in LFM case studies. Its efficiency decreases sharply with the particle size and with the dirtiness of the surfaces, so, upstream washing or drying processes are needed, with all the drawbacks associated.

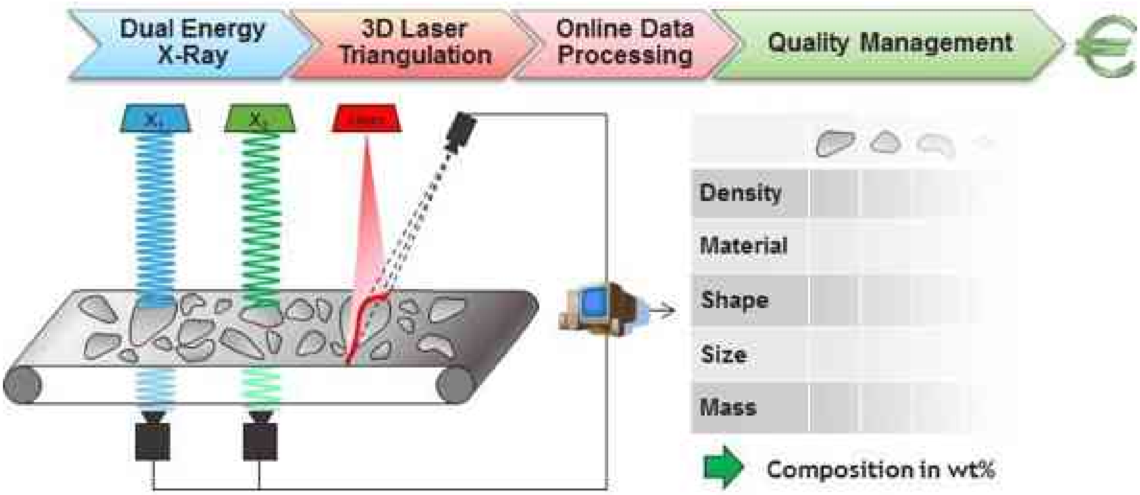


Figure 9. Sensor based separation (Maul, 2016)

5 WASTE RECOVERY AND RECYLING CASE STUDIES

In this chapter three case studies of landfill mining are presented. The first two, one in Flanders and another in Germany, are presented in a summarized form, while the third case study, carried out in Denmark, is comprehensively described.

5.1 Case study 1: Landfill mining in Bornem (Flanders)

The OVAM developed the exploring of Bornem landfill site (identification of the specific landfill body, identification of the composition of the landfilled waste, identification of the geo-physical and -chemical characteristics of specific surroundings of the landfill site), mining (digging up of the waste, (pre-)treatment of the waste to make it suitable for material reuse or valorization).

The criteria were based on the content of the landfill site, the period of landfilling of the stored waste, the volume of the landfill body, the actual or future use of the location, the accessibility, the proximity to neighboring landfill sites and the need to remediate the location.

Figures 9 and 10 show the two alternative processing flow-sheets, corresponding to 500 t each, used in the mining phase of the ELFM project, in Bornem, Flanders. In this project the organic fraction could be prepared for solid recovered fuel (SRF) while the sludges had to be landfilled. The ferrous and nonferrous metals could be recycled. The separated gravel and glass could be separated but these products can be recycled only if complying with legal standards.

