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Proceedings of the  
4<sup>th</sup> International Symposium on  
**Enhanced Landfill Mining**

5 - 6 February 2018  
Mechelen, Belgium

**Editors**

Peter Tom Jones  
Lieven Machiels





## PREFACE

Over the past few years Enhanced Landfill Mining (ELFM) – defined as “*the safe exploration, conditioning, excavation and integrated valorisation of (historic, present and/or future) landfilled waste streams as both materials (Waste-to-Material) and energy (Waste-to-Energy), using innovative transformation technologies and respecting the most stringent social and ecological criteria*” – has gained considerable momentum.

Firstly, three large-scale, multi-partner ELFM-related projects (ETN NEW-MINE, Interreg RAWFILL and COCOON) – which were submitted in ultra-competitive EU programmes – have received EU funding. Secondly, the ELFM concept has enjoyed widespread press attention, incl. multiple documentaries and featured articles, such as the January 8, 2018, Special Report in the “50 Ideas to Change the World” Series of the *Financial Times*. Thirdly, on March 14, 2017, the European Parliament formally endorsed the ELFM concept in its “Waste Package”, which concerned the adaptation of four EU Directives. The endorsement consisted of an Amendment to the Landfill Directive, which was to provide for the embryonic architecture for future ELFM activities.<sup>a</sup>

Nevertheless, despite these evolutions and, concurrently, the many research breakthroughs, we are still waiting for the first, full-scale industrial, resource-recovery-driven ELFM project to take place. Multiple barriers seem to persist. Legislation for ELFM on the EU and national level has not yet come to terms with the dynamics of the – disruptive – ELFM concept, which is corroborated by the fact the ELFM Amendment of the European Parliament was blocked out in the 2017 Trilateral meeting between the European Parliament, the European Commission and the European Council. Concurrently, market barriers for ELFM remain: ELFM-derived products need to compete with primary resources and several industries are still reluctant to absorb ELFM-derived materials. Thirdly, local communities may take

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<sup>a</sup>In Article 5, the following paragraph has been added: “*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.*” The justification for this change is that Enhanced Landfill Mining does not only enable the recovery of valuable materials which can be brought back into the cycle, but also allows for recovering land area, taking into account that a large part of the EU's 500,000 historic landfills are situated in a (semi-) urban environment.

some convincing about ELF M projects *in their backyard*. This bewildering force field provides the intriguing context for the *Fourth International Symposium on Enhanced Landfill Mining (ELFM IV)*.

Building upon the three previous editions (2010 (Belgium), 2013 (Belgium) and 2016 (Portugal)), *ELFM IV* provides the floor to a host of both Invited Speakers (with *Keynote Lectures/papers*) and Regular Speakers (through a call for papers) to shed light on the recent progress in both the technological and non-technological aspects of ELF M within the wider circular economy context. Several Invited Speakers provide review/position papers on the status of key ELF M domains, such as geophysical methods for landfill exploration, state-of-the-art sorting technologies, solar and plasma gasification, multi-criteria assessment results of ELF M projects etc. As such the audience receives a comprehensive overview of the wide ELF M research and innovation domain.

*ELFM IV* offers a total of 50 papers, which are grouped according to 4 thematic categories:

1. Geophysics, remediation, preprocessing and metal extraction technologies for Enhanced Landfill Mining
2. Thermal valorisation technologies for Enhanced Landfill Mining
3. Upcycling technologies for Enhanced Landfill Mining
4. Multi-criteria assessment for Enhanced Landfill Mining

The wide diversity of participants reflects the multi-actor, “quadruple helix” approach that is endorsed by EURELCO, the European Enhanced Landfill Mining Consortium. Such an approach is essential to *obtain* and *maintain* the “Social License to Operate”, in which ELF M is fully integrated in a wider, system-level transition to a low-carbon, circular economy.



**Peter Tom Jones, for the *ELFM IV* Organising Committee**

Senior Research Manager SIM<sup>2</sup> KU Leuven  
General Coordinator EURELCO & ETN NEW-MINE

## ACKNOWLEDGEMENTS

The *ELFM IV* Symposium is organised by SIM<sup>2</sup> KU Leuven and i-Cleantech Vlaanderen, further supported through the EURELCO network (European Enhanced Landfill Mining Consortium), the MSCA-ETN NEW-MINE project (EU Horizon 2020 Marie-Sklodowska Curie European Training Network NEW-MINE) and EIT RawMaterials, *i.e.* the strongest consortium ever created in the world in the raw materials field.

ETN NEW-MINE (funded within the European Union's EU Framework Programme for Research and Innovation Horizon 2020 under Grant Agreement No 721185) and EIT RawMaterials are formally acknowledged for their financial support. Furthermore, the organising committee also wants to thank the International Scientific Committee, which was composed of EU Horizon 2020 MSCA-ETN NEW-MINE Supervisors and EURELCO Working Group Leaders and Steering Committee Members; for their review of the *ELFM IV* papers.

## ORGANISERS

### i-Cleantech Vlaanderen vzw (Coordinator EURELCO Network)

i-Cleantech Vlaanderen vzw (a non-profit organisation that was established in 2012 by the Flemish Government. The main activities are promoting and implementing cleantech in Flanders (BE). With regard to Enhanced LFM, i-Cleantech Vlaanderen is the coordinator of EURELCO (EU Landfill Mining organisation) and the Interreg Europe COCOON project. Furthermore, i-Cleantech Vlaanderen is the leader of the EURELCO Working Group on communication and is a key partner in the Interreg North-Western Europe RAWFILL project on geophysics of/for Landfill Mining.



### SIM<sup>2</sup> KU Leuven (Coordinator ETN NEW-MINE)

SIM<sup>2</sup> KU Leuven is the coordinator of the ETN NEW-MINE project. SIM<sup>2</sup> KU Leuven is a leading, interdisciplinary research cluster at KU Leuven uniting the research groups working on Sustainable Inorganic Materials Management. SIM<sup>2</sup> KU Leuven's mission is to perform cutting-edge fundamental, strategic and applied research contributing to cost-effective, zero-waste valorisation of End-of-Life waste, mining waste and industrial process residues, covering the full value recycling/recovery chain. ELF M is one of the key focus domains of SIM<sup>2</sup> KU Leuven, which was one of the driving forces behind the Flemish ELF M Consortium and, subsequently, the EURELCO Consortium.



With the support of ETN NEW-MINE, EURELCO & EIT RawMaterials Partners

### NEW-MINE

NEW-MINE is the EU Horizon 2020 Marie-Sklodowska Curie Training Network for Resource Recovery Through Enhanced Landfill Mining. NEW-MINE trains 15 early-stage researchers (ESRs) in all aspects of landfill mining, in terms of both technological innovation and multi-criteria assessments. The technological innovation follows a value-chain approach, from advanced landfill exploration, mechanical processing, plasma/solar/hybrid thermochemical conversion and upcycling, while the multi-criteria assessment methods allow to compare combined resource-recovery/remediation ELF M methods with the "Do-Nothing", "Classic



EU TRAINING NETWORK FOR RESOURCE RECOVERY THROUGH ENHANCED LANDFILL MINING

remediation” and “Classic landfill mining with (co-)incineration” scenarios. By training the ESRs in scientific, technical and soft skills, they become highly sought-after scientists and engineers for the rapidly emerging landfill-mining and broader raw-materials industries of Europe.

## EURELCO

EURELCO is an open, quadruple helix network that supports the required technological, legal, social, economic, environmental and organisational innovation with respect to Enhanced Landfill Mining within the context of a transition to a resource efficient, circular, low-carbon economy. Currently, EURELCO hosts 58 contributing organisations representing a total of 3 EU Member States. Within the framework of EURELCO, three EU-funded projects have been developed: EU MSCA-ETN NEW-MINE, Interreg Europe COCOON, and Interreg NEW RAWFILL.



## EIT RawMaterials

EIT RawMaterials, initiated by the EIT (European Institute of Innovation and Technology) and funded by the European Commission, is the largest and strongest consortium in the raw materials sector worldwide. Its vision is the European Union where raw materials are a major strength. Its mission is to boost competitiveness, growth and attractiveness of the European raw materials sector via radical innovation and guided entrepreneurship.



EIT RawMaterials unites more than 100 partners – academic and research institutions as well as businesses – from more than 20 EU countries. They collaborate on finding new, innovative solutions to secure the supplies and improve the raw materials sector all along its value chain – from extraction to processing, from recycling to reuse.

EIT RawMaterials aims to significantly enhance innovation in the raw materials sector by sharing of knowledge, information and expertise: Entrepreneurs, Start-ups and SMEs receive funding and support through our partner network and collaboration activities.



## **ORGANISING COMMITTEE**

Peter Tom Jones	SIM <sup>2</sup> KU Leuven, i-Cleantech Vlaanderen
Annick Vastiau	i-Cleantech Vlaanderen
Katleen Vandormael	i-Cleantech Vlaanderen
Piet Wostyn	SIM <sup>2</sup> KU Leuven
Lucian Al. Onisei	SIM <sup>2</sup> KU Leuven
Yves Tielemans	Group Machiels
Hilde Thevis	Group Machiels
Pascal Dubois	Associate Hilde Vautmans, MEP

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Dr. Lieven Machiels	KU Leuven
Prof. Lieve Helsen	KU Leuven
Prof. Yiannis Pontikes	KU Leuven
Prof. Karel Van Acker	KU Leuven
Prof. Thomas Pretz	RWTH Aachen
Prof. Bernd Friedrich	RWTH Aachen
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Prof. Alexander Feil	RWTH Aachen
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Hans Groot	Deltares
Dr. Annick Vastiau	i-Cleantech Vlaanderen
Prof. Fred Nguyen	ULiège & KU Leuven

## KEYNOTE SPEAKERS



**Werner Annaert.** General Director at Go4Circle (Belgium), the umbrella association for (currently 220) private companies active in collection, sorting, recycling, treating and processing waste and contaminated soil.



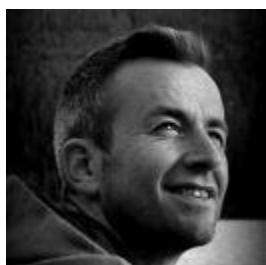
**Maurice Ballard.** Director of CleanTechPunt vzw. Coordinator of the “DE LOCALS” Group in Houthalen, a group representing a number of local inhabitants living in the vicinity of the Remo landfill site in Houthalen-Helchteren, Belgium.



**Enrico Bernardo.** Associate professor of Materials Science and Technology at the University of Padova, Department of Industrial Engineering, since 2014. Co-chair of Advanced Ceramics and Glasses research group, scientist in charge at University of Padova for CoACH-ETN, NEW-MINE and FunGlass european projects.



**Ilse Bilsen.** Project Manager at the Unit Environmental Risk and Health at VITO.



**Jonas Cautaerts.** Business Developer for Colruyt Group – DATS 24.



**Nele De Belie.** Professor in Durability of Cement Bound Materials at Ghent University since 2000; head of the “Concrete and Environment” group within the Magnel Laboratory for Concrete Research; chair or member of several (inter)national scientific committees (e.g. within RILEM); author of more than 300 publications in scientific journals and conference proceedings and editor of 5 books; expert in (bio)deterioration, bioconsolidation, self-healing, self-cleaning, concrete with supplementary cementitious materials, life cycle assessment, design for recycling.



**Ranajit Ghose.** Associate Professor at the Section of Applied Geophysics and Petrophysics, Faculty of Civil Engineering and Geosciences of Delft University of Technology, Netherlands. Editor-in-Chief of the ISI journal Near Surface Geophysics. Specialist in high-resolution seismics, shear waves, wave propagation in fractured media, soil physics and poroelasticity, geotechnical geophysics, and physics-based integrated approaches.



**Lieve Helsen.** Full professor at the Department of Mechanical Engineering of the KU Leuven since 2005, Head of the KU Leuven Thermal Systems Simulation (The SySi) research group, Academic Head of the Thermal Systems Field within EnergyVille, member of the Board of Directors of the KU Leuven Energy Institute.



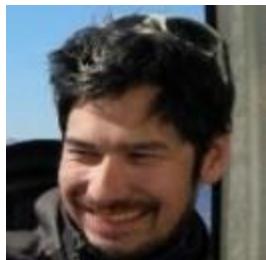
**Zoran Jovanovic.** Deputy Head of the Professorship of the Renewable Carriers at ETH-Zurich with 14 years of Industrial R&D (Research Scientist at The Dow Chemical Company, Midland, MI, USA), 3 years of renewable energy process development and project management (Principal Engineer at Sundrop Fuels, USA).



**Joakim Krook.** Associate professor at Linköping University, Sweden. Specialised in multidisciplinary systems analysis research on landfill and urban mining, Steering Committee Member of EURELCO, WP leader in COST action MINEA, advisory board member of research programmes such as “Anthropogenic resources” at TU Vienna, Austria and “In situ resource recovery from waste repositories” Cardiff University UK. Supervisor in ETN NEW-MINE.



**Patrick Laevers.** More than 15 years of experience in the international waste-management industry, progressing through various multi-site managerial roles, incl. at Renewi plc, Shanks (Managing Director of Belgium) and Group Machiels. PhD in Engineering obtained at VUB, Belgium.



**Fred Nguyen.** Professor at University of Liège, Belgium. Expert in hydrogeophysics and in inverse modelling formulated as a deterministic problem or as a stochastic one using for example training images and the probability perturbation method. Participates in several projects targeting geophysics for landfill mining such as MINERVE and RAWFILL.



**Roland Pomberger.** Professor Waste Processing Technology and Waste Management at Montanuniversität Leoben. Specialist in mechanical waste treatment, hazardous waste and refuse derived fuels (RDFs), 20 years of industrial expertise as manager of Saubermacher, Head of the Austrian Water and Waste Association (ÖWAV) working group “Resource protection and resource efficiency”).



**Yiannis Pontikes.** Associate professor at the Department of Materials Engineering, KU Leuven. He is leading the Secondary Resources for Engineered Material (SREMat) research group, that consists of approximately 15 post-doctoral and postgraduate researchers. SREMat has built an expertise on the valorisation of residues towards ceramic, cement and inorganic polymer (geopolymer) formulations, from the level of binder synthesis all the way to full scale prototypes. He is one of the founders of the *Journal of Sustainable Metallurgy*, where he serves as the managing editor.



**Thomas Pretz.** Professor at RWTH Aachen. Head of department at IAR (Department of Processing and Recycling). Expert in organisation of municipal and industrial waste management, waste collection logistics, minimisation of waste production and optimisation of separate collection processes. Supervisor in ETN NEW-MINE.



**Rolf Stein.** CEO at Advanced Plasma Power Ltd., Swindon, UK. APP is a leading technology provider for Waste to Energy & Fuel plants able to treat a wide range of feedstocks including Municipal Solid Waste, waste biomass and Commercial/Industrial waste, using proven and patented Gasplasma® technology.



**Andrea Winterstetter.** Post-Doctoral Researcher at the Flemish Institute for Technological Research (Vlaamse Instelling voor Technologisch Onderzoek, VITO); PhD completed in 2016 at TU Vienna, Austria (Christian Doppler Laboratory for “Anthropogenic resources”); Focus: Multidisciplinary evaluation and classification of anthropogenic resource mining projects.

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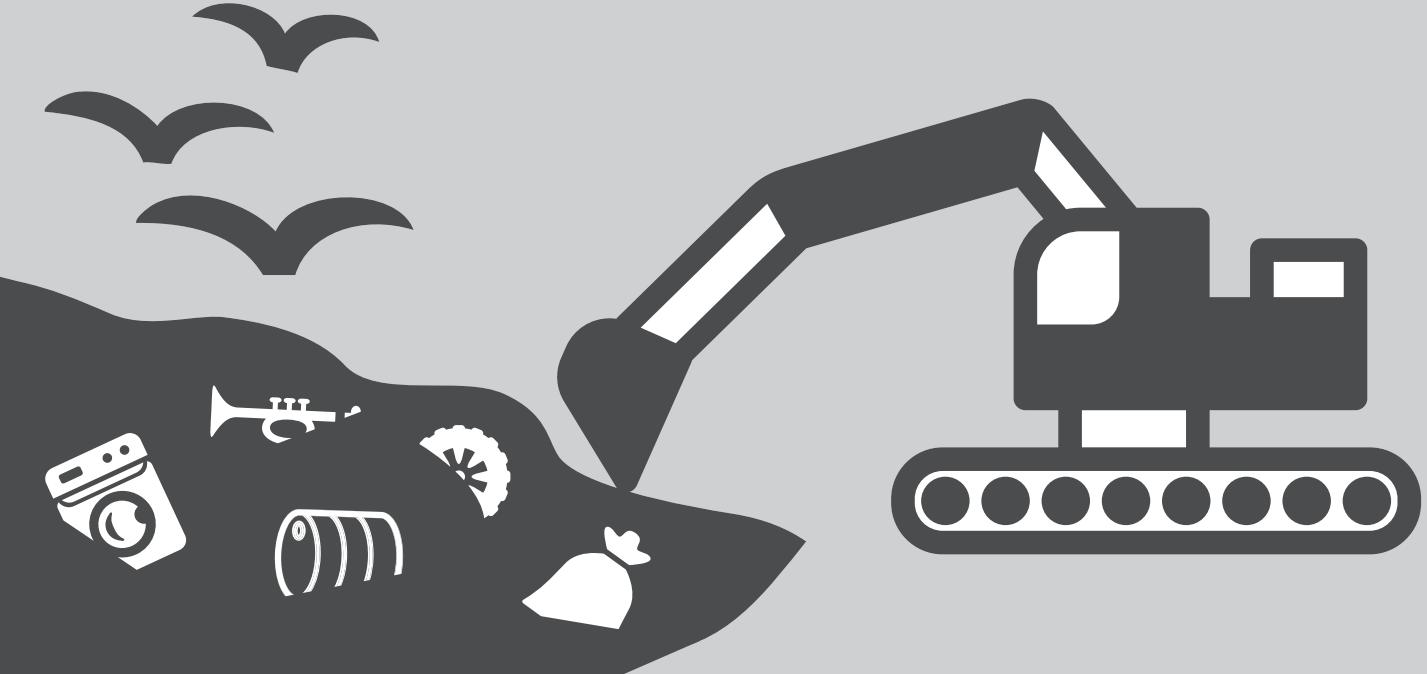
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## Session 1

# Geophysics, remediation, preprocessing technologies and metal extraction technologies in Enhanced Landfill Mining





# **MANAGING PAST LANDFILLS FOR FUTURE SITE DEVELOPMENT: A REVIEW OF THE CONTRIBUTION OF GEOPHYSICAL METHODS**

**Frédéric NGUYEN<sup>1</sup>, Ranajit GHOSE<sup>2</sup>, Itzel ISUNZA MANRIQUE<sup>1</sup>, Tanguy ROBERT<sup>1</sup>, Gaël DUMONT<sup>1</sup>**

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## **Introduction**

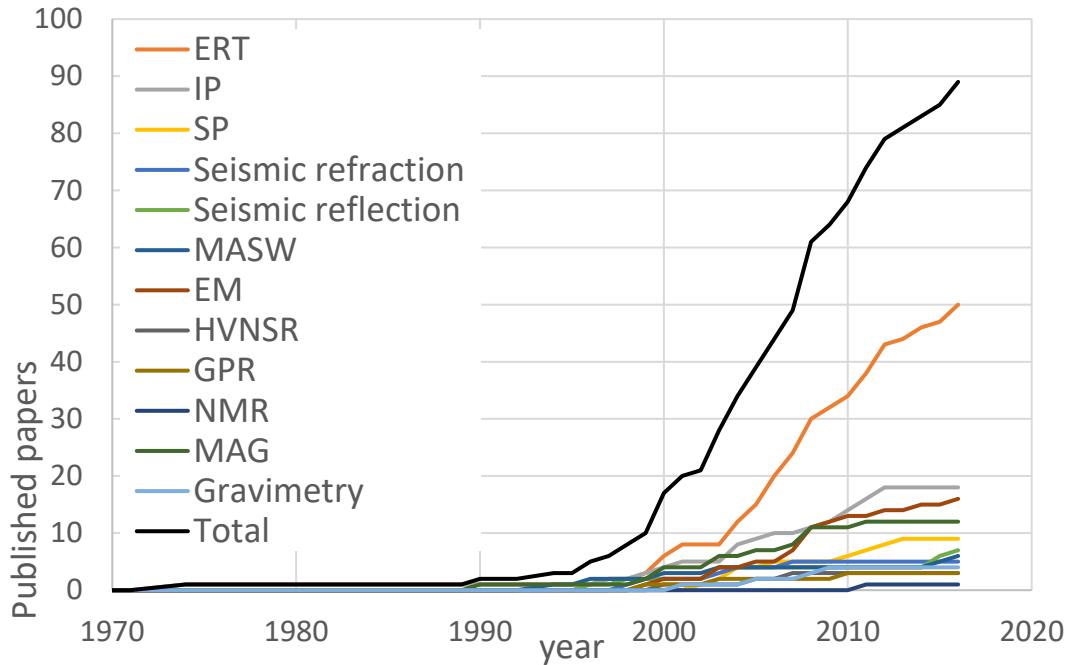
For more than 100 years, Europe has been discarding its unwanted waste materials in landfill (LF) sites.<sup>1</sup> Estimates suggest that there are at least 500,000 of these sites – some closed, some still operational – in the EU-28. An additional factor that concerns many experts is that a lot of these LFs are located in semi-urban environments. Fortunately, as a result of the EU's Landfill and Waste Directives, most of the still-operational LFs are “sanitary” LFs that are equipped with state-of-the-art environmental protection and methane-collection systems. For these LFs, a leachate-recirculation system – which allows biodegradation to take place more quickly, thereby increasing LF-gas production and shortening the exploitation time – can be installed. However, its success depends very much on the difficult-to-control water content, which affects both the completeness and the kinetics of biodegradation, and therefore the effectiveness and viability of subsequent LF-mining operations.

Although most of the currently operating LFs are sanitary, this still leaves a high proportion of Europe's LFs in a “non-sanitary” condition. These LFs, which generally predate the EU's Landfill Directive of 1999, have limited, poor or no protection technologies. As a result, such deposits could cause serious environmental problems, ranging from local pollution concerns (health, soil and water) and land-use restrictions to global impacts in terms of greenhouse-gas emissions. In order to avoid environmental and health problems, far-reaching remediation measures are needed in the short-to-medium term. Remediation, however, is a costly and environmentally impacting affair. In this context, the non-conventional Enhanced Landfill Mining (ELFM) concept offers a real way forward by transforming a large fraction of the excavated material into higher-added-value products in addition to recovering the land. In fact, the net economic balance of the combined remediation-ELFM activity can even be positive (especially for larger LFs) and generate revenues, which can then be used to cover the costs of remediating/mining the smaller, less-economic LFs. This

means that for most of the EU's LFs, LF-mining operations will become an attractive solution. However, the primary obstacle to the development of ELFM initiatives in Europe is a lack of knowledge about resources – materials and energy – in terms of volume, content, extraction feasibility and environmental impact.

While the surface components of LFs are a very familiar part of our urban landscapes, the vast majority of the valuable resources reside and interact below surface, which is generally inaccessible to any direct form of observation. Any planning of LF mining requires us to have a good estimation of the extent, volume and nature of the buried waste, whereas accelerated LF biodegradation requires close control over the water content. Conventional approaches to exploration, characterisation and monitoring involve defining a drilling grid, which is often investigated blindly, without any prior knowledge of the spatial distribution of the resources. Furthermore, to assess the environmental impacts of LFs, we are forced to rely on sparse borehole observations to infer the presence and the extent of potential leaks, which is additionally problematic as the subsurface is highly heterogeneous in many aspects (*e.g.* concentrations and flow paths). As such, these conventional approaches usually lead to LF mining operations with very high risks, and frequently low returns, due the uncertainty about resources and incomplete LF biodegradation. The environmental impacts, on the other hand, are poorly quantified and this can lead to a dangerous underestimation of the environmental and health effects.

Advances in non-invasive, geophysical science and the technologies for exploration, characterisation and monitoring, allow us to reduce the costs and the environmental footprint of conventional surveys, to increase gas production, to accelerate mineralisation, to lower the environmental risks of sanitary LFs, and to better address the environmental effects associated with LFs. In the past decade, the number of reported geophysical studies in the literature has significantly increased (Figure 1). In this contribution we review the most recent development and trends for geophysics applied to landfills in terms of survey objectives.



**Figure 1:** Published papers (source: Scopus) concerning landfills and geophysics. ERT: Electrical Resistivity Tomography, IP: Induced Polarisation, SP: Self-Potential, MASW: Multiple Analysis of Surface Waves, EM: Eletro-Magnetic, HVNSR: Horizontal to Vertical Noise Signal Ratio, GPR: Ground Penetrating Radar, MAG: Magnetic.

## Geophysical investigation of landfills

The study of landfills is conventionally carried out using intrusive methods such as core drilling or trenching, combined with various laboratory analyses (e.g. composition, humidity, temperature, organic content, microbiology).<sup>2,3</sup> This methodology is time-consuming and costly and often provides sparse and local information.<sup>3</sup> Non-invasive geophysical methods could represent a pre-investigation strategy that would help designing the drilling grid and would provide indirect information on the waste material with a greater spatial coverage than boreholes and can reduce health and safety issues compared to conventional drillings.<sup>4,5</sup> A multi-method approach reduces the non-uniqueness of the interpretation that may result from the analysis of a single physical parameter distribution. A multi-scale non-invasive investigation is also generally more cost-effective than drillings and sampling when applied to large areas. A common approach is to provide a rapid acquisition method to locate the boundaries of the disposal site, followed by an estimation of the landfill depth and further characterisation of the waste mass.<sup>6,7</sup>

## **Parameters of interest for landfill mining operation**

The site extension and depth determine the volume of waste buried in the pit and influence possible economies of scale. The waste composition (metallic content, organic content, and aggregates) are critical as these will determine the potential revenues associated with the operation. Different kinds of reusable materials can be recovered: Ferrous metals; Non-ferrous metals; Glass; Plastics; Combustible waste; Stones and construction waste; Waste of electrical and electronic equipment; Reclaimed soil used as landfill cover material. Waste from the mid 1960s to the mid 1990s is likely to yield the most valuable materials as this corresponds to a period of increased disposal of potential valuable materials and predates widespread recycling activities.<sup>8</sup> The occurrence of non-degraded organic waste might impede some valorisation process. The water content of the material influences the profitability of landfill mining operations. Leachate arrival during trenching or digging would slow down the waste material extraction from the pit. The moisture content also affects the material separation efficiency<sup>8</sup> as any form of material or energy recovery requires mechanical treatment of the waste (such as shredding, drum screen or metal extraction), whose efficiency is limited by the water content (clogging, formation of sticky sludge), and may therefore also require an expensive drying process. During energy valorisation of waste through incineration, the calorific value of humid waste is reduced, as a result of the energy needed to turn the waste humidity into water vapour.<sup>10</sup>

## **Physical properties of waste**

Waste deposits are characterised by various and heterogeneous (geo)physical signatures. In most cases, waste material is characterised by low densities and low seismic wave propagation velocities. Similarly, the electrical resistivity is generally low, due to the high electrical conductivity of the leachate and the increase in temperature resulting from waste biodegradation. These parameters generally contrast with the characteristics of the surrounding environment, so that geophysical prospecting methods can be used to characterise landfill geometry (size, shape and volume) and the internal characteristics of the waste mass (composition, humidity, temperature, compaction, density).

The electrical resistivity of landfills is generally low due to the high electrical conductivity of the leachate and the increase in temperature due to biodegradation of the waste. In saturated media, many authors<sup>5,11-14</sup> have shown that the electrical resistivity of waste is generally between 0.5 and 30 Ω.m. In the unsaturated zone, the electrical resistivity is several tens (> 30) Ω.m, or sometimes less in the presence of metal objects, garden waste (with high water retention) or ashes.<sup>11</sup>

The electrical chargeability signature of municipal solid waste (MSW) deposits is emphasised by many authors.<sup>15-21</sup> Chargeability anomalies reach hundreds of mV and waste material contour is well depicted in both chargeability and normalised chargeability inverted sections.<sup>20</sup> The high values of chargeability are often attributed to the presence of metal scrap,<sup>15,17,22</sup> resulting in the electrode polarisation phenomenon. However, some authors also explain high chargeability in waste deposits by organic material content,<sup>15,23</sup> wood content<sup>24</sup> or the layering of plastic sheets that would act as electric capacitors.<sup>25</sup>

The magnetic susceptibility of solid waste is mainly related to the presence of ferromagnetic objects and is often 2-4 orders of magnitude above that of sedimentary rocks.<sup>26,27</sup> Municipal waste is characterised by relatively low densities that are intrinsic to their composition and their low compaction compared to the natural host rocks/sediments. Generally, the density varies from 1 to 2 t/m<sup>3</sup> (e.g. 1.6 t/m<sup>3</sup> in<sup>28</sup>). Kavazanjian<sup>29</sup> published a unit weight profile starting from 0.6 t/m<sup>3</sup> at the surface to 1.3 t/m<sup>3</sup> at 45 m and higher.

The mechanical properties of landfills often offer relatively good contrast with those of natural soil, but generally lower contrast than for electrical properties. The use of seismic methods is favoured when the host formation is made of highly competent rocks. The heterogeneous compaction of waste (resulting from the use of landfill compactors, and then from its own weight) influences the seismic parameters: the higher the compaction rate, the higher the mechanical wave velocities. In saturated medium, water or leachate affects the P-wave propagation. The P-wave velocity in saturated waste is slightly larger or equal to the P-wave velocity in water (1450 m/s). Soupios<sup>30</sup> observed propagation speed of P-waves of about 1670 m/s in saturated solid waste, while Meju,<sup>5</sup> Abbas<sup>39</sup> and Konstantaki *et al.*<sup>34</sup> find much lower values, between 180 and 700 m/s, for an unsaturated solid waste material. The saturation effect on the S-wave propagation velocity is limited because water and gas do not transmit shear forces. However, the saturation influences the Poisson's ratio.

## Geophysical methods as landfill investigation tools

Multi-method geophysical surveys can be used for the detection, delimitation and characterisation of former landfill sites. The combined use of magnetometric, electromagnetic, gravimetric, seismic and electrical methods allows the estimation of the site extension and depth, and gives some insight in the waste material composition. Geophysical methods (*i.e.* magnetic and electromagnetic methods) might be used to identify a valuable fraction in the waste composition, such as metal. Geo-electrical methods are used to estimate the waste water content, which strongly affects the profitability of landfill mining operations. A prior knowledge of the site to

be studied, even partial, represents an undeniable advantage for the design of the geophysical survey and for geophysical data interpretation.

### **Extension**

Electrical methods are particularly well suited to delineate the lateral extent of a landfill given the strong resistivity contrasts that exist between the waste mass and the natural formation. In terms of contrast between MSW and host formation, various authors<sup>11,14,20,31</sup> have shown that the natural environment resistivity is often one or two orders of magnitude higher than humid MSW resistivity. Electrical resistivity tomography (ERT) can detect the borders of a landfill. The simultaneous acquisition of chargeability data is sometimes implemented. While the host formation is characterised by a very low chargeability (except for clays and mineralised rocks) and tabular or uniform resistivity, municipal waste landfills present chargeability anomalies up to 10-100 mV and irregular resistivity distribution.<sup>19</sup> The electromagnetic mapping method offers a fast and relatively cheap method to access the electrical resistivity/conductivity of the site, and is often used for preliminary investigation on large landfills. Electromagnetic methods are advantageously combined with magnetometric methods.<sup>6</sup>

### **Depth/thickness**

The bottom geometry and sometimes the depth of some landfills has been successfully evaluated with ERT.<sup>14,16,18,20</sup> However, difficulties in estimating the exact depth of the waste deposit could result from the site feature (e.g. no sharp contrast at the bottom of the landfill), or be intrinsic to the ERT method (loss of resolution with depth and the equivalence phenomenon of the ERT method). Few conclusive studies are available for seismic reflection or seismic refraction on old landfills. The analysis of the dispersion of surface waves (MASW) takes advantage of the propagation properties of surface waves that contains a large part of the recorded seismic wavefield and energy. The method allows to characterise the evolution of the shear-wave velocity with depth.<sup>4,32</sup> Although the method seems adapted to detect the transition between a compact host formation and waste material, few landfill studies offer a sufficient depth of investigation.<sup>32</sup> The HVNSR method, which utilises the horizontal-to-vertical spectral ratio of ambient vibrations, is sensitive to both the transmission properties of the S-waves and the thickness of the deposit; these two effects are often impossible to discriminate with a single method.

### **Composition**

The influence of the moisture content, pore fluid conductivity and waste temperature often dominates the other contributions for electrical properties, and therefore appears to control the distribution of the electrical resistivity of solid waste. An example of this phenomenon is shown by Chambers,<sup>31</sup> whose electrical images show

little variation in the saturated zone although the buried wastes have quite different electrical characteristics (matrix resistivity). A joint interpretation of electrical resistivity tomography and induced potential is particularly useful to differentiate waste of different nature (*e.g.* Household organic waste, industrial, clinker).<sup>17,23,33</sup> The waste composition differentiation is more difficult for waste deposits composed solely of MSW. The magnetic method can help detecting large metallic object (drums, fridge, etc.) inside the waste mass. S-wave velocity (obtained with the MASW method) may differ with type of waste deposits, primarily distinguished by their densities.<sup>36</sup> Higher values are recorded in waste deposit sites that accepted inert materials in the past.<sup>32</sup>

### **Water content**

The resistivity contrast between the saturated zone or at least the levels of free leachate (0.5-20 Ω.m) and the unsaturated zone (tens of Ω.m) is relatively large and often detected using ERT.<sup>11,14,30,31</sup> Dumont<sup>12</sup> established that geo-electrical methods (ERT and borehole EM) can be used to estimate the moisture content over large areas, provided that environmental parameters (temperature and leachate electrical conductivity) can be measured at several locations. Since a liquid can transmit compressional waves, seismic refraction using P-waves can also detect the depth of the water level.<sup>30</sup> The P-wave/S-wave velocity ratio distribution is interpreted in terms of leachate bearing (high Vp/Vs) and gas bearing (low Vp/Vs) zones.<sup>34</sup>

### **Geophysical methods applicability**

Some natural sediments present a similar electrical resistivity as the waste material. The most common material is clay, but Doll<sup>35</sup> also mentioned possible confusion with evaporite. Clay formations are also characterised by a strong chargeability signature. Igneous and metamorphic rocks are often characterised by relatively high magnetic susceptibilities. In this case, waste material with low metal content may not be distinguished from the host formation. The detection of the landfill borders with the seismic refraction method appeared not trivial when the landfill is installed over unconsolidated sediments.<sup>7</sup> An adaptation of the seismic interferometry method seems to improve the delineation of heterogeneities in waste in a MSW landfill.<sup>37,38</sup>

All the technical infrastructure present around or on top of a LF site may favour or impede the use of a particular geophysical method. The bottom sealing system and the covering layers also influence the choice of the geophysical methods. While a covering HDPE membrane is invisible for EM techniques, it hampers the use of the ERT method. In order to inject electrical current in the waste material (and measure the resulting potential), it is necessary to puncture the covering membrane. Nevertheless, the use of non-intrusive (less-intrusive) investigation methods is

favoured compared the conventional investigation techniques such as drilling or trenching. Asphalt or concrete (e.g. car park areas) layers induce similar issues. A clinker covering layer, or metallic infrastructure elements (e.g. degasification wells, cables) would most likely induce a strong magnetic response.

## Conclusions

A significant increase of geophysical studies applied to landfills is reported. The target of the surveys may range from mapping landfill boundaries to advanced characterisation of hydrodynamics. Landfill investigation necessitates the quantification of the waste deposit volume (extension and depth) and the characterisation of the waste material in terms of composition, mineralisation or compaction state and water content. Generally, a multi-scale geophysical investigation is essential to provide an attractive and cost-effective alternative/complementary solution to the traditional “drilling-sampling-analysis” characterisation methodology. In this paper, the role of each individual method has been presented and case studies have been reviewed, in order to select the optimal combination of geophysical methods given the landfill survey objectives.

## Acknowledgment

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# THE STATE-OF-THE-ART IN SENSOR-BASED SORTING

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## Introduction

Quality control in food and nutrition industry demands sophisticated technologies to identify specific material properties of single particles. Technology for these tasks has been developed during the last 50 years and today automation of quality control even for small particles like pies or potato chips is state-of-the-art. Also the harvesting technology is using sensor-based systems and sorting as a first step of quality control in the food chain. The technology has to deal with small and sensible particles characterised by widespread shapes and particle mass.