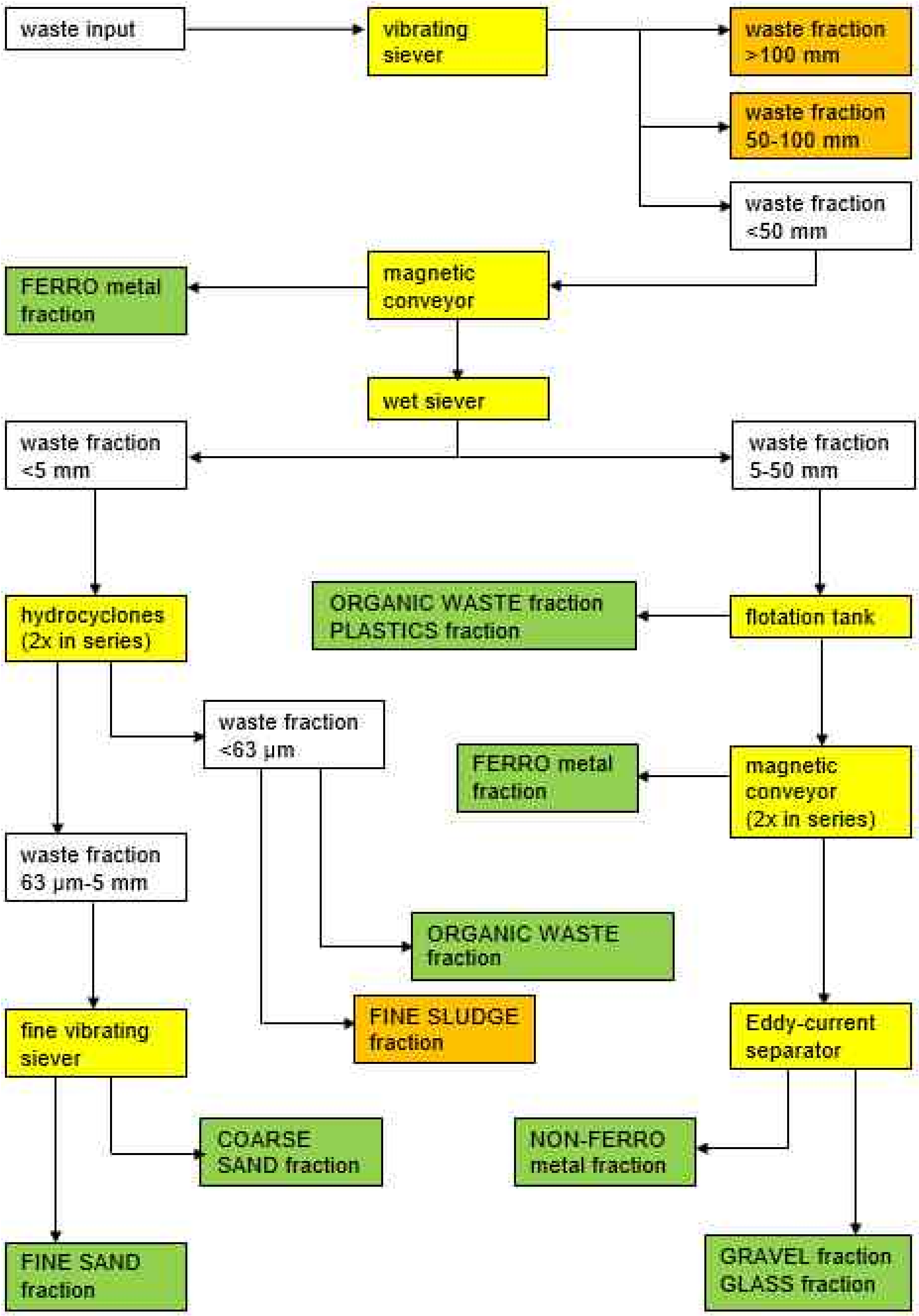


Figure 10. Bornem case study ELFM diagram (1) (Umans, 2016)

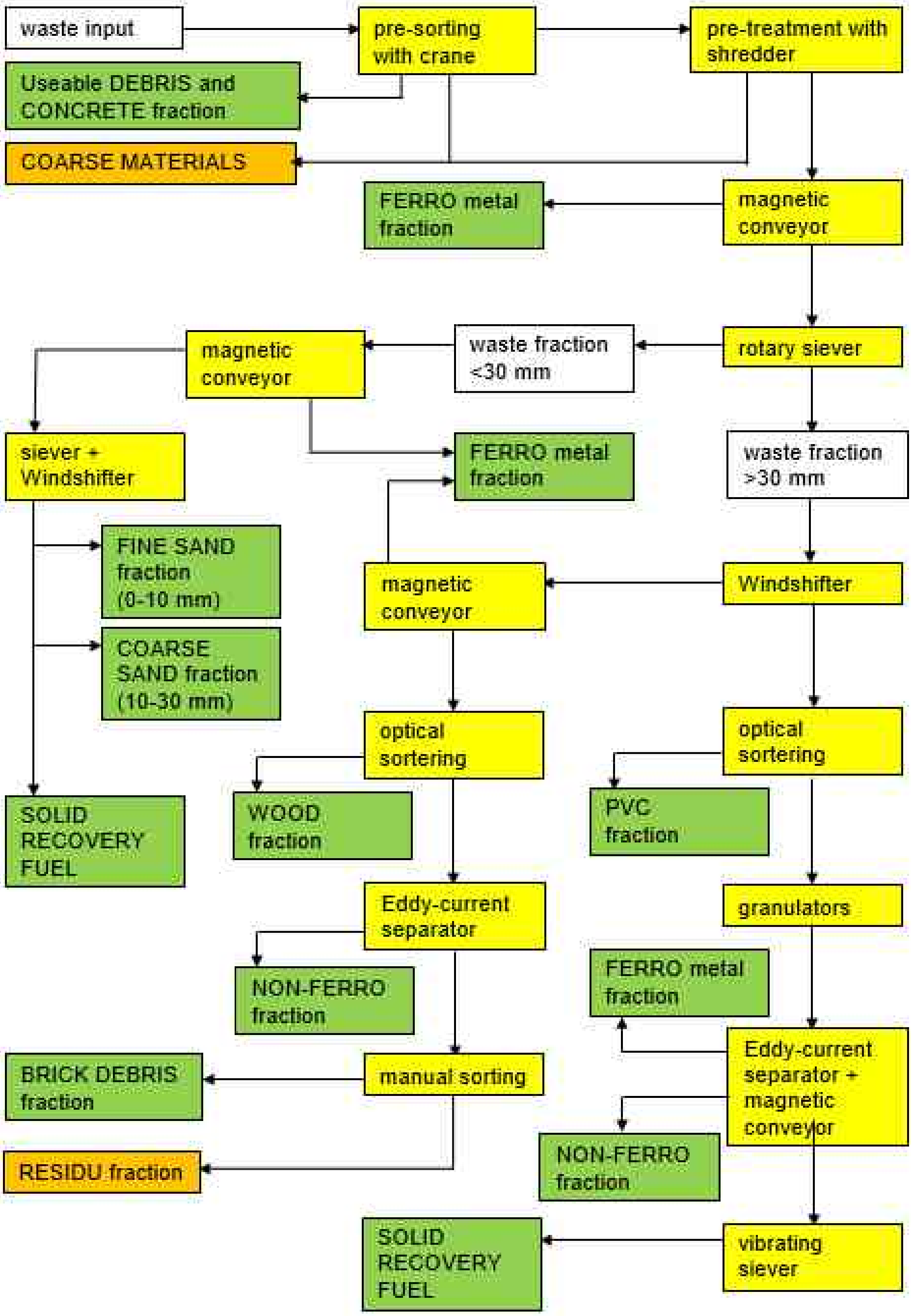


Figure 11. Bornem case study ELFM diagram (2) (Umans, 2016)

5.2 Case study 2: TönsLM project (Germany)

In the TönsLM project state-of-the-art processing technology was chosen for upscale processing trials of excavated waste materials (Maul and Pretz, 2016). The excavated material was disposed on a MSW landfill in the late 1980s; the authors observed that the long disposal time leads to degradation processes of the organic materials which lead to a high amount of fines of > 70 mass-percent (< 60 mm). During the disposal time the fines aggregated as a soil-like surface layer on single particles. The authors perceived that the surface defilement and the high share of material below 60 mm lead to restrictions of the mechanical and sensor-based processing of the material. Nevertheless, they achieved a purity in PP of the final 3-dimensional plastic output streams of more than 80 mass-percent. Figure 12 shows the flowsheet used in the project.

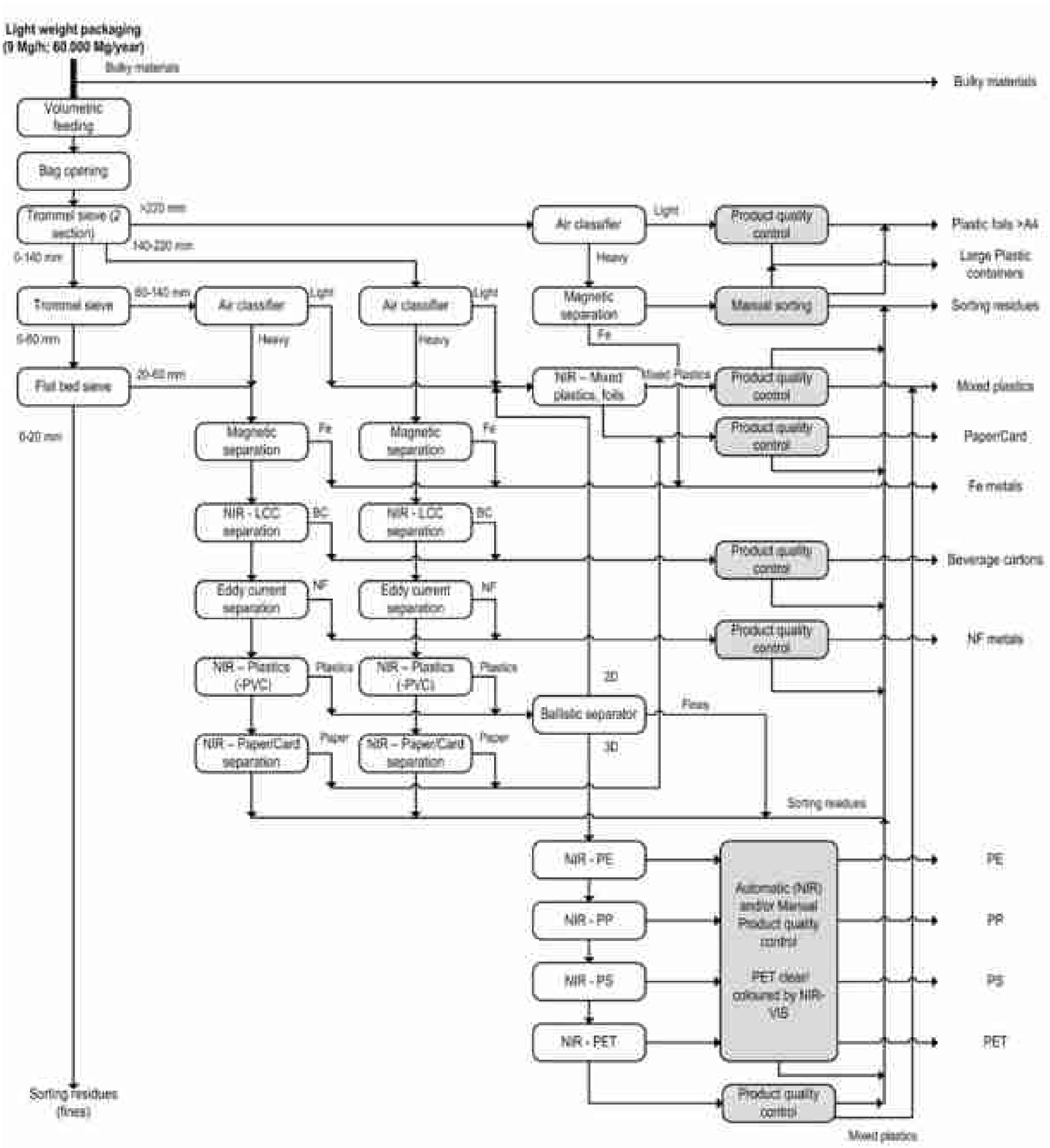


Figure 12. TönsLM project plant (Maul et al, 2016).

5.3 Case study 3: Landfill Mining demonstration project at Skårup Landfill (Denmark)

To evaluate the possibility of landfill mining in Denmark a fundamental demonstration and research project at Skårup Landfill (Co-funded by the Environmental Technology Development and Demonstration Program (MUDP)) was initialized by the waste company Renosyd in cooperation with different partners and the Danish Environmental Protection Agency (DEPA).

The excavation and sorting was done during the period august to october 2016 and was finalized and reported in the begining of April 2017.

The aim of the project is to provide insights about the technological and economic benefits and environmental aspects of excavation and sorting of pre-landfilled waste from Skårup Landfill, located in Skanderborg – by so-called Landfill Mining (LFM)

The target is to develop an application-oriented assessment tool/procedure to plan, select and perform future LFM-projects at different landfills in Denmark and abroad. In the project, an outline of a business model is prepared and a range of factors influencing the economy and social benefts of LFM projects is discussed.

The following is examined and developed in the project:

- Develop guidelines/paradigms to decide on future landfill mining projects.
- Knowledge about the technical barriers and solutions to landfill mining.
- Knowledge about environmental aspects of landfill mining (working safety and environmental effects)
- Obtain more knowledge about the costs and revenues, etc.:
  - Costs associated with mapping and exposing of the landfill.
  - Costs associated with excavation of the landfill.
  - Costs associated with sorting, cleaning and management of the waste.
  - Revenues from sale of recycables.
  - Future savings on treatment of leachate and landfill gas management.

SITE CHARACTERIZATION AND PREPARATION

Prior to the start of the project we applied for a environmental approval which was approved on May 23, 2016 subject to compliance with a number of conditions that must be met and documented before, during and after the project.

Prior to the physical excavation and management of waste, a detailed pre-characterization of the actual landfill unit was carried out. Both registrations of waste and other historical material about the area and the landfill were collected by means of e.g. interviews with “old” employees, environmental status and former investigations. Furthermore, a non-invasive screening of the landfill stage was initiated to get a three-dimensional description of the material conditions in the waste. Finally, a test excavation was done to get more information about the composition of the waste and the conditions for excavation. This pre-characterization of waste is important for correct planning of the main LFM project.

Historic site characterization

Unit 1 of Skårup Landfill has been filled with waste during the period of 1979-1981 and contains approximately 45.000 m^3 of waste consisting of household waste, slaggs, construction and demolition waste and domestic waste from both the private and public sector.

A thorough historic examination of the landfill was done, and it was expected to find the following waste composition:

- 40% soil (fine fraction)
- 5-30% waste for incineration
- 20-25% construction and demolition easte (excl. hazardous waste)
- 1-2% iron and metals
- 15% residual fraction (slaggs, ashes, sludge etc.)