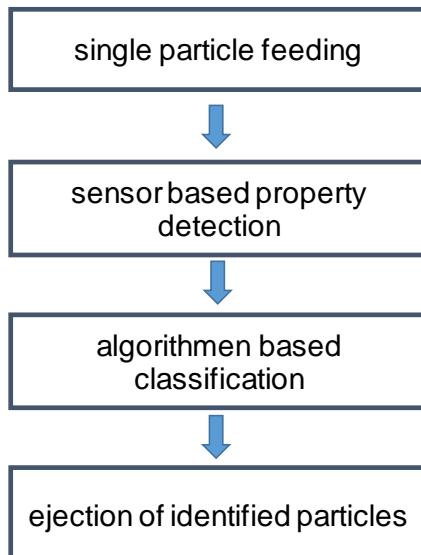
Derived from the food sector during the last 20 years the technology of automated single particle identification and automated sorting has been adapted to the tasks of waste processing, now known as sensor-based sorting (SBS) technology.

Comparing SBS technology with conventional physical separation processes, the advantage of SBS is that particle property identification and separation decision can be separated. In practice this means that an interpretation of measured data is possible while typical physical separating processes combine both the property identification and the driving force for the separation. Well known processes of this conventional type of sorters are air classifiers, magnetic and eddy current separators and all separators based on density as the crucial material property.

## Basics

Sensor-based sorting is the automated type of manual picking. Both processes are following the same process chain shown in Figure 1. The “sensors” that human beings can use are based on visible light and mass feeling when picking particles. Training of people ensures that they can identify specific properties before they start manual picking. The basic conditions for material flow streams that are provided as feedstock for automated SBS systems request a pre-processing of flow streams making them feasible for the separation process:

1. All particles must be liberated and presented to the SBS system independently from neighbouring particles.
2. Identification of material properties includes the position in x-y coordinates in order to link detection results with ejection commands. Therefore a clear definition of the “2-D shape” is necessary.
3. The velocity of particles between the identification area and the ejecting zone must be stable to assure that detected particles are ejected precisely.



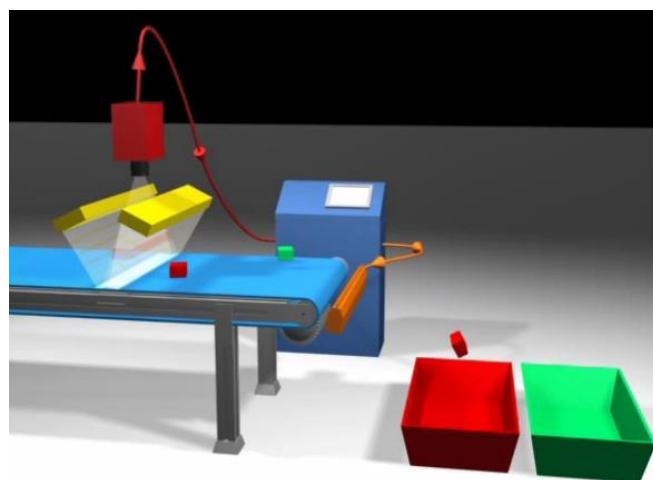
**Figure 1:** Process chain of single particle sorting

To liberate particles from each other is a task for shredders. They can open bags and conglomerates of waste particles by tearing forces with only low impact on particle size reduction. If higher humidity is present, fine particles will stick on the surfaces without any option of cleaning them in a dry way, only offering friction. The result often is a single particle with impurities of humidity and fine particles on the surface. Most SBS systems work with reflecting systems, meaning that impurities sticking on the surface of a particle influence the result of identification or sometimes make it impossible to get reliable surface based information of the mean material property. The SBS systems depends on the precise knowledge of the position of each particle inside the sensor system. Position finding is only possible if all particles can be characterised in a bounding box without any influence of particles around. In particular, film material can cover a wide area with only low mass and is able to hide smaller pieces or overlap with other particles. The identification of more than one particle represented in a bounding box hinders a distinct sorting decision. In order to realise sufficient throughput and sorting efficiency, a separation of 2D and 3D particles is also recommended to operate SBS systems successfully.

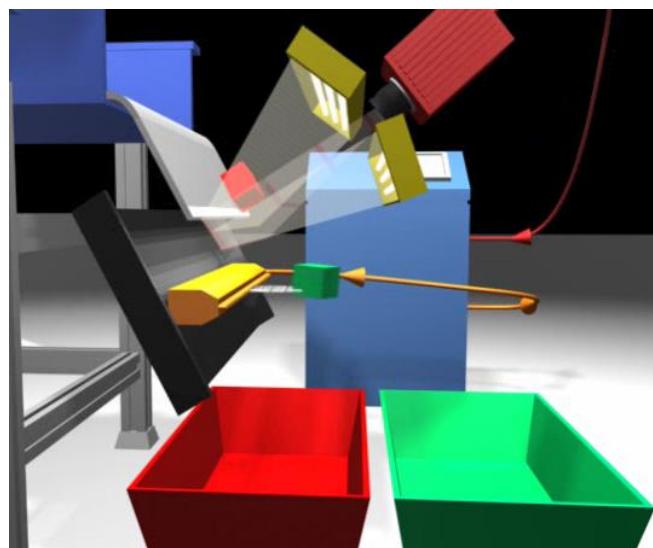
Separated flow streams due to shape also allow a specific adjustment of SBS units to ensure that the relative speed of particles cannot influence the separation result negatively. Most SBS systems are working with an ejecting system using air nozzles. One or more nozzles open for milliseconds to hit a particle detected to be ejected, and change its trajectory. If fine particles and dust are present in the feedstock, these fine and light impurities will be carried with the air from nozzles contaminating the eject flow.

## Sensor-based sorting

The SBS technology used in waste processing and recycling plants composes two different basic types, the belt-type (“B-type”) and the chute-type (“S-type”), shown in Figure 2 and Figure 3.



**Figure 2:** Belt-type SBS



**Figure 3:** Chute-type SBS

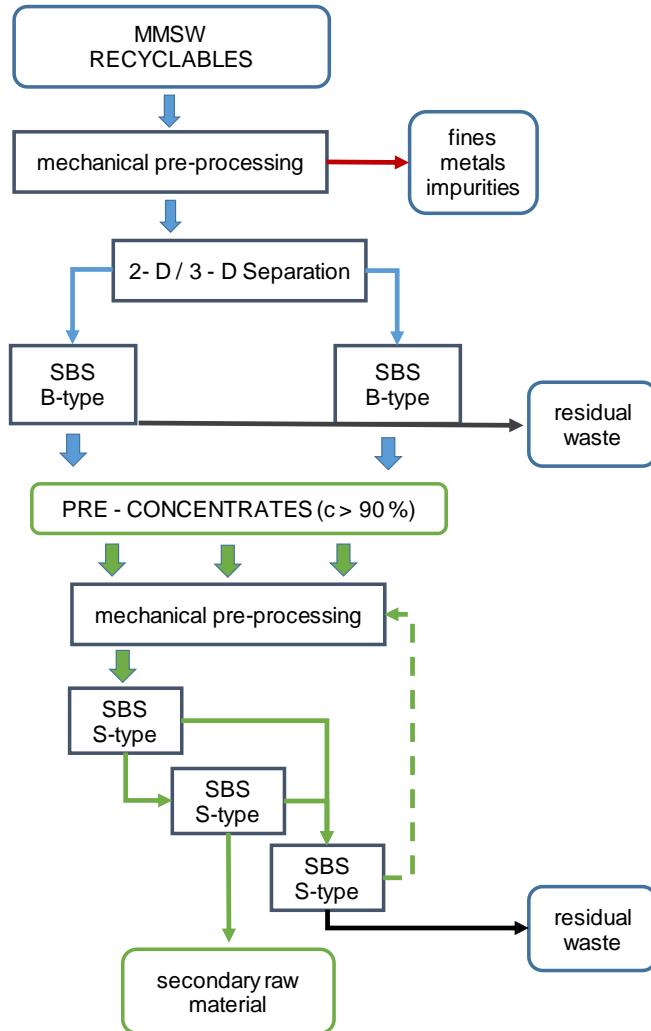
Although both types use the same technology of identification and separation, the way how the particles are fed to the system is different. To understand where in a flowsheet the different types can be utilised, a general flowsheet of waste processing is provided in Figure 4. The basic condition for belt-type SBS operation is that particles are able to stay on a belt driven with velocities between 1.5 and 4 m/s, without any relative speed to the belt. Depending on the material type and the dominant shape of particles, utilisation is possible for particles from 10 mm to even 300 mm in size. The technique is suitable for different waste types, such as municipal solid waste (MSW), commercial and industrial waste, scrap, packaging-waste, organic waste with a higher wood content and paper and cardboard.

The chute-type is chosen when particles show a shape and transport behaviour that is characterised by a relative speed compared to the main transport system in a separator. Examples are small particle less than 10 mm, glass cullets, plastic flakes or metal pieces with a more or less round shape, but also construction and demolition waste (C&D) up to particle sizes of 300 mm. Smallest particles sorted with S-type SBS are in glass recycling where SBS utilisation is used for particles up to 1 mm fine.

When processing waste to generate secondary raw materials, sorting processes can be designed both as single-stage or multi-stage processes. In a multi-stage design, the same equipment is used with different parameterisation to reach different separation goals. In stage 1, the process is used with the aim of having a maximum yield of the desired materials. In stage 2, the sorter is adjusted to further clean the concentrate, producing the required quality. In stage 3, the process is used as a scavenger collecting all particles that can be used in an additional run to increase both the yield and the mass recovery.

What is named mechanical pre-processing in Figure 4, is the most important element of the utilisation of SBS technology in waste processing. The main goals of this process are:

1. Limitation of particle size distribution: The majority of mechanical separation processes can only work successfully when particle size distribution offers a limitation to a range of 1:3 to 1:4 (relation between the smallest particle size ( $d_l$ ) and the largest one ( $d_h$ )). In case of SBS technology, the limiting factor is given by the nozzle design. Calibre and pressure determine the mass of particles that can be ejected. In case of S-type SBS units, the velocity of the particles passing the chute must be nearly the same to ensure liberation of particles. Depending on the predominant shape of particles, the particle size range must be smaller than 1:3, e.g. for glass cullet or plastic flake sorting.



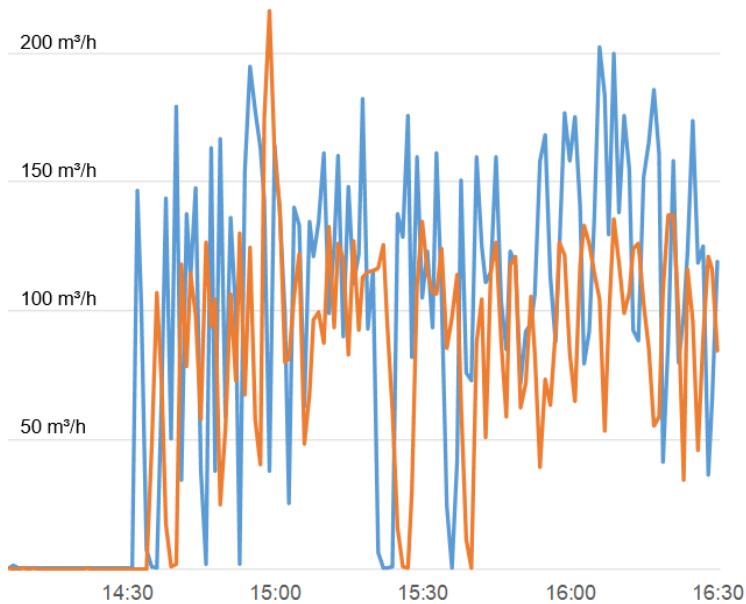
**Figure 4:** General flow sheet of waste processing and recycling processes

Particle size for the most processes on first level cannot be reduced because only the undestroyed original size of the former product offers the opportunity to gain information that cannot be detected by physical or chemical properties. Often the combined "article" information received by image processing based on VIS and the chemical information about e.g. the plastic composition provides the basics for the final sorting decision.

2. Particle shape: Due to the aerodynamic drag the behaviour of 2D and 3D particles is different when moving with higher velocities. To reduce the aerodynamic influence in the sorting process a shape selection in the feedstock of SBS units is required.
3. Materials composition: Waste is always a mixture of several materials with different densities. Due to density, both trajectories and fall velocity are different. In order to limit influences of different fall velocities, the particle size distribution is narrowed and pre-sorting of heavy components like metals

and minerals is done before starting a sorting process for materials with lower densities on a level of 1 kg/cm.

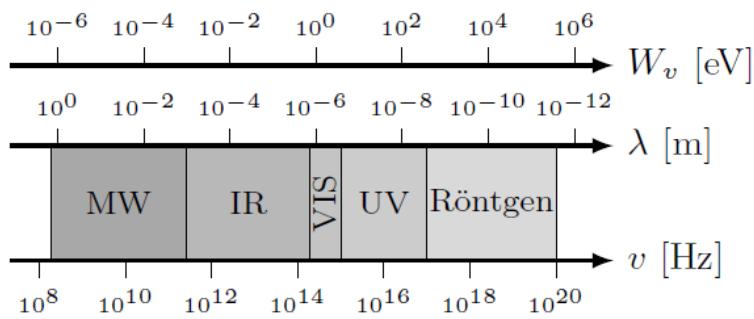
4. Continuous feeding: Sorting units require feeding a specific volume per time unit. If volume is varying, a discontinuous feeding of a SBS unit occurs where phases of overload and underload alternate. An overload will result in unsuccessful liberation of particles and decreasing sorting efficiency, hence resulting in quality problems and reduced yield. An underload period means that sorting capacity is wasted. The first phase of waste processing is always combined with shredding and sieving processes. They are both characterised by discontinuous operating conditions, as shown in Figure 5. The blue line gives the volume delivered from a single shaft shredder and the yellow line describes the volume of drum screen overflow > 60 mm as feedstock for further sorting. The variation of volume flow used for the sorting unit's feedstock is about 1:3. It is undoubtedly so that sufficient sorting e.g. with a SBS is not possible with such large variation in feeding rate.



**Figure 5:** Feeding rate of a waste treatment plant with single shaft shredder and drum screen

## SBS in waste processing lines

SBS technology today is using the electromagnetic spectrum shown in Figure 6. The most common sensors are working in the near infrared (NIR), the visible light spectrum (VIS) and the x-ray spectrum (Roentgen). The particle size range is limited in most cases to 30 to 50 mm. The exclusion of fine particles offers the opportunity to sort the waste size spectrum of 50–300 mm in two lines both with narrowed particle size spectra. The types of utilisation are widespread: a rough overview is given in Table 1.



**Figure 6:** Electromagnetic spectrum utilised for SBS

**Table 1:** Examples for SBS utilisation using B-type units

Utilisation	NIR	VIS	X-RAY
MSW – plastics, wood	x		
Packaging waste – plastics, beverage carton	x	x	
Comingled waste – plastics, paper	x		
Scrap – “meat balls”			x
NF-Scrap – different metals and alloys	x	x	x
Green waste – plastic & mineral impurities	x		x
PET bottle recycling – colour, PET-type	x	x	
RDF/SRF from MSW - impurities	x	x	x
C&D waste–wood & gypsum cardboard	x		

While the first level of waste processing only produces pre-concentrates with limited quality, during the second phase a beneficiation to secondary raw materials quality improvement is aimed for. These processes need to reduce the particle size by shredding with shears or other comminution processes working on a higher velocity level than the single shaft shredders of the first processing level. Resulting particle sizes of about 10 mm enable an advanced cleaning of particles surfaces. The final sorting of clean products is done mostly with S-type SBS units. Some utilisations are listed in Table 2, where an inductive sensor (IND) for metal detection is added.

**Table 2:** Examples for SBS utilisation using S-type units

Utilisation	NIR	VIS	IND	X-RAY
Plastic recycling –colour, plastic type	x	x		
Paper – type of printing ink	x			
NF-Scrap – different metals and alloys	x	x		x
Glass – colour and heat resistant glass		x	x	x
PET bottle recycling	x	x	x	

## **Conclusion**

The state-of-the-art in sensor-based sorting means that nearly all waste treatment processes focusing on products for material recycling and respectively fuels for energy recovery are using sensor-based sorting technology. The market offers technical solutions for most applications, and is characterised by constant development and improvement of the software. New software applications are created for new waste types, originating from new products ensuring that well-established recycling systems aren't jeopardised by new material compositions. The efficiency and sorting ability today is on a very high level, although pre-processing of waste flows presented to SBS technology is often poor. The technical obstacles to feed sophisticated sorting equipment constantly and well-dosed are significantly lower when particle sizes are smaller and article properties are destroyed. Therefore, the efficiency of SBS technology in the second phase of processing leading to high quality secondary raw materials is much higher, offering qualities sometimes with impurity rates of only 5 ppm.

# **EXPLORING THE POTENTIAL OF ELECTROMAGNETIC SURFACE MEASUREMENTS FOR THE CHARACTERISATION OF INDUSTRIAL LANDFILLS**

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## **Introduction**

Enhanced landfill mining<sup>1</sup> (ELFM) could optimise the economics of landfill remediation. Landfill exploration is considered as a key aspect of ELMF as it can contribute to evaluating the amounts and properties of waste material. Geophysical measurements carried out at the landfill surface offer a non-invasive, non-destructive and rapid approach to the identification of subsurface structures. In contrast to most geophysical studies on landfill sites described in literature, this study does not focus on determining the environmental risks arising from disposed waste. Instead, the ELMF potential of disposed waste is investigated. The aim of this work is to explore the suitability of surface measurements with frequency-domain electromagnetic induction (FDEM) and ground penetrating radar (GPR) measurements for characterising waste layers, and more in particular their geometry and electric properties. The geophysical measurements were made with real-time GPS positioning,<sup>2</sup> followed by trench excavation. Additional trench profile measurements were made to validate the electromagnetic property distributions derived from the surface measurements.

## **Materials and Methods**

**Site description** The site is part of a former paint factory in Ghent, Belgium, which started its activities in 1958. From 1941, the site was the location of a textile production facility. The investigated area was covered by gravel and used for on-site traffic. On the described site, a transect with a length of 33 m was investigated. In the context of environmental site assessment, previously conducted soil investigations indicated a contamination with heavy metals and polycyclic aromatic hydrocarbons.

**FDEM survey** The described site was surveyed using a FDEM sensor, in particular a DUALEM-421S<sup>3</sup> (DUALEM Inc., Milton, Canada). This sensor incorporates six

transmitter-receiver coil combinations: three in a horizontal co-planar (HCP) configuration, with inter-coil distances of 1 m, 2 m, and 4 m, and three in perpendicular configuration (PRP), with inter-coil distances of 1.1 m, 2.1 m, and 4.1 m. As a rule of thumb, HCP configurations sense the ground to a depth of around 1.5 times the inter-coil distance, while for PRP configurations this factor is 0.5. However, also the electrical conductivity of the subsurface is a determining factor of the actual penetration depth. For surveying, the sensor was fixed on a sled towed by a quad bike. The exact position of the quad bike was recorded using a Trimble differential GPS. The GPS and geophysical data were logged synchronously at respective frequencies of 1 Hz and 4 Hz.

**FDEM data processing** The recorded GPS data were translated into sensor position data according to the constraint method described in Delefortrie *et al.*<sup>4</sup> The sensor data were then converted into apparent electric conductivity ( $EC_a$ ) data.<sup>5</sup> Subsequently, the surface data were inverted to obtain a distribution of true electrical conductivity, based on the forward formulations given by Ward and Hohmann.<sup>6</sup> A new FDEM-inversion approach was developed based on the application of an update step of the Ensemble Kalman Filter algorithm,<sup>7</sup> with a one-dimensional, multi-layer conductivity model. From the Bayesian standpoint, the algorithm starts with given prior estimations of electric conductivities in the form of Gaussian probability distributions. The electrical conductivity is constraint to positive values by using logarithmic prior distributions. To avoid abrupt conductivity variations, the conductivity value in a single layer was assigned a minimum correlation with the corresponding values in neighbouring layers. In the update step, measurement data are used to invert the profile or, in Bayesian terminology, to compute samples of the posterior distributions. The mean of the posterior distribution is taken as the final estimate for the inverted, true conductivity; the variance of the posterior distribution serves as a measure of the uncertainty on the estimated conductivity. Using the outlined one-dimensional approach all measurement locations were inverted independently.

**GPR survey** For the GPR survey, a dual-frequency, time-domain system was used, more specifically a Utility Scan DF impulse GPR, with 300 and 800 MHz as centre frequencies (Geophysical Survey Systems, Inc., Nashua, New Hampshire, USA). A transmitter antenna emits short electromagnetic pulses and, as contrasts in material properties are encountered during propagation into the subsurface, energy is reflected to the surface and recorded at a receiver antenna.<sup>8</sup> The reflections are recorded with their corresponding arrival time. A two-dimensional representation of multiple time series is called a radargram. The GPR survey was conducted along the same transect as the EMI survey.

**GPR data processing** In a first step, a correction for the so-called time zero, *i.e.* the travel time required for the radar pulse to enter the subsurface after leaving the antenna, was made. Secondly, the recorded travel times were transformed into depths using an estimation for the propagation velocity.<sup>9</sup> Afterwards, a background removal was applied to the GPR data to reduce background noise.<sup>9</sup> As a final step, the amplitudes of all arrival times were normalised by automatic gain control.<sup>9</sup>

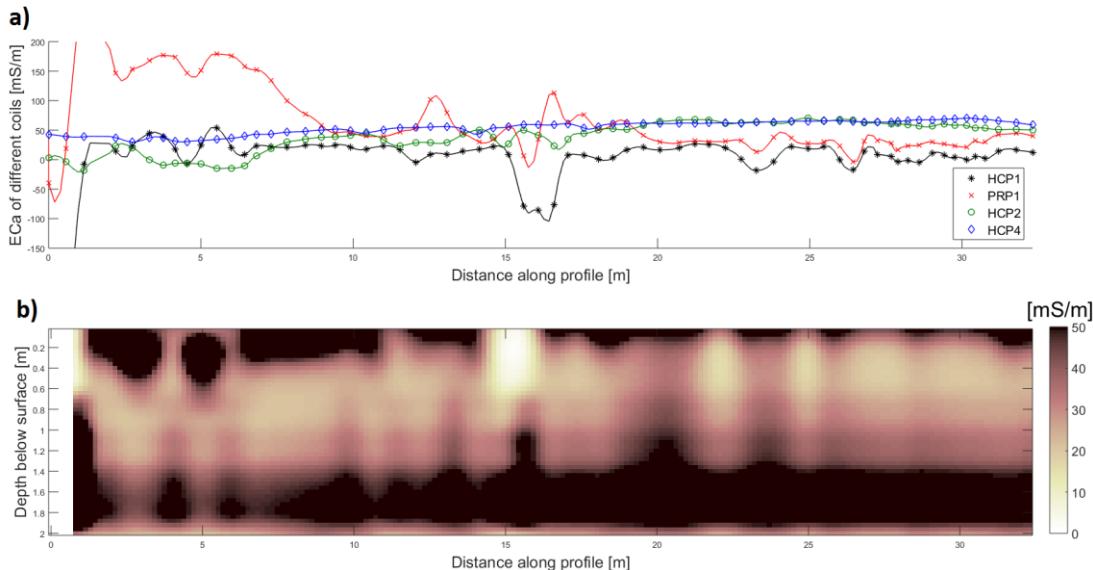
**Validation data** After the surface measurements, a trench of approximately 1 metre depth was excavated along the survey area. A profile description was made based on visual observations. The profile (Figure 3a) showed various, though distinct, layers of different materials, of which seven main types were discriminated. The material occurring at the bottom of the trench (type 3) was identified as, presumably burnt, municipal solid waste. The origin of the above-lying sandy material (type 2) was unclear. Most likely, this waste had an industrial origin, but no further (standard waste material) characterisation was conducted. Three augerings were made in the bottom of the trench (near 2 m, 19 m and 31 m distance along the profile in Figure 3) which allowed to derive the thickness of the municipal solid waste layer and indicated the underlying natural material consisted in clay. Afterwards, additional profile measurements of electrical conductivity ( $EC_p$ ) and relative dielectric permittivity (RDP) were made with a UGT UMP-1 handheld-sensor (Umwelt-Geräte-Technik GmbH, Muencheberg, Germany) at the locations indicated in Figure 3b and 3c. Since a measurement with the UGT UMP-1 requires penetration of electrodes, not all materials could be investigated.

## Results and discussion

The inverted profile and the recorded apparent electric conductivities are shown in Figure 1. Negative values and distinct peaks in the  $EC_a$ -data are possibly caused by near-surface metal pieces. Such effects are clearly visible in the inversion result (*e.g.* at 16 m, Figure 1), but are neglected for the overall evaluation of the subsurface structure. For further descriptions of the results, the profile is considered as two separate parts. The part showing complex layering, from 0 m to approximately 10 m distance, and the homogenous part from 10 m to the end of profile, showing three distinct layers. From 0–10 m along the profile, a relatively high electrical conductivity was estimated for the top layers. Below 0.6 m, a layer of lower conductivity is seen, while the conductivity rises again for the bottom layer (approx. at 1.2 to 1.3 m depth). The conductivity at the pit bottom appears to be slightly higher on the homogeneous part of the profile. This observation is consistent with the shape of the  $EC_a$ -signal of the HCP2 coil configuration (Figure 1a). The layer of high conductivity at the bottom corresponds to the occurrence of the municipal waste (Figure 3a). The higher conductivity of this waste material was confirmed by the profile measurements of

electrical conductivity, as shown in Figure 3b. According to the inversion results, in the homogenous part of the profile, roughly three layers can be discriminated, which agrees with the layering of material 1, 2 and 3 in the profile description (Figure 3a). Additionally, the  $EC_a$  signal for the 4 m HCP coil configuration (Figure 1a) suggests that the conductivity at a depth larger than the excavated trench is more homogeneous than at the exposed part. From 2–2.5 m depth downwards, natural clay was found which can be assumed to be more homogeneous.

The results of the GPR survey are shown in Figure 2. For the first 10 meters of the profile, the GPR signal shows strong attenuation as from 0.2–0.3 m depth, indicating the presence of relatively high conductive material. This is consistent with the electrical conductivity distribution estimated from the FDEM inversion. From 10 m onwards, a strong reflection can be observed at a depth of around 0.6 m, slightly inclined towards to the centre of the profile. This strong reflector seems to correspond with the layer boundary between the sandy material and the municipal waste (Figure 3a). A similar RDP contrast was shown by the profile measurements. The boundary between the top layer (type 1) and the sandy layer does not show in the GPR profile, likely because of the similar RDP of the materials.

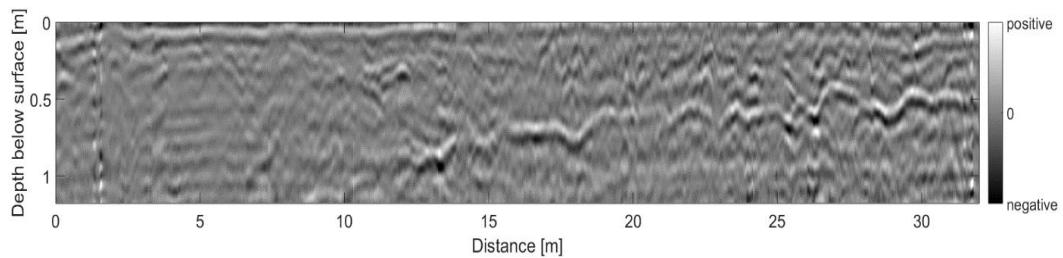


**Figure 1:** a) FDEM measurement data used for the inversion (PRP2 and PRP4 data neglected to reduce metal artefacts in the inversion results) b) Smoothed inversion results for the electric conductivity

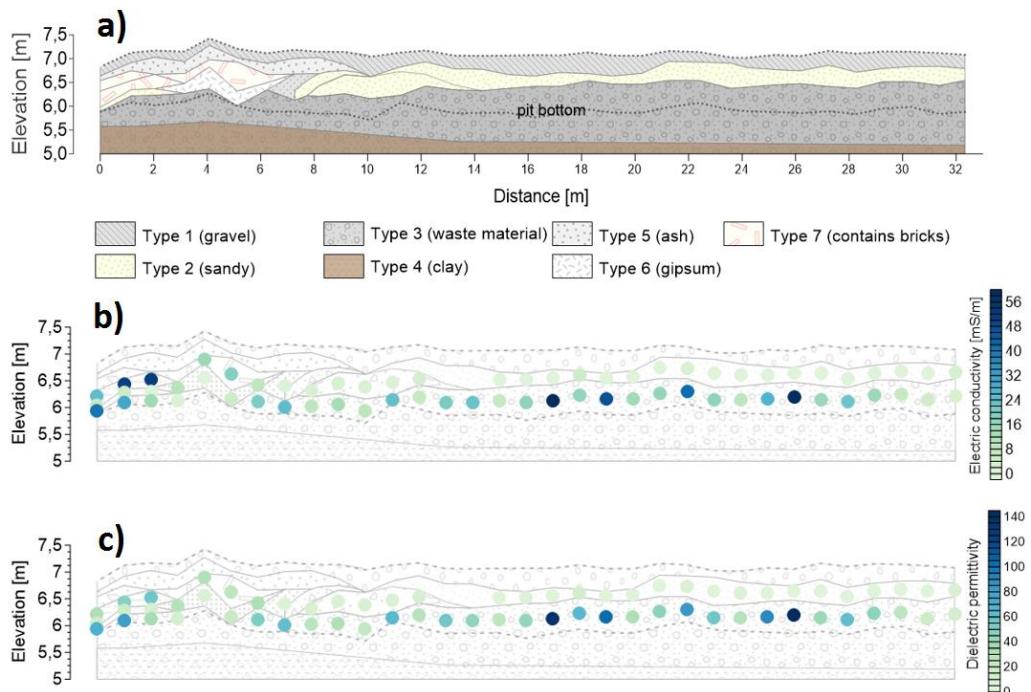
The contrast observed in both RDP and electric conductivity between the sandy material and the municipal waste allows making a good estimation of depth of the waste material type (type 3). This illustrates that both FDEM and GPR can contribute to the characterisation of the spatial distribution of disposed waste materials. The more complex organisation of disposed materials in the first part of the profile could

only partly be reconstructed as only the strong contrasts in material properties can be resolved from the surface measurements. The FDEM measurements, representative of relatively large subsurface volumes here appear to provide insufficient (vertical) resolution to discriminate the complex sequence of disposed materials. For GPR, the high-conductive material in the upper 50 cm prohibited to retrieve detailed information from RDP variations at larger depths.

The outlined approach, combining GPR and FDEM measurements with targeted processing, allowed a localisation of different material by relative electric properties and therefore, it is assumed that the approach presents a contribution to determine the ELF M potential of a site.



**Figure 2:** GPR data from the 300 MHz antenna after processing (data from 800 MHz antenna not shown here for brevity)



**Figure 3:** Schematic representation of the profile description made, indicating the main types of material discriminated (c), and profile measurements of electric conductivity  $EC_p$  (a) and RDP (b) made with a UGT UMP-1 BT soil moisture meter

## Future steps

The EMI data were inverted using only a rough estimate of the subsurface electric conductivity as obtained from the profile measurements. Notwithstanding promising results were achieved using the profile measurements as calibration data, the collection of reliable calibration and validation data sets for FDEM inversion presents an important topic for future research, particularly considering the generally complex subsurface context of landfill sites. Furthermore, FDEM inversion could be optimised by including data of other subsurface properties, such as the magnetic susceptibility.

## Acknowledgements

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# FINE FRACTIONS FROM LANDFILL MINING: POTENTIAL AND MAIN CHALLENGES TO OVERCOME

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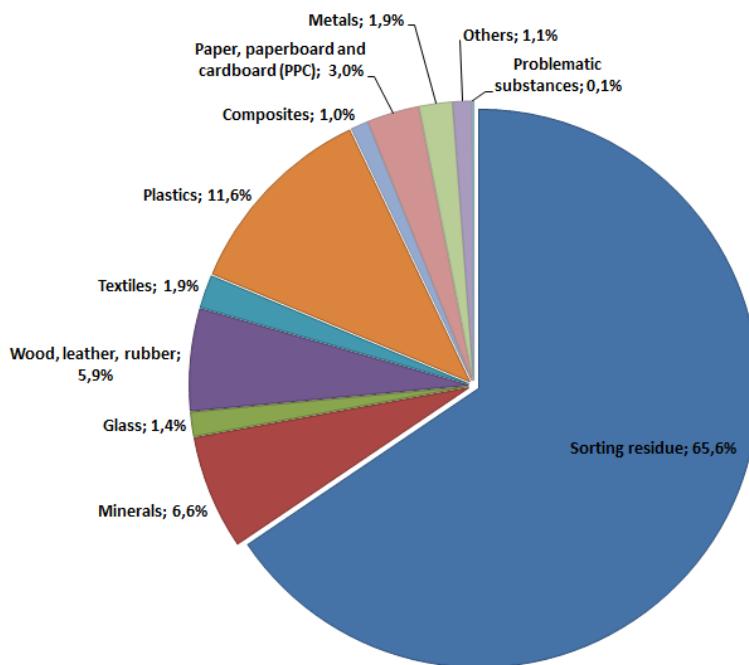
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## Introduction

Several investigations on landfill mining (LFM) and Enhanced landfill Mining (ELFM) have shown that a typical composition of excavated waste from a Municipal Solid Waste (MSW) landfill is – in the order of magnitude – 55 wt% of a mixture of fine materials (“Soil”), 15 wt% of mixed inert materials (“Stones” + “Glass” + “CDW” (construction and demolition waste) + “Inert”), 7 wt% of wood, leather, rubber and textiles (together), 5 wt% of plastics, 5 wt% of paper and cardboard, 5 wt% of organics, 2 wt% of total metals (Fe + non-Fe metals) and 6 wt% of other materials (“Other” + “Non-MSW” (non-municipal solid waste)).<sup>1</sup> The mixture of fine materials (sometimes also referred to as “soil”, “soil-like” or “soil-type” fraction in other studies) is denoted herein as “fine fractions”, since this fraction is also composed of other fractions (e.g. plastics, textiles, rubber, leather, wood, glass, metals, etc.). The fine fractions (commonly considered as the material with a particle size from < 60 to < 10 mm, depending on the author) have been identified as 40-80 wt% of the total mined material in several investigations.<sup>2</sup>

Due to their quantity, composition and characteristics, the fine fractions are of utmost importance to assess the feasibility of a LFM project. This is the case because, to this day, material and energy recovery in LFM has been restricted to the coarse fractions in most of the projects, while the fine fractions have been re-directed to the landfill with poor or no treatment despite their recovery potential.<sup>3,4</sup> A detailed study on the material composition of the fine fractions (< 40 mm) of mined waste from a Municipal Solid Waste (MSW) landfill in Austria<sup>5</sup> reveals the following composition (Figure 1): the largest sub-fraction of the “fine fractions” accounts for the fraction “Sorting residue”, representing 65.6 wt% (wet basis). This fraction corresponds to what in the present paper is referred to as the “soil-like” fraction, due to its resemblance to soil in appearance; nevertheless, the composition and properties of this fraction can differ strongly from those of soil. At the same time, the soil-like

fraction is composed to a major extent of an organic sub-fraction and a mineral sub-fraction, similarly to soil.



**Figure 1:** Composition of fraction < 40 mm from mined MSW landfill in Austria (modified)<sup>5</sup>

The three following, most abundant constituents of the fine fractions in that study correspond to the fractions: "Plastics", "Minerals" and "Wood, leather, rubber", with amount to 11.6 wt%, 6.6 wt% and 5.9 wt% (wet basis), respectively; while contents of 1.9 wt% of metals and textiles (each) were reported. This information suggests that the fine fractions can contain an interesting amount of materials that could be recovered and, therefore, to ignore their potential and keep on directing them to the re-disposal pathway is to be questioned.

Analyses<sup>6</sup> of the chemical composition of the fine fractions (< 10 mm) from the Remo landfill, Belgium, report a composition of 45 wt% SiO<sub>2</sub>, 9 wt% CaO and 5 wt% Fe<sub>2</sub>O<sub>3</sub>. Mineralogically, few data on the composition of the fine fractions are available. One of these is the composition of the fine fractions (< 40 mm) from an Austrian landfill, which was investigated in the LAMIS project and showed 34 wt% quartz (SiO<sub>2</sub>), 30 wt% calcite (CaCO<sub>3</sub>), 16 wt% dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>), 15 wt% muscovite (KAl<sub>2</sub>[(OH,F)<sub>2</sub>AlSi<sub>3</sub>O<sub>10</sub>]) and 5 wt% kaolinite (Al<sub>4</sub>[(OH)<sub>8</sub>Si<sub>4</sub>O<sub>10</sub>]), which confirms the presence of SiO<sub>2</sub> and CaO as main components and further suggests that also MgO and Al<sub>2</sub>O<sub>3</sub> are present in significant amounts.

It is important to point out that the composition of MSW changes according to geographic region, its development level, culture and many other factors.<sup>7</sup>

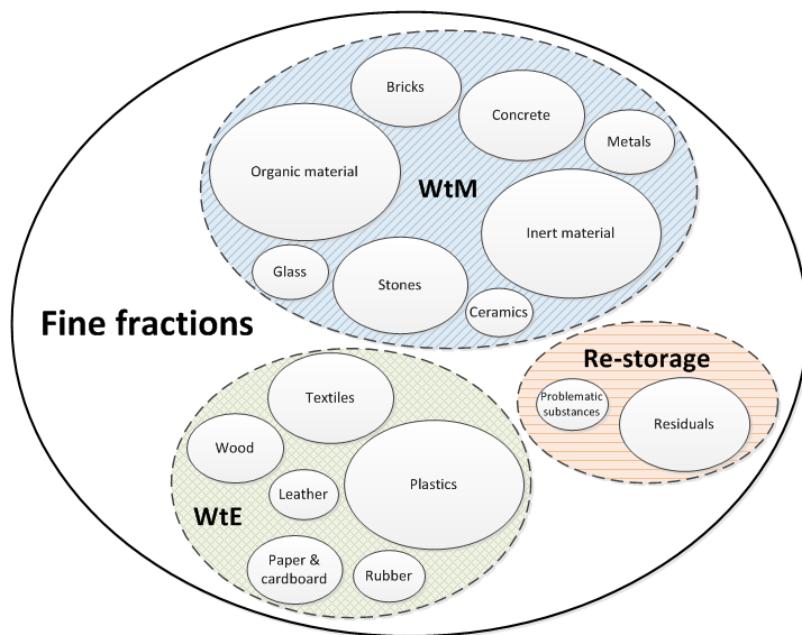
Additionally, the internal conditions to which the disposed waste in a landfill is exposed to (*e.g.* aerobic/anaerobic conditions, moisture, temperature and pressure) can vary significantly from site to site, as well as the operation procedures, local weather conditions and legislation, among many others. Even between landfills that appear to be very similar to each other (in terms of size, volume, region, received type of waste and climatic conditions), the straightforward application of information from one landfill to the other without sampling appears unfeasible.<sup>8</sup> Moreover, previous research has stressed that the costs and benefits in LFM projects are always case-specific and cannot be generalised.<sup>9</sup> The specific conditions of a given landfill will determine if landfill mining and land reclamation are feasible for the site.<sup>10</sup>

Furthermore, studies have also highlighted the importance of a proper exploration of the landfill as one of the initial phases of a LFM project.<sup>6,11,12</sup> During the exploration phase of a landfill mining project, test excavations or drillings into the landfill are necessary to assess the composition of the landfilled material.<sup>13</sup> The validation and utilisation of non-invasive exploration methods, such as geophysical exploration, will also play a critical role in LFM and ELFM projects. Thus, in order to evaluate the material and energy recovery potentials of the fine fractions from a specific landfill, adequate and proper quantitative and qualitative characterisations of the disposed waste are to be performed and several factors are to be taken into account. In order to be able to direct a relevant amount of the fine fractions towards Waste-to-Energy (WtE) and Waste-to-Material (WtM), some technological, legal and economic challenges are to be overcome and a new approach to process the fine fractions is to be implemented. The potential of the fine fractions for material and energy recovery, as well as the main technological challenges that this represents, are the main topics discussed in this paper.

## Potential for WtM and WtE

Previous LFM investigations have shown that the fine fractions are mainly composed of a soil-like fraction and an inert fraction, as well as of smaller amounts of plastics, metals, wood, paper and cardboard, textiles, leather, rubber and, in some cases, problematic substances.<sup>2</sup> These fractions could be separated from each other and be directed towards energy or material recovery, according to their properties. For this purpose, liberation of individual particles is required, which might require a thorough material processing (*e.g.* drying, washing). It might be the case that a certain amount of these fractions is not suitable for any of the previously referred pathways; as a result, this residual fraction could be re-stored, perhaps at the same landfill, till new technologies for its exploitation are available. Alternatively, the fine fractions could also be thermally valorised as a whole, but this would likely require additional fuel to compensate for its low calorific value. The potential of each of the fractions that

constitute the fine fractions towards energy and material recovery proposed in the present paper is shown in Figure 2.



**Figure 2:** Potential of the fine fractions towards WtE and WtM

In order to minimise the overall impacts and improve the efficiency of the utilisation of resources, the EU has employed a hierarchical concept for the management of waste (Directive [2008/98/EC] of the European Parliament and of the Council on waste); where waste management has been given five main priorities. These priorities are shown in Figure 3 from the highest (top) to the lowest priority (bottom). Prevention targets the avoidance of waste, while preparing for re-use, recycling and recovery aim to valorise waste materials. Disposal, as a last resort, targets the elimination of waste. Therefore, according to the European waste management hierarchy, preparing for re-use and recycling are to be preferred, as far as they are feasible and represent a better environmental solution, to energy recovery from waste. In other words, WtM is, in general, to be considered before WtE. The quality of the retained materials in the landfill and the WtM and WtE technologies available for material valorisation will, among others, determine the feasibility of ELFM.<sup>6</sup>



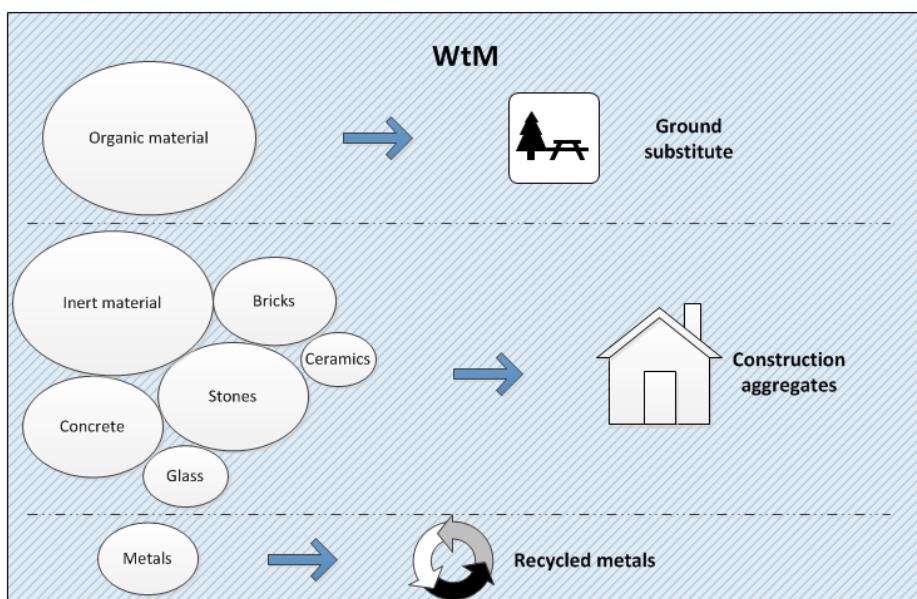
**Figure 3:** Waste management hierarchy<sup>14</sup>

### Waste-to-Material

This concept refers to the recovery of materials from waste. These recovered materials are commonly referred to as secondary raw materials. In theory, these materials can be directly reused, recycled or processed in such a way that they can be used again. In the case of LFM, the quality of the recovered materials might exclude its direct re-use and, as already stated, limit the recyclability of some of them. Nonetheless, previous LFM investigations have revealed that interesting amounts of metals, Fe plus non-Fe metals, could be recovered from the fine fractions for recycling.<sup>2</sup> Besides metals, two other, highly interesting fractions from the fine fractions for material recovery are the soil-like and inert fractions; which could be used in various applications (*e.g.* soil-like fraction as ground substitute and inert fraction as construction aggregate) if the heavy metals and organic pollutants contents are low. These fractions are of utmost importance, because combined they account for most of the fine fractions and, therefore, they are presently the materials which are mainly sent back to the landfill for re-disposal; hindering the overall economic and environmental feasibility of a LFM project.

It is known from previous studies<sup>2</sup> that the soil-like fraction is, in some cases, composed of the material used to cover the waste (daily, intermediate or final cover material) during the operation of the landfill. In many cases, materials with a low permeability (*e.g.* clay) have been used for this purpose. The intermediate and daily cover materials usually consist of a 15-30 cm layer of *e.g.* soil, clay or compost,<sup>15</sup> although this can vary depending on local regulations and site-specific, operational procedures. The presence of large amounts of fine fractions in excavated waste can be explained by the use of intermediate or daily covers in landfills, while a low amount of fine fractions could be related to open dumpsites.<sup>16</sup> Furthermore, it is not rare to find landfill sites where a variable amount of C&D waste was mixed with the cover material to give a better load capacity to the platforms for the transit of the trucks on the landfill area, as well as the usage of other received materials in combination with the main cover material, such as soil, compost and dry sewage

sludge, as daily cover materials. A significant percentage of the fine fractions can also be formed through the weathering of mineral wastes and through the humification and mineralisation of biowaste.<sup>2</sup> Thus, it can be suggested that the soil-like fraction is mostly composed of an organic sub-fraction and a mineral sub-fraction, which could be sorted out from each other by further processing. As for the inert fraction, which has been identified as mainly composed of C&D waste, stones, minerals, glass and ceramics in previous studies, a relevant amount of organic matter could also be present due to the presence of soil and waste mixtures. The recovery of these organic and inert materials could yield an organic fraction, which could be used, among others, as ground substitute or soil improver, and an inert fraction, which could be suitable for the substitution of mineral aggregates (*e.g.* sand) for construction purposes, provided that they comply with the corresponding quality and characteristics stipulated in the local regulations. Figure 4 conceptually shows the recovery of metals, construction aggregates and a ground substitute from the fine fractions.



**Figure 4:** Material recovery from organic and inert fractions of LFM fine fractions

For metals, glass, ceramics, stones and other inert material, waste-to-material might be possible if the materials can be separated adequately.<sup>6</sup> Fine fractions have been also used as cover material in landfill to build a methane degradation layer.<sup>17</sup> When the level of pollutants is low, the fine fractions could be used as future landfill cover.<sup>4</sup> The material can be used as cover material after assessing the geotechnical suitability.<sup>10</sup> The hydraulic conductivity (DIN 18130-1) of a fine fraction from an Austrian landfill investigated in the LAMIS project accounted for  $5.3\text{--}5.7 \times 10^{-8}$  m/s.<sup>18</sup> One potential end-use for fines excavated from a landfill could be as clean fill off-site.<sup>12</sup> The fine fractions of most recent landfilled MSW might even be able to be used

as soil fertiliser or compost at green areas and gardens,<sup>6,19</sup> provided that the pollutant concentrations meet the corresponding requirements for such use. Landfill mined materials should be characterised for heavy metals of environmental concern before they are applied on land.<sup>20</sup> Amounts of inorganic pollutants, such as Cr, Cu, Pb and Zn, in the calorific fractions (*i.e.* plastics, textiles, rubber, leather, wood and paper and cardboard) of the same order of magnitude as in MSW have been found.<sup>21</sup> However, besides the total contents, also the leachability and the mineralogical bonding of these possible contaminants have to be assessed.

According to a previous study,<sup>10</sup> the fine fractions complied, for most parameters of most samples, with the heavy metal limit values from the US EPA standards to be used as compost for non-edible crops. It has been reported that the concentrations of almost all heavy metals (except for Pb, Cd and As in some cases) in waste samples (< 10 mm and < 4 mm) met the pollutant ceiling concentrations, set by the US EPA and the EU limits.<sup>22</sup> Fines from older disposed MSW might exceed pollutant concentrations and would then need further treatment to be used as soil fertiliser or compost.<sup>6</sup>

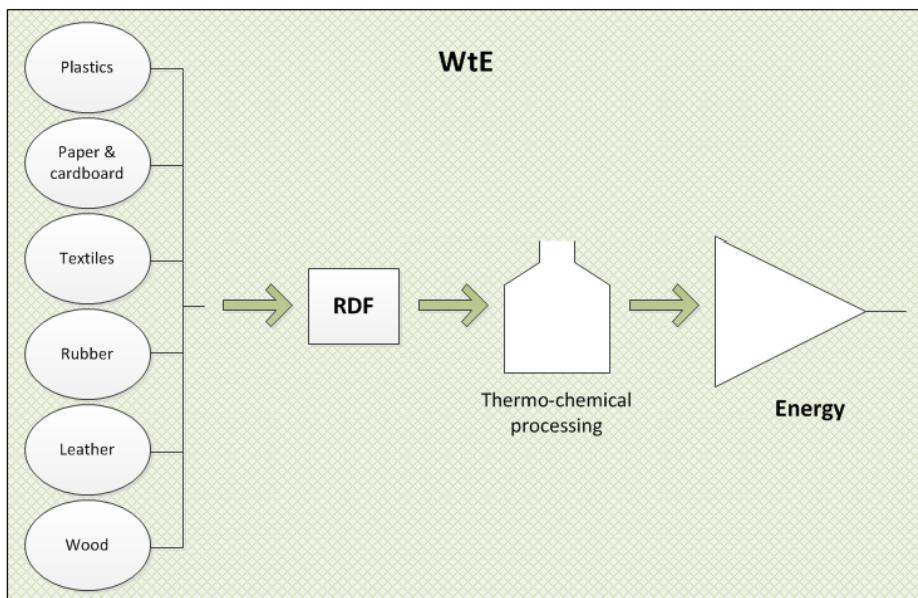
Moreover, landfills could be transformed into temporary storage sites,<sup>23</sup> which have been defined as structurally and environmentally-safe storage places that would permit *in-situ* material recovery from waste materials, facilitating the access to the potentially future resources later on, when the technology to recover certain materials is available, and allowing the implementation of improvements to these sites, such as reshaping and volume reduction. Temporary storage would bring us a step closer towards a circular economy, creating a connection between the past, present and future regarding resource availability.<sup>6,13,19,24,25</sup>

German landfill mining and site remediation investigations reported reductions of 8-30 vol% after re-landfilling and re-compacting the excavated MSW without recycle or reuse of the waste fractions.<sup>26</sup> The compaction of re-landfilled MSW results in a considerable volume decrease due to the reductions of pore spaces and voids caused by the degradation of the organic waste fractions.<sup>26</sup> The extent of the reduction depends on the degree of degradation of the organic fraction and the compaction of the MSW in the landfill before the excavation.<sup>12</sup> Additional volume reductions can be expected if the fine fractions are reused or recycled.<sup>12</sup>

Some other end uses might arise in the future, depending on available markets, material quality and regulatory framework for reuse.<sup>20</sup> Both the increasing market prices for recuperated materials and the legal framework will set the conditions to justify new waste processing technologies.<sup>27-29</sup>

## Waste-to-Energy

Energy recovery from waste refers to the generation of electricity and/or heat by processing waste materials, as well as to the production of energy carriers (e.g. methane, refuse derived fuel (RDF) and syngas). RDF is an alternative fuel, produced from diverse kinds of waste materials, which can partially or completely replace the usage of conventional fuels, such as fossil fuels, in various industrial applications (e.g. cement and power plants). As already mentioned, relevant amounts of materials such as plastics, paper and cardboard, wood, textiles, leather and rubber, which could be suitable for the production of RDF, can be found in the fine fractions. These materials are very likely to fail meeting the required quality criteria for material re-use and recycling; whilst recovered wood, textile, leather and rubber materials are hardly recycled or re-used. However, assuming that these materials could be recycled, their value on the recyclables market would most likely be very low with high recycling costs. Moreover, these materials are composed of carbon to a major extent and they possess, in a dry state, high calorific values. Calorific values of 3,9-9 MJ/kg DM have been determined for the fine fractions (< 20 mm) from two Austrian landfills<sup>5</sup>. Provided these circumstances are there, the recovery of these materials in order to produce RDF, thereby exploiting its WtE potential, can be suggested as an interesting option. Figure 5 displays the usage of the calorific fractions from the fine fractions for the production of energy:



**Figure 5:** Energy recovery from calorific fractions of LFM fine fractions

Mined waste from landfills may be used to improve combustion through co-incineration at MSW incineration plants; helping to avoid auxiliary fuel consumption and releasing landfill space.<sup>30</sup> Concurrently, thermo-chemical based technologies, such as gasification, pyrolysis and incineration, to process the fine fractions from

landfill excavated waste materials have been tested to a certain extent in the last years.<sup>24</sup> Incineration with energy recovery would be possible with the fines fraction (< 18 mm) after the removal of coarse inert material.<sup>9</sup> The EU standard that states the specifications and classes for solid recovered fuels (SRF), which is a type of RDF, is the BS EN 15359:2011; where the net calorific value (linked to water content) and chlorine and mercury contents are among the most important properties. A case-study reported that the limit values for SRF usage in cement or power plants, according to the Austrian guideline BMLFUW 2002, were not exceeded by the fines fraction (< 40 mm) from LFM.<sup>5</sup>

## Main challenges to overcome

There are a large number of factors that play a very important role in LFM and ELF M projects (e.g. landfill site's particularities, excavation and material processing procedure and utilised equipment, sampling and laboratory analysis procedures and followed guideline, among many others) and, therefore, very much attention must be paid to the singular characteristics of a site while analysing and comparing information between different projects. The challenges discussed below, together with the economic and legislative aspects, represent some of the main challenges in order to start full-scale recovery of resources from landfills.<sup>1,13,31</sup>

### Variations in composition and properties

In order to identify the material and energy recovery potentials and possible alternative uses of the fine fractions, and to be able to design an appropriate material processing and final disposal method during the planning phase, the characterisation of the fine fractions is an essential first step.<sup>16,32</sup> Some key aspects to be considered are: the material, chemical and mineralogical composition, size and volume of the site, type of the landfilled waste, location of the site, historic operation procedures of the site, extent of degradation of the disposed waste, types of markets and uses for the recovered materials and environmental and health risks.<sup>6,10,33</sup> Compaction and expansion of solid waste components, as well as the material's contamination and degradation make excavated material more difficult to sort and characterise than fresh MSW.<sup>12</sup> As it has been reported in previous investigations, a variable quantity of problematic substances could be present in the fine fractions. These are substances that, due to their toxic or undesired characteristics, would hinder or limit the further usage of the produced or recovered materials from the fine fractions. The presence of trace amounts of hazardous chemicals would most likely limit the quality of the fines fraction for further use.<sup>34</sup> Some problematic elements that have been found in the fine fractions are, for example, heavy metals, chlorine and sulphur; which can be toxic at certain concentrations and speciation, form harmful compounds when released to the environment and damage the equipment with

which this material is being handled or processed. The risk due to the elevated pollutant concentrations should be evaluated before such material can be reused outside of a landfill.<sup>20</sup> To reduce the concentration of metals such as Cr, Cu, Ni and Zn from the fine fractions could be an option to enable the usage of this fraction for other purposes.<sup>6</sup> In general, metal concentrations, except those of As, Be and Cd, were found below EU, UK and US regulatory threshold values, for use in unrestricted settings, for the fine (< 0,425 mm) and intermediate (> 0,425 and < 6,3 mm) fractions.<sup>20</sup>

The first step to identify an adequate processing of the fine fractions from excavated landfills is to determine the leaching properties of the material at laboratory scale.<sup>35</sup> These tests can bring valuable information about the compliance with existing standards and norms. Hence, the further processing of these fractions is to be aimed to remove these problematic fractions (*e.g.* using sensor-based sorting equipment to sort out materials containing chlorine), as far as the available technology allows it, to produce a RDF with the adequate properties for the corresponding thermo-chemical processing technology; as well as to recuperate an organic and an inorganic fraction, whilst concentrating the undesired elements and compounds in a residual fraction, which might be suitable for further processing for the recovery of certain elements (*e.g.* heavy metals) in the near future.

### **Source for surface defilements in coarse fractions**

During disposal time, fines adhere as a soil-like layer to the surface of other materials,<sup>36</sup> leading to limitations in the final sorting outputs, due to decreased sorting performance of the sensor-based sorting units. This has also been reported in other investigations,<sup>5</sup> in which the fines adhered to other waste fractions as impurities, contaminating the rest of the waste fractions and decreasing their quality and value. Results from a previous study show that all manually sorted size categories contained impurities of the other sorted fractions.<sup>37</sup> Contamination of all fractions with fines (adherent soil) showed an increasing trend with age, which in high levels will likely prove to be an insurmountable obstacle to recycling most of the excavated waste fractions, unless further processing takes place.<sup>12</sup> This adhered soil-like layer, also known as surface defilements, can lead to efficiency losses of sensor-based sorting.<sup>36</sup> If the surface defilements can be removed, it would be easier to use plastics from LFM as a secondary resource. Further analyses on the sorted plastics show that the mass share of the surface defilements in the final sorted products can be as high as 7.5 wt%.<sup>36</sup> Drying of the material might increase the amount of the fines, as in moist conditions some fine particles tend to stay attached to bigger particles.<sup>37</sup> This could improve the quality of the coarse fractions and raise the overall efficiency of the material processing. Composting (aerobic biodrying) has been suggested to dry the excavated waste prior to thermal valorisation; this would improve the removal of

the material contamination due to adhered fines, the efficiency of the sieving steps and reduce the ash generation during the thermal processing.<sup>26</sup> In contrast, the assessment of the implementation of a wet processing (*e.g.* washing units), in order to decrease the amount of surface defilements in the coarse fractions, merits further investigation.

### **Reach of available technologies for processing the fine fractions**

The particle size is a very important factor for an optimum separation process; conventional waste sorting techniques (*e.g.* metals separation, density classification and sensor-based sorting equipment) cannot be applied below a certain particle size of the material.<sup>38</sup> Also, the removal of Fe materials from the fine fractions slows down separation processes and requires a relatively dry material.<sup>4</sup> Therefore, the ability of the technologies for processing the fine fractions, regarding the particle size, needs to be extended in order that smaller particle sizes (< 3 mm) can be handled as well. The planning of a suitable treatment process for recovering waste fractions in a LFM project requires not only knowledge on the composition of the landfilled waste, but also with respect to the treatability of the different fractions.<sup>37</sup> One of the main technological aspects of ELFm is the development of a processing plant that enables maximum resource recovery.<sup>6</sup>

## **Conclusions**

The specific conditions of a given landfill will determine if landfill mining and land reclamation are feasible for the site. The primary recoverable waste fractions from the fine fractions are metals, complementary materials for RDF production, soil-like and inert fractions. The soil-like fraction recovered from the fine fractions could have potential as a ground substitute, such as cover material for operational landfills, material to form embankments, soil for non-edible crops and formation of bio-soils to be used in environmental remediation activities. This fraction could, theoretically, be used as fertiliser at green areas and gardens, provided the material complies with all applicable regulations for such purpose. Particle size and nutrients content are relevant parameters to evaluate the usage possibility of the fine fractions for soil applications. For metals, glass, ceramics, stones and other inert material, WtM might be possible if the materials can be separated adequately. Characteristics such as moisture content, ash content, calorific value and amount of organic carbon, total carbon, hydrogen and nitrogen are needed to assess the efficiency for WtE applications.

When the level of contamination of paper and cardboard, plastics, textiles and wood (calorific fractions in general) recovered from a landfill is too high or their quality is too low, WtE could be the most suitable valorisation route. The quality of the retained

materials in the landfill and the WtM and WtE technologies available for material valorisation will also, among others, determine the feasibility of ELFM. Landfills and dumpsites without leachate and biogas collection networks could be attractive candidates for LFM projects, since the economic and environmental assessments for the mitigation of their environment pollution would not include investments in such infrastructure and, thus, would likely raise the feasibility of this kind of project.

The planning of a suitable treatment process for recovering waste fractions in a landfill mining project requires not only knowledge on the composition of the landfilled waste, but on the treatability of the different fractions as well. In order to identify the material and energy recovery potentials and possible alternative uses of the fine fractions, and to be able to design an appropriate material processing and final disposal method during the planning phase, the characterisation of the fine fractions is an essential first step. Some key conditions to be considered are: the composition and type of the landfilled waste, location of the site, historic operation procedures of the site, extent of degradation of the disposed waste, types of markets and uses for the recovered materials and environmental and health risks. One of the main technological aspects of ELFM is the development of a processing plant that enables maximum resource recovery. These, together with the economical and legislative aspects, represent some of the main challenges in order to start full-scale recovery of resources from landfills.

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# BUT, IS IT ALL DIRT!? ADVANCED CHARACTERISATION OF ELFM MATERIAL BY THE CHARACTERISE-TO-SORT TECHNOLOGY

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## Introduction

Several research projects are triggered by the vision to reuse the resources disposed on landfills, but face struggles due to lack of information of its disposed material. Conventionally, waste composition is still analysed manually, which is time-consuming and unpleasant work. Due to the high associated costs it is difficult to analyse representative (*i.e.* large) amounts of solid waste material. Even if intensive work is executed to obtain required information on material composition and its resource potential, this information is hampered by the low material quality as landfilled material is usually highly defiled on the surface. Other degradation effects on the material are due to the long disposal under high pressure and the long presence in a high-temperature and humid environment. All these impacts lead to changes in the outer appearance of the disposed materials, which makes it difficult to sort the material with image recognition or even human sorters. The lack of a fast, reliable and objective characterisation makes it hard to plan the remediation action, which, in the end, would lead to the recirculation of the disposed resources into the value chain.

## Characterise-to-Sort

The Characterise-to-Sort (CtS) project meets the need for rapid, continuous, automatic, objective and reliable characterisation with a newly developed device combining different sensors. A picture of the device is shown in Figure 1. Current sensor techniques in solid waste characterisation mainly focus on surface properties, *e.g.* near-infrared, colour, hyperspectral or X-ray fluorescence, making them less

useful for defiled landfilled materials. To overcome this limitation, a technology that sees “through” the material was adopted: X-ray transmission (XRT).

By measuring at two energy levels, called Dual Energy (DE-XRT), it is possible to determine material properties such as the average atom number and density. DE-XRT is based on the fact that the X-ray attenuation of a given material varies with the X-ray energy. Apart from the well-known examples in the medical sector and airport security, XRT is used in the food industry to recognise contaminants and in the mining industry to remove impurities from coal. In the waste industry, XRT is already used for RDF purification or in combination with colour detection for sorting of construction and demolition waste, applying a binary (accept/reject) logic. To accurately interpret the information gathered by DE-XRT, extra information such as the 3D volume of the object is employed. This is measured by 3D laser triangulation (3DLT). 3DLT is a well-known technology in the industry that can measure the geometry of objects at high resolution (sub-mm) using a laser and a camera. The combination of these technologies allows to fully characterise a waste stream on the level of individual particles with respect to volume, mass, shape and composition. In addition, the material and shape measurement is complemented by an RGB detector, bringing in additional information, which can be used to better differentiate the materials using image processing and machine learning algorithms.



**Figure 1:** The Characterise-to-Sort device. A feeding chute situated on the left delivers the material on the conveyor belt. The conveyor belt transports the material through the sensor zone equipped with X-Ray, 3D and RGB sensors. At the right the material is collected into a container at the bottom (not shown).

Within the CtS project, three residue streams from different waste processing plants were adopted as model streams for the technology development:

- Shredder fluff (wind sifter light fraction) from a scrap recycling plant;
- Wind sifter light fraction of a mixed construction and demolition waste sorting plant;
- Residue plastic fraction from a sensor-based PMD sorting plant.

These streams were manually sorted into a plethora of homogeneous material fractions: *e.g.* wood (hard, plywood, fibreboard), cardboard, paper, textile, stones, ceramics, glass, metals (stainless steel, copper, aluminium, iron, brass, zinc, tin, lead), electrical wires, plastics (foils, soft plastics, hard plastics, PE, PP, PET, PVC, ...), insulation materials, entangled fractions, *etc.* A selection of pictures of the manually sorted material fractions is shown in Figure 2. While these streams are very heterogeneous and complex, they are certainly less defiled and cleaner to work with than landfill waste. Therefore, they are ideally suited for the initial development of the CtS technology, allowing to gradually advance the technology from a lower to a higher level of complexity.



**Figure 2:** Selection of manually sorted material fractions (15-35 mm) from the fluff (wind sifter light) fraction of a scrap recycling plant that will be used to train the CtS device to identify different materials. From left to right: top row: rubber, insulation, plastic foils, stones, and hard plastics – bottom row: wood, composite materials, stainless steel, wires, printed circuit boards.

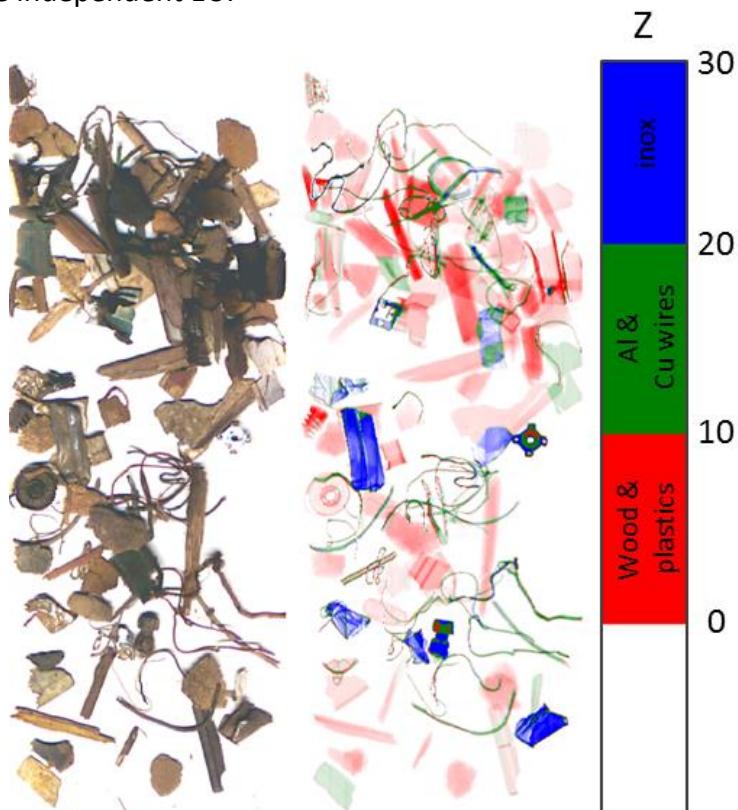
## Machine learning

The above material fractions are fed to the CtS device to be used as training material. In the first stage the device parameters are optimised for an optimal discrimination of the materials present in the described waste streams. Subsequently, detector response ranges can be attributed to specific material fractions. An example image is shown in Figure 3. When different materials should have similar X-ray responses, information about the thickness, provided by 3DLT, can assist the differentiation. The

CtS device provides material and shape information on the individual particle level and calculates tailor-made statistics on stream level. The results are compared to manual sorting. In a later stage RGB information, shape analysis and object recognition techniques are considered to further enhance the material identification.

The development of methods to extract the relevant information from the sensor data is the topic of on-going research. The technology will allow to optimise existing and to develop new recycling processes, and assess secondary raw material quality, based on accurate, representative and objective data.

The CtS technology determines mass, volume, shape and material type on the level of individual particles. This information can be used to estimate the resource inventory of complete waste streams and potentially whole landfills, which is key for an improved planning and execution of any ELFM activity. In this way Characterise-to-Sort can contribute to the successful implementation of the ELFM process scheme for a resource independent EU.



**Figure 3:** Colour (left) and X-ray (right) images of a mixed waste stream containing wood, plastics, aluminium, Cu wires and inox particles. The right image shows the atomic number (Z) on the colour scale and the integrated density as the transparency. Both are calculated from the low and high energy X-ray transmission images.

# THE REDEVELOPMENT OF THE EYSELS LANDFILL SITE, TURNHOUT, BELGIUM

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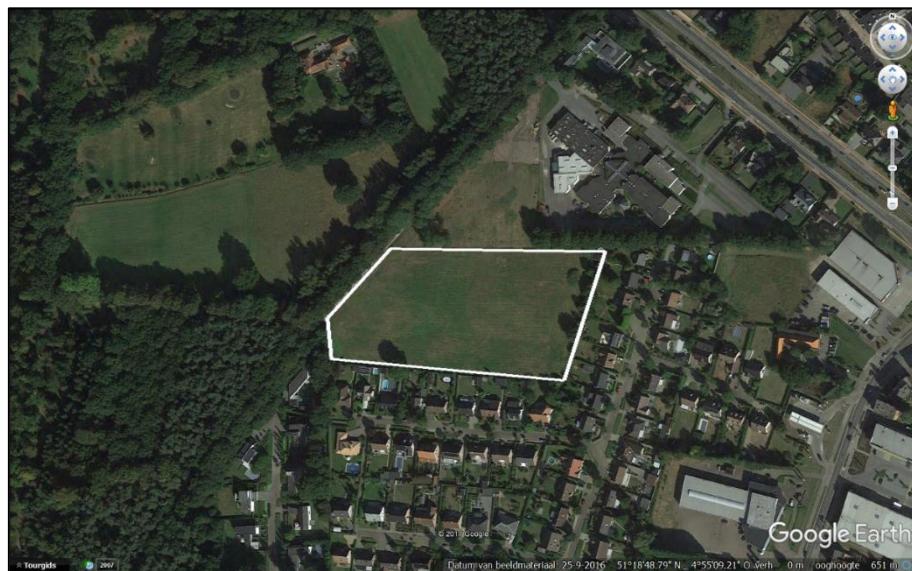
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## Introduction

The investigated landfill site, which is called “Eysels”, is located in Turnhout, in the north of Belgium. The location (Figure 1) is about 50 kilometres east from the company’s head office in Stabroek, also Belgium. At the time of World War II, the two-hectare large landfill site (aerial view shown in Figure 2) was excavated and the excavated soil was used in the construction of the nearby ring road. After the war, the excavated pit was refilled with household waste from the city of Turnhout. The landfill activities took place until approximately 1963. Until 2015, the abandoned site was used as a meadow land for horses (Figure 2), while the neighbourhood was further developed as a residential area.



Figure 1: Site Location of the Eysels landfill site



**Figure 2:** Aerial View of the Eysels landfill site

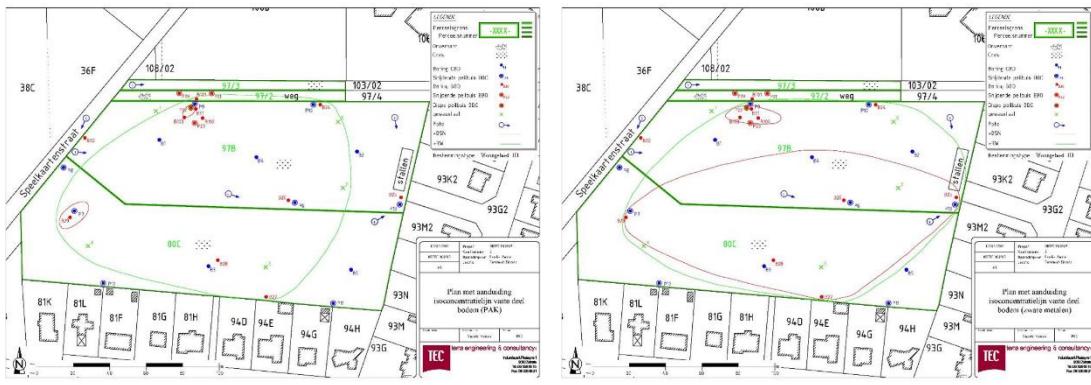


**Figure 3:** Meadow Land

## Landfill Site

The historical waste disposal activities also caused a soil contamination with heavy metals, mineral oil and Polycyclic Aromatic Hydrocarbons (PAH's). However, this soil contamination did not pose an urgent environmental risk, nor was there the risk that contaminations could spread to the nearby groundwater. As a result, no further remediation measures were imposed by the authorities. Although the whole site is located within residential area, it stayed abandoned for over 50 years.

In 2015, the site was ultimately purchased by the Aertssen group, with the aim of developing a new, pleasant and contemporary living environment. In doing so, it was an explicit choice to first remediate the existing landfill in a sustainable way.



**Figure 4:** Contamination Contours PAH's and Heavy Metals

## Remediation Project

Following the acquisition in 2015, the landfill mining project was first drafted in a voluntary Soil Remediation Project, which was approved by OVAM, the Public Waste Agency of Flanders, on July 26<sup>th</sup>, 2016. Subsequently, the landfill mining project started.

The remediation mainly comprised the selective excavation of the landfill with the contaminated soil, the sieving and sorting of the excavated materials, the external treatment/disposal of waste and contaminated soil, reuse on-site of sieved/cleaned soil and a complete reshaping of the site. By sieving and sorting on-site, the amount of material for disposal (and subsequently the supply of primary materials) could be reduced to less than 15% of the initial, excavated volume.



**Figure 5:** Remediation Works



**Figure 6:** Waste Disposal Front



**Figure 7:** Sorting Activities

## **Redevelopment**

The redevelopment and creation of the residential area is programmed to start in 2018. The area will accommodate in total 62 families and shall provide over 6,300 m<sup>2</sup> of green and open space.



**Figure 8:** Redevelopment Plan



**Figure 9:** Artist Impression from West to East



**Figure 10:** Artist Impression from East to West

## Conclusions

After more than fifty years an old landfill site makes room for a new sustainable residential area. Over 25,000 m<sup>3</sup> of disposed inert waste material could be reused on the site. Less than 15% of the initial disposed material was sent off-site to a licensed treatment centre.