Test Excavations

A small excavation was done to confirm or deny the general assumptions about the composition of the waste. From the upper plateau of Stage 1 is excavated about 3 m in depth. The firste 2 metres contain a mixture of soil, debris and slag.

Figure 13. Test excavation (photo May 2016) on top of Stage 1 Skårup Landfill

The waste is very heterogeneous and relatively compact, due to compactation. The test excavation gave the impression that the waste contained less soil than expected, but this could only be assessed with reservations due to limited experience. Observations showed th following:

- More iron and metals than expected (radiator, bike, wires, etc.)
- C&D - size from about 50 cm and downwards
- A lot of wood - large timber and many smaller pieces - partially decomposed.
- A lot of plasticfoil and some large film from agricultural use
- A single car tires
- No gas odor, but the smell of oil
- No mineral wool noticed and no asbestos roof plates

Non-invasive screening techniques (Georadar and -Tracer)

Before excavation we did testexcavations, tested non-invasive screening techniques, which is a combination of georadar (GPR) og tracer-analyzes to get a three-dimensional picture of inside the landfill. The picture show the content of the landfill and different substances and also the presence of larger items. The method is often used in order to examine contaminated soil and groundwater, but not previous used to document the waste composition of landfill in Denmark. Similar methods has been used in Flanders, Belgium with some good results (E. Van De Vijver et al. 2016).

It is expected that the method can give a valuable input about the content of he waste compositon inside older landfills and be used as a method in the future to find new locations with a high content of recyclables.

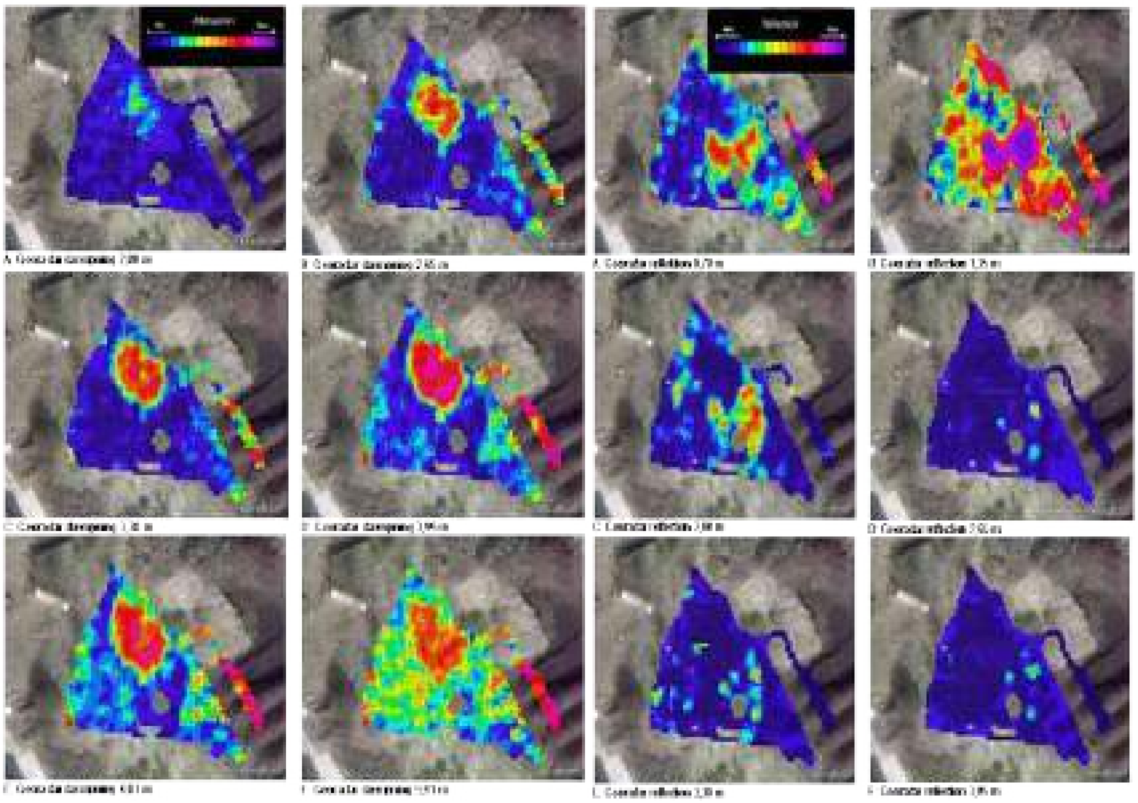


Figure 14. Georadar-reflection and Georadar-attenuation of the radar signals at different depths in the scanned area

Attenuation of radar signals tells about how much signal is absorbed in the material and strata penetrated. This absorption is due mostly conductive materials or mixtures of high salt or high amount of iones in general. The results are visualized through the horizontal section of the attenuation rate at different depths, as shown in figure 2 (left).

The reflections of the radar signals tell about how compact the areas are. This can result from larger objects, compressed layer, rocks and stones, metal objects etc. The results are visualized through the horizontal section of the reflection intensity at different depths, as shown in Figure 2 (right).

Two interpretations of the results of Groundtracer measurements were made. Within the start up of the excavation, an evaluation of which waste types that may have given rise to the observed measurements were made. These assessments are based primarily on the experiences of GroundTracers employees with interpretations of the soil, underground installations and structures as well as contaminants in the soil. As previously described, it is very sparsely with experiences of similar non-invasive studies on landfills.

After the excavation was carried out, a comparison of GroundTracer- measurements with the actual excavated types of waste from the various areas of the landfill. The intention was to obtain knowledge and experience with interpretation of non-invasive measurements on pre-landfilled waste so that the technique in future could be used for more targeted predictions on the content of waste types inside a landfill.

An overall interpretation of how there can be variations in the landfill composition was done. These interpretations were presented and evaluated before excavation work was begun. The results for all three resulst are shown below.