# **EXPLOITING SECONDARY RAW MATERIALS FROM EXTRACTIVE WASTE FACILITIES: A CASE STUDY**

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## **Introduction**

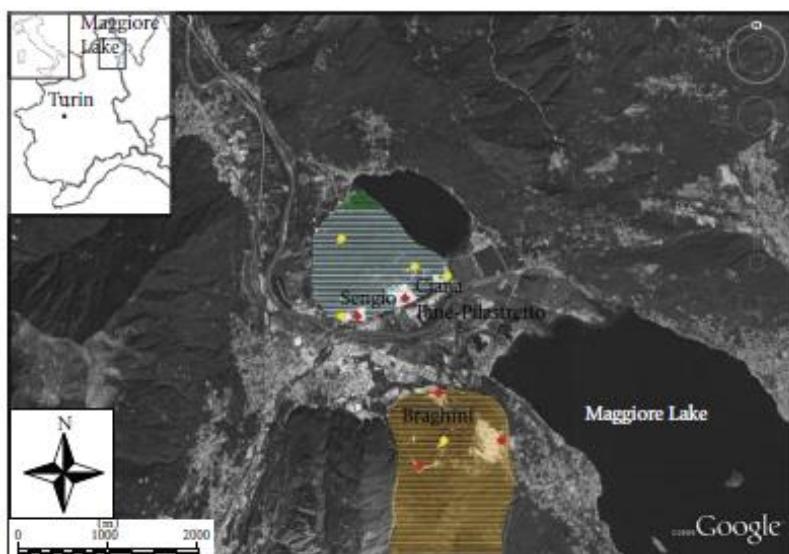
In recent years, resource scarcity has emphasised a need to transition from a linear to a circular flow of resources.<sup>1</sup> Securing supplies of critical and secondary raw materials (CRM/SRM) for the manufacturing industry is at the forefront of industrial challenges, especially in Europe, USA and Asia.<sup>2-5</sup> A key step towards achieving resource efficiency, is to recover these materials from anthropogenic waste deposits, such as urban landfill sites and extractive waste facilities.<sup>6</sup> This means breaking away from the traditional linear use of resources to a closed-loop approach that allows maximum recovery of resources from waste.<sup>7</sup> The management of extractive waste deposits and resource recovery is closely linked to the concept of urban mining.<sup>8</sup> In this paper, we present a case-study illustrating the feasibility of recovering SRM from extractive waste (EW) facilities and discuss the pros and cons of undertaking such activities.

## **Materials and methods**

### **Pilot site description**

Montorfano granite EW facilities, subject of the present study, are in the Montorfano and Verbania territories, Verbano-Cusio-Ossola district (VCO, NE Piedmont Region, Italy). The VCO area is characterised by high tourism and is one of the most important quarrying districts in Italy, thanks to the vital dimension stones quarried, such as *Serizzo* and *Beola* (orthogneisses), granites and marbles. Specifically, the granites occur in the southern Verbano area, close to the entrance of the Ossola Valley, between Cusio and Verbano Lakes. They are typically pink (*Rosa Baveno*), white (*Bianco Montorfano*) and green (*Verde Mergozzo*) in colour. The investigated area is part of a wider EW area, interested in granite exploitation present in Montorfano (Sengio and Ciana Tane-Pilastretto waste facilities – Montorfano massif) and Baveno (Braghini waste facilities – Monte Camoscio) territories (Figure 1). In the past, large

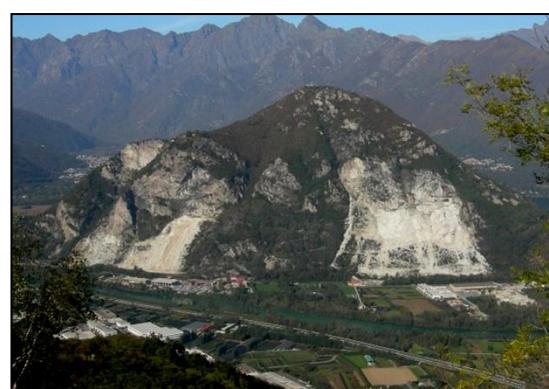
amounts of EW have been produced and stocked on the lower side of the hill (Montorfano and Baveno), forming EW facilities of differing shapes (Figures 2 & 3). The large volume of waste rock is a clear example of the problems connected to mining activities: exploitation in this territory have caused, and are causing, an evident hazard for the population, as well as significant environmental and aesthetic impacts on this tourist area.



**Figure 1:** Geographic context of the studied area. In the northern part (Montorfano area), it is possible to individuate both white granite (1) and green granite 2). The orange area defines the Baveno-Mottarone pluton (3). Furthermore, in the image the exploited quarry dumps are represented (red points) and the ancient quarry waste area, potentially useful for a future exploitation (yellow points).<sup>9</sup>



**Figure 2:** Example of EW facilities present in the Montorfano area



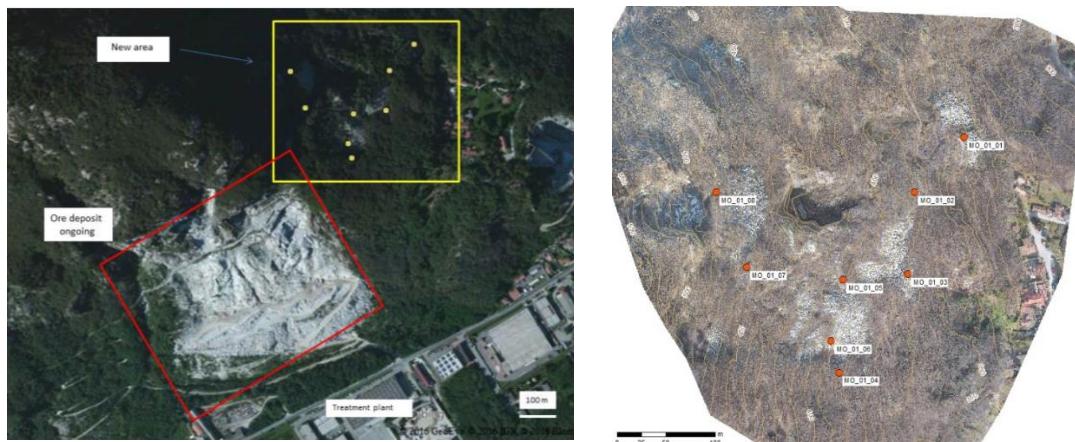
**Figure 3:** Southern side of Montorfano Massif

In 1995, Minerali Industriali Group invested in a dedicated dressing plant to exploit and convert granite waste rock, present in the Sengio and Ciana-Tane-Pilastretto (Montorfano) and Braghini (Baveno-Mottarone) EW facilities, into new ore-deposits

for feldspar and quartz exploitation. Such deposits are being progressively exhausted as a result of continuous exploitation. The feeding material is treated by crushers and mills to reduce each grain size class to 1.25 mm as the maximum grain size dimension. This is then sieved to both obtain different grain size materials and to separate powder granite from other products. Finally, the material passes through electromagnetic separators, which select the ferromagnetic minerals from the final product by appropriate physical-chemical properties. The main product is commercially known as F60P (quartz feldspar mixture), produced at around 65,000 t/year. By-products, obtained after the enrichment of produced "waste" (mainly powder granite and fractions enriched in ferromagnetic minerals) commercially known as SNS-sand (premix for building uses), NGA-coarse black sand (used for industrial sandblasting), SF-wet feldspar (for the ceramic industry), and SF100 and SF200 (used as fillers in cement industries), are added to the F60P production. The total amount of by-products is about 110,000 t/year.

### Field survey and characterisation

The Montorfano pilot site field activity focused on the new EW facilities NE of the Ciana-Tane-Pilastretto and Sengio mining areas (Figure 1 & 4). Samples were collected using a hammer and chisel due to block size (Figure 2). The sampling area for each sample is around 10 m<sup>2</sup>. Each sample constituted of small pieces of chips rock from different blocks.



**Figure 4:** a) Location of the samples in the new investigated area. The dot points represent the samples location; b) Locations of sampling points on top of orthophoto with contour lines.

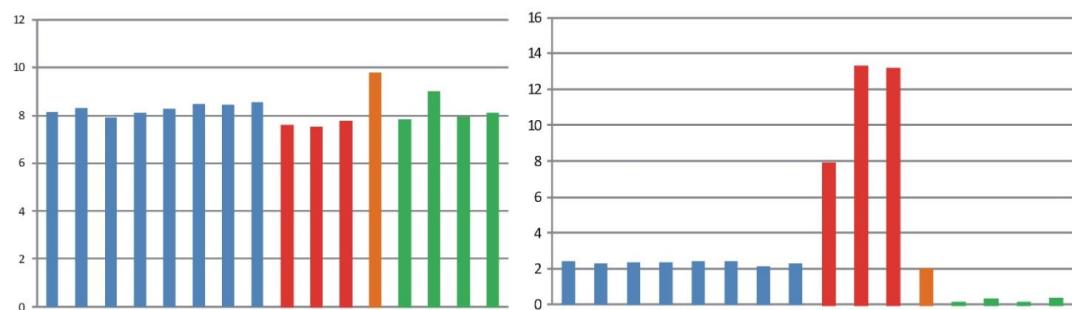
During the sampling campaign (summer 2016), other samples from the treatment plant (Minerali Industriali) were collected in order to characterise the feeding material (from Sengio, Ciana-Tane-Pilasteretto and Braghini areas) and the product and by-products in order to understand if and where an enrichment in CRM (*e.g.* rare-earth elements, REEs) is possible. A total of 16 samples were collected: 8 samples

from Montorfano EW facilities and 8 samples from the treatment plant. All samples were prepared at the Mineral Dressing and Sampling Laboratory (Earth Sciences Department, University of Torino) and characterised (geochemical analysis) at an external certified laboratory. For the Montorfano material, alkalis and  $\text{Fe}_2\text{O}_{3\text{tot}}$  content are important for the feldspar industry, while REE concentrations provide additional revenues.

## Results and discussion

### Geochemical characterisation

The sampled materials show highly homogeneous geochemical features ( $\text{Al}_2\text{O}_3$ : 13.38-14.65;  $\text{Fe}_2\text{O}_3$ : 2.09-2.41,  $\text{TiO}_2$ : 0.21-0.23,  $\text{CaO}$ : 1.33-2.01,  $\text{MgO}$ : 0.29-0.45,  $\text{K}_2\text{O}$ : 4.49-5.18,  $\text{Na}_2\text{O}$ : 3.26-3.51) for major elements. The alkalis ( $\text{K}_2\text{O}+\text{Na}_2\text{O}$ ) and  $\text{Fe}_2\text{O}_{3\text{tot}}$  content are shown as histograms in Figure 5.

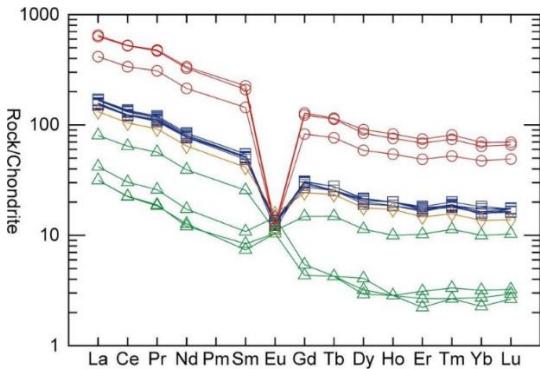


**Figure 5:** Concentration of alkalis (left) and  $\text{Fe}_2\text{O}_{3\text{tot}}$  (right) in the Montorfano pilot (all samples; values in wt%). Blue (left): rock waste; red (second from left): treatment plant, magnetic fraction; orange: feeding material; green (right): treatment plant, non-magnetic fraction.

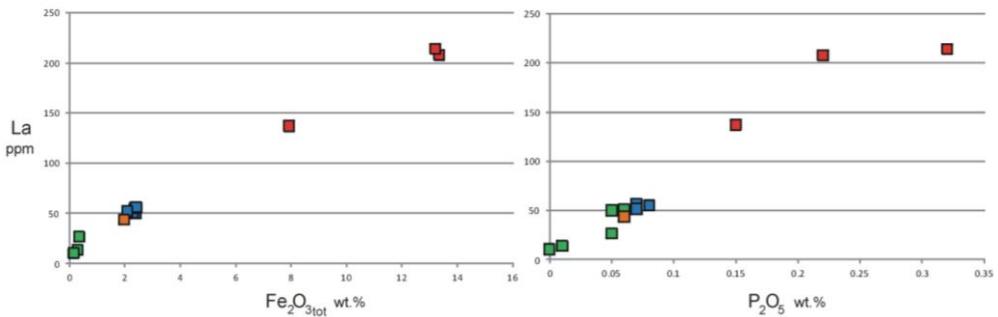
For minor and trace elements concerning waste rock and feeding material, a relatively high REE content was found, typical of felsic, strongly differentiated magmatic rocks. In particular, the chondrite-normalised REE diagram (Figure 6) shows a strongly coherent pattern characterised by strong enrichments in light REEs (LREE: especially La, Ce, Pr, Nd, Sm: up to 100 times chondrite), and slight enrichments in heavy REEs (HREE: Gd to Lu, relatively flat patterns with up to *ca.* 10 times chondrite values).

As for the enriched fraction (output from processing) there are strong differences concerning the absolute concentrations: all samples from the magnetic fraction show LREE enrichments up to almost 1,000 times with respect to chondrite, *i.e.*, they are much more concentrated than in the feeding material, and can be up to one order of magnitude more concentrated than in the upgraded non-magnetic portion (Figure 6

& 7). Considering La+Ce, the average concentration ranges from 164 ppm (waste rock) to 585 ppm (magnetic fraction), down to 45 ppm (non-magnetic fraction; 63 ppm also considering the strongly anomalous MO\_02\_04 sample). Y and Sc are also enriched in the magnetic fraction.



**Figure 6:** REE pattern for all samples, normalised to chondrite, logarithmic scale (chondrite values from Nakamura, 1974). Blue: waste rock; red: treatment plant, magnetic fraction; green: treatment plant, non-magnetic fraction, orange: treatment plant, feeding material.



**Figure 7:** La-Fe<sub>2</sub>O<sub>3</sub> and La-P<sub>2</sub>O<sub>5</sub> correlations. La as ppm, Fe<sub>2</sub>O<sub>3</sub> and P<sub>2</sub>O<sub>5</sub> as wt%. Blue: rock waste; red: treatment plant, magnetic fraction; green: treatment plant, non-magnetic fraction; orange: feeding material.

### Volume of the raw materials on the site

The total volume of the Montorfano pilot site was calculated at about 560,000 m<sup>3</sup> (about 1,008 Mt). Assuming that about 20% must be subtracted from this volume to be treated in Sasil treatment plant, it is possible to estimate that the resources directly treatable in the Minerali Industriali plant should be about 0.8 Mt. Considering a feeding amount to the plant of nearly 0.175 Mt/year, it is possible to estimate 4.5 years (at least) for the production lifetime. The data, given by the company, with regards to the main products and by-products from the treatment plant are reported in Table 1. Main applications include: F60P: feldspar for ceramic industry, F60-40: feldspar for ceramic industry, Gravel and sands: for buildings and infrastructures; SF and SF100: for bituminous concrete; SN: for brick production; SNG: for external pavement and industrial surface treatments and SNS: for external pavement.

**Table 1:** Yearly quantity and values connected to products and by-products arising from the treatment plant (value from Minerali Industriali documents)

Main Product And BY-PRODUCTS	Production (t/y)	Value (€)
F60P (Main Product)	65,400	1,430,800
F60-40 (feldspar concentrate with Fe<0.4%. Class <500 µm)	21,000	526,500
Gravel and sand	61,500	615,700
SF and SF- 100 (fine sands, magnetic concentrate, from dust aspiration; SF100 refers to class: <100 µm)	5,800	79,500
SN (black sand; magnetic concentrate)	1,800	16,500
SNG (black sand, magnetic concentrate. Class >600 µm)	6,900	102,500
SNS (black sand, magnetic concentrate, coming from the production line for F60-40)	1,950	19,400
Type A (filler)	11,500	NO INFO
<b>TOTAL</b>	<b>175,850</b>	<b>2,822,900</b>

## Conclusions

This paper presents the results connected to the site characterisation of extractive waste (EW) and EW facilities, focusing on an Italian case-study (Montorfano quarrying area). The wastes are stored in EW facilities, which need to be monitored for environmental and health impacts, but which can also be considered as potential new mining areas: *e.g.* for industrial mineral (feldspar) production. The Montorfano case-study is a paradigm for how the recovery of EW from EW facilities can be economically sustainable (22 years of working activity). Minerali Industriali exploits granite waste to produce main products for ceramic industry and several by-products (for other applications) coming from the advanced treatment of the waste produced during the dressing activity. The results from the characterisation phase demonstrate that the investigated area (not yet mined) can guarantee feeding material to Minerali Industriali dressing plant for other 4.5 years after the recovery of all the materials present in the still exploited EW facilities. Furthermore, the presence of REEs in the magnetic by-products suggests the potential exploitation of CRM, to be confirmed after a focused characterisation and treatment.

## Acknowledgements

The authors wish to dedicate the present work to Dr. Alberto Trentin, Fassa Bortolo, for his fundamental contribution during the past field activities (2009). This work is part of SMART GROUND project and has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 641988.

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# IN-SITU RECOVERY OF Cr AND Ni FROM LANDFILLED NEUTRALISATION SLUDGE

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## Introduction

Significant amounts of a Cr-Ni-rich neutralisation sludge from acidic waste waters are produced by industry in Europe each year. This sludge is landfilled, as it is considered being a hazardous waste due to its high heavy metal content. It is estimated that > 10 Mtonnes of such sludge is present in EU landfills. Heap leaching is a low-cost, controlled process whereby complex or low-grade ores are stacked in low heaps and irrigated in a controlled manner with a leaching solution to extract the optimum amount of a metal from the ore.<sup>1-2</sup> In several cases, heap leaching could be easily applied to landfilled materials since material stacking, bottom lining and drainage water collection and treatment installations are already in place. Heap leaching of primary low-grade Cu, Au and U ores has been practised for decades.<sup>2</sup> However, the application of heap leaching technology to much more complex mineral waste materials is new.<sup>3</sup> Spooren *et al.* were among the first to report experimental research regarding heap leaching of a mineral waste material, showing the potential to recover Cr and V from silicate rich slag materials.<sup>4</sup> In the present work, the feasibility of in-situ recovery of Cr and Ni from neutralisation sludge by heap leaching is studied.

## Materials and Methods

The studied sludge material is generated by neutralisation of acidic waste waters with Ca(OH)<sub>2</sub>. A sample of the Cr- and Ni-rich sludge was taken from a fresh truckload of material upon arrival at an operating landfill. Samples were taken at different positions within the truck and mixed to obtain a representative sample. The sludge is very fine (99% < 44 µm) with a moisture content of 47 wt% X-ray diffraction (*PANalytical X'PERT PRO* equipped with a Cu anode) and elemental analyses (ICP-AES after MW destruction, *Perkin Elmer, Optima 3000 DV*) were performed on dried sample (at 80°C) that was ground to < 125 µm. Indeed, grinding was required due to agglomeration of the material upon drying. Furthermore, the particle size distribution

(PSD) of the material was measured through laser diffraction (*Microtrac S3500*) of the powder dispersed in water with a dispersing agent.

In order to determine the leachability of key elements (Fe, Cr, Ni) from the neutralisation sludge as a function of pH, 5 g of the dried neutralisation sludge was stirred for 60 min in 50 mL of a H<sub>2</sub>SO<sub>4</sub> (*Merck*, 95% -97% pa) solution. Several H<sub>2</sub>SO<sub>4</sub> molarities were tested, namely 0.005 M, 0.01 M, 0.02 M, 0.03 M, 0.04 M and 0.05 M. At the end of the experiment the *pH* and the metal concentrations in solution were measured. To simulate heap leaching of the material, an up-flow column leaching experiment was set up. The sludge material (500 g) was mixed with 20 wt% quartz sand to enhance permeability and then packed into the column. A leach solution saturated in gypsum (0.04 M CaSO<sub>4</sub>), with addition of a *pH* = 2.2 buffer (0.5 M Na<sub>2</sub>SO<sub>4</sub>/0.05 M NaHSO<sub>4</sub>) was percolated through a column (diameter 5 cm, filling height 20 cm) with a flow rate of approximately 7 ml/h. The lixiviant was collected after passing through the column in fractions of 2,500 mL (*i.e.* L/S = 5).

## Results and discussion

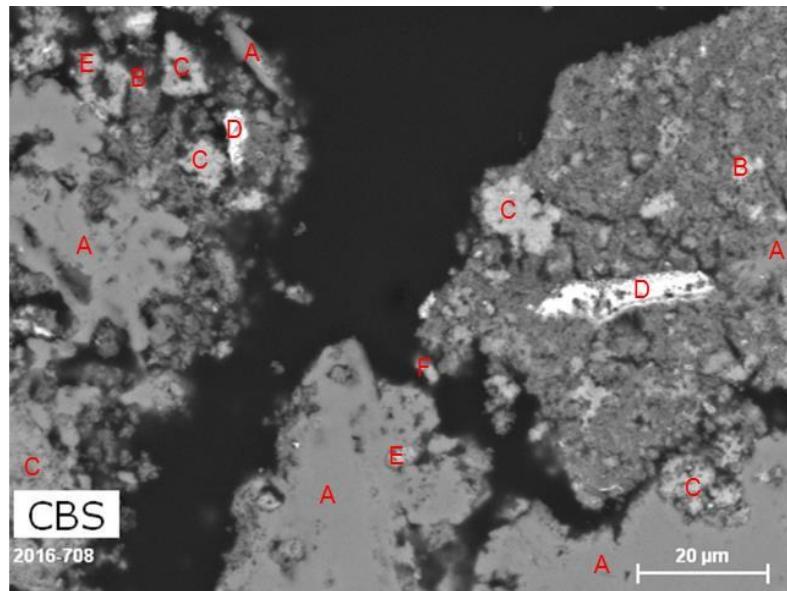
The studied sludge material mainly consists of calcium (23 wt%), iron (11 wt%) and sulphur (8.5 wt%). Chromium (2.6 wt%) and nickel (1.4 wt%) are economically important elements and are present at significant concentrations (Table 1). The mineral phases present in the material are mainly gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O) (~60 wt% dm) and fluorite (CaF<sub>2</sub>) (20 wt% dm) but also calcite (CaCO<sub>3</sub>), magnetite (Fe<sub>3</sub>O<sub>4</sub>) and amorphous iron hydroxide phases are present. The mineral phases in which Cr and Ni are present in the sample were determined after dissolving gypsum and drying the remaining residue on which XRD analyses were performed. Cr was observed to be present in spinel phases, such as possibly Mg-Cr-Fe spinel (MgCr<sub>0.4</sub>Fe<sub>1.6</sub>O<sub>4</sub>) and Ni-Cr spinel (NiCr<sub>2</sub>O<sub>4</sub>), while Ni is also present in Ni-Fe spinel (Ni<sub>0.6</sub>Fe<sub>2.4</sub>O<sub>4</sub>) and as NiO. Since XRD analysis cannot determine the chemical composition of spinel phases, SEM-EDX analyses provided an indicative chemical composition of such phases and showed their presence as embedded minerals within the gypsum matrix (Figure 1). The Cr spinel structure, according to SEM-EDX, could comprise FeCr<sub>2</sub>O<sub>4</sub>, but also Cr<sub>2</sub>O<sub>3</sub> was observed. Furthermore, the investigated sludge has a small particle size ( $d_{50}$  = 5.5 µm,  $d_{99}$  = 44 µm), which can be beneficial for efficient metal leaching due to a large available surface area. However, in the case of heap leaching a particle size distribution (PSD) with  $D_{80} > 6$  mm is desired to allow for optimal permeation of the material by the leaching liquor.<sup>1</sup> Therefore, when applying heap leaching, the studied material requires to be granulated to particles of larger sizes.

**Table 1:** Elemental composition of Ni- and Cr-rich sludge as determined by ICP-AES analysis after acid digestion

Element	Total concentration major elements (wt%)	Element	Total concentration minor elements (mg/kg dm)	Element	Total concentration minor elements (mg/kg dm)
Na	0.29	Ti	110	Mo	881
Mg	0.29	V	94	Sb	7
Al	0.13	Cr	25,800	Ba	22
Si*	0.18	Mn	1,730	Pb	24
S	8.45	Co	310	P	<150
K	0.024	Ni	15,200	Se	<5
Ca	23.0	Cu	640	Cd	<0.5
Fe	11.4	Zn	22	Sn	14
F**	8.90	As	14		

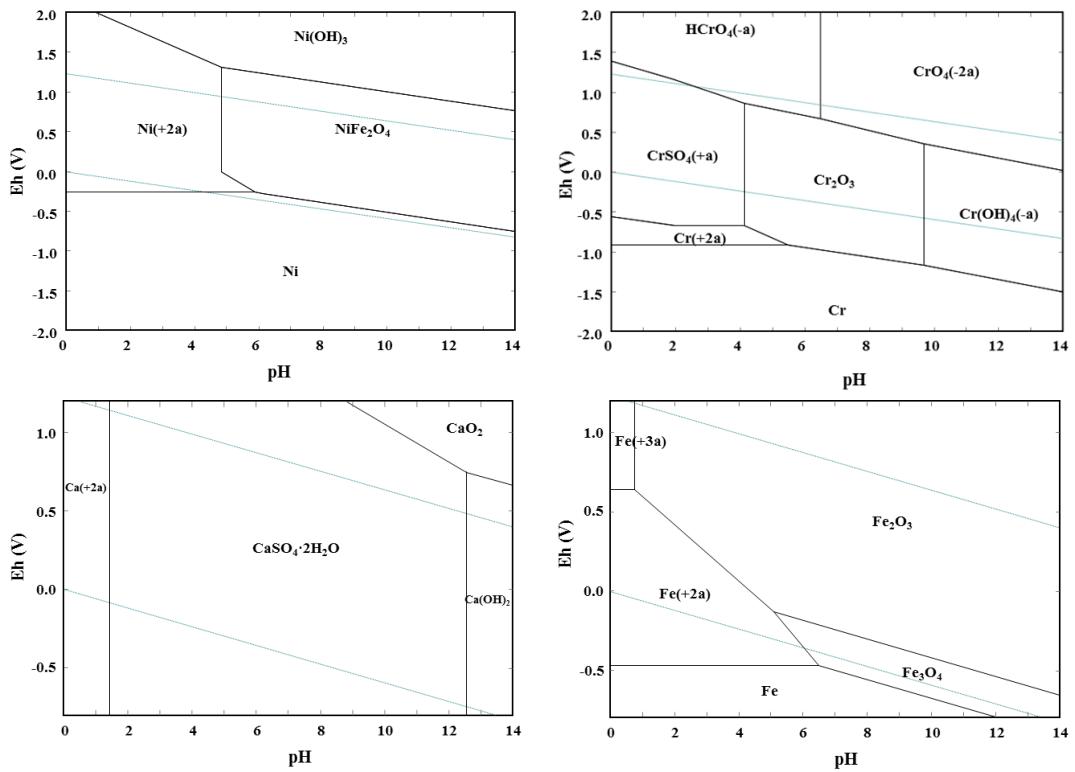
\*determined by EDXRF analysis on the solid sample.

\*\*F content was measured by hydropyrolysis followed by ion chromatography.

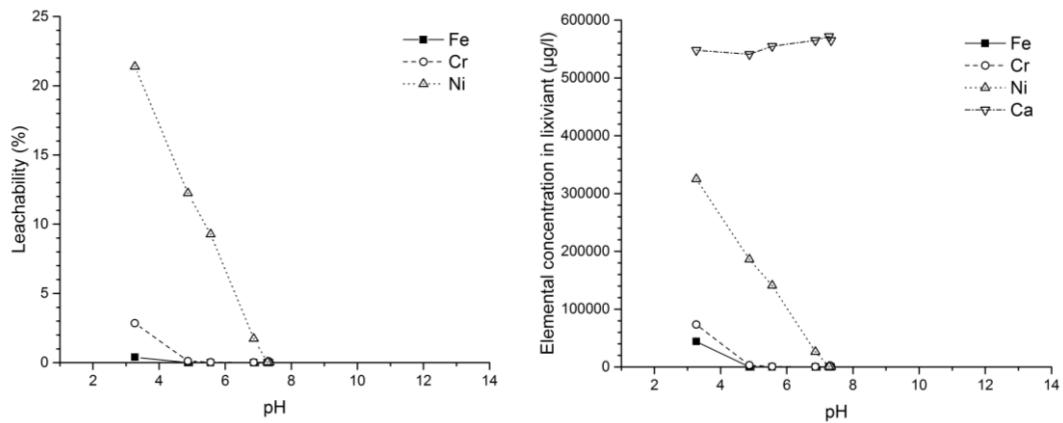


**Figure 1:** SEM image of the Cr-rich sludge. A =  $\text{CaSO}_4$ ; B =  $\text{Cr}_2\text{O}_3$ ; C=  $\text{CaCO}_3$ ; D =  $\text{FeCr}_2\text{O}_4$ ; E =  $\text{NiFe}_2\text{O}_4$ ; F =  $\text{Fe}_3\text{O}_4$

Thermodynamic models of the studied system (Figure 2), in combination with preliminary leaching tests (Figure 3), showed that selective extraction of Cr and particularly Ni from the material could be possible in the pH range 4-6 so as not to dissolve Fe. It needs to be observed that gypsum leaching is pH independent in the tested pH range (3.3-7.3), as the measured Ca concentration in the leachate is similar at all tested pH values.



**Figure 2:** Eh-pH diagram for Ni, Cr, gypsum and Fe (calculated by using HSC Chemistry 8.0 software at 298 K)

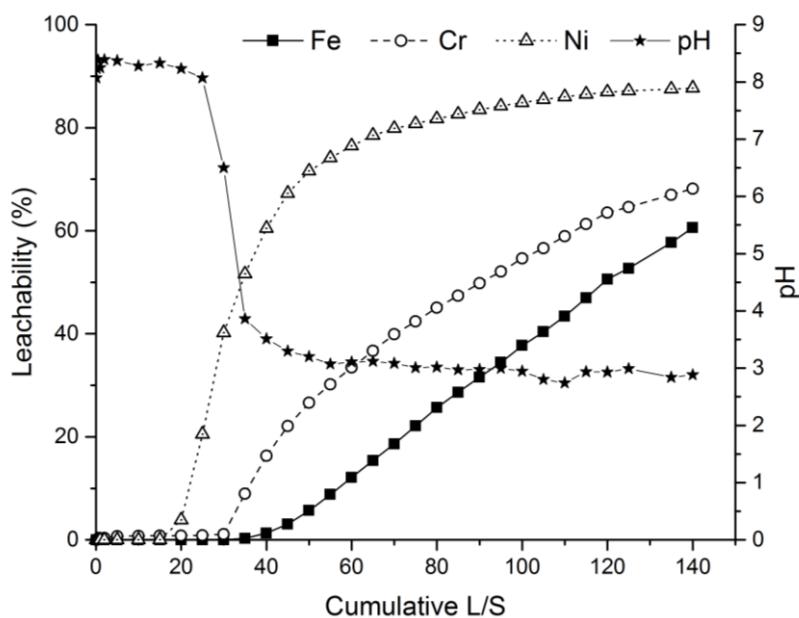


**Figure 3:** Leachability of Fe, Cr and Ni from the neutralisation sludge material (left) and concentrations of Fe, Cr, Ni and Ca in the leachates (right) as a function of pH

However, a major challenge for this material remains the solubility of gypsum in water ( $K_{sp} = 3.14 \times 10^{-5}$ ,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). An explorative column experiment, whereby the material was leached with a 1 M  $\text{HNO}_3$  solution and almost entirely dissolved, demonstrated that the pH must be well controlled to avoid complete dissolution of the material. Furthermore, although the solubility constant of calcium sulphate dihydrate (*i.e.* gypsum) is low, leaching with fresh leaching solution or water would slowly wash away the gypsum since the dissolution reaction will not reach

equilibrium (Le Chatelier's principle). In industrial heap leaching applications, recirculation or regeneration of the lixiviant is often applied to improve economics by (i) concentrating metals for better recovery and (ii) reusing leaching liquor to minimise the use of solvents/reagents. It is plausible to assume that in a heap leaching set-up fresh leaching liquor will be saturated in gypsum through gypsum dissolution after a first leaching cycle. When the liquor is then subsequently circulated through the heap, the dissolution of gypsum will be avoided since the dissolution reaction of gypsum will be already in equilibrium.

A column experiment was set up to test the concept proposed above. A leach solution of  $pH = 2.2$  saturated in gypsum was percolated through a column packed with the neutralisation sludge which was mixed with 20 wt% sand to enhance permeability. The column leaching experiment lasted for 9 months without interruption. Over this period no significant dissolution of the matrix material was observed. The leachability of Fe, Ni and Cr as a function of cumulative liquid to solid ratio (L/S) of recovered lixiviant and the measured  $pH$  of the lixiviant are shown in Figure 4.



**Figure 4:** Leaching results of Fe, Cr and Ni as a function of cumulative L/S for the column leaching test of neutralisation sludge

The  $pH$  curve clearly shows that the neutralisation sludge has a buffering capacity of 0.16 eq/l (due to the presence of calcite,  $\text{CaCO}_3$ ), which maintains the  $pH$  around 8.3 until a cumulative L/S of 25 is reached. At this point, the buffering capacity of the matrix material is consumed and the  $pH$  drops sharply to  $pH = 3$ .

At the onset of the *pH* drop, at *pH* = 8.1, Ni starts leaching selectively without dissolution of Cr or Fe. When the *pH* further drops to 3.9 also Cr starts leaching together with a very small fraction of the available Fe. At lower *pH* also Fe starts leaching significantly. It needs to be noticed that over 50% of Ni was leached before Fe dissolution started. Given the high Fe concentration within the starting material (Table 1) with respect to concentrations of Cr and Ni, dissolution of a small fraction of Fe leads to high Fe concentrations in the lixiviant (800-1000 mg/l) with respect to that of Cr or Ni (< 150 mg/l). At the end of the experiment, at a cumulative L/S of 140, 87.7% of Ni present in the neutralisation sludge was extracted, as well as 68.2% of Cr and 60.6% of the total available Fe. XRD analyses confirmed that the residue after leaching was still mainly composed of gypsum and fluorite. However, magnetite and calcite were no longer observed.

## Conclusions

Based on the above results it can be concluded that the selective leaching of Ni from the studied neutralisation sludge can take place within a *pH* interval of about 4-7. In this range Cr and Fe do not dissolve. The neutralisation sludge has a strong buffering capacity. When applying heap leaching to the neutralisation sludge, it is advisable to circulate the leaching solution in order to work with a Ca-saturated medium to avoid gypsum dissolution. The fine-grained nature of the material necessitates granulation of the material prior to heap leaching to allow for a good permeability of leaching liquor. This will be tested in future work.

## Acknowledgements

The presented work was performed within the METGROW+ project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690088. This work reflects only the author's view and the Agency is not responsible for any use that may be made of the information it contains.