However, it is very little that can be derived from the measured data; but Figure 3 shows an overall outline of the interpretations with the meanings of the colored areas:

- Red - Can be an area with stones, large items and bulky waste
- Green - Connecting top layer about 1.4 m thickness
- Blue - Homogeneous conductive area 6 m below surface

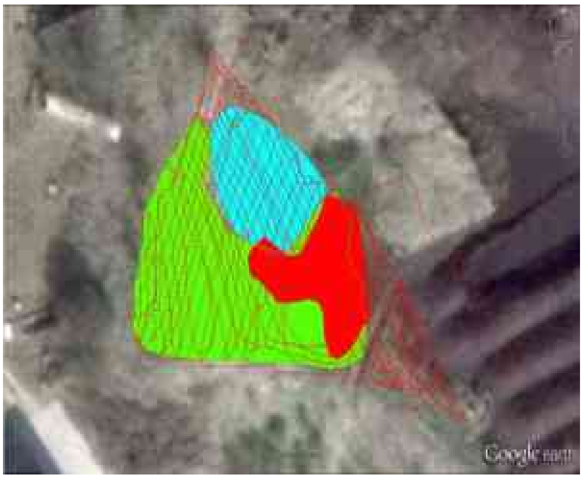


Figure 15. Map of the overall interpretation of the GroundTracer results before the excavation was initiated. Explanation of color codes are given in the text.

The excavated and sorted waste fractions did not turn out as expected based on waste records for the period. It was expected that the majority would be bulky waste and mixed waste; but it was found that the excavated area consisted mainly of household waste with minor amounts of bulky waste. We didn't see significant variations in the waste composition, which unfortunately means that we arent able to point large territorial waste variations that can be compared with the GroundTracer results.

Landfill gas measurement

Prior to start-up of excavation and sorting of waste from stage 1, gas samples and measurements was carried out within the area of excavation. 10 soil-air probes (PL201-PL210) of Ø12 mm aluminum spike was drilled into 1 meters below the surface. The results showed a methane concentration beween 5-50%, as shown in figure 4.

Figure 16. Interpretation of methane diffusion, respectively. >50 vol % and >5 vol %

A high content of methane (>50 vol.%) was detected in the measuring points PL201 and PL204. PL201, PL202, PL204 and PL206 smelled of hydrogen sulphide. In these points a content of hydrogen sulfide >5 ppm was detected, which is the limit value in work environmental legislation in Denmark. The measurment illustrated the need for the workers to carry gas detectors during the work and continous monitor and survey the gasconcentration.

METHOD – EXCAVATION AND SORTING OF WASTE

The excavation and the subsequent sorting operations were the main part of the project which ran from 8th of August to 11th of October 2016. During this period, weekly planning meetings were initiated. The work was documented in a daily journal, photographs and timesheets, and all waste fractions were weighed on the weighbridge of the Renosyd landfill.

Excavation and sorting of the coarse waste fraction were carried out using an excavator with a sorting grapple. This pre-sorting could separate bulky items from the rest of the waste: e.g. tree roots, tires, lumber, furniture, major foundation bricks, carpets and large, heavy pieces of plastic film

After pre-sorting, the waste was passed through a vibrating sorting plant where it was separated into three particle size fractions:

- A fine fraction (<40 mm); this fraction consisted of soils and small pieces of waste
- A mid-size fraction (40-51 mm)
- A coarse fraction (>51 mm)

Magnets were mounted at the outlet of the coarse- and mid-size fractions in order to separate magnetic metal.

Moreover, at the outlet from the coarse fraction, a plastic foil suction module was mounted, which blew the light plastic fractions into a separate closed container.

During the excavation, it appeared that the waste composition was significantly different than expected based on the historical data collected. The waste consisted for the most part of household waste with minor amounts of bulky waste. This meant that the sorting processes had to be adjusted, and there were performed re-sorting of some of the mid-size and coarse fractions to achieve a better fractionation of the waste.

The sorting plant consiseds of three sections: the feed box, vibrationsbox and three outlet band. At the outlet band a special fitted plastic sucktion and 2 magnets was mounted.

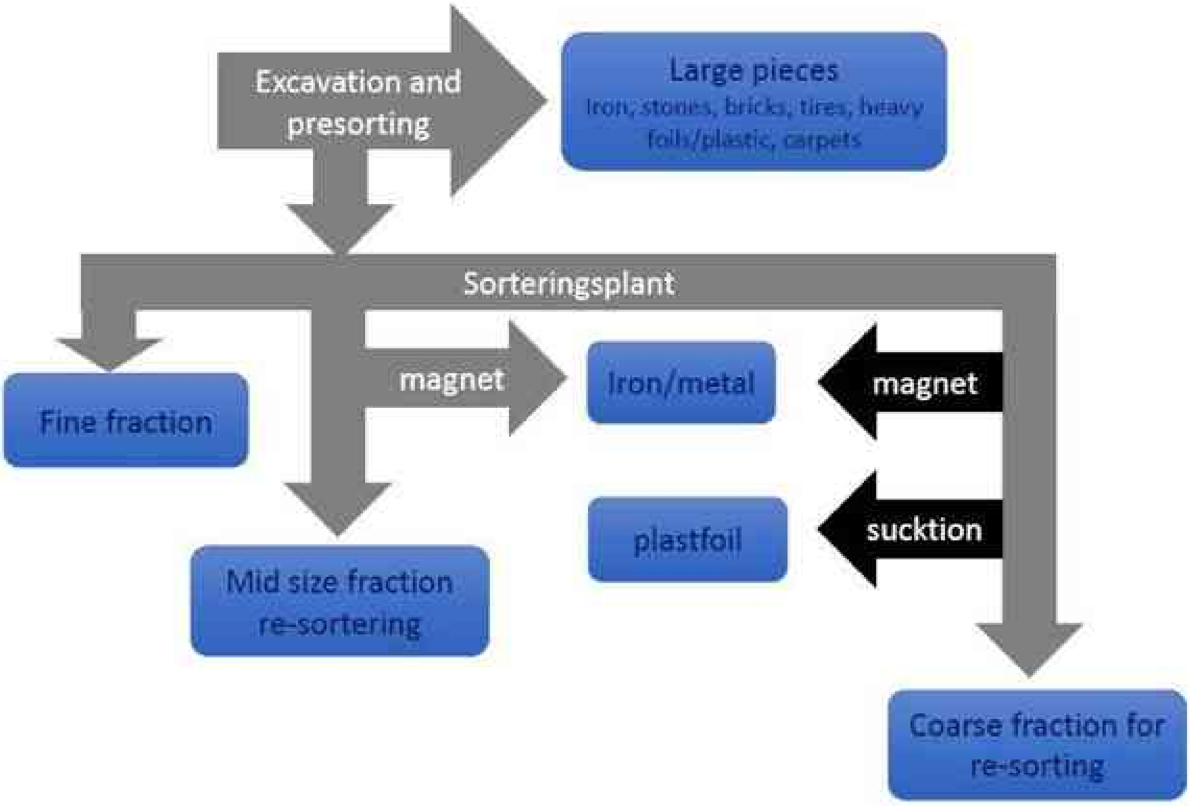


Figure 17. Sortingscheme Skårup Landfill

After the mechanical sorting, a sample of 500 kg of the mid-size fraction was hand-sorted to make a detailed characterization of the waste in different material types. The results of the hand-sorting test were used to estimate the material composition of the excavated material as shown in table 1.

During the project, a total of 2,084 tons of waste was excavated and sorted, and took about 195 working hours. That means a productivity of approximately 10.5 tonnes/hour - a result that is significantly worse than expected. We had much to learn and experience in the beginning, and the crew was affected by personnel changes and lack of relevant experience. On the other hand, we had ideal weather conditions durring the project. We believe based on the experiences gained, that it would be possible to sort 15-20 tonnes/hour, but even on the best days we didn't reach higher than the 10-12 tonnes/hour.

RESULTS AND DISCUSSION

After the characterization and weighting of the different fractions, the results are shown in table1 where the inventory of the combustible fraction is carried out based on the results of the manual after sorting.

Table 1. Final sorting results, Skårup Landfill

Waste Fraction	Total tons	%
Soil	1.578	75,7
Stones and Brick	266	12,8
Plast foil/film	72	3,5
Wood	53	2,5
Textiles, carpets, carpet residues	44	2,1
Metal/Iron	32	1,5
Hard plastics (PVC)	23	1,1
Glass	8	0,4
Rubber (tires and small rubber parts)	8	0,4
	2.084	**100,0**

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Business Case and LFM Scenarios

Following the practical implementation and recorded project costs economic calculations were made on implementation of typical LFM projects using the specific methods of excavation and sorting from this project.

In the implementation of LFM project, one of the objectives was to develop a comprehensive business model for LFM, where individual business factors were assessed and estimated economicaly. However, since there aren´t two landfills which are identical, the content and output of such an assessment will vary. At the same time, the incentives to do LFM can be different, and therefore it would be unrealistic to make a business model that can be used for general implementation of LFM projects. Instead, it was decided to develop a paradigm for the items to be included in a commercial assessment of an LFM project so that both the administrative and the practical experiences are accounted for and assessed. As a help to use the paradigm several different scenarios based on “real” conditions from Skårup Landfill were described. For each of these scenarios, we have performed calculations showing the overall economy of implementation as shown in table 2.

Table 2. Costs and revenues (1 Euro ~ 8 DKK)

Costs	**Explanation and additional comments**	**Cost level**
Design and planning	Historical site characterization and other preparations, environmental permit contact with authorities and application costs.	25.000 – 37.500 €. /site
Pre-investigation	Additional environmental studies, test excavations, non-invasive tests, GPS surveying, gas exploration.	6.250 – 18.750 €. /site
Establishment of work area and facilities	Development of workplace assessment, Plan for safety and health, gas instruction, establishment of staff facilities, the establishment of utility facilities, the establishment of electricity and diesel supply, transport of machinery, establishment of facilities for hazardous waste, and establishment of building fences. e.g. temporary establishment of tenthall/-workspace.	6.250 – 10.000 €. /site 2.500 – 12.500 €. /site
Excavation of topsoil/cover	Equipment and personnel costs	1,9 – 3,1 €. /m^2
Excavation and sorting (pre-, coarse and aftersorting)	Equipment and personnel costs	50 – 62,5 €. /tonnes
Recovering and final cover	Equipment and personnel costs as well as compost materials	7,5 – 12,5 €. /m^2
Clean up after projectactivities	Dismantling of fences, staff facilities and other installations. Repatriation of miscellaneous equipment.	3.125 – 8.750 €. /site
Re-landfilling	Re-landfilling (internal/external) - can be deposited on the same cell or in a new cell without paying landfill tax. Alternatively deposited at another landfill dump at the existing tariff but without paying the landfill tax.	0 €. /tonnes re-landfilling. 25 - 75 €. /tonnes at another landfill. No landfill tax.
Incineration of waste	If combustible fractions are removed from the landfill for e.g. incineration, tax shall be paid for this part of the waste - Incineration tariff (incl. taxes,	63,75 €. /tonnes

	etc.).	
Crushing	Concrete is crushed and used as crushed concrete. Stones can be crushed and used as crushed granite, but the costs are higher.	2,5 - 5 €. /tonnes
Light contaminated soil	Costs for recycling of light contaminated soil - incl. transportation costs	12,5 – 18,75 €. /tonnes
Heavy contaminated soil	Costs for the treatment and transportation is depending on the degree of pollution	43,75 – 75 €. /tonnes
Hazardous Waste	Storage and disposal	625 - 750 €. /tonnes
Transportation	Internal transportation of waste fractions is included in the reported costs for the various factions. Transportation costs for the separated fractions to external customers must be incorporated.	3,1 – 12,5 €. /tonnes Depending on the location
Income and savings	**Explanation and additional comments**	**Revenues**
Income from the sale of (recyclable) materials	Depends on the quality of the excavated materials, and local market conditions. In the project, it has only been possible to remove and recycle/sell the metal fraction, combustible material and the crushed concrete.	Depending on the materials. e.g. iron/metal (112,5 €. /tonnes). Crushed concrete (2,6 €. /tonnes). Mix of crushed asphalt/concrete for roadconsruction purposes 0/32 mm (12,5 €. /tonnes).
Saving on treatment and management of leachate	There is a need to pay a fee to the municipal treatment plant until the plant will switch to passive mode, but this will depend on a decision by the supervisory- and approval authorities. Can be calculated as the treatment cost incl. annual operating, maintaining costs	50 €. /m^2 (for Skårup Landfill)
Reversal of final provision	All landfills owners shall provide financial provision for the future, predictable costs generated by the waste received. The timeframe is set to at least 30 years. The size of the guarantee must be given as a basic amount per tonnes of waste	15 €. /m^2 (for Skårup Landfill)

	landfilled. At the closure of a landfill cell/unit there is an interruption of the planned, long-term economic drag. It is therefore appropriate to adjust the finansial provision, equal to the expected cost, which is linked to the waste.	
Reversal of landfill tax	It has not been possible to and remove any waste with tax refunds in this project, but in the case of refund tis will be made at the applicable tax rate.	59,4 €. /tonnes

In addition to the above economic components, several essential factors of a more general character, which is likely to be the crucial incentives to do LFM. It is often not possible to valuate these factors, as they are dependent on external and/or local circumstances. These factors will be included in many cases, both the strategic and political considerations behind a decision of a LFM project.