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# SORTING WITH BALLISTIC SEPARATORS

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## Introduction

The ballistic separator is a standard MRF (material recycling facility) processing equipment.<sup>1</sup> The machine exists in various types specialised for different applications. Figure 1 shows a section of a MRF flow scheme with the symbolised ballistic separator. In many MRF's the ballistic separator is positioned after infeed and a subsequent drum screen. The drum screen prevents oversized material (approximately 250-300 mm) from entering the following sorting steps. With the ballistic separator, not only a classification but three physically different mass flows are available. In Figure 2 the fractions are as follows: three-dimensional or hard fraction (rolling, 3D), two-dimensional and soft fraction (2D) and a screened, fines fraction (< 50 mm). A multiple deck design can produce up to seven fractions depending on the deck arrangement.<sup>2</sup> Conglomerates of input material are loosened up due to the agitation (crankshaft eccentricity > 50 mm) on the screen deck. The spread of each fraction (corresponding to the machine width) is optimal for feeding sorting systems such as magnets, eddy current systems or automated systems (NIR, X-Ray, metal detection). Screen deck geometry and inclination<sup>3</sup> allow to adapt the machine to various materials regarding purity and yield.<sup>4</sup>

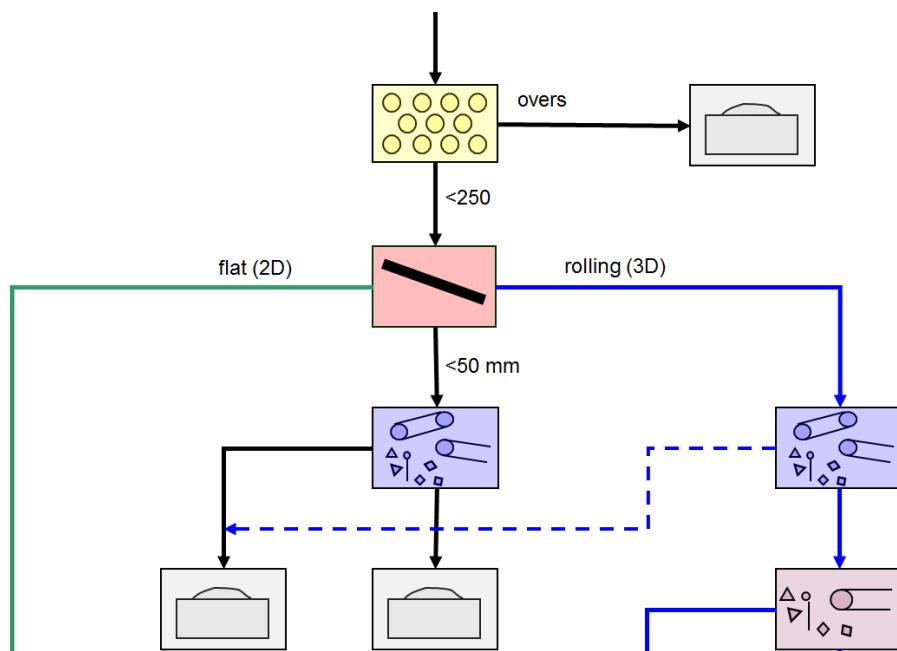


Figure 1: Section of typical MRF flow scheme with ballistic separator

## Working principle

Material to be sorted is fed from the top into the machine (see Figure 2). Inside the ballistic separator a set of inclined screen elements (paddles) form the screen surface. The paddles are positioned next to each other mounted to two synchronously rotating crankshafts. This leads each paddle to perform a circular movement with different angle phase. Some models have the shaft-paddle assembly fixed to a pivoting frame in order to adapt the inclination without tilting the complete machine. Three fractions are being produced: "Three-dimensional or hard", "Fines" and "Two-dimensional and soft".

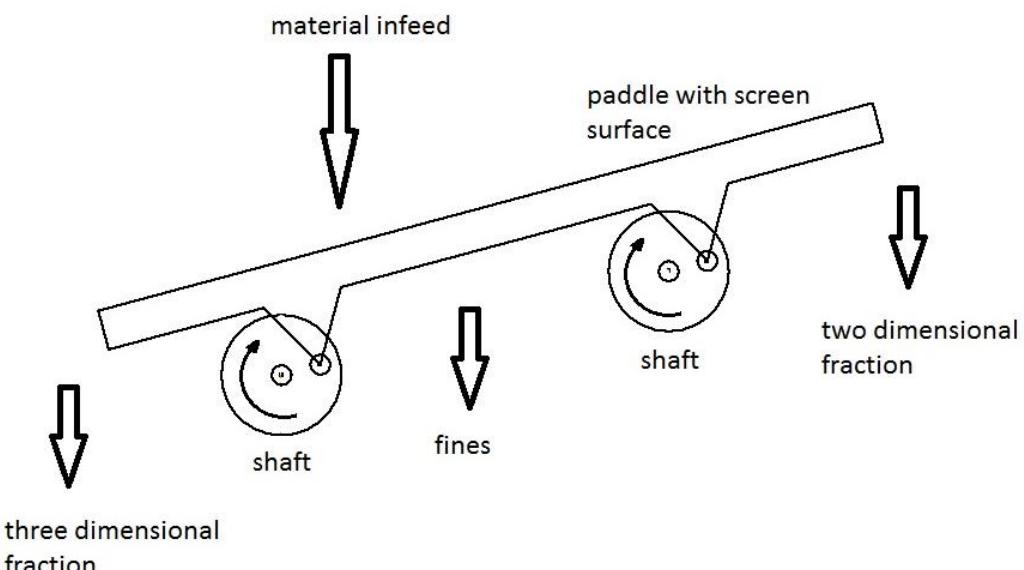


Figure 2: Ballistic separator working principle

The multi paddle design produces a higher transport speed of the "Two-dimensional and soft" fraction than a one paddle design. Another advantage of the multi paddle design is the better dynamic behaviour of the machine. Depending on the input material (wrappings, abrasive material, humidity) a focus should be on maintenance (cleaning and lubrication). In plant design, the access, static and dynamic loads have to be considered.

**Example 1: Sorting of film fraction with hard plastics, PET and metals (density 30 kg/m<sup>3</sup>)**



**Figure 3:** a) Input material<sup>5</sup> b) Three-dimensional or hard fraction c) Two-dimensional and soft fraction d) Fine

**Table 1:** Sorting results of Example 1

	Total proportion (wt%)	Purity (%)	Yield (%)
three-dimensional or hard fraction	45	92	83
two-dimensional and soft fraction	53	84	92
Fines (<45 mm)	2		

A second treatment of the two-dimensional fraction on a ballistic separator enhances the purity to 96%.<sup>4</sup> In real plants this is achieved by combining two or more decks in an appropriate way (stacking).

**Example 2: Sorting of co-mingled material (packaging waste with paper) (density: 60 kg/m<sup>3</sup>)**



**Figure 4:** a) Test setup with STT5000 ballistic separator<sup>6</sup> b) Three-dimensional or hard fraction  
c) Two-dimensional and soft fraction d) Fines

**Table 2:** Sorting results of Example 2

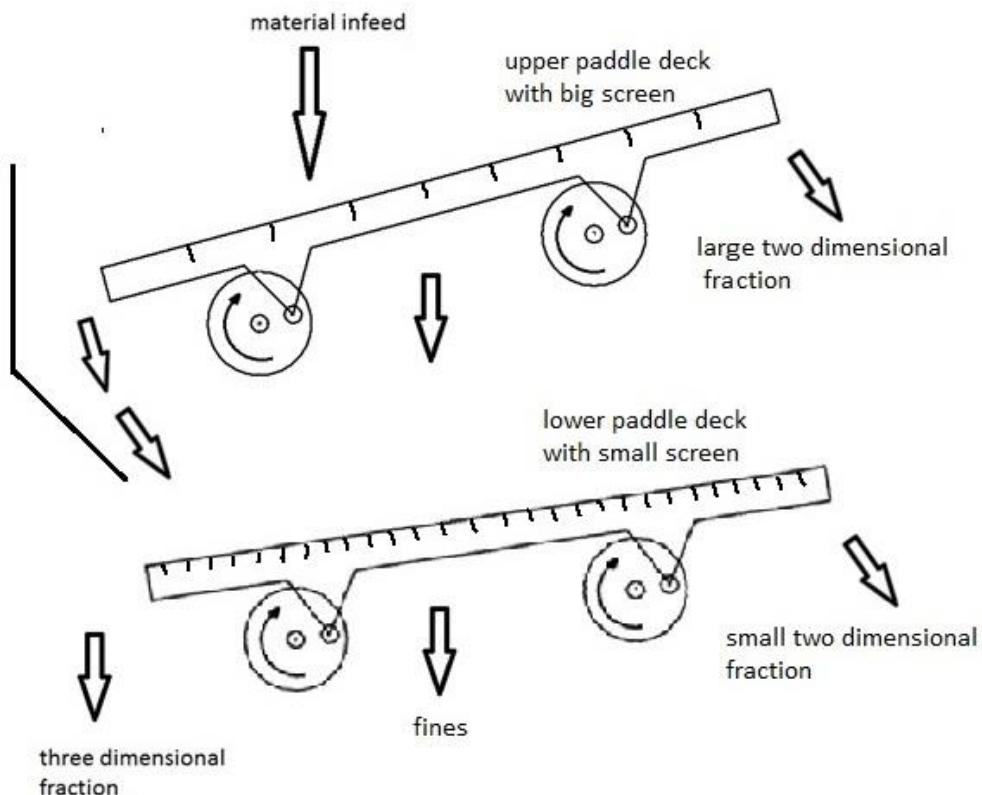
	Total proportion (wt%)	Purity (%)	Yield (%)
three-dimensional or hard fraction	35	86	91
two-dimensional and soft fraction	64	95	93
Fines (<50 mm)	1		

An increase of paddle inclination affects the purity of the three-dimensional or hard fraction in a negative way and the purity of the two-dimensional and soft fraction in a positive way.

## Combination of decks

The combination of two or even three decks offers the opportunity to gain up to seven fractions in one process step. The inclination of a paddle deck affects directly the purity and yield of the two-dimensional and the three-dimensional fraction: With increasing inclination the purity of the two-dimensional fraction increases and the yield decreases. The same is valid for the three-dimensional fraction and vice versa: With decreasing inclination the purity of the three-dimensional fraction increases and

the yield decreases. Figure 5 shows a sketch of a two-deck installation with different screen sizes and screen inclinations: The infeed material is first processed on the upper paddle deck, which is aiming to produce a large two-dimensional fraction with high purity. Hence, the inclination of the upper paddle deck is set rather steep (the absolute angle is depending on the screen geometry). The three-dimensional fraction and the screen fraction of the upper paddle deck is fed to the lower paddle deck. As a result, the lower paddle deck has to process less volume than the upper paddle deck. Thus, it can operate with smaller screen size if desired. The lower paddle deck is adapted for a high purity in the three-dimensional fraction, which means that the inclination is less steep than the inclination of the upper deck.



**Figure 5:** Two deck ballistic separator

## New application to landfill mining

The availability of a ballistic separator for heavy duty applications<sup>7</sup> such as treatment of construction and demolition waste (C&D) as well as landfill mining waste could lead to better sorting processes with respect to effectiveness, wear and energy consumption. Figure 6 shows fractions derived at a test with a STT6000 ballistic separator fed with excavated, landfill mining material. Results are available in the paper of Garcia López (this volume).<sup>8</sup>



**Figure 6:** a) three-dimensional or hard fraction b) two-dimensional and soft fraction

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# **TOWARDS NEAR-ZERO-WASTE RECYCLING OF MINE TAILINGS AND METALLURGICAL PROCESS RESIDUES THROUGH A NOVEL SOLVOMETALLURGICAL PROCESS BASED ON DEEP EUTECTIC SOLVENTS**

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## **Introduction**

The primary mining and metal processing industry has been landfilling and/or stockpiling vast quantities of metal-containing tailings. This extractive waste is considered as one of the largest waste streams in Europe. In the long term, tailing ponds and the associated landfills may represent a major environmental and health liability. The presence of hazardous metals (*e.g.*, As, Cd, Tl, Hg) and sulfides in tailings can lead to an important environmental hazard in the aftercare period of a tailing pond, for example due to the occurrence of acid mine drainage (AMD) and related heavy metal leaching to surface and ground waters.

Nonetheless, the tailings problem can also be considered as an opportunity. The presence of easily accessible, base and critical metal-containing tailings, can mitigate the fact that Europe does not have unrestricted access to ore deposits. The combination of advanced hydro-, solvo- and biometallurgical methods can obtain high solubility of the targeted metals (*e.g.*, In, Ge, Ga, Sb, W, PGMs, REEs, Co, V, Mo, W) and low solubility of the mineral matrix. Within this context, it would be possible to valorise the tailings in three different ways: (1) recovery of valuable metals, (2) concentration and stabilisation of hazardous elements, and (3) production of a clean mineral fraction for added-value applications.

In this work, a new solvometallurgical approach is used based on metal extraction using deep-eutectic solvents (DESs).<sup>1</sup> Since DESs were first reported in 2003, they have been considered as a cheaper alternative to ionic liquids (ILs) due to their easy preparation, just by mixing readily available bulk components. DESs are mixtures of one or more hydrogen bond donors (HBDs) and one or more hydrogen bond acceptors (HBAs), which, when mixed in the proper ratio, show a large decrease in the melting point compared to that of its components.<sup>2</sup> DESs share most of their

physicochemical properties with ILs, *e.g.*, low volatility, wide operational window, and tailored properties by appropriate selection of their constituents. The current research focusses on the design of DESs for high affinity metal separations. The solvent design is based on the correct selection of HBD, HBA, and the ratio between them. The solubility of different metal oxides in DESs was experimentally determined as function of the HBD and the DES's water content. The obtained insights were used for the solvent selection and further optimisation of solvometallurgical leaching processes of a zinc smelting residue.

## Experimental procedure

The DESs were prepared *via* the heating method. According to this method, appropriate amounts of HBD and HBA are weighed, placed in a sealed flask, and then heated while stirring until a clear liquid is formed. The mixtures were heated at 333.2 K in a thermostatic bath with temperature controller. The DESs selected for this work were: (1) glycolic acid : choline chloride at molar ratio 2:1 (GlyA:ChCl(2:1)); (2) lactic acid : choline chloride at molar ratio 2:1 (LacA:ChCl(2:1)); and (3) levulinic acid: choline chloride at molar ratio 2:1 (LevA:ChCl(2:1)). The molecular structures of the DESs' components are presented in Figure 1.

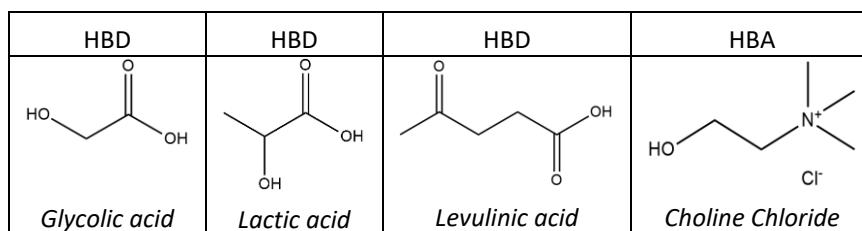


Figure 1: Molecular structure of the DESs' constituents

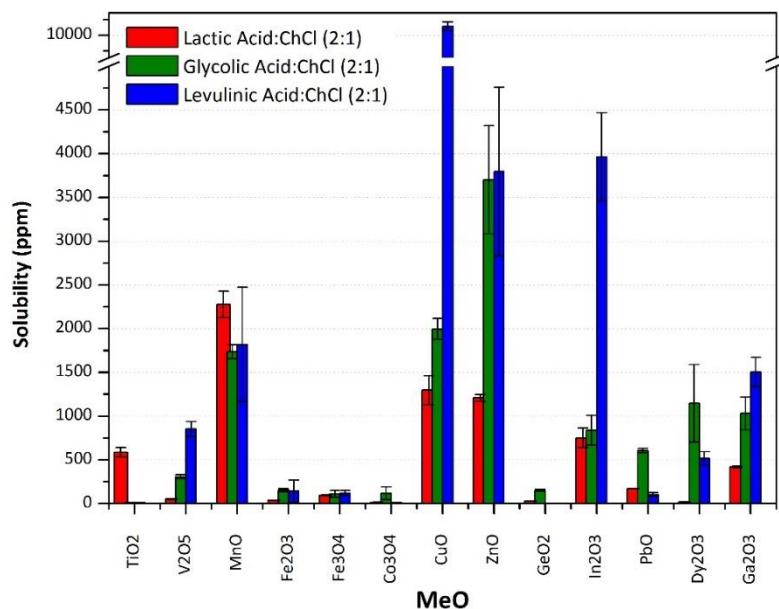
The solubility of different metal oxides ( $\text{TiO}_2$ ,  $\text{V}_2\text{O}_5$ ,  $\text{MnO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{Co}_3\text{O}_4$ ,  $\text{CuO}$ ,  $\text{ZnO}$ ,  $\text{GeO}_2$ ,  $\text{In}_2\text{O}_3$ ,  $\text{PbO}$ ,  $\text{Dy}_2\text{O}_3$ ,  $\text{Ga}_2\text{O}_3$ ) in the selected DESs was experimentally determined by mixing an excess of oxide in 1.5 mL of DES at 40°C for 48 h and 2,000 rpm (Eppendorf Thermomixer C). The obtained solution was filtrated using syringe filters (pore size 0.45  $\mu\text{m}$ ). The filtered sample was diluted with 10 v/v% solution of Triton X-100, and analysed by Total Reflection X-Ray Fluorescence (TXRF).<sup>3</sup>

After consideration of the obtained solubility data, the DESs' potential for metal recovery from an industrial tailing sample (*i.e.*, zinc smelting residue) was also evaluated. The solid residue was leached within the following parameters: *liquid-to-solid ratio* 10:1,  $T = 40^\circ\text{C}$ ,  $t = 48$  h, and stirring speed of 1,000 rpm (Eppendorf Thermomixer C). The pregnant leach solution was centrifuged at 4,000 rpm for 10 min (Eppendorf 5004), diluted in 2 v/v%  $\text{HNO}_3$  solution and analysed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES).

A zinc smelting residue, termed “goethite”, originated from Nyrstar (Balen, Belgium) was studied. The residue is produced by the precipitation of Fe from Zn-rich leach solutions in the roasting-leaching-electrowinning process of the Nyrstar Balen plant. Currently, the residue is dry stacked at the plant site. The approximately composition of the residue (expressed in ppm and on dry basis) is as follows: Zn: 58,800; Fe: 241,000; Pb: 17,800; Cu: 4,280; As: 3,320; Ca: 55,100. Furthermore, the main phases are (in wt%): gypsum = 16.0; magnetite = 25.4; jarosite = 9.7, franklinite = 9.6. Besides, 37.6 wt% of the residue is found as amorphous phases, most likely to be ascribed as goethite.

## Results and discussion

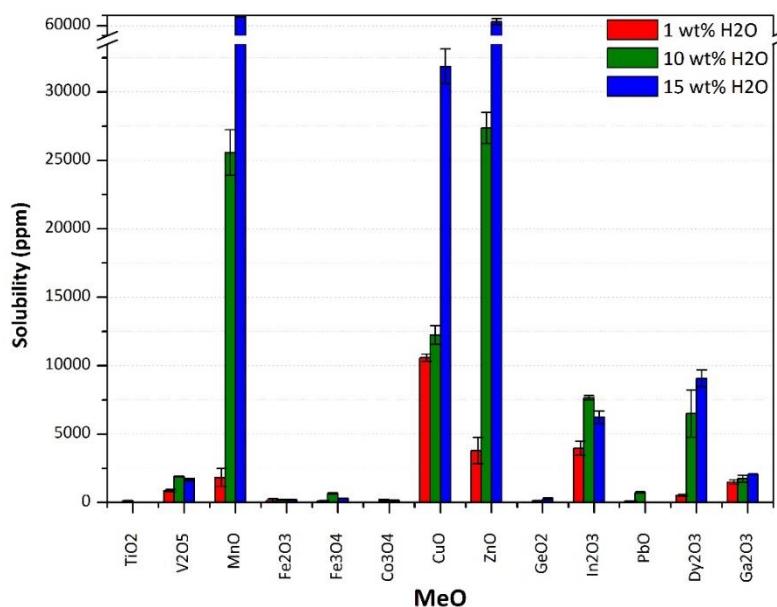
In a previous work, Abbott and co-workers showed that when choline chloride was used as HBA, the use of a carboxylic acid (malonic acid) as HBD would lead to much higher solubilities of metal oxides compared to amides (urea) or polyols (ethylene glycol).<sup>4</sup> We expected that the selection of carboxylic acid-based DESs with lower viscosities (*e.g.*, substitution of dicarboxylic acids by monocarboxylic acids)<sup>5</sup> and higher carboxylic acid content (*i.e.*, higher HBD:HBA molar ratio) would improve the solubilities of metal oxides. Consequently, only HBDs based on monocarboxylic acids with rather low alkyl chain length were considered (Figure 1). The experimental solubilities of different metal oxides in the selected DESs are depicted in Figure 2.



**Figure 2:** Solubility of metal oxides in carboxylic acid-based DESs

It can be observed that for most of the studied metal oxides, the solubility decreases in the following order: LevA:ChCl(2:1) > GlyA:ChCl(2:1) > LacA:ChCl(2:1). It is worth mentioning that the solubility of metal oxides such as CuO, ZnO, In<sub>2</sub>O<sub>3</sub>, and MnO is

much higher compared to the solubility of  $\text{Fe}_2\text{O}_3$  and  $\text{Fe}_3\text{O}_4$ . These differences in solubility are of great interest for industrial applications where co-dissolution of Fe is undesired. Besides showing the highest solubilities, LevA:ChCl(2:1) is also the cheapest and least viscous DES from the selected ones. Therefore, it was chosen to further investigate the effect of the water content on the solubility of metal oxides. The obtained results are shown in Figure 3.

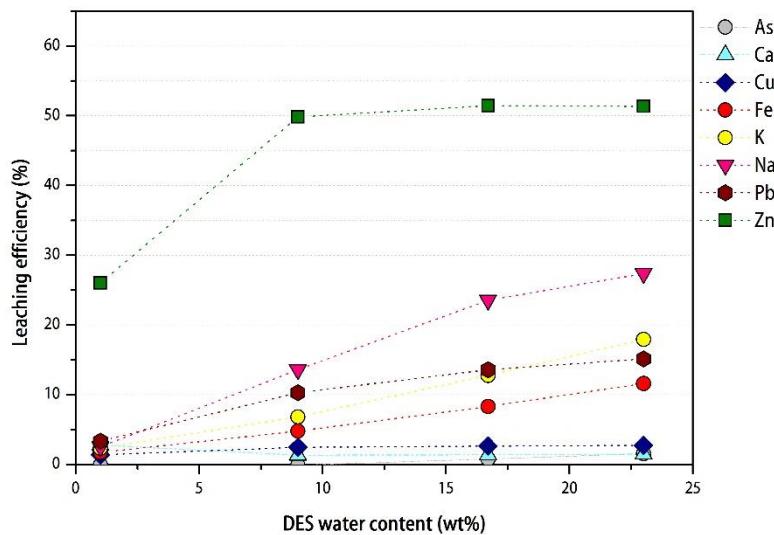


**Figure 3:** Effect of the DES's water content on the solubility of metal oxides

From Figure 3 it can be observed that the addition of water to the DES produces a high solubility increase for most of the studied metal oxides. It is also remarkable that the solubility of some metal oxides (*e.g.*,  $\text{Fe}_2\text{O}_3$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{Co}_3\text{O}_4$ ) is, proportionally, much less increased when compared to other metal oxides (*e.g.*,  $\text{ZnO}$ ,  $\text{CuO}$ , or  $\text{MnO}$ ). Moreover, by comparing Figure 2 and Figure 3, it can be noticed that the DES's water content is much more influential on the solubility of metal oxides than the HBD type. Furthermore, increasing the water content drastically decreases the viscosity of the DES, and consequently, the operational costs (*e.g.*, DES recovery and pumping costs).

The obtained solubility data suggest that the selective separation of Zn and Cu from Fe can be possible. This separation could be of great interest for the valorisation of the residue produced during the Zn smelting process. The strategy for the zero-waste recycling of this type of residue is its separation in three different fractions: (1) a Zn (Pb-Cu) rich stream to be recirculated, (2) a stream rich in hazardous components, such as As, and (3) a residual fraction, containing preferably most of the Fe. In this work, the aforementioned residue is leached with LevA:ChCl(2:1) aiming at the production of a Zn rich stream. The experimentally determined leaching efficiencies

(of the most representative metals) are shown in Figure 4. Additionally, a summary of the leachate composition is also shown in Table 1.



**Figure 4:** LevA:ChCl(2:1) leaching efficiency as function of the water content of the DES. Leaching conditions are:  $T = 40^\circ\text{C}$ ,  $t = 48\text{ h}$ ,  $L:S\text{ ratio} = 10$ , 1,000 rpm, particle size < 1 mm.

From Figure 4, it can be noticed that LevA:ChCl(2:1) ( $\text{H}_2\text{O}$  wt%  $\geq 9$ ) can solubilise up to 50 wt% of the Zn and 15 wt% of the Pb; while only 10-15 wt% of Fe, and < 1 wt% of As are co-leached. The leaching efficiency of Cu (< 5%) is much lower than what would be expected with basis on the solubility experiments.

**Table 1:** Composition of the pregnant leach solution

wt% $\text{H}_2\text{O}$	Zn (ppm)	Fe (ppm)	Pb (ppm)	Cu (ppm)	As (ppm)	Ca (ppm)
1	1,531	416	66	6	-	152
9	2,934	1,157	186	11	-	74
17	3,031	2,007	238	11	2	76
23	3,023	2,799	269	12	4	81

The composition analysis of the pregnant leach solution (Table 1) shows that increasing the DES's water content boosts the amount of co-leached Fe much more than the amount of extracted Zn (*i.e.*, Fe concentration in leaching solution is one-third of Zn at 1 wt%  $\text{H}_2\text{O}$ , while Zn and Fe concentrations are in the same range at 23 wt%  $\text{H}_2\text{O}$ ). Nevertheless, the preliminary results show that DESs are a promising alternative for the selective recovery of Zn from Fe-Zn rich industrial waste streams.

## Conclusions

In this work, carboxylic acid-based DESs has been tested for the solubilisation of different metal oxides ( $\text{TiO}_2$ ,  $\text{V}_2\text{O}_5$ ,  $\text{MnO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{Co}_3\text{O}_4$ ,  $\text{CuO}$ ,  $\text{ZnO}$ ,  $\text{GeO}_2$ ,  $\text{In}_2\text{O}_3$ ,  $\text{PbO}$ ,  $\text{Dy}_2\text{O}_3$ ,  $\text{Ga}_2\text{O}_3$ ). It has been found that LevA:ChCl(2:1) exhibits the highest solubilities for the studied metal oxides. Moreover, it was also found that for all the studied DESs, the solubility of iron oxide ( $\text{Fe}_2\text{O}_3$ ,  $\text{Fe}_3\text{O}_4$ ) is rather small compared to other metal oxides ( $\text{ZnO}$ ,  $\text{CuO}$ ,  $\text{MnO}$ ). Furthermore, it has been determined that an increase of the water content of the DES drastically increases the solubility of some metal oxides ( $\text{ZnO}$ ,  $\text{CuO}$ ,  $\text{MnO}$ ), while it has a negligible effect in some others ( $\text{Fe}_2\text{O}_3$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{Co}_3\text{O}_4$ ). Those results suggested that the selective Zn recovery from residues of the Zn smelting process, composed predominantly of Fe- and Zn-, via a solvometallurgical leaching using DESs could be feasible. Experiments on industrial Zn smelting residue using LevA:ChCl(2:1) showed leaching efficiencies of up to 50% for the Zn, while only of 10% for Fe, when DESs with water content  $\geq 9$  wt% were used. Nonetheless, a higher water content lowered the selectivity against Fe, and resulted in higher Fe impurities in the leachate, compared to a leaching process with lower water content.

## Acknowledgements

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# **LANDFILL MINING OF A MIXED MUNICIPAL SOLID WASTE AND COMMERCIAL WASTE LANDFILL: APPLICATION OF EXISTING PROCESSING TECHNOLOGY – OPPORTUNITIES AND LIMITATIONS**

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## **Introduction**

Several research projects on “landfill mining (LFM)” have been conducted in the past. Recent examples for these projects are “Landfill Mining Austria – Pilot Region Styria (LAMIS)”<sup>1</sup> and the LFM project “MINE” under the leadership of FCC Austria Abfall Service AG, which was co-funded by the Austrian Research Promotion Agency and conducted in cooperation with the Horizon 2020 project “EU MSCA-ETN NEW-MINE”. The project “MINE” was initiated to find out whether it is possible to detect hotspots (volume elements that e.g. contain relatively high amounts of metals) inside a landfill and whether a separation of high value materials is possible using a state of the art mechanical-biological-treatment-plant on site. This plant was neither built nor especially adapted for the task of processing landfill mining material, in order to find out whether the built-in machines can handle the excavated material. Most importantly the potential economic risks and opportunities of such a project should be evaluated for a company contemplating a LFM project.

## **Materials and methods**

The project involves the recovery of valuable material from an existing landfill site in Halbenrain (Austria), which was mainly used to deposit household and commercial waste. The sector of planned raw material recovery is located in a part of the landfill, which was filled in the years 1997-1999 and is currently in the aftercare phase. The project envisaged the experimental landfill mining of around 5,000 tonnes from a defined area of 2,000 m<sup>2</sup> of the landfill site. The excavated material was processed in the existing MBT plant at the project site. The generated output fractions were either sold or properly deposited at the extraction area.

Because accurate records of the amount of landfilled material have been available since the second half of 1990 and these have been carried out in digital form since 1997, statements on the composition of the landfill body could be made. In total, the landfill was filled with 62 wt% of commercial waste, 22 wt% of sludge (from galvanic processes, effluent sludge and tannery sludge) and 16 wt% household waste.

If one combines the information about the temporal and spatial separation with that of the materials delivered, different interesting areas of the landfill body could be distinguished. Afterwards an evaluation of each individual area with respect to its content was made. Based on these evaluations a promising landfill compartment was defined as a hotspot and chosen for the exploitation of landfill mining material. This hotspot is characterised by the fact that, with increasing depth, high metal concentrations were expected due to delivery recordings. The LFM material was excavated layer to layer. Each layer was then dried separately in a rotting tunnel to keep them separated. This way a spatial resolution is maintained.

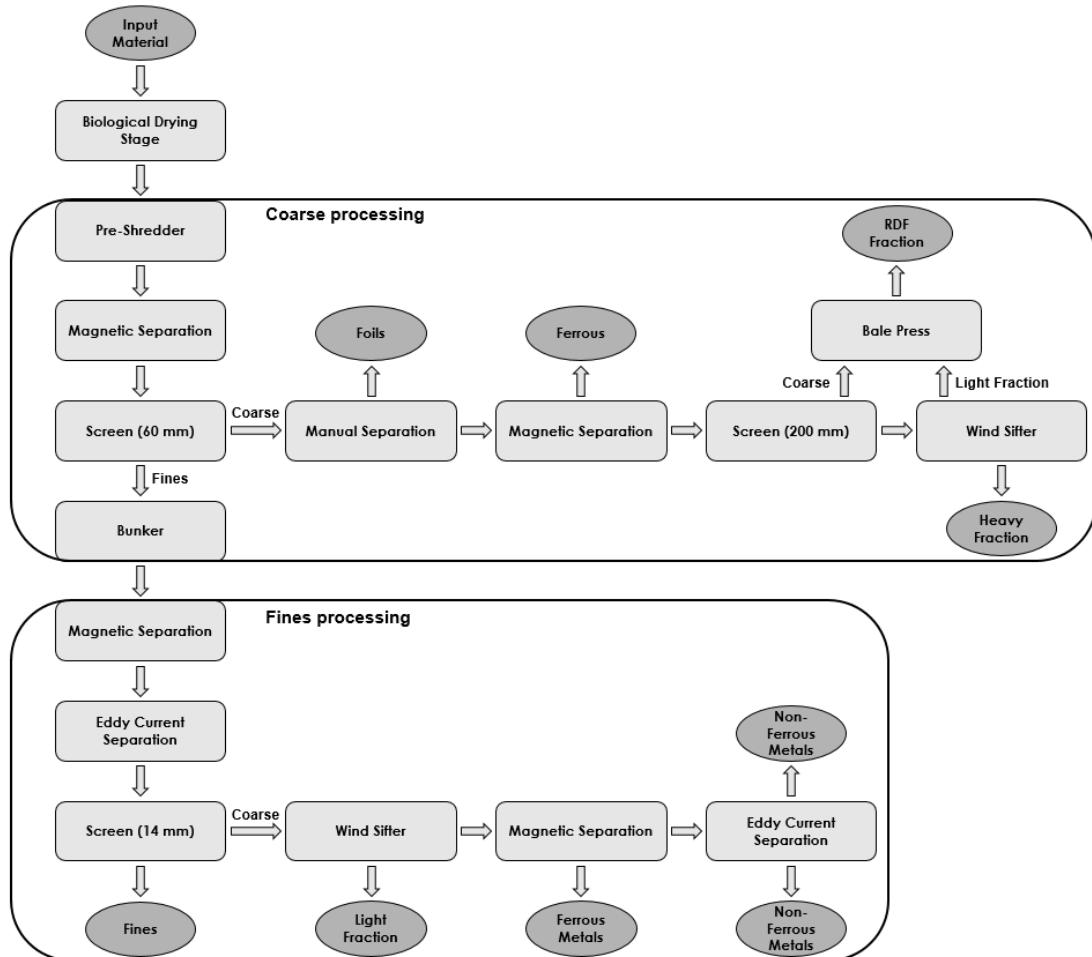


**Figure 1:** Sampling point for the exploitation of landfill mining material

The landfill material was excavated by means of an excavator, transported to the processing plant with trucks and then filled into rotting tunnels. There it was dried prior to the mechanical treatment. The drying time was initially set to approximately one week. However, as described in the results section, it was found that a three week drying time was necessary in order to ensure a successful mechanical treatment. Figure 2 presents the processing scheme of the MBT plant. The processing of landfill material can be divided into three steps:

- Drying stage
- Coarse processing (> 60 mm)
- Fines processing (< 60 mm)

During the whole drying process, fresh air was used. For this drying stage three rotting tunnels were applied. The drying process lasted on average three and a half weeks.



**Figure 2:** Processing scheme of the MBT plant on the landfill in Halbenrain, used within landfill mining project

The mechanical processing is divided into two stages, which were conducted on different days: “coarse processing” and “fines processing” (See Figure 2). After the biological drying stage, the material from each rotting tunnel (*ca.* 300 - 400 m<sup>3</sup>) passed the “coarse processing” stage at first. In this process a fines fraction (< 60 mm) was produced which was then stored in a bunker for one to three days until the “coarse processing” was finished and “fines processing” could be conducted. Afterwards the qualities of the non-ferrous metal products were analysed in a laboratory, determining the purity of the products. Additionally, trials with an eddy current separator were conducted with the fines < 14 mm. Within these trials non-ferrous metal products were produced.

# **Results**

## **Excavations**

During the excavation work low odour emissions were found and the stability of the embankment has proven to be problem-free. The space requirement for reaching the desired depth has been found to be larger than originally expected, since among other factors the quantity of covering material was underestimated.

## **Drying process**

For the drying stage a residence time of one week was planned at first. During the tests it was found that this residence time was not sufficient, since the waste was still too wet to enable mechanical processing. As a result of this, at the beginning machines and conveyor belts clogged. In an iterative process, the residence time was extended to about three and a half weeks, so that mechanical treatment was possible.

## **Mechanical processing**

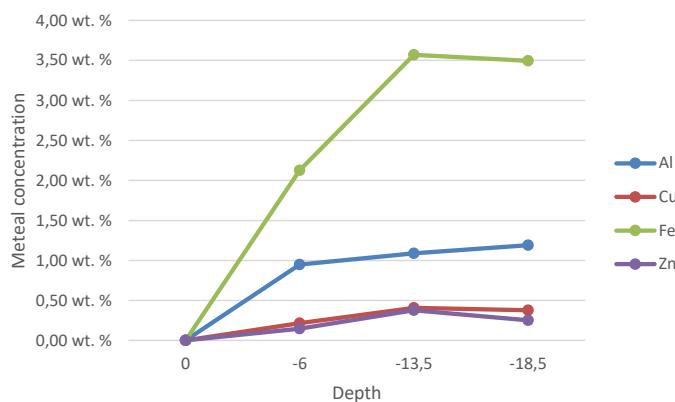
The manual foil separation of high-density polyethylene (HDPE), polyethylene terephthalate (PET) and low-density polyethylene (LDPE) films was reduced after a week to the removal of LDPE foils since the remaining parts were marginal. The eddy current separation of the medium grain (14-60 mm) significantly improved the yield of non-ferrous metals. During the excavation a gas drainage was found. In doing so, stones were excavated, which subsequently caused increased wear on machine components. In combination with the clogging of different aggregates due to the initially too high humidity of the material from the biological drying stage, this factor had a negative effect upon the motivation of the employees. The plastic foil fraction exhibits considerable amounts of defilements. The influence on a possible use of this fraction as RDF is questionable. Although the plastic products obtained were contaminated, they did not undergo visual changes. The wind sifter heavy fraction (60 - 200 mm), which has not been further processed, contains a considerable amount of ferrous and non-ferrous metals. In particular, the amount of ferrous metals is significant but characterised by corrosion and impurities, *e.g.* plastic foils. The fines fraction contained sewage sludge as well as sludge from tanneries, which is in agreement with the documentation of the landfill. This is demonstrated by the high copper and aluminium content of the fine fraction. In Table 1 the quantities of all output fractions, produced throughout the complete "MINE" project, can be seen.

**Table 1:** Output quantities of mechanical processing stages within “MINE”

Fraction	tonnes	wt%
RDF fraction > 60 mm	408	13.2
Residuals	697	22.5
Ferrous metal products	65	2.1
Non-ferrous metal products	4	0.1
Windshifter light fraction	90	2.9
Fines (< 14 mm)	1312	42.4
Windshifter heavy fraction	186	6.0
Plastic foils (only produced during half of the process time)	23	0.7
Impurities (stones)	10	0.3
Material losses	296	9.6

### Prediction of Hotspots

The mechanical processing results show that the predicted hotspots correspond to the amount of metals found in the layers. As predicted, increased metal concentrations were detected with increasing depth (Figure 3).