Table 3. Other externalities

Released landfill volume/costs of establishing a new landfill	In this project, the non-recycled residual waste was re-landfilled in the same cell where it was excavated. This required a dispensation, and is usually not possible, since the landfill cell doesn't comply with the requirements in the Landfill Directive. This problem should be discussed with the authorities in each case. However, providing more landfill capacity could be a significant incentive for LFM. In principle, a LFM project will release new landfill capacity corresponding to the amount of waste removed for recycling. Renovation of landfill area to meet the applicable requirements, may in some cases be attractive rather than establish new landfill to provide new capacity.
Savings of extra ordinary aftercare costs	There is a great uncertainty about the length of the aftercare period. The effect of a longer aftercare period is considered to have a significant economic impact
Release of areas for new purposes	After restoration of the areas in some cases could be used for residential, industrial or recreational purposes. LFM of landfills could be included as an option in urban or other planning.

Addressing environmental impacts	Leaching of harmful substances from landfills in some cases contribute to an environmental hazard to either ground- or surface water. In some cases, LFM could be a viable option to eliminate these environmental hazards.

As a basis for the calculations is primarily used economic assumptions and results from this project, and basic information about Skårup Landfill. It should be emphasized that the basic information is case-specific. When assessing other LFM projects it is necessary to use local and specific site data.

The results of the calculations on the selected scenarios show that, overall, there will be a cost of implementing LFM and very little revenues. Depending on the different circumstances the total LFM costs is calculated to be between 3,5 to 97 € per tonnes of waste.

CONCLUSIONS

The projects have shown that several factors influence on the economics of a landfill mining project. It´s very hard to describe all the costs and revenues that influence on a project before you start excavating, even though you make good historic descriptions and take other measure precautions such as test excavations and use non-invasive methods. The situation often changes and unexpected things happens which might affect the economics in a negative way.

Sale of excavated materials such as metals is a very important factor and considered as one of the most significant factors that contributes positive to the economics of a project. Thequality of materials is often poor, contaminated or degraded and hard to sell. A lot of externalities influense on the economics, and at this point it is hard to see when a landfill mining project will turn out with more revenues than costs.

6 OUTLOOK

Landfill mining has been proclaimed as an integrated strategy to address unwanted impacts of landfills, reclaim land or landfill void space and recover deposited materials and energy resources. Although such an ambitious approach displays a wider societal potential than conventional landfill closure and aftercare, it also adds complexity to the implementation and assessment of such projects.

Recent reviews demonstrate multiple challenges for sound implementation of landfill mining in terms of needs for further development of know-how and technologies as well as a better understanding of influencing market and policy conditions. In essence, the continued emergence of the area suffers from a deficit in knowledge, practical experience and records of accomplishment. This is especially so when it comes to the capabilities, efficiencies and limitations of different technologies and processing schemes for separation, treatment and recovery of previously deposited materials. While few real-life projects have been reported, most of the research on landfill mining technologies instead involves sporadic laboratory or small-scale pilot trials. To conclude, we know very little about which quantities of different materials and energy resources that actually can be produced from the full-scale processing of deposited waste, and even less about at what quality levels.

In order to facilitate trustworthy assessments of the feasibility and performance of landfill mining, there is thus a massive need for more applied research on the technical processing of deposited waste. Such research must go beyond state-of-the-art by gradually increasing the scale of operations and involving long-term efforts targeting continual process development and improvements. Fortunately, some on-going initiatives address such engineering challenges and an example is the MSCA-ITN research project NEW-MINE, in which 15 PhD-students jointly work on developing efficient processing technologies throughout the whole landfill mining value chain.

The challenges of landfill mining is however not just a matter of developing efficient technologies for separation, treatment and recovery. Instead, the economic feasibility, environmental impacts and societal consequences of engaging in such projects rely on the realization of a large number of project-specific, technical, organizational, market and policy factors and conditions. Research on what type of landfills and local settings that are suitable for landfill mining, pros and cons of different business models and organizational set-ups, the marketability of extracted resources and needs for policy interventions are therefore all important topics. Understanding how all these multifaceted elements interact throughout the landfill mining value chain and jointly contribute to the outcome of such projects is challenging but indeed fundamental for the further emergence of the area. This calls for a multidisciplinary systems perspective, which is precisely the approach of the future work of WG 2.2 Resources in Landfills of COST action MINEA.

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References

Breitenstein, B. and Goldmann, D. 2014. Metal recovery by mechanical processing from fine fractions with grainsize < 60 mm generated during landfill mining. Proceedings 2nd Symposium on Urban Mining (SUM), Bergamo, 20 May 2014

Calvo, 2016. Literature Review Report on practices and technologies for waste valorization from landfills. STSM report, of COST action MINEA.

Cleall, P., Sapsford, D., Harbottle, M., Crane, R. and Sinnett D. 2016. In situ resource recovery from waste repositories. Workshop "Technologies for material recovery from landfills and mining residues", Novi Sad, 23/24 September 2016, presentation available at http://www.minea-network.eu/event.php?id=4

Crane, R.A., Sinnett, D.E., Cleall, P.J., and Sapsford, D.J., 2017 "Physicochemical composition of wastes and co-located landscape designations at legacy mine sites in south west England and Wales: implications on resource potential" Resources, Conservation & Recycling, 123:117-134

EURELCO, 2016. Report on science and technology in enhanced landfill mining. Internal Report (unpublished).

Krook, J., Svensson, N., Eklund, M., 2012. Landfill mining: a critical review of two decades of research. Waste Management 32, 513 - 520.

Maul A., Feil, A. and Pretz T. 2014. Pre-conditioning of old-landfilled material for further upscale processes , Proceedings 2nd Symposium on Urban Mining (SUM), Bergamo, 20 May 2014.

Maul A. and Pretz T. 2016. Landfill Mining from the processing perspective - a view on mass balance and output streams, Conference: Third International Academic Symposium on Enhanced Landfill Mining, ELFM III, Lisboa, Portugal, February 2016.

Maul, A. 2016. Development, optimisation and modelling of a separation process for enhanced landfill mining materials. Workshop "Technologies for material recovery from landfills and mining residues", Novi Sad, 23/24 September 2016, presentation available at http://www.minea-network.eu/event.php?id=4

Maul A., and Pretz T.. 2016. Landfill Mining from the processing perspective a view on mass balance and output streams. Proceedings of the 3rd International Symposium on Enhanced Landfill Mining, Lisbon, Portugal 8/10 February 2016
Rosendal, R (2009) Landfill Mining - Process, Feasibility, Economy, Benefits and Limitations,RenoSam.
Peppicelli, C, Harbottle, M.J., Sapsford, D.J. and Cleall, P.J., 2018 "Changes in metal speciation and mobility during electrokinetic treatment of industrial wastes: implications for remediation and resource recovery" Science of the Total Environment, 624:1488-1503

Sapsford, D.J., Cleall, P.J., Harbottle, M.J., 2017 "In situ resource recovery from waste repositories: exploring the potential for mobilisation and capture of metals from anthropogenic ores." Journal of Sustainable Metallurgy, 3(2):375-392

Rosendal. R: Landfill Mining - Waste for re-use and incineration with energy recovery - Gerringe Landfill, Denmark. Proceedings Sardinia 2013, 14th International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy; 30 September - 4 October 2013 by CISA, Environmental Sanitary Engineering Centre, Italy.

Rosendal, R.; Danish Experiences on landfill Mining, Linnaeus Eco-Tech 2014, 24-26 November Kalmar

Rosendal, R.; The economics of landfill mining – focus on the length of the aftercare, Proceedings Sardinia 2015, 15th International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy; 5 – 9 October 2015 by CISA Publisher, Italy

Steiner, M. 2016. Landfill mining caused by flood protection: Dismantling and removal of a former dumpsite. Workshop "Technologies for material recovery from landfills and mining residues", Novi Sad, 23/24 September 2016, presentation available at http://www.minea-network.eu/event.php?id=4

Umans, L. 2016. Mining of waste from old landfill sites for re-use or recycling. Workshop "Technologies for material recovery from landfills and mining residues", Novi Sad, 23/24 September 2016, presentation available at http://www.minea-network.eu/event.php?id=4

Wang X., Geysen D., Van Gerven T., Jones P.T., Guo M. and Blanpain B. 2016. Physical separations in metal recovery from landfilled stainless steel slags. Proceedings of the 3rd International Symposium on Enhanced Landfill Mining, Lisbon, Portugal 8/10 February 2016

Wills, B.A. (1997). Mineral Processing Technology (6th ed.), Oxford, Butterworth-Heinemann.

Workshop on “Technologies for material recovery from landfills and mining residues”, Book of abstracts, Karl, U., Krook, J. and Carvalho, M.T, Eds, 23/24 September 2016, Novi Sad, Serbia.

Zeiner, A., Münnich, K., Wanka, S., Fricke, K. (2014). Mining of MSW landfills: Reduction of masses to be landfilled by treatment of the fine fraction, Proceedings 2nd Symposium on Urban Mining (SUM), Bergamo, 20 May 2014

Danmark uden affald - Ressourceplan for affaldshåndtering 2013-2018, Vejledning fra Miljøstyrelsen nr. 4, 2014

Landfill Mining of shredder waste in Denmark – SHERMAN case AV Miljø Landfill, Global Waste Management Symposium in Palm Springs, California on January 31 – February 3.

Van De Vijver, E., M. Van Meirvenne: Delving into the potential of multi-receiver electromagnetic induction surveying for enhanced landfill exploration in view of ELFM 3rd International Symposium on Enhanced Landfill Mining | Lisbon – Portugal | 8th – 10th February 2016.

Annex: History on Working Group Structure and activities

On the 6th June 2016, the 1st MINEA Core Group Meeting took place in Lisbon, Portugal. Teresa Carvalho (Centro de Recursos Naturais e Ambiente, Portugal), the leader of the MINEA Working Group on the resource potential of waste in landfills, outlined the work programme for the 1st Grant Period (1st May 2016 – 31st April 2017), including a workshop on technologies for material recovery from landfills and a call for Short-Term-Scientific Missions in the field of landfill mining.

On 23/24 September 2016, the Workshop “Technologies for material recovery from landfills and mining residues” took place at the University of Novi Sad, Serbia. Experts from more than 10 countries shared the latest research findings on treatment and recovery technologies. The following experts volunteered to become a Working Group Member Alenka Mauko Pranjic , Dragana Strbac, Gintaras Denafas, Joakim Krook, John Esguerra , Mait Kriipsalu, M. Teresa Carvalho, Mika Horttanainen , Paul Einhäupl , Pedro Haro, Peter Cleall, René Rosendal, Stuart Wagland, Tsitsino Turkadze, Vladimir Sedlak.

In December 2016, Ms Marisa Álvarez (Universidad Politécnica de Madrid, Spain) visited the Instituto Superior Técnico (Portugal) for a Short-Term-Scientific-Mission and complied information on landfill mining technologies.

On 24th February 2017, during the 2nd MINEA Management Committee (MC) Meeting at the Geological Survey of Slovenia, the MINEA MC appointed Joakim Krook (Linköping University, Sweden) as WG Leader and Teresa Carvalho as Vice-Leader. Due to distinct differences between urban landfills and tailings, the MC split the Working Group in two sub-groups. From this time onwards, MINEA WG2.1 focuses on the resource potential of waste in landfills and WG2.2 on the resource potential in residues from extractive industries.