**Figure 3:** Amount of metals, found in increasing depth

### Financial aspects

The analyses have shown that the non-ferrous metal concentrates produced are of marketable quality. The iron concentrates are of poor quality due to corrosion and because part of the contaminants from the conveyor belt were included into the ferrous fraction through the overband magnets. Due to the market price of 0 € for RDF at the time no profit could be made. Taking everything into consideration, the sole financing of LFM at the site in Halbenrain by the recycling of valuable materials using the MBT plant has proven to be impossible. The produced non-ferrous concentrates are promising, but quantities are too low to make their separation

profitable. For the economic realisation of LFM projects of this size, the extraction of metals from the largest fraction < 14 mm is indispensable. However, the mechanical processing technology reaches its limits at this point. Further trials have shown that while concentrates can be produced, the quality of these is very poor. From this it can be concluded that, in an ideal case, further processing of the fines < 14 mm must be carried out wet-mechanically.

## Risks and Dangers

From today's point of view, there is no negative impact on the environment at the site in Halbenrain, since hardly any gases that are harmful to the environment were emitted to the extent that this could be investigated with the available measurement methods. LFM can also be considered as non-problematic regarding work safety. It is also stated that the organics, if they are biodegradable, have been reduced to a large extent. As the only organic fraction, wood could be found to a greater extent in the wind sifter heavy fraction of 60 - 200 mm. An incalculable risk would be the discovery of hazardous waste, e.g. asbestos, dust or oil barrels, which could lead to health risks as well as environmental damage and thus highly increase expenses. This risk should be minimised when exploring the landfill and potentially contaminated areas should not be used for Landfill Mining projects.

## Conclusion

With the available plant on site, landfill mining is theoretically possible. Though the current process does not enable an economically viable treatment of the tested landfill material. In order to enable economically viable processing of landfill material especially the treatment of the fine fraction < 14 mm has to be improved, showing great potential due to its high mass fraction. All in all, landfill mining will not be pursued in the near future on site.

## Acknowledgement



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# BALLISTIC SEPARATORS FOR C&D AND LANDFILL MINING APPLICATIONS: TECHNICAL FEATURES OF HEAVY DUTY BALLISTIC SEPARATORS

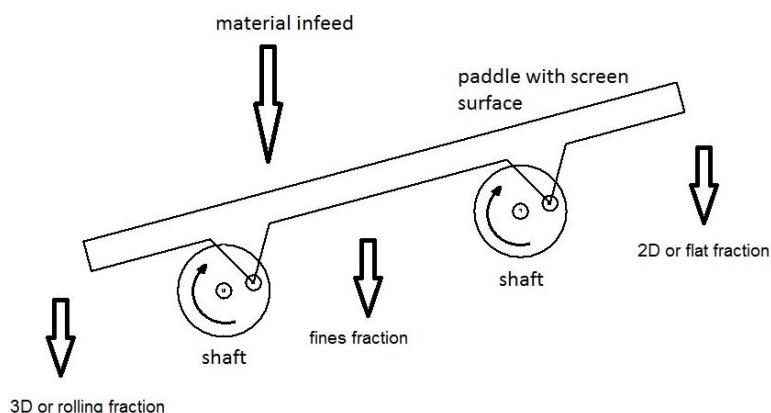
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## Introduction

Ballistic separators are typical sorting machines in mechanical recycling plants. Normal applications are the sorting of paper and cardboard, co-mingled, household waste, plastic bottles and film.<sup>1,2</sup> The main task of the ballistic separator is the separation of a waste stream in three fractions, a mainly two-dimensional or soft fraction (2D or flat fraction), a mainly three-dimensional or hard fraction (3D or rolling fraction) and a fines fraction, with all material smaller than the screen size.<sup>3</sup>



**Figure 1:** Operating principle ballistic separator

Typical ballistic separators on the market consist of two eccentric shafts mounted on a stiffening frame, a set of paddles, depending on the sorting width and a machine body. The durability and construction details of such common machines don't allow the handling of heavy waste streams with big and heavy single parts, like stones and concrete pieces. Apart from this, the processing of material with high moisture content can be a problem.<sup>3</sup>

## Requirements and conditions for a heavy duty ballistic separator

To bring the advantage of ballistic sorting to the application of construction and demolition waste (C&D), heavy commercial and industrial waste (C&I) and landfill mining, a special machine design is needed. A machine with the possibility to handle high feed capacities and single pieces bigger than 1,000 mm and more than 100 kg allows avoiding pre-shredding or pre-sorting processes. This helps to sort big items in one step and save wear and energy costs for shredders. The new machine requires a very robust design and enough space to discharge the non-shredded material. Also, the conveyor and sorting components following the machine have to be dimensioned for the heavy material stream.

## Technical details and features – STT6000

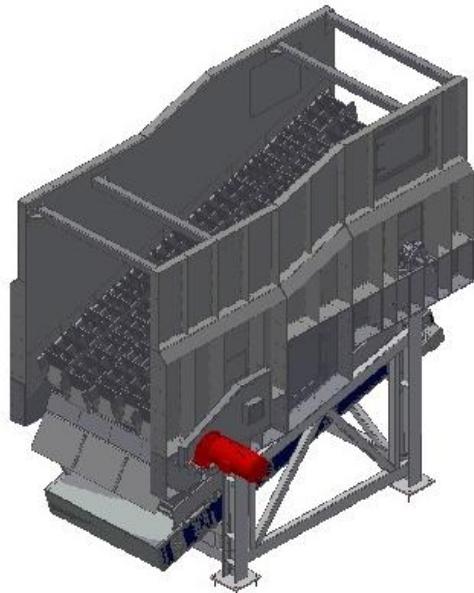
### Overview

The ballistic separator type STT6000 has a couple of design features to handle heavy, un-shredded waste streams. Table 1 shows the main data of the machine.

**Table 1:** Technical specification of Stadler ballistic separator Type STT6000

<b>Feed capacity up to approx.</b>	200 m <sup>3</sup> /h (with 200 mm screen)
<b>Feed size max</b>	2000 mm x 1000 mm x 1000 mm
<b>Machine weight</b>	25 000 kg
<b>Overall width</b>	2970 mm (without engine)
<b>Overall length</b>	6030 mm
<b>Overall height</b>	6040 mm
<b>Screen area</b>	14.15 m <sup>2</sup> (2358 mm wide and 6000 mm long)
<b>Drive concept</b>	electric drive
<b>Main engine power</b>	30 kW

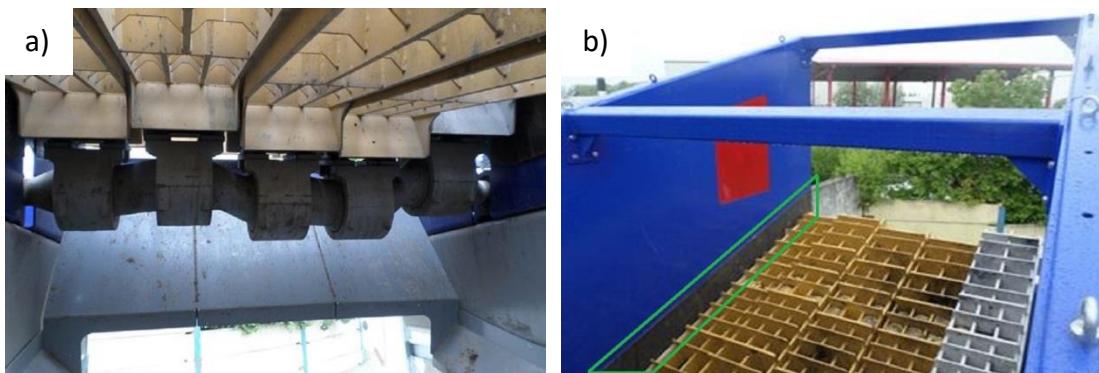
Figure 2 provides a schematic view of the ballistic separator type STT6000. The base frame, which simultaneously serves as a support for the shafts and the sidewalls, is directly mounted to the steel construction. A five paddle design with an angular offset of 72° ensures a maximum movement between the single paddles and reduced vibrations and residual moments. Two shafts with a major diameter of 280 mm are cast in one piece and transfer the forces from the paddles to the base frame.



**Figure 2:** Ballistic separator STT6000 with fines discharge conveyor

### Features

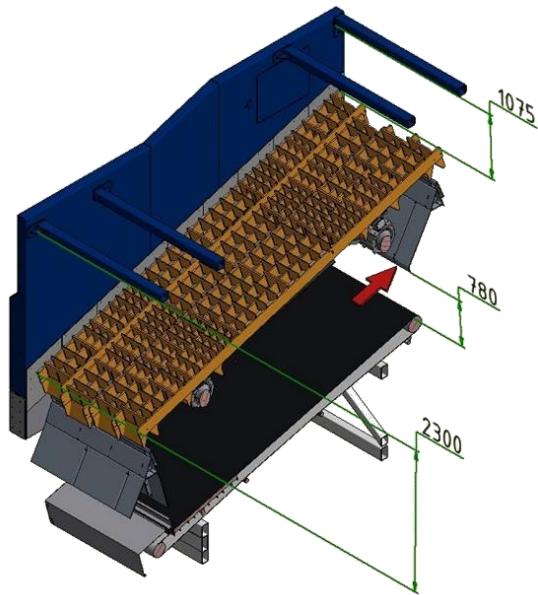
Both shafts are directly mounted to the base frame and have no intermediate support bearings or a support frame inside the machine. All fines falling through the paddle screen can enter the fines discharge conveyor without any barriers. Because of the large shaft diameter long material can hardly wrap around the shaft body (Figure 3a). Replaceable wear protection, made of wear-resistant steel, on high wear areas protects the side walls (Figure 3b).



**Figure 3:** a) Shaft, view from machine interior; b) Hardox planking (green box)

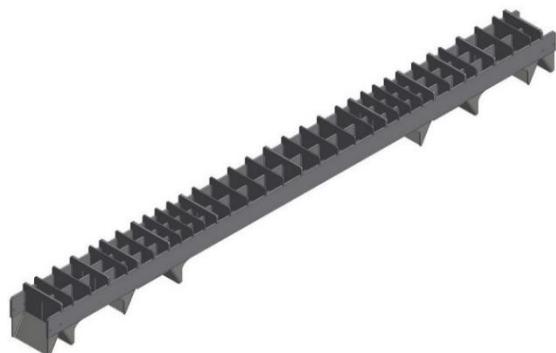
The eccentric bearings of the shafts are protected by a combination of a labyrinth and a rotor sealing. The sealing gap can be greased from outside during operation through lubrication holes by an automatic system. All dirt and liquid from the outside will be pushed out of the sealing before reaching the bearings. The bearings don't need any additional greasing and run with the optimal quantity of grease to avoid overheating. The discharging points for the flat and rolling fraction are large enough

to pass bigger single parts and avoid clogging objects. Under the paddles, there is enough space for long materials, such as iron rods, to get through the grids and turn around on the fines conveyor belt (Figure 4).



**Figure 4:** Sectional view with dimensions of discharging points

Every paddle is a single piece welding construction without changeable screen for a maximum of stiffness and robustness and also made of wear-resistant steel to withstand impacts from heavy single parts. Possible screen sizes are 200 mm, 120 mm and 90 mm. Smaller screen sizes are not available because of the risk of blockage with moist infeed material (Figure 5).



**Figure 5:** Welded paddle with 200 mm screen

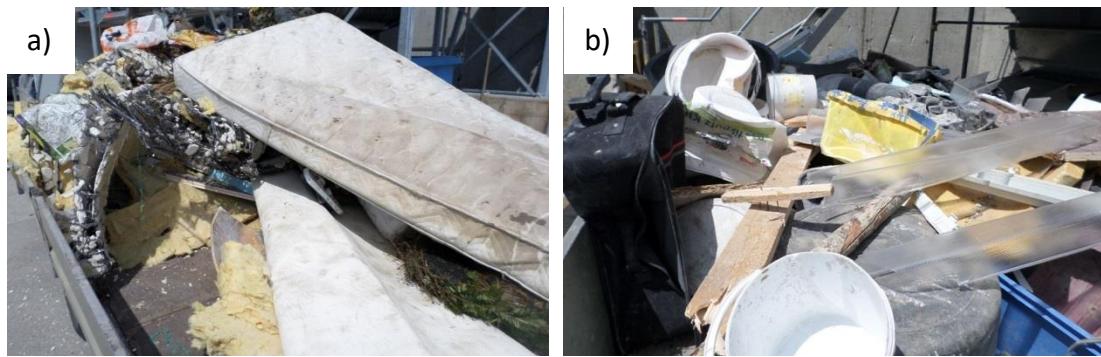
The adaption of quality and yield of the flat and rolling fraction can be done by a change of inclination of the paddles. Possible inclinations are 15°, 17.5° and 20°, the flatter the paddles, the more material reaches the flat fraction.

## **Implementation in flow schemes**

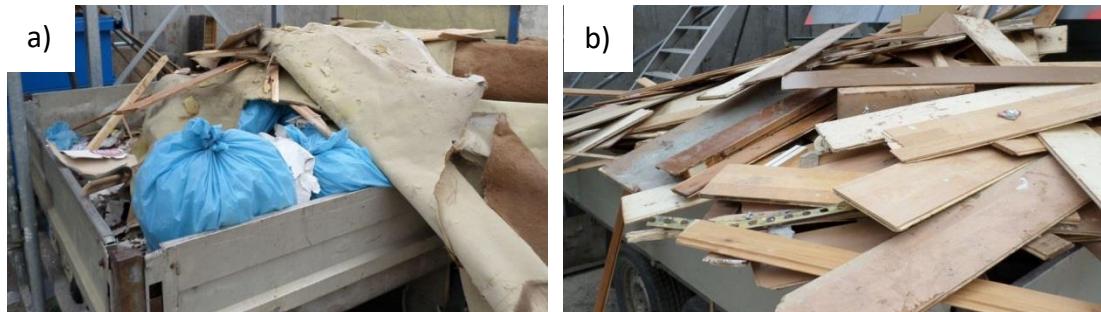
The ballistic separator type STT6000 is designed as a pre-sorting machine. The type and layout of the sorting process and all following devices behind the ballistic separator depend basically on the input material and the screen size of the paddles. The rolling fraction consists of a mixture of hard particles, such as wood, concrete, bricks, rigid plastic and metal in different particle sizes. Because of the high single part weight of input materials up to 200 kg and sharp edges in the material pieces, it is necessary to absorb the impact on a sloping chute behind the paddles at the rolling side of the machine. On this chute the material can slide, without damaging the belt, to the transport conveyor for the next sorting steps. A possibility could be to add a robot sorting system that picks out all fractions except the minerals. Normally this fraction has the biggest mass portion and should remain on the conveyor belt. Typical robot sorting systems can handle single pieces up to 30 kg.<sup>5</sup> The flat fraction of the waste consists mainly of soft particles like film, paper and textile. The transport conveyor has to proceed in a straight line away from the machine to prevent large film from being caught at the sidewalls or the machine frame of the ballistic separator. The processing of the waste stream in one line enables the use of large belt widths for the flat transport conveyor and also the use of NIR sorters with a high possible throughput at the same time. The processing of the fines fraction depends on the screen size of the paddles. As a pre-sorting machine, the STT6000 removes all oversize material and allows the material smaller than 200 mm to pass typical sorting devices like magnets, eddy current systems or other automated systems, also other ballistic separators with a smaller screen size are possible. The fines discharge conveyor should have a steel reinforced belt to protect the belt surface against damage.

## **Typical sorting results**

Because of the high crankshaft eccentricity and the high cross ribs of the paddles towards the conveying direction, also more two-dimensional but soft objects can reach the flat fraction. Depending on the quality and composition of the non-shredded infeed material, the sorting result can show flat but hard objects in the rolling fraction and three-dimensional but soft objects in the flat fraction. Figure 6 and 7 show typical examples for the sorting results of C&I waste and light C&D waste. Especially closed bags and mattresses are typical examples. Usual waste streams and their objects, like film, textile, rigid plastic or metals behave similar to the well known machine types of ballistic separators.



**Figure 6:** a) Flat fraction C&I waste; b) rolling fraction C&I waste



**Figure 7:** a) Flat fraction light C&D waste; b) rolling fraction light C&D waste

## Conclusion

The adaption of a ballistic sorting process to heavy waste streams is possible with a corresponding machine design and dimensioning. Also non-shredded and non-pre-sorted materials can be handled on the ballistic separator type STT6000. First findings with landfill mining material show the feasibility of a sorting process on a machine of this size.

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# **THE POTENTIAL OF THE BALLISTIC SEPARATOR TYPE STT6000 AS A FIRST STEP FOR THE RECOVERY OF REFUSE DERIVED FUEL FROM LANDFILL MATERIAL: A CASE STUDY AT MONT SAINT GUIBERT LANDFILL (BELGIUM)**

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## **Introduction**

Landfill mining has received a growing interest in recent years due to previous investigations, which show that landfills could deliver a stream of secondary raw materials and energy.<sup>1</sup> Factors such as the age of the landfill, type of landfill and its location have an impact on the type of materials stored and, hence, its landfill mining potential. The uncertainty of the composition of a landfill can complicate its mining activity and increase the risks and the costs of a mining project. One of the possible revenues from landfill mining projects comes from the recovery of Refused-Derived-Fuels (RDFs). RDF can be used as a (partial) replacement of fossil fuels in cement plants, conventional thermal power plants, industrial plants; for incineration in furnaces with energy recovery; and in gasification and pyrolysis. While Solid-Recovered-Fuels (SRFs) must comply with the classification and specifications established in the EN 15359 standard,<sup>2</sup> RDF doesn't need to comply with any standard or specification, but should only meet the specifications established between the producer and the user of the fuel. SRF/RDF consist of mixtures of waste materials such as plastics, paper, textiles and wood, which can be ideal to replace traditional fuels provided the following characteristics are met: high calorific value, low moisture and ash content, high biomass content and low content of chlorine, sulphur and heavy metals. Among the advantages of the utilisation of RDF are the reduction of the use of fossil fuels, the reduction of greenhouse gas emissions, the recovery of the energy contained in waste and the possibility of receiving subsidies for the production of energy under special regimes. The disadvantages include the

perception that the energy recovery from these fuels is opposed to recycling and that the facilities must be subject to more restrictive emission limits when replacing traditional fuels, making it necessary to install more complex gas treatment systems. RDF can be obtained from Municipal Solid Waste (MSW) by different treatment types. Generally, these treatment processes consist of a particle size reduction, a thermal drying process and the final preparation of SRF/RDF, resulting in:

- Removal of inert fractions and incombustible materials by the use of different sieves, air sifters and ballistic separators;
- Removal of materials containing undesired elements like Cl, S, Hg and PVC by sensor based sorting technologies (*e.g.* NIR);
- Removal of non-ferrous metals by eddy current separators;
- Adjustment of the moisture content as requested by the client, *e.g.* for pelletisation processes;
- Reduction of the particles size by a shredder or a cutting mill;
- Homogenisation through mixing.

However, these processes are extensive, complex and costly when applied in landfills since the composition of the material is very heterogeneous and, in many cases, the waste presents a high moisture content. Besides, the uncertainties that landfills keep in relation to their composition make the mechanical processing more challenging. Therefore, new technologies/strategies have to be employed to adopt proven technologies and to enhance the production of RDF from landfills.

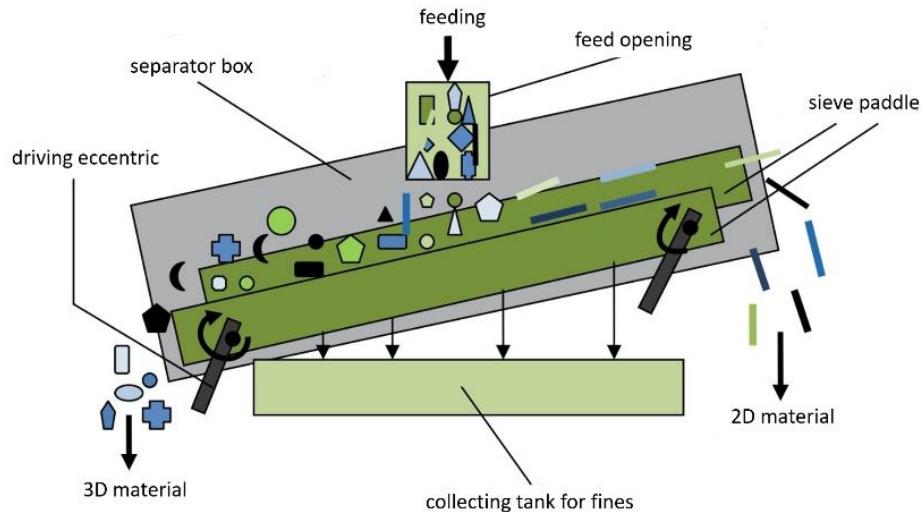
The case study presented in this paper is studied in the EU MSCA-ETN NEW-MINE Project and attempts to draw the reader's attention to recent advances in mechanical processing achieved through the use of a Ballistic Separator, type STT6000, as a first step for the production of RDF from excavated waste of a landfill. The main objective of this test was to study the efficiency of the Ballistic Separator as the initial step of the mechanical treatment without a pre-shredder, keeping the original particle size of the material throughout the pre-processing. A secondary objective, which is not included in this paper, is the possible validation of the geophysical measurements with the results of the material characterisation after the sampling campaign.

## **Materials and methods**

### **Ballistic Separator STT 6000**

A ballistic separator, as seen in Figure 1, is a processing unit designed to separate solid waste depending on the characteristics size, density and shape. It consists of inclined paddles with specific mesh sizes, which carry out a circular movement induced by two crankshafts located transversally at the top and bottom of the ramp.

The inclination of the equipment and the oscillating movement of the paddles allows the gravimetric separation of the flow in three different fractions: 3D fraction (rolling and heavy, 2D fraction (light and flat) and the sieved fraction (fines).



**Figure 1:** Schematic diagram of a ballistic separator adopted from M. Hans<sup>3</sup>

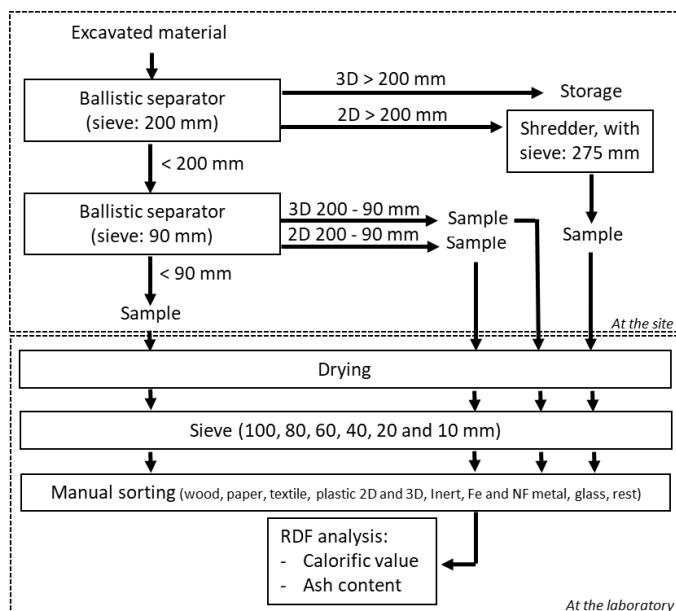
The ballistic separator STT 6000 (Figure 3), developed and built by Stadler Anlagenbau GmbH, is a robust and resistant separator to process large waste streams from construction and demolition (C&D), as well as MSW and industrial waste. The STT6000 was tested at the landfill site of Mont-Saint-Guibert (MSG) in Belgium and it showed a treatment capacity of 180 Mg/h with landfilled C&D waste (bulk density,  $\rho_1 = 1.20 \text{ Mg/m}^3$ ) and ca. 80 Mg/h with mixed landfilled MSW ( $\rho_2 = 0.60\text{--}0.80 \text{ Mg/m}^3$ ), directly after the excavation and without pre-treatment.

### Excavation site description

In September 2017, 200 m<sup>3</sup> of landfilled material was excavated from the MSG landfill. The firstly excavated area, which is described in this paper, had dimensions of 5x6x8 m (l\*w\*h), from which the top 4 m consisted of a clay cover layer, which was previously removed. The excavation point was selected based on the information obtained from geophysical measurements. The gathered geophysical data showed lateral differences in bulk conductivity which are an indication for different waste materials. The excavated material was classified visually *in-situ* and identified as prevailingly mixed MSW, including some C&D waste. Directly after the excavation, the material was transported to the ballistic separator as the first step of the mechanical processing, in order to separate the waste into different fractions, which after being characterised will help to correlate the geophysical information with the real composition of the disposed waste materials.

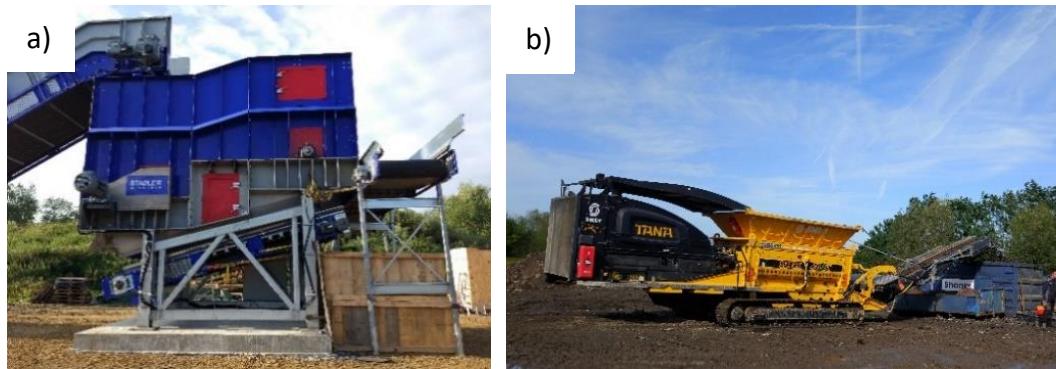
## Mechanical processing and sampling

The processing consisted of two ballistic separation steps, one with a 200 mm and another with a 90 mm screen cut. After the ballistic separation, a mobile MSW shredder, TANA Shark 440DT, was used to reduce the particle size of the output flow 2D > 200 mm first to 275 mm (see Table 1) and secondly to 70 mm (not included in the Table 1). The shredder with the 70 mm sieve served as a preparation step for future tests in a thermochemical conversion process, while the 275 mm shredder fraction was used for the material characterisation. Figure 3 depicts the flowchart of the implemented methodology.



**Figure 2:** Flowchart of the methodology

Sampling of the output streams of the ballistic separator and the shredder was done according to the German Directive “LAGA PN 98” and “PN 78”, with exception of the output 3D > 200 mm, which could not be sampled according to the protocol due to the large size of individual pieces. In this case, the composition was calculated by manually sorting and weighting of individual pieces. The samples taken from the output flows 2D < 275 mm and 2D 200-90 mm were further analysed to study their potential use as RDF.



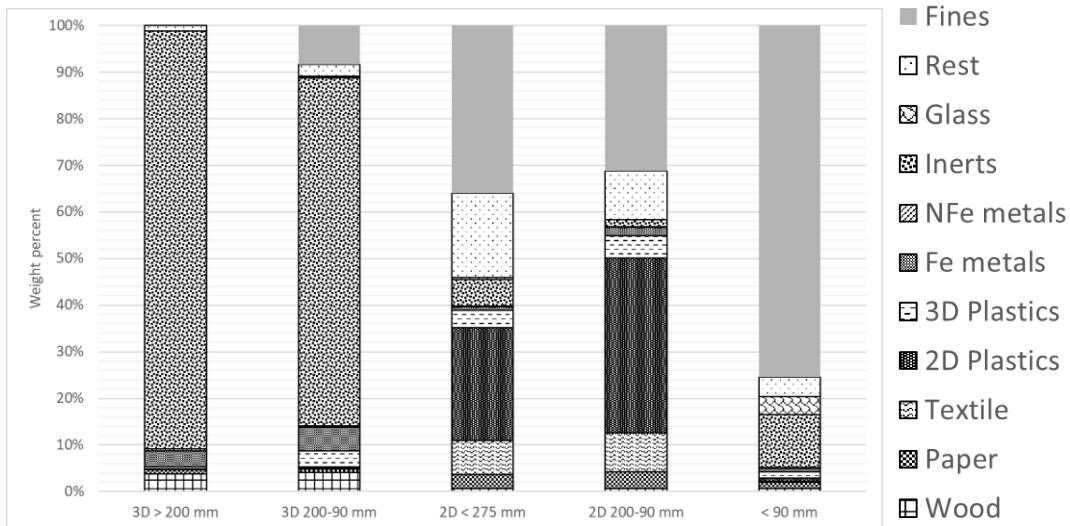
**Figure 3:** Equipment used during the mechanical treatment with: a) Ballistic separator STT 6000 and b) Shredder TANA Shark 400 DT

## Results and discussion

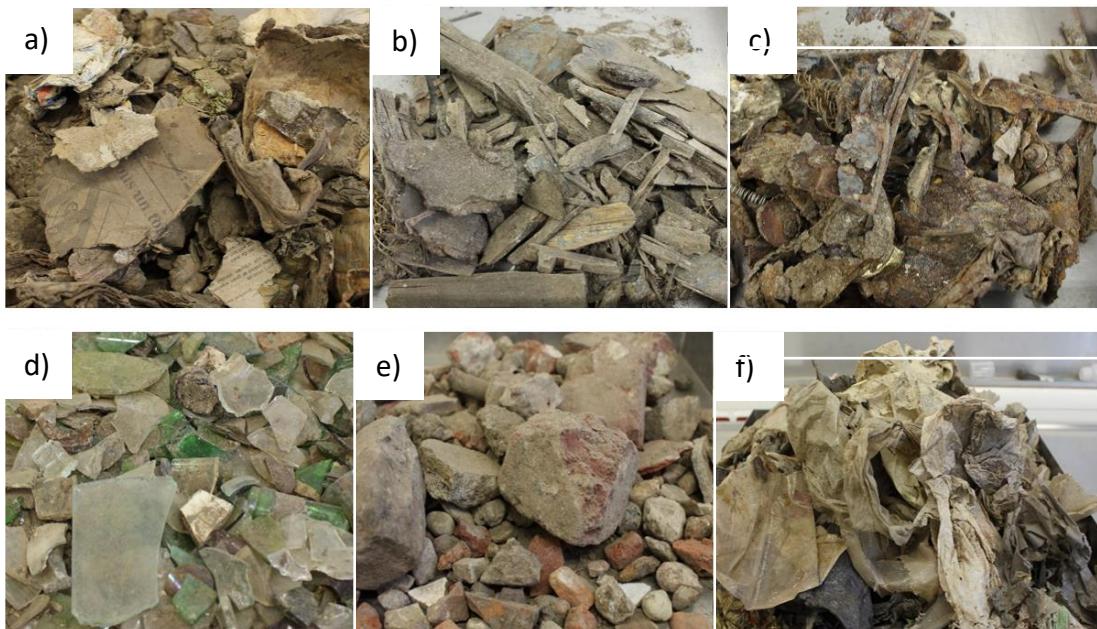
### Characterisation of the output flows of the Ballistic Separator STT6000

The composition of five output flows was studied: 3D > 200 mm, 2D > 200 mm, 2D 200-90 mm, 3D 200 - 90 mm and < 90 mm. The materials have a moisture content of 31 wt%, 32 wt%, 12 wt% and 28 wt%, respectively. After the material was dried and sorted into categories, two promising flows were detected as potential RDF recovery flows without the need for further treatment: 2D > 200 mm (referred as “2D < 275 mm” in Figure 4) and 2D 200-90 mm. These flows had a higher concentration of combustibles (wood, paper, textile, plastic 2D and rest) than the other three flows.

A high share of fines (< 20 mm) in the flows < 90 mm, 2D < 275 mm (or 2D > 200 mm) and 2D 200-90 mm was found with a concentration of 75 wt% dm, 36 wt% dm and 31 wt% dm, respectively. Possibly, the shredder cut the big pieces of different categories into small ones, while losing some of the RDF to the fine fraction, which could increase the number of fines in the last three flows. Besides, the 2D plastics tend to retain more impurities than other fractions, which contaminates the flow of fines < 20 mm. In Figure 4, the composition of each output flow is compared. Figure 5 shows examples of materials found in the < 90 mm flow.



**Figure 4:** Composition of all the output flows of the mechanical process



**Figure 5:** Example of material categories after the drying process, with: a) Paper, b) Wood, c) Metals, d) Glass, e) Mineral fraction, f) 2D Plastic

## RDF Analysis

For the evaluation of the use of the 2D 200-90 mm and the 2D < 275 mm fractions as RDF, several investigations were carried out according to the European Standard CEN/TC 343.<sup>2</sup> The composition (wt% dm) and the gross calorific value (GCV, kJ/kg dm) of two samples from the 2D 200-90 mm output stream are shown in Table 1. The results of the RDF analysis are summarised in Table 2.

**Table 1:** Composition and GCV of two samples from the 2D 200-90 mm flow

	Wood	Paper	Textile	2D Plastic	3D Plastic	Rest	Fines <20 mm
Samp. 1	Mass (w% dm)	0%	3%	10%	32%	7%	12%
	CV (kJ/kg)	16066	15356	23024	40953	33101	23360
Samp. 2	Mass (w% dm)	1%	2%	3%	45%	2%	7%
	CV (kJ/kg)	17866	15108	22399	41009	28194	23294
							1890

**Table 2:** RDF characteristics of the 2D 200-90 mm flow

Sample name	mm	B1: 2D 200-90 mm (1) 200 – 90	B1: 2D 200-90 mm (2) 200 – 90	
Particle size	mm	07.12.2017	07.12.2017	
Entry date		Test method		
<b>Investigation results:</b>				
Moisture content	w% ar	33	32	DIN EN 14346
Dry matter	w% dm	67	68	DIN EN 14346
Loss on ignition 550°C	w% dm	63	57	DIN EN 18122
Calorific value, GCV (wf)	kJ/kg d	<b>22105</b>	<b>22683</b>	DIN 51900

From the results obtained in this study, it can be concluded that processing excavated landfill material with ballistic separation, as a first step of the mechanical treatment, can yield fractions with appealing calorific values, such as 22,105 kJ/kg and 22,683 kJ/kg, from high throughputs and without the need of additional equipment, making the recovery of RDF in landfill mining projects more efficient. Further information about the influence of the initial moisture content on the GCV and the concentration of chlorine, sulphur and mercury has to be obtained, in order to determine the quality of the produced RDF. This information will be published in future publications, together with the results of the output flow 2D < 275 mm.

## Acknowledgements

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## Annex

**Table i:** Composition (wt% dm) of each output flow of the ballistic separator STT6000

Output flow	2D < 275 mm	3D >200 mm	2D 200-90 mm	3D 200-90 mm	<90 mm
Total mass (w%)	2%	4%	4%	10%	80%
<b>Wood</b>	<b>1%</b>	4%	<b>1%</b>	4%	1%
<b>Paper</b>	<b>3%</b>	1%	<b>4%</b>	1%	1%
<b>Textile</b>	<b>7%</b>	0%	<b>8%</b>	0%	0%
<b>2D Plastics</b>	<b>24%</b>	0%	<b>38%</b>	0%	1%
<b>3D Plastics</b>	4%	1%	5%	3%	1%
<b>Fe metals</b>	1%	3%	2%	5%	1%
<b>NFe metals</b>	0%	0%	0%	0%	0%
<b>Inerts</b>	6%	90%	2%	75%	11%
<b>Glass</b>	0%	0%	0%	0%	4%
<b>Rest</b>	18%	1%	10%	3%	4%
<b>Fines &lt; 20</b>	36%	0%	31%	8%	75%

# **SOLVOLEACHING OF (LANDFILLED) INDUSTRIAL RESIDUES AND A LOW-GRADE LATERITE ORE WITH DILUTED HCl IN THE IONIC LIQUID ALIQUAT 336**

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## **Introduction**

The EU and the rest of the world are experiencing an ever-smaller metal supply and an ever-increasing amount of industrial waste. On the one hand, economically relevant metals such as nickel, chromium, antimony, lead or zinc are needed for everyday life and modern technologies. Despite their importance, many governments are facing problems to ensure their supply. On the other hand, environmentally-harmful sludges from steel, alumina or zinc refining are produced in the order of millions of tonnes per year. These sludges are frequently disposed in landfills, and could pose an environmental hazard if rainwater infiltrates the waste and percolates the surroundings. Accordingly, the landfilling costs, dependent on the local taxes and the sludge composition, are increasingly growing.

The objective of this study is to analyse the efficient recovery of economically relevant metals from low-grade nickel laterite ores and (landfilled) industrial processes residues, using “solvoleaching”. Attention is also paid to maximising the extraction yield of hazardous elements so that the remaining solid that was not dissolved (consumed) during the solvoleaching process, can be reused as construction material or agricultural amendment.

Solvoleaching consists of applying organic liquids (complexing agents, solvents, acidic extractants, organic acids etc.) for extracting metals from a solid, with the aim to reduce the volume of the aqueous phase (< 50%), compared to conventional leaching.<sup>1</sup> In addition, it can result in higher selectivity for (a) targeted metal(s) than conventional hydrometallurgical leaching. Here, a system based on solvoleaching is applied to a low-grade nickel laterite ore and three industrial residues. Specifically, the four different materials examined were: (1) a low-grade nickel laterite ore from Poland (LAT), (2) a chromium-rich sludge from the stainless steel industry (CRS), (3) jarosite residue from zinc production (JAR) and (4) a zinc-rich sludge from the metal industry (ZRS). These materials are significant because there are large deposits of nickel laterite ores in Poland that can be exploited as an open pit mine for the recovery of this relatively expensive metal (12,230 \$/t, London Metal Exchange, 9

November 2017), and, concurrently, there are millions of tonnes of sludge being disposed every year.

## Materials and methods

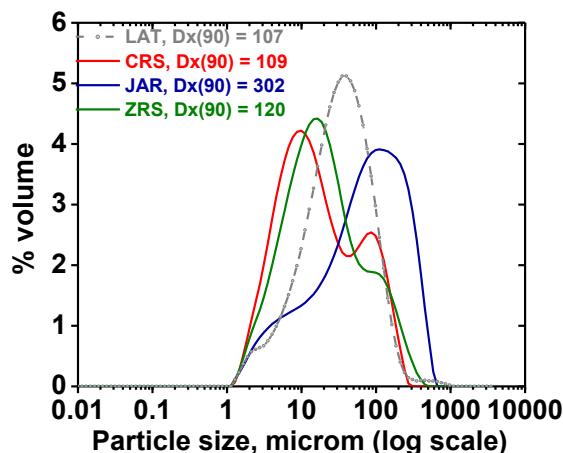
The four materials investigated have different characteristics. LAT is composed of Mg-Fe-Ni silicates, hydroxides and oxides, while JAR contains Na-K Fe sulphate hydroxides, Pb and Zn sulphides, and Na-Ca aluminium silicate hydrates. CRS and ZRS are mainly constituted by Ca sulphate hydrate (mostly gypsum). In the former, CaF<sub>2</sub>, Cr-Ni oxides and Ni-Cr-Mg iron oxides are present, while in ZRS, CaCO<sub>3</sub>, Ca-Zn hydroxide hydrates, Zn oxide and Fe sulphate hydroxide hydrates are present. Depending on the material, there is a different major element that predominates: silicon in LAT (23 wt%), elemental sulphur in JAR (30 wt%) and calcium in CRS and ZRS (25 wt%). All materials contain much higher concentrations of iron (10-15 wt%) in comparison to those of the economically relevant metals (1-4 wt%). Depending on the material, these are: 1.1 wt% Ni and 0.5 wt% Cr in LAT; 2.2 wt% Cr and 1.6 wt% Ni in CRS; 3.2 wt% Pb, 2.5 wt% Zn and 8.7·10<sup>-2</sup> wt% Sb in JAR; and 4.1 wt% Zn in ZRS. Iron is an unwanted element for the downstream processes and when dissolved in the leachate, it needs to be removed before the recovery of the desired metals, because iron would compete with them, decreasing the extraction yields of the elements of interest.

The materials were dried for 48 h at 105°C and sieved to 400 µm size on a vibratory shaker Analysette 3 from Fritsch. No pre-treatment other than comminution or manual disaggregation and sieving was applied, in order to avoid highly costing processes. The remaining moisture content was verified with a HC103 Mettler-Toledo moisture analyser, (1/50 mg/s, 150°C drying temperature). The particle size distributions were analysed by laser diffraction with a Malvern 3000 laser diffractometer, using water as the dispersant medium and 1.555 as the refractive index of the solid samples. The external specific surface area was calculated *via* the Brunauer–Emmett–Teller (BET) equation, determined with a Quantchrome NOVA 2200e analyser, after degasification of the samples under vacuum at 100°C for 25 h. The content of nitrogen, carbon and hydrogen was measured in a Thermo Scientific FLASH 2000 Elemental Analyser. The lixiviant used was Aliquat® 336 (a mixture of quaternary ammonium chlorides) containing ≤ 20 wt% water and different amounts of HCl (from 0.03 to 2.5 M HCl). The content of HCl in Aliquat was calculated measuring the HCl concentration of aqueous solutions with a refractometer (Anton Paar Abbemat Series) and extrapolating the results in a polynomial equation (Adj. R<sup>2</sup> = 0.99998).

The solvoleaching experiments were performed by mixing the dried materials with the lixiviant, at a liquid/solid ratio of 10 mL/g, using thermoshakers at 60°C, for 4 h, at 2,000 rpm. The metal content in the leachate was analysed *via* Total Reflection X-ray Fluorescence (TXRF) with a Bruker S2 PICOFOX™.

## Results and discussion

All the dried and sieved materials had a very fine grain size: 90 vol% was < 107-120 µm for LAT, CRS and ZRS, and was < 302 µm for JAR (Figure 1). The external specific surface areas varied depending on the origin of the materials: lower values were for the materials coming from a hydrometallurgical iron precipitation process (9, 62 and 63 m²/g in JAR, CRS and ZRS, respectively), while higher values were for the natural laterite ore (166 m²/g). The CHN analysis showed that no nitrate or ammonium phases were present in the materials and carbon was only present in ZRS (4 wt%), in the form of calcite.



**Figure 1:** Volume percentage of particles within the respective size, for nickel laterite (LAT), Cr-rich sludge (CRS), jarosite (JAR) and Zn-rich sludge (ZRS) materials

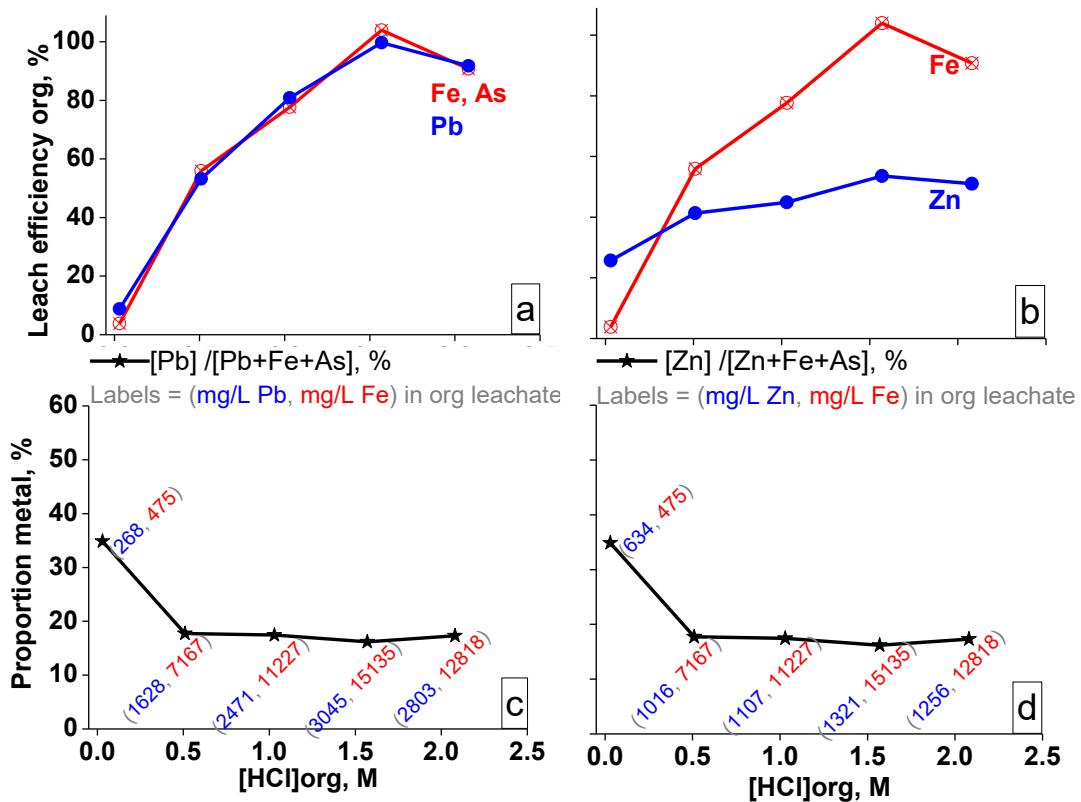
There are three major groups of solvolixivants: (1) mineral acids in water-miscible organic solvents, (2) organic acids (alone or in water) and (3) extractants (alone or in water-immiscible organic diluents). A screening test for rapid comparing, assessing and scoring of different solvolixivants was performed, taken at least one example of each solvent group. Based on the leaching yields, the selectivity and the price, the quaternary ammonium chloride ionic liquid Aliquat 336 was selected for the next tests where the effect of the HCl concentration in Aliquat 336 on the leaching was studied. In all cases, Aliquat 336 (apolar) was saturated with water and then, forcedly mixed with different HCl solutions (polar) to prepare the different dilutions of HCl in Aliquat 336. The remaining HCl aqueous solution not uptaken by Aliquat 336, was discarded and the homogeneous organic solutions of HCl/Aliquat 336 were used as lixiviants. A strong effervescence reaction was observed when adding the lixiviant to

the ZRS, probably due to the exothermic reaction of HCl with calcite, which forms CO<sub>2</sub> gas, matching with the gas escape noticed when opening the vials at the end of the tests. After leaching, the formation of a small volume of aqueous solution (immiscible with the HCl/Aliquat 336 leachate), was observed. The volume of the aqueous solutions was larger when Aliquat 336 had higher content of HCl and when leaching LAT and JAR than when leaching CRS and ZRS. The water may come from the lixiviant itself, from the reaction of HCl with oxides and hydroxides, and from redox reactions, *e.g.*, oxidation of sulphides.

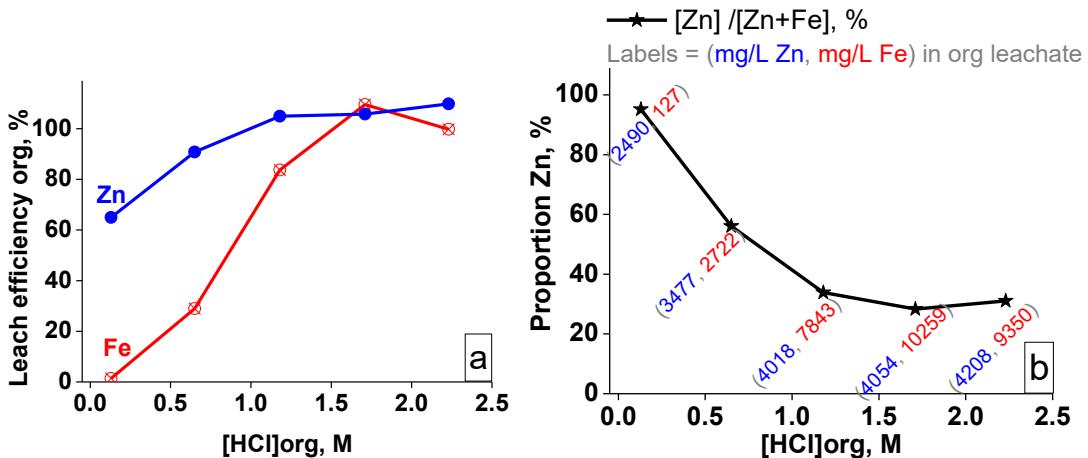
In the case of JAR and ZRS, the main metals remained in the organic leachate (HCl/Aliquat 336). Only antimony from JAR was concentrated in the aqueous leachate. The leaching efficiencies of Pb, Zn and Fe increased with the amount of HCl in Aliquat 336, but the process is more selective towards the desired metals at the lowest HCl content (Figure 2 and Figure 3). The leaching behaviour of As, Pb and Fe from JAR was identical, what indicates their association in the same mineral phases, *i.e.*, in galena. The selective leaching of Zn against Fe in ZRS remained at higher amounts of HCl in Aliquat 336 than in the case of JAR. This is beneficial because it provides higher leaching efficiencies of Zn without dissolving more iron. However, at above 1.5 M HCl in Aliquat 336, Fe and Zn were totally dissolved in ZRS. This may be caused by the high dissolution of calcite by HCl, which would increase the temperature and, therefore, the solubility in diluted HCl of sulphates (the main solid phase in the sludge).

In the case of LAT and CRS, the main metals (Ni and Cr) went to the newly formed aqueous leachate and the iron remained in the organic leachate. This provides an advantageous situation to concentrate and separate the economically relevant metals from iron. In this case, the leaching efficiencies cannot be calculated because of the inability to accurately determine the volume of the newly created aqueous leachate. However, rough estimations gave values > 90% of Ni leached from LAT and > 90% of Ni and > 90% of Cr from CRS, with almost no iron.

The mechanism underlying this kind of solvoleaching process could be thought as a double process. One would be the dissolution of mineral phases such as hydroxides and sulphides in JAR, or oxides and sulphates (namely gypsum) in CRS, by HCl. The other mechanism would be the formation of soluble anionic chloro complexes  $[MeCl_4]^{2-}$ ; that would go to the Aliquat 336 leachate *via* anion exchange  $(A336)_2MeCl_4$  (with Me = Ni, Zn, Fe, Pb) and soluble cationic aquo complexes that would go to the aqueous leachate ( $[Ni(H_2O)_6]^{2+}$ ,  $[Cr(H_2O)_6]^{3+}$ ). Depending on the affinities and the stability constants of the metal-complexes formed, the metals will distribute differently between the aqueous and the HCl/Aliquat 336, leachates.



**Figure 2:** Leaching efficiencies of Fe, As, Pb, Zn (a, b) and content of Fe, Zn and Pb in the leachate (c, d: labels = concentration (mg/L) in the leachate, curve = proportion related to Fe) in the JAR at different HCl concentrations in Aliquat 336 ([HCl]org)



**Figure 3:** Leaching efficiencies of Fe and Zn (a) and content of Fe and Zn in the leachate (b: labels = concentration (mg/L) in the leachate, curve = proportion related to Fe) in the ZRS at different HCl concentrations in Aliquat 336 ([HCl]org)

## **Conclusions**

This work focussed on the recovery *via* solvometallurgical leaching of valuable metals like Zn, Pb, Ni and Cr from LAT, JAR, CRS and ZRS. The selective dissolution against the main impurities (Fe) was also assessed. The content of HCl in the ionic liquid Aliquat 336 had a major influence on the leaching efficiencies and the selectivity: the lower the acid content in Aliquat 336, the higher the selective leaching, and the lower the leaching efficiency. Only in the case of Pb from JAR, there was no change in its leaching selectivity against Fe: the leaching of Fe, As and Pb from JAR was coupled together and had the same tendencies, suggesting that the major Pb mineral phase (galena) has also Fe and As entrapped. Although leaching tests were performed with one organic lixiviant, two immiscible leachates were normally produced: the corresponding organic one (a large part of the total volume) and an aqueous leachate (a small part of the total volume). This is important for the separation of the metals, because the different metal complexes formed showed different affinities towards one or another leachate. Thus, Ni and Cr were concentrated in the aqueous leachate, while Pb, Zn and Fe in were concentrated in the organic leachate.

## **Acknowledgements**

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# RECOVERY OF RARE EARTHS FROM E-WASTE RESIDUES BY AN INTEGRATED APPROACH

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## Abstract

The objective of this work is the recovery of rare-earth elements (REEs) and magnesium (Mg) from several waste streams to produce new REE-Mg alloys of high performance and low cost. The selection procedure of the waste residues, the characterisation results and the general description of the recovery processes are presented; TOPSIS and LCA methodology, which were used as tools for the identification of the best process routes, are introduced as well.

## Introduction

This paper describes the first outcomes from the research activities performed within the EU REMAGHIC project, which is focused on the recovery of rare-earth elements and magnesium from secondary sources to produce new REE-Mg alloys with improved mechanical properties, reduced weight and low cost, which can find application in several industrial sectors, such as the automotive, aeronautic and biomedical industries.<sup>1,2</sup> The aim is to reduce the European dependency of critical raw materials (REEs and Mg) from non-European countries and to partially mitigate the “Balance Problem”, that is defined as the balance between the demand by the economic markets and REEs in ores.<sup>3,4</sup> The Balance Problem implicates that the REE industry has to find new applications for REEs that are available in excess, or to search for substitutions for REEs that have limited availability and that are high in demand.

The first task of the project was the selection of the potential sources of REEs. Several parameters were taken into account, such as the REEs concentration and the relevance from the balance perspective. Afterwards the residues were characterised by different techniques in order to gather information about their composition. For each waste stream, combinations of several processes, namely pyrometallurgical, hydrometallurgical and iono/solvometallurgical processes, have been applied. The results collected during the experimental activity represent the input data for the TOPSIS and the LCA methodology, which can be regarded as useful tools for the selection of the best process routes from both technical and environmental point of view.

## Results and discussion

### Residues selection

A preliminary study was performed to identify the most promising REE-containing waste residues. Among several waste streams, which include waste electrical and electronic equipment (WEEE or e-waste) and industrial by-products, three materials were selected: lamp phosphors (1), cathode-ray tubes (CRT) phosphors (2) and nickel metal hydride (NiMH) batteries (3). The choice was supported by a decision matrix, which took into account several factors. First of all, REEs concentration was considered, which is very high both in lamp phosphors and in NiMH batteries.<sup>5-8</sup> Moreover, the number of REEs contained in these residues is limited, so that the recovery process is facilitated. Furthermore, in contrast to REE ores and industrial by-products (such as red mud and phosphogypsum), there are no radioactivity issues related to e-waste. Another important parameter considered in the selection process was the Balance Problem perspective. Recycling of fluorescent lamps, CRTs and NiMH batteries will generate a supply of lanthanum, europium, terbium, yttrium, cerium and gadolinium. Most of these REEs can be used in other applications whilst lanthanum, cerium and especially yttrium can find new uses in the magnesium alloys, thus contributing to partially mitigate the Balance Problem.<sup>3,4</sup>

### Characterisation

The selected waste streams were characterised by ICP-OES, SEM/EDS and XRD in order to gather information about their chemical and mineralogical composition. The elemental composition of the lamp phosphors and the identified mineralogical phases are reported in Table 1 and 2, respectively:

**Table 1:** Lamp phosphors – elemental composition (wt%)

Si	Ca	Y	La	Ce	Eu	Tb	Gd
18.9	7.1	6.3	0.9	0.7	0.4	0.3	0.1

**Table 2:** Lamp phosphors – mineralogical composition (wt%)

Compound	Concentration
Yttrium europium oxide	9.0
Lanthanum cerium. terbium phosphate	3.0
Magnesium cerium terbium aluminium oxide	1.5
Magnesium cerium gadolinium aluminium oxide	0.3
Glass	60.0
Fluorapatite	13.0
Barium silicate	3.0
Calcite	3.0
Strontium magnesium phosphate	0.6

As shown in Table 1, the fluorescent powder represents an interesting source of yttrium (6 wt%), which is present as oxide in the red phosphor YOX ( $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ ).<sup>3-9</sup> Yttrium can find new applications in the Mg alloys and its recovery from the selected waste stream was the main purpose of the investigated technologies. An added value is, however, represented by the presence of terbium (0.3 wt%), which has a high economic value. Terbium (together with lanthanum and cerium) is present in the phosphate ( $\text{LaPO}_4:\text{Ce}^{3+}, \text{Tb}^{3+}$ , LAP) and aluminate ( $(\text{Ce}, \text{Tb})\text{MgAl}_{11}\text{O}_{19}$ , CAT) phosphors and its recovery is very challenging due to the fact that these compounds are much more resistant towards attack from acids.<sup>4</sup> Table 3 shows the concentration of the main elements present in the CRT phosphors, while the mineralogical phases are reported in Table 4.

**Table 3:** CRT phosphors – elemental composition (wt%)

Zn	S	Y	Si	Al	Pb	Eu
30.6	16.5	15.5	7.2	2.0	1.7	1.0

**Table 4:** CRT phosphors – mineralogical composition (wt%)

Compound	Concentration
Yttrium europium oxysulphide	23
Zinc sulphide	46
Glass	25
Aluminium	1.5

The analysis of CRT phosphors showed yttrium concentrations of about 15 wt% (together with 1 wt% of europium). The red phosphor ( $\text{Y}_2\text{O}_2\text{S}:\text{Eu}^{3+}$ ) is the only one containing REEs, whilst the blue and green phosphors are based on zinc sulphide (the green phosphor is  $\text{ZnS}:\text{Cu}$  and the blue phosphor is  $\text{ZnS}:\text{Ag}$ ).<sup>4</sup> Finally, the characterisation of the NiMH batteries is reported in Tables 5-6. As shown in Table 5, NiMH batteries represent an interesting source of lanthanum and cerium, which can be used as mischmetal in the Mg alloys.

**Table 5:** NiMH batteries electrode powder – elemental composition (wt%)

Ni	La	Ce	Co	Zn	Fe	Mn
56.9	12.3	4.0	5.2	1.1	0.5	0.4

**Table 6:** NiMH batteries electrode powder – mineralogical composition (wt%)

Compounds	Concentration
$\text{LaNi}_5$ (hydrogen storage alloy based on mischmetal -mainly lanthanum, cerium and neodymium- and nickel incl. cobalt, aluminium and manganese)	45
Metallic nickel	15
Nickel hydroxide	35
Others (electrolyte, Co, Zn, graphite, etc.)	5

### Recovery routes

REE recovery from the selected waste residues was performed by an integrated approach which combined different techniques, namely pyrometallurgical, hydrometallurgical and iono/solvometallurgical processes. REE recovery from the lamp phosphor waste was performed by a leaching step with  $\text{H}_2\text{SO}_4$  followed by precipitation with oxalic acid in the HydroWEEE process.<sup>10,11</sup> The recovered product is a mixed REE oxalate that was further treated by calcination giving a mixed REE oxide. Y/Eu separation from this oxide was then investigated by leaching and solvent extraction with a phosphonium ionic liquid. Tb, La and Ce recovery from the lamp phosphors residue was enhanced by applying a pyro-treatment before leaching (roasting in the presence of  $\text{Na}_2\text{CO}_3$ ). The obtained leachate was then subjected to a solvent extraction step with di-(2-ethylhexyl)phosphoric acid (D2EHPA) followed by oxalate precipitation and calcination. An alternative approach is the leaching of the Tb-rich residue with organic solvents (the so-called solvometallurgical leaching), where metal recovery is performed using non-aqueous solutions.<sup>12</sup> Regarding the CRT phosphors, a thermal pre-treatment was investigated to convert the  $\text{ZnS}$  to  $\text{ZnO}$ , thus avoiding  $\text{H}_2\text{S}$  release during the leaching step.  $\text{ZnO}$  was then selectively removed from the roasted phosphors by leaching with acetic acid, giving access to the REE content. Y and Eu recovery from the residue was then studied by leaching with methanesulfonic acid, followed by precipitation with oxalic acid. A pyrometallurgical treatment was investigated for the recovery of lanthanum and cerium from NiMH

batteries. This pre-treatment allowed obtaining a metal phase rich in nickel and other minor metallic compounds, whilst the REEs are concentrated in the slag phase as oxides. After leaching with mineral acids, REEs are recovered by solvent extraction with ionic liquids. The recovery process is based on the “split-ion extraction”, which allows the extraction of rare-earth ions from concentrated chloride solutions to an organic phase consisting of nitrate ionic liquids (Aliquat 336 NO<sub>3</sub>).<sup>13</sup> La and Ce recovery from NiMH batteries was also investigated by direct leaching of the black electrode powder with hydrochloric acid; REE recovery from the leachate was finally performed by split-anion extraction.

### **Life Cycle Assessment and TOPSIS methodology**

Life Cycle Assessment (LCA) and TOPSIS methodology (Technique for Order of Preference by Similarity to Ideal Solution) were employed for the evaluation of the most promising routes for further upscaling activities. LCA studies allowed the assessment of the environmental performance of the different process combinations developed within the project. The balance between the resources needed and the emissions to the environment of these new technologies was investigated based on the Life Cycle Assessment, a tool standardised by the ISO 14040/14044 norm. The TOPSIS methodology was then applied as decision making method to support the selection. This choice was based on its main advantages, *e.g.*, it is easier to implement and consider different criteria with different units, and different weighting, which is the case of REMAGHIC project. The criteria were defined according to seven Key Performance Indicators (KPI): (1) TRL (Technology Readiness Level) [1-9], (2) Process efficiency [%]; (3) Waste generation [kg]; (4) Toxicity [Comparative Toxic Unit (CTUe)], (5) Global Warming Potential (GWP) [CO<sub>2</sub>e]; (6) Material cost [€]; (7) Income [€].

## **Conclusions**

Yttrium, lanthanum and cerium recovery from a selection of three waste residues was investigated by a combination of different techniques within the REMAGHIC project (pyro-, hydro- and iono/solvometallurgical processes). The recovered rare-earths can find new applications in REE-Mg alloys, thus offering a unique opportunity to partially mitigate the Balance Problem.

## **Acknowledgements**

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# **SELECTIVE SOLVOMETALLURGICAL LEACHING OF LEAD AND ZINC FROM JAROSITE RESIDUES FROM THE ZINC INDUSTRY**

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## **Abstract**

The relatively new branch in extractive metallurgy called solvometallurgy was investigated for selective leaching of Pb and Zn from iron-rich jarosite residues, which are typically landfilled. After screening of several lixivants, the ionic liquids [A336][Cl] and [C101][Cl], equilibrated with HCl, leached the most Pb and Zn of the ionic liquids investigated. When the ionic liquids were equilibrated with relatively lower HCl concentrations, the dissolution of Fe decreased drastically and, thereby, the selectivity for Pb and Zn improved. [A336][Cl] equilibrated with 0.5 M HCl leached 62 wt% Pb, 27 wt% Zn and 7 wt% Fe, while [C101][Cl] equilibrated with 0.5 M HCl leached 73 wt% Pb, 31 wt% Zn and 10 wt% Fe.

## **Introduction**

The extractive metallurgy of industrial process residues is complex because the relevant metals are present in low concentrations, and often locked in complex matrices (sulphides, oxides, phosphates or silicates).<sup>1</sup> As a result, it is difficult to recover these metals. Most hydrometallurgical leaching processes suffer from substantial acid consumption and poor selectivity, resulting in leachates with high concentrations of impurities. However, by replacing the aqueous phase in hydrometallurgical processes by organic solvents with dissolved reagents, it is possible to attain high selectivity and reactivity because non-hydrated anions have a greater affinity to bind to metal ions. This approach to extractive metallurgy, based on the use of organic solvents instead of an aqueous phase, is called “solvometallurgy”.<sup>1</sup> In this work, solvometallurgical leaching was carried out on industrial jarosite residue samples. The residue was produced as a by-product during purification and refining of zinc from its sulphide ore (ZnS, sphalerite). Due to its high rate of generation and relatively high Pb and Zn content, jarosite could be an important resource for these metals.<sup>2</sup>

## Results and discussion

The jarosite sample was dried and milled to a fine powder of a size smaller than 1.65 µm (D90). Powder-XRD analysis revealed that Pb occurs in the form of anglesite ( $\text{PbSO}_4$ ) and Zn in the form of sphalerite ( $\text{ZnS}$ ). In order to determine the elemental composition, the two samples of the material were completely dissolved in acid using a microwave digester. The digested acidic solutions were analysed by both TXRF and ICP-OES. The analysis results of duplicates and the two techniques were comparable. The results are shown in Table 1. Solvometallurgical leaching of jarosite was investigated to leach Pb and Zn. A series of 14 lixivants were screened to select the best candidate (Table 2). The lixivants tested include organic acids, acidic extractants, basic extractants, neutral extractants, and HCl dissolved in alcohols and ionic liquids. The highest amounts of Pb and Zn were leached by the quaternary ammonium chloride ionic liquid Aliquat® 336 ( $[\text{A}336]\text{[Cl]}$ ) and the quaternary phosphonium chloride ionic liquid Cyphos® 101 IL ( $[\text{C}101]\text{[Cl]}$ ) after their equilibration with aqueous solutions of HCl.

**Table 1:** Elemental composition of the jarosite residue

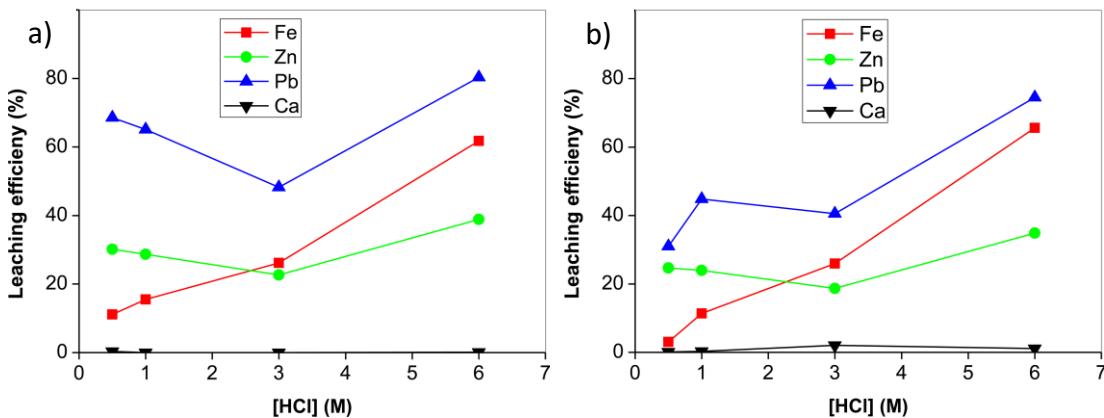
	Fe	Pb	Ca	Zn
Concentration [g/kg ]	175	40	25	24

**Table 2:** Concentrations of Pb, Zn and Fe in the leachates

No.	Lixiviant	Pb [mg/L]	Zn [mg/L]	Fe [mg/L]
1	26.5 M formic acid	0	110	2,101
2	17.5 M acetic acid	0	15	934
3	2.5 M Versatic acid	0	0.4	3
4	1.4 M di-(2-ethylhexyl)phosphoric acid (D2EHPA)	0	29	580
5	Cyanex 272 (equilibrated with water)	0	134	150
6	Cyanex 272 (unequilibrated)	0	37	90
7	$[\text{A}336]\text{[NO}_3\text{]}$ (equilibrated with 5 M HNO <sub>3</sub> )	0	24	2
8	$[\text{C}101]\text{[NO}_3\text{]}$ (equilibrated with 5 M HNO <sub>3</sub> )	0	157	207
9	Ethanol	0	67	639
10	1.2 M HCl in ethanol	11	688	3,450
11	5.4 M HCl in 1-octanol	117	660	11,000
12	TBP equilibrated with 12 M HCl	166	928	15,757
13	$[\text{A}336]\text{[Cl]}$ equilibrated with 12 M HCl	722	952	12,978
14	$[\text{C}101]\text{[Cl]}$ equilibrated with 12 M HCl	2,615	1,316	14,272

Leaching parameters: Stirring 2 hours, 60°C, 2,000 rpm, S/L ratio 1:10)

Next, the effect of different HCl concentrations in [A336][Cl] and [C101][Cl] were investigated. The leaching efficiency of Pb, Zn, and Fe increased with increasing HCl concentration in the ionic liquid (Figure 1).



**Figure 1:** Leaching efficiency with a) [C101][Cl] and b) [A336][Cl], equilibrated with different HCl concentrations. Leaching parameters: contact time 2 hr, 60°C, 2000 rpm, S/L ratio 1:10

The leaching efficiencies of [C101][Cl] equilibrated with 0.5 M HCl were 68% Pb, 30% Zn and 11% Fe and they increased to 80%, 39% and 61%, respectively, with the ionic liquid equilibrated with 6 M HCl. Similarly, for [A336][Cl], the leaching efficiencies increased from 31% Pb, 25% Zn and 3% Fe to 74% Pb, 34% Zn and 66% Fe when the HCl concentration used for equilibration was increased from 0.5 to 6 M. Although equilibrating the ionic liquids with 6 M HCl leached more Pb and Zn, it also leached more Fe. The co-dissolution of Fe interferes in the downstream processes of the metal recovery. Therefore, ionic liquids equilibrated with 0.5 M HCl are preferred due to their better selectivity against Fe. Consequently, the ionic liquids equilibrated with 0.5 M HCl were chosen as the lixivants for further studies on the leaching process, resulting in the following optimised parameters values: residence time 2 h, temperature 45°C, solid/liquid ratio 1:15 and stirring speed 1,500 rpm (Table 2).

Consequently, the ionic liquids equilibrated with 0.5 M HCl were chosen as the lixivants for further studies on the leaching process, resulting in the following optimised parameters values: residence time 2 h, temperature 45°C, solid/liquid ratio 1:15 and stirring speed 1,500 rpm (Table 3).

**Table 3:** Leaching efficiencies for jarosite at the optimised conditions

Lixiviant	Pb [%]	Zn [%]	Fe [%]
[A336][Cl] eq. with 0.5 M HCl	62	27	7
[C101][Cl] eq. with 0.5 M HCl	73	31	10

Conditions: contact time: 2 hrs, temperature: 45°C, Solid/liquid ratio: 1:15, and stirring speed: 1,500 rpm

## Conclusion and future work

The presence of HCl in the lixiviant is critical for leaching Pb from jarosite. All the lixiviants without HCl did not leach any Pb. [A336][Cl] and [C101][Cl] equilibrated with HCl leached the highest amount of Pb and Zn. The selectivity is strongly influenced by the concentration of HCl used for equilibrating the ionic liquid. The selective leaching of Pb (62–73%) and Zn (27–31%) against Fe (7–10%) from the studied jarosite residue took place with [A336][Cl] and [C101][Cl] after equilibration with 0.5 M HCl. When the ionic liquids were equilibrated with higher concentrations of HCl, the Fe dissolution increased more than the valuable metal dissolutions and thus resulted in a poor selectivity. Presently, work is on-going to up-scale the leaching experiments on the jarosite residues from milligram to gram scale. Next, the recovery of the metals from the leachate will be investigated by non-aqueous solvent extraction or with non-aqueous ion exchange.

## Acknowledgements

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# ASSESSMENT OF MULTIPLE GEOPHYSICAL TECHNIQUES FOR THE CHARACTERISATION OF MUNICIPAL WASTE DEPOSIT SITES

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## Introduction

The characterisation of former landfills (also illegal ones) or many brownfields and polluted sites is a major issue nowadays. Environmentally speaking, these sites represent a potential risk towards pollution of groundwater. From an economic point of view, waste reuse/recycling and landfill mining are gaining attention. Likewise, reactivating the biodigestion process to enhance methane production and, therefore, energy production, is also considered. Finally, the rehabilitation of such sites represents a good method of regaining space in densely populated area where space is lacking.

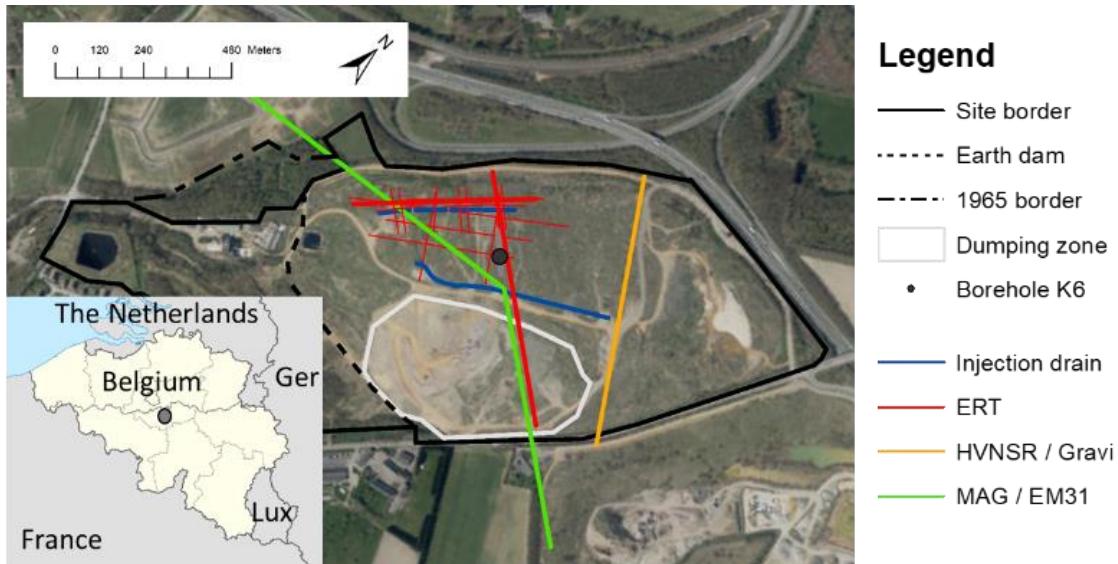
In the exploration of landfill sites, parameters of importance are the thickness of waste layers and their horizontal extent. Another area of research and interest is the characterisation of the state of digestion and the degree of humidity of waste inside a landfill. Indeed, one can try to accelerate the biodegradation process to stabilise the landfill and as a consequence, gain energy when power plants treat the gas (methane) derived from a landfill. In the current research project, a large spectrum of geophysical methods was used to characterise a large landfill site situated in Wallonia, Belgium. Electrical resistivity tomography (ERT), electromagnetic induction (EMI), magnetometry (MAG) profiling and mapping, gravimetry and seismic acquisitions (MASW and HVNSR) were performed. Afterwards, water recirculation experiments (aiming at accelerating the waste biodegradation process) were conducted and monitored with Time-Lapse ERT.

## Site and methods

### Site description

All field tests were performed on the landfill site of Mont-Saint-Guibert in Wallonia, Belgium (Figure 1). This large engineered landfill (26 ha wide; up to 60 m deep; 5.3 million m<sup>3</sup> of waste) has been active since 1958. The 11 million tonnes of waste

disposed comprise municipal solid waste, non-hazardous and non-toxic industrial waste, and bulky waste. The cover layers, dams and roads are composed of inert waste and clinker. The site infrastructure includes a bottom leachate collection system and 200 vertical gas extraction wells. During the past 25 years, more than 1 billion m<sup>3</sup> of landfill gas have been produced.



**Figure 1:** The Mont-Saint-Guibert technical landfill sit

## Methods

The geophysical campaigns were organised between 2012 and 2015. Some of the campaigns covered the full extent of the deposit (electromagnetic and magnetic mapping). Slower methods (and therefore costlier) only provide some linear or vertical profile information (electrical resistivity tomography, seismic methods). The geophysical survey locations are found in Figure 1.

The electromagnetic mapping was conducted with an EM31 (GEONICS) in vertical dipole mode on the former and new landfill. Both the in-phase (magnetic susceptibility) and the quadrature-phase (electrical conductivity) components of the induced magnetic field were recorded. The magnetic vertical gradient data were acquired with a cesium vapour MAGMAPPER G-858 gradiometer (GEOMETRICS) and a GSM-19-GW Overhauser-effect gradiometer (GEM-Systems). Seismic data were acquired with the DacqLink2 logger, 24 4.5 Hz geophones and a 8 kg sledgehammer. As there was no ability to detect first arrivals, advantage was taken of the surface wave propagation features (these concentrate a large part of the tremor energy). The MASW allows the estimation of the vertical shear-wave velocity ( $V_s$ ) profile inside the waste dump. The HVNSR data were recorded with a CityShark microseismic station and a Lennartz Electronic LE-3Dlite sensor (1Hz). Both MASW and HVNSR data were analysed with the GEOPSY software. Several ERT profiles were acquired on the N-W

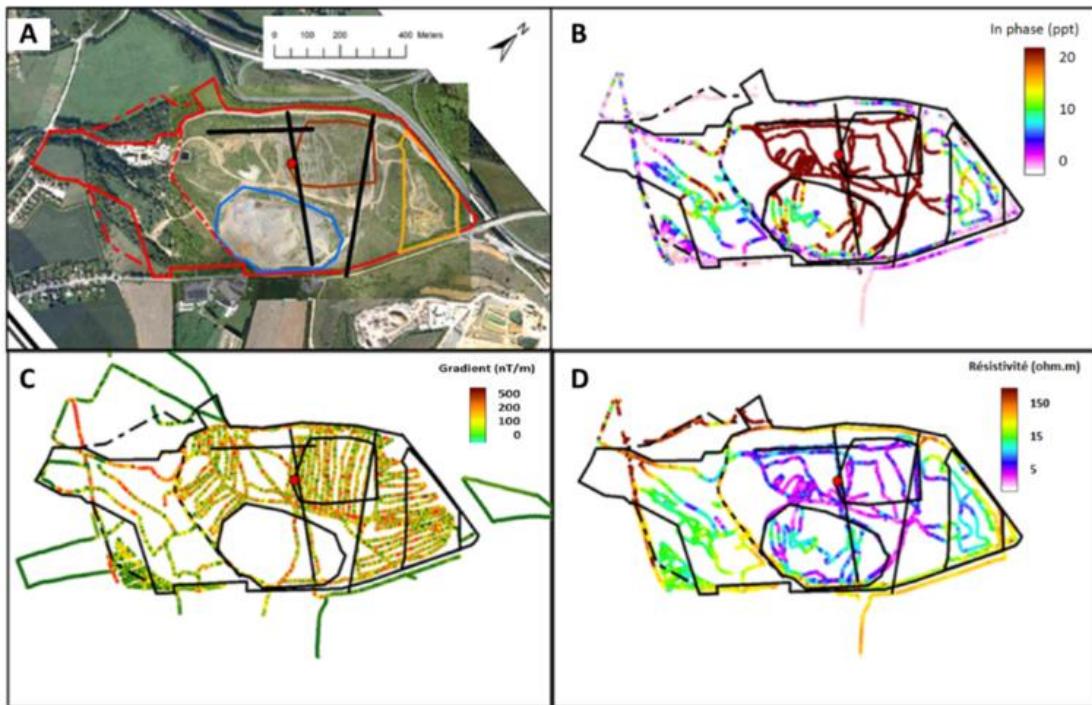
zone of the landfill with a multi-channel ABEM terrameter LS, both for characterisation and for monitoring of recirculation of the leachate experiments (Figure 1). A long transversal profile completed the ERT data set. The multigradient acquisition protocol was used with a 2.5 m to 5 m electrode spacing.

## Results

### Mapping

Given the metal content of the waste material (2 wt%) and the presence of clinker (28 wt%), the magnetometric and gradiometric mapping logically allows a quick and cheap delineation of the horizontal border of the site. The vertical magnetic field gradient (Figure 2c) increases the resolution of the magnetic observations by emphasising the effect of the near-surface anomalous sources. The transition between natural soil (a few 10 nT/m magnetic field vertical gradient), on the one hand, and the roads and the waste deposit, on the other hand (a few 100 nT/m), is clearly detected.

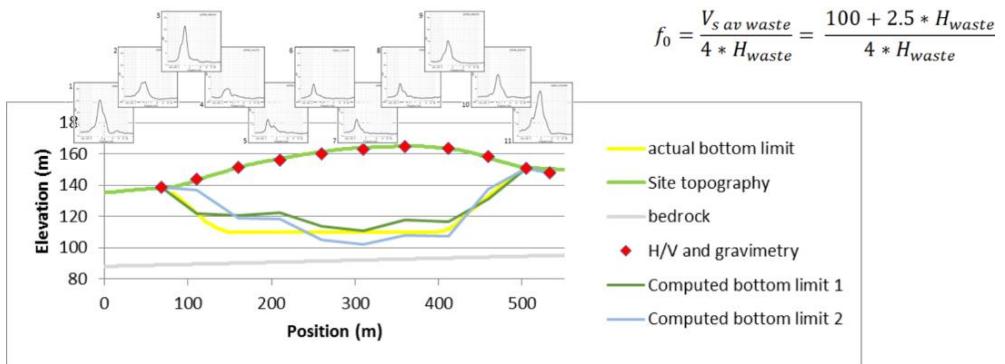
Provided that the geological target is conductive and covered by a thin layer of cover material, the EM mapping appears as an efficient and cheap method. The differentiation between the waste deposit and the host formation surrounding the landfill is very clear (Figure 2d). The resistivity inside the waste dump is only a few  $\Omega\text{.m}$ . The value is smaller in the more recent part of the landfill ( $5 \Omega\text{.m}$ ), as compared to the older landfill zone. In the present day deposition area (no more organic materials allowed since 2010). In contrast, the host formation outside of the landfill is characterised by higher resistivities (30-100  $\Omega\text{.m}$ ) (Figure 2d). The in-phase component of the EM31 signal (Figure 2b) is sensitive to the presence of magnetic materials in the upper part of the landfill. The signal is saturated in the new part of the landfill site and slightly negative over the two roads surrounding the site. The in-phase signal outside the field is close to zero.



**Figure 2:** Electromagnetic and magnetic mapping of the landfill: a) site description; b) Electrical resistivity (EM31 in-phase); c) magnetic vertical gradient; d) EM31 out-of-phase

### Thickness estimation

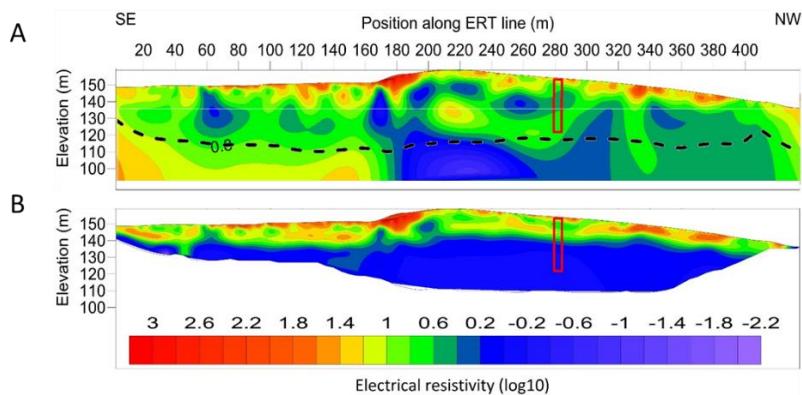
The thickness estimation of this particular engineered landfill was difficult with conventional geophysical methods, since surface surveys generally have a limited depth of investigation and decreasing spatial resolution and sensitivity with increasing depth. The use of combined MASW and HVNSR methods was investigated to estimate the landfill depth. Using MASW it was established that the shear-wave velocity ( $V_s$ ) varies from 100 m/s at the surface to 180 m/s at 16 m depth. It is then assumed that the  $V_s$  still increases by 5 m/s/m with depth. For the landfill depth estimation, 11 HVNSR data were recorded across the landfill (Figure 1; Figure 3). The resonance peaks are clearly identified and their frequencies, ranging from 1.10 to 1.85 Hz, are correlated to the site topography (Figure 3). However, it is not clear if the resonance phenomenon results from the waste-sand interface or from the sand-bedrock interface impedance contrast.



**Figure 3:** HVNSR resonance peaks and HVNSR transversal profile

### Water content estimation

Because of the high contrasts in electric resistivity provided by borehole investigation, it is expected that geoelectrical methods might enable the accurate imaging of electrical resistivity and, related to this, the water distribution inside the waste material.

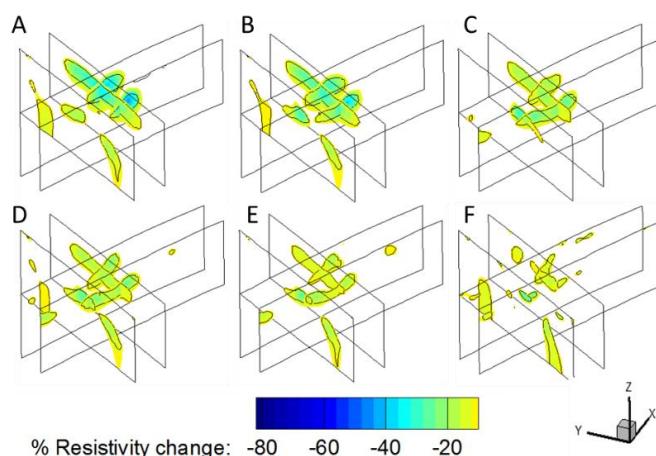


**Figure 4:** ERT transversal profile inverted with a basic inversion process (DOI in dotted line); b. Advanced inversion process. The borehole location is indicated by a red rectangle.

The transversal ERT profile was inverted with (1) a standard inversion procedure (robust norm on the data) and (2) a reference model to impose the depth and electrical resistivity of the saturated zone (see Dumont *et al.*<sup>1</sup> for more details). Hereby, the importance of incorporating prior information in the inversion to achieve a coherent result is shown. In the standard inversion (presented in Figure 4a), the depth to the water table is overestimated with respect to borehole information. The transition between the unsaturated and saturated zone appears rather smooth, while it is known to be sharp from borehole EM investigation.<sup>1</sup> With the reference model process (Figure 4b), the unsaturated zone was in accordance with borehole data as the depth to the water table was imposed.<sup>1</sup> The saturated zone appeared relatively homogeneous in the model.

## Water recirculation monitoring

In this study, ERT monitoring was used and temperature measurements were performed. Hereby, large horizontal recirculation drain efficiency for superficial waste humidification in a large retrofit technical landfill was assessed. Of particular interest was the extent of the injected plume, the flow anisotropy, the existence of preferential flow paths, and the persistence of moisture increase. 60 m<sup>3</sup> of water was injected and electrical resistivity was monitored hourly. A total of four 2D ERT profiles was acquired for each time frame. The southern tomography, along the drain, ensures that the drain is studied over its entire length. The other profiles are used to assess the recirculated liquid flow behaviour and the residence time of the added water as a function of the injected volume. Data are presented for several time periods after the injection time, *i.e.* 1, 2, 3, 12, 18 and 48 h (Figure 5). The southern profile shows that the injection drain is used on almost its entire length. The leachate plume extension changes during the 3 first hours following the injection. Initially, it has a smaller horizontal extent (Figure 5a). Afterwards, the horizontal extent increases along the field slope, while the thickness and the magnitude decrease.



**Figure 5:** ERT monitoring of the 60 m<sup>3</sup> injection after different time intervals: A. 1 h; B. 2 h; C. 3 h; D. 12 h; E. 18 h and F. 48 h after injection. The black line is the “70% of local maximum” threshold.

The observed changes are extremely high (< -40%) and focus on the injection drain (Figure 5a). As the injected liquid flows from the drain towards the North, the resistivity magnitude decreases (-25%, from 24 Ωm to 18 Ωm) close to the drain location while it increases down the slope (Figure 5c). The leachate plume extension is about 2,500 m. Three hours after the injection, water arrives at the bottom part of the field test, close to the peripheral drain (Figure 5c, profile west). During the next 2 days, the magnitude of the resistivity progressively decreases. After 48 h, only a small fraction of the waste mass has its water content increased by a few percent (Figure 5f).

## **Conclusions**

Frequently encountered problems with former and/or illegal waste deposit sites have been addressed and several geophysical techniques have been assessed allowing to find partially and/or totally missing information of these sites. For landfills, important issues are their precise identification/localisation, the characterisation of their lateral and vertical extents, and the characterisation of their waste constituents.

Globally, the full geophysical campaign, which necessitated less than 2 weeks of surveying for a couple of technicians and one week of data treatment for an engineer, offers a good understanding of the site extension, depth, volume and water content. This information was acquired at low cost (compared to a “drilling-sampling-analyses” approach) and offers important information for site rehabilitation studies, water mitigation processes for enhanced biodegradation or landfill mining operation planning. Additionally, the recirculation experiment resulted in a better understanding of the suitability of a large horizontal drain for water recirculation on a large retrofit landfill. There was a particular interest to understand the influence of the drain horizontality, the effects of waste compaction and neighbouring gas wells on the water flow and the persistence of the water content increase through time.

## **Acknowledgments**

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# METHODS FOR INVESTIGATION OF OLD GLASS WASTE DUMPSITES

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## Abstract

An old glass dumpsite in southern Sweden was mapped and investigated to locate glass abundance zones (“hotspots”) and understand physicochemical parametres of the waste. Global Positioning System (GPS) was used for mapping the site while a geophysical method of Electrical Resistivity was used for detecting glass hotspots in the dump. Test pits were excavated and samples taken, after which hand sorting, sieving and X-Ray Fluorescence (XRF) scanning of the waste were used for physicochemical properties. Geophysical mapping was found to be a feasible non-destructive tool in locating glass hotspots. In terms of composition, glass was found to be the most abundant fraction at 90% average from all 4 sampling points. From particle size distribution, particles > 11.3 mm were more abundant (75% average) than particles < 11.3 mm. XRF scanning yielded As, Cd and Pb concentrations of 3,700 mg/kg, 500 mg/kg and 5,300 mg/kg, respectively. In conclusion, it is possible to locate glass hotspots and excavate them carefully in readiness for metal extraction while avoiding the need for complicated sorting post-excavation.

## Introduction

In the “Kingdom of Crystal” in southern Sweden, there are a number of old and unregulated dumpsites that were used for crystal and art glass waste disposal since the 16<sup>th</sup> century. Studies indicate that these glass dumpsites contain metals such as As, Cd and Pb in elevated concentrations.<sup>1</sup> According to Höglund *et al.*<sup>1</sup>, 22 glass dumps in the area contain over 420,000 m<sup>3</sup> of contaminated masses (both soil and glass waste) with further estimations of As, Cd and Pb burdens of 420 tonnes, 30 tonnes and 3,100 tonnes, respectively. The hazardous nature of the sites poses risks to both human health and the environment.<sup>2</sup> Reasonably, Swedish authorities have classified a number of these sites as high risk, including the site under investigation in the current study, Alsterfors, which has an infiltration rate to groundwater of about 1,200 m<sup>3</sup>/year and combined As, B, Cd, Pb and Sb leakages to the Alsterån River of over 20 kg/year.<sup>1</sup> There is a need for remediation in these sites.<sup>3</sup> Therefore, the

Swedish Government has conceived a remediation plan that consists of excavating the contaminated masses and landfilling them as hazardous wastes.<sup>1</sup>

However, landfilling these materials would mean losing resources that could be extracted back into material cycles if metal extraction methods could be developed. Recent research has shown the possibility to recover metals contained in the glass waste as opposed to further landfilling, and the outlook is promising.<sup>4</sup> With this progress, establishment of investigation methods for dumpsites is needed to locate and quantify the waste for excavation. Geophysical methods could contribute to the investigation, as they can be useful in locating wastes and estimating their volumes.<sup>5</sup> Furthermore, as waste management and resource recovery cannot be well planned and implemented in the absence of accurate and reliable waste composition data,<sup>6</sup> understanding waste composition is important. In formulating waste management strategies, understanding the wastes' physicochemical behaviour can provide insight into waste handling issues such as secure storage of excavated materials in "bank account" cells for future use when metal extraction technologies are fully developed. Therefore, the aim of this study was to investigate the feasibility of using geophysical mapping as a non-destructive method for detecting glass abundance zones (herein referred to as "glass hotspots") for further excavation and resource recovery. Additionally, the study aimed to assess waste composition and physicochemical properties in order to measure its suitability for metal extraction.

## **Materials and methods**

### **Site description**

Alsterfors glassworks is situated in Uppvidinge municipality, Kronoberg County, in southern Sweden. It was active between 1886 and 1980, producing a mix of crystal and art glasses. The glassworks site covers approximately 4,200 m<sup>2</sup>, of which approximately 2,600 m<sup>2</sup> is the dumpsite area, containing about 5,200 m<sup>3</sup> of contaminated materials.<sup>1</sup> The dumpsite is on the northern side of the glassworks and has a depth of up to 3 m.

### **Global Positioning System (GPS) and geophysical mapping**

GPS mapping was done and coordinates evaluated using the coordinate systems SWEREF 99 TM (Swedish Reference System) and RH2000 (National Height Measurement System) for horizontal projection and vertical elevation respectively. For geophysical mapping, an Electrical Resistivity method was employed using an ABEM Terrametre LS. To create geophysical lines (gradients), 80 metre-long electric cables were systematically laid over the landfill in parallel and 15 metres apart, and electrodes were spaced 1 metre apart. The instrument generated Figure 1, which was used in planning for excavation.

## **Excavations and sampling**

Test pits (TP) were planned and located along the geophysical lines created, and excavated at 10-metre intervals on the lines. Excavation was achieved using a 4.5 tonne excavator and according to the method used by Kaczala *et al.*,<sup>7</sup> where test pit materials from every half metre were heaped separately for sampling. Sampling was then carried out according to the Nordtest Method NT ENVIR 004-1996/05 for sampling from stockpiles, as a guide. Samples were collected in sample bags from all points, while from glass hotspots additional samples were collected in 14 litre buckets for particle size characterisation.

## **Sample analyses**

After collection, the samples were sieved to particle sizes > 63 mm, > 31.5 mm, > 20 mm, > 16 mm, > 11.3 mm, > 8 mm, > 4 mm and > 2 mm. Each sieving operation was followed by hand sorting and subsequent weighing of individual fractions to assess their contribution to the overall sample weight. For the smaller fractions (> 2 mm and < 2 mm), hand sorting involved the use of magnifying lenses. X-Ray Fluorescence (XRF) analysis for metal content of all glass fractions <11.3 mm was then done.

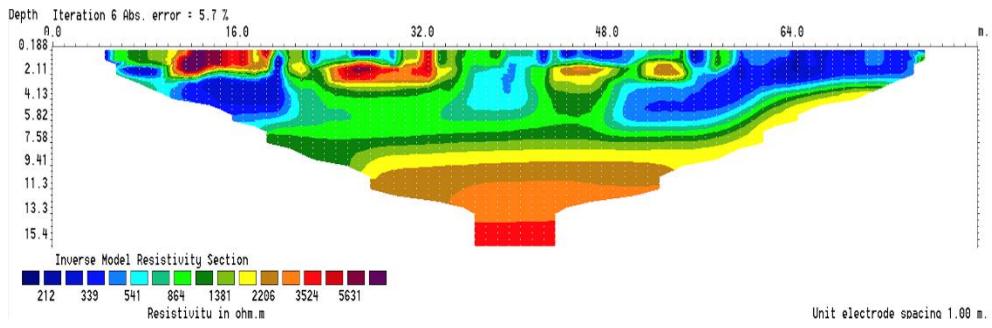
## **Data analysis**

Obtained data was analysed statistically using Graphpad Prism.

## **Results and discussion**

### **Geophysical mapping and test pit excavations**

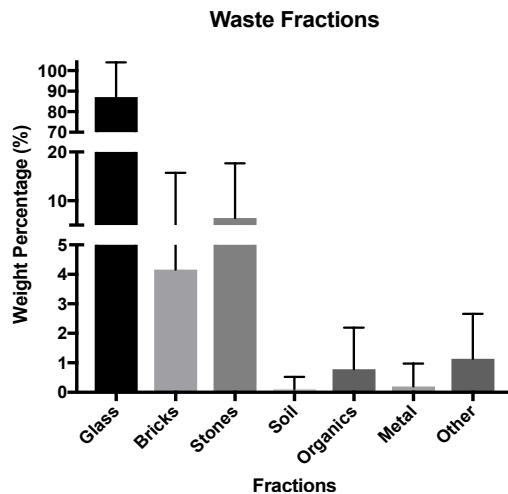
Results obtained from electrical resistivity measurements are shown in Figure 1, with markings at 16 metre-intervals on the 80 metres long line across the landfill. The figure provided crucial information about glass hotspots and guided the excavation. The colour progression on the resistivity scale (in the legend) from dark blue to dark purple corresponding to resistivity progression from low to high resistivity respectively, was used to indicate the hotspots. Regions of higher resistivity (orange to dark purple) were assumed to correlate with high glass presence. After test pit excavations, glass was found in the region between 10 m to 20 m along the line in the figure, and at a maximum depth of 2.5 m. The region around 30 m ( $\pm 2$  m) had glass in the top half-metre depth, followed by big stones and later a bigger stone at the 2 m-depth layer. Upon further excavation, the points of lower resistivity (40 m, 50 m and 60 m) along the line were found to contain mainly soil with the water table within reach.



**Figure 1:** Electrical Resistivity measurements

## Waste fractions

Different types of waste were found around the dumpsite, including used tyres, metallic objects (such as empty drums and vehicle parts,) and construction materials (such as bricks and roofing sheets). However, thorough waste assessment focused on waste composition around glass hotspots. Figure 2 shows the abundance of the waste fractions (where ‘organics’ indicates planks, sticks, etc., ‘other’ indicates plastics, textiles, etc.). Glass was found to be the most abundant fraction, followed by stones, bricks and the rest of the waste at averages (in wt%) of 87%, 6%, 4% and 3%, respectively. Soil was more notable in the fine fraction (< 4 mm). In addition, high standard deviations were observed in glass, bricks and stones, which can be attributed to the wide result ranges of 38.46-100%, 0-61.54% and 0-44.30% in the three fractions, respectively.



**Figure 2:** Average weight percentages of waste fractions, with  $n$  between 27 and 28

## Particle size distribution

In the current study, particle size distribution was important as it provided valuable information for the valorisation process (sorting and glass metal extraction), both of which are size-dependent for efficiency. The samples (S1, S2, S3 and S4) showed a similar size trend as shown in Figure 3. The fractions > 63 mm were dominating followed by the > 31.5 mm and > 20 mm fractions, respectively. Furthermore, when

particles from all the samples were categorised into two main size categories of > 11.3 mm and < 11.3 mm, a comparison showed that particles > 11.3 mm were more dominant than particles < 11.3 mm at ranges of 63-75% and 25-37%, respectively.

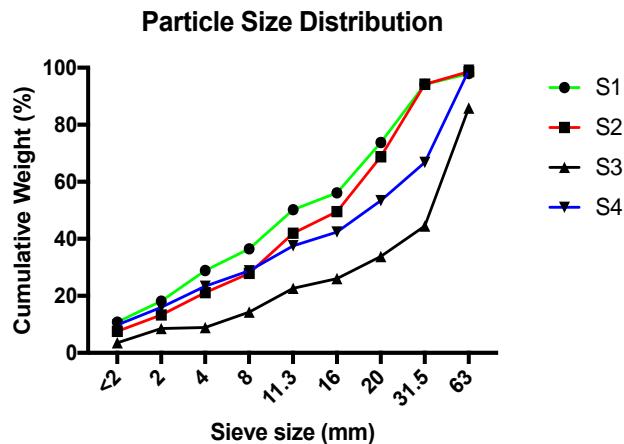


Figure 3: Averages of particle size distribution presented in cumulative weights

### Metal concentrations

According to the XRF results, the mean concentrations of three metals As, Cd and Pb were found to be 3,700 mg/kg, 500 mg/kg and 5,300 mg/kg, respectively. Figure 4 details the variations in terms of data spread. Using the Swedish guidelines for hazardous waste (Avfall Sverige<sup>8</sup>) as a benchmark, with limits for As, Cd and Pb stand at 1,000 mg/kg, 100 mg/kg and 2,500 mg/kg, respectively, the observed concentrations qualify the material to be classified as hazardous waste. While metal concentrations in materials from this particular site are not as high as those observed (19,761 mg/kg, 847 mg/kg and 323,977 mg/kg for As, Cd and Pb respectively) from other sites,<sup>4</sup> the high metal recovery potential from glass would make these materials available for other artistic applications once the metals have been extracted rather than further landfilling.

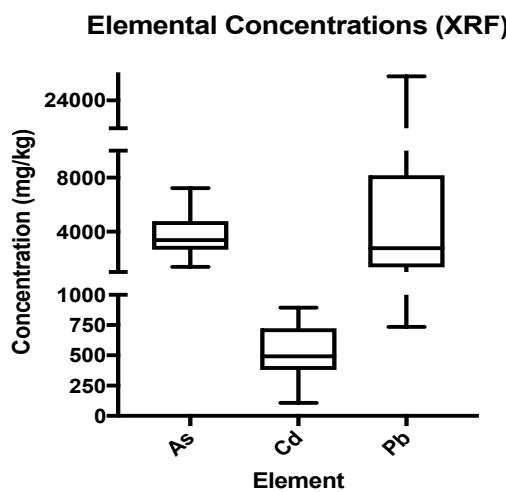


Figure 4: Elemental concentrations of As, Cd and Pb using XRF

## Conclusions

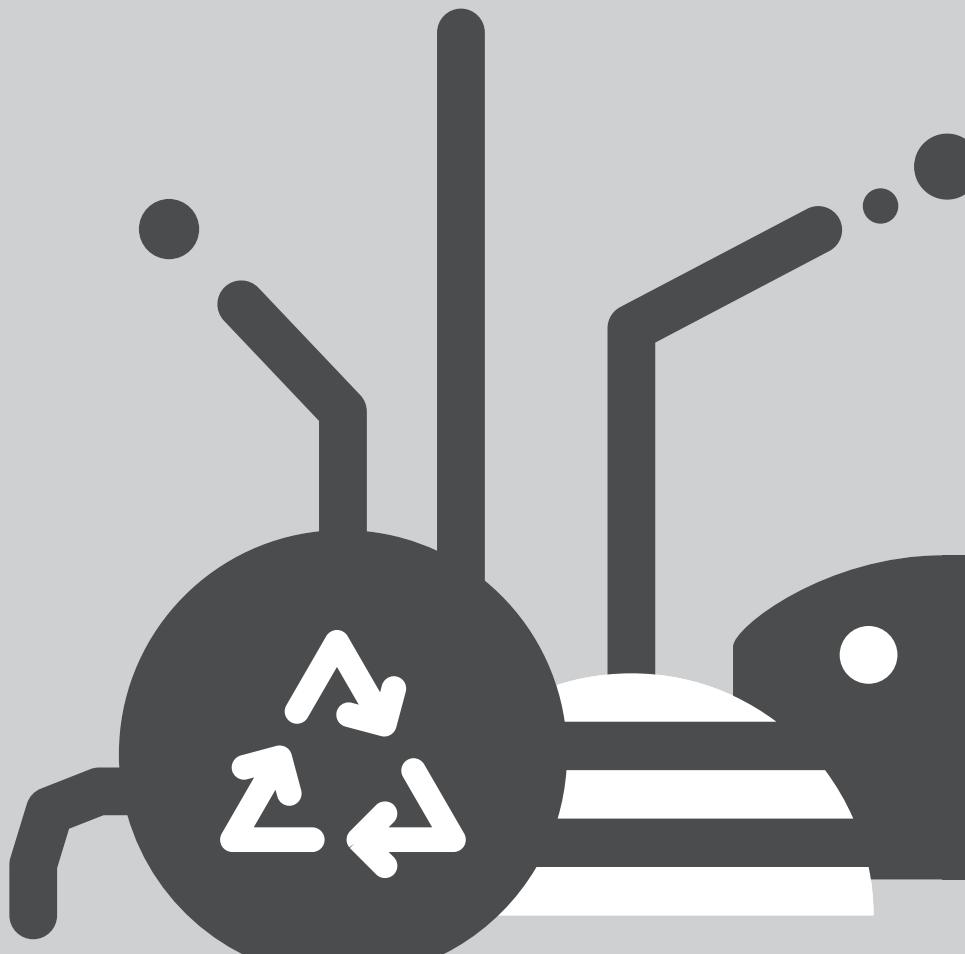
The study identified the use of GPS mapping accompanied by residents around the site as useful in mapping the exact site location in the absence of substantial initial site details. The study also found geophysics to be a useful and non-destructive tool in identifying landfill glass hotspots, which can be carefully excavated to reduce the need for sorting after excavation. Furthermore, waste characterisation on glass hotspots showed that they contain glass that can readily undergo the metal extraction process without complicated sorting requirements, as the hotspot material contained 90% glass on all 4 hotspots investigated. However, soil content in the hotspots may have been underestimated due to sieving being done on wet samples, where soil particles are expected to attach to other fraction surfaces. A verification step, through drying before sieving, would be important to quantify the actual amount of soil. Furthermore, particle size distribution showed particles > 11.3 mm to be more abundant, at a maximum of around 75% of all particles. From the findings, it is possible to locate glass hotspots and excavate them carefully in readiness for metal extraction while avoiding the need for complicated sorting post-excavation. The findings would be valuable in resource recovery from dumpsites.

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## Session 2

# Thermal valorisation technologies for Enhanced Landfill Mining





# SOLAR GASIFICATION OF WASTE: A CRITICAL REVIEW

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It is well known that concentrated solar energy can provide heat at temperatures that are suitable for effective endothermic gasification of carbonaceous waste into valuable fuels. However, the inherent intermittence of solar energy precludes its exploitation for powering industrial gasification processes as these generally require a continuous supply of rather steady energy input. One way to overcome this limitation is sought in hybrid gasifier concepts that are capable of complementing solar energy with electricity and/or combustion heat of either fossil or renewable fuels that can be exploited in the absence of sufficient insolation. These gasifier concepts, however, generally face substantial engineering challenges to deliver design solutions that (i) suppress the heat losses during off-sun operation due to thermal re-radiation and (ii) provide similar temperature gradients ensuring seamless product output when switching between the two modes of operation.

Instead of conceptualising solar gasifiers separately from the conventional energy-powered gasifiers and then seek the “hybridisation bridge”, a more practical way to approaching the integration of concentrated solar power into industrial gasification processes is based on delivering the process heat *via* sensible heat contained in the gasifying agent (steam and/or air). This approach allows for adopting any of the conventional gasifier concepts that have already been demonstrated at industrial scale and then considering the gasifying agent as the heat transfer fluid (HTF) dispatching the heat supplied by any combination of energy sources. Moreover, based on recent advances in using concentrated solar power to heat air to temperatures as high as 1,200°C and storing that heat in an advanced thermal energy storage system represented by a cascade of sensible heat storage (SHS) and thermochemical storage (TCS), the solar energy can be dispatched continuously at a constant temperature into the gasifier, thereby eliminating the need for an additional energy source.

This talk will review the current status of developing methods for storing and dispatching solar energy as heat to power high-efficiency waste gasifiers.

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# ADVANCED WASTE TO RESOURCES BY PLASMA GASIFICATION

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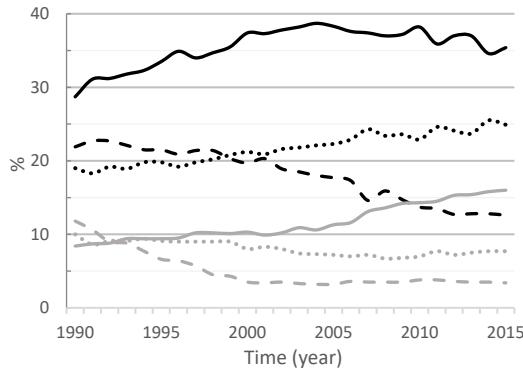
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## Introduction

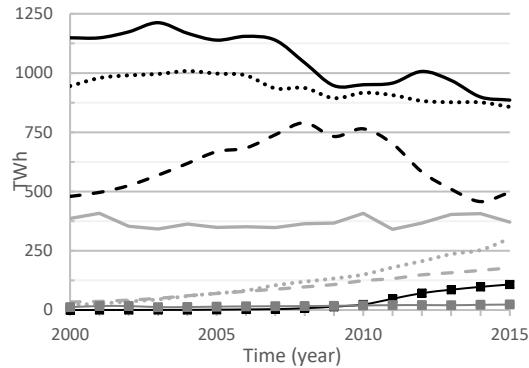
Fossil fuel burning and land-use change have led to an exponential rise in atmospheric CO<sub>2</sub> concentration since 1750, which in turn has led to a distinct increase in average global temperature, threatening a climate change with catastrophic and irreversible damage to the hemisphere.<sup>1</sup> The international community has recognised the severity of the threat of global warming and has agreed on actions to mitigate the impact of climate change.<sup>2,3,4</sup> Even though the global greenhouse gas (GHG) emissions are still rising,<sup>5,6,7</sup> the man-made GHG emissions in the EU are on a downward trend (*e.g.* 22.1% reduction in 2015 compared to 1990 levels).<sup>8</sup> Despite the EU's small share (less than 10% in 2012) in global GHG emissions, the EU is taking up an exemplary role in fossil decarbonisation and is paving the way towards a fossil-free circular economy.

This transition towards a renewable and sustainable society requires the implementation of challenging changes in all sectors; transportation, industry and the residential sector. The relatively positive headway in the EU climate targets can be linked mainly to the building sector as a result of energy efficiency improvements and a less carbon-intensive mix for space heating (*i.e.* about two thirds of the *final energy consumption (FEC)* in households). FEC is a term defined by EUROSTAT as the energy which reaches the final consumer's door. Figure 1 depicting the *final energy consumption* in EU households shows that the share of fossil fuels is decreasing, while the penetration of renewables (95% solid biofuels, 4% geothermal energy) is steadily increasing. Even though natural gas has maintained the largest share in household energy use over the last two decades, a trend of electrification of residential energy systems can be seen. A similar shift in the transportation sector is taking place, where the car industry is promoting and investing in electric drive systems. The choice of electricity as the energy carrier can be regarded as more sustainable because of the decreasing carbon footprint of electricity generation. Figure 2 shows the evolution of *gross electricity generation* (defined as the total amount of electrical energy produced by transforming other forms of energy) by fuel from 2000 till 2015. The share of fossil fuels has clearly decreased, while electricity production from

renewable energy sources (RES), such as solar, wind and bio-energy is steadily increasing, adding up – together with hydropower – to 29.8% in 2015.<sup>9</sup> Even more fossil-free electricity generating alternatives (such as geothermal and tide, wave and ocean energy) are being developed and the rate of newly installed capacity continues to grow.



**Figure 1:** FEC in EU households by fuel; gas (black full), electrical energy (black dotted), total petroleum products (black dashed), renewable energies (grey full), solid fossil fuels (grey dashed), and derived heat (grey dotted)<sup>10</sup>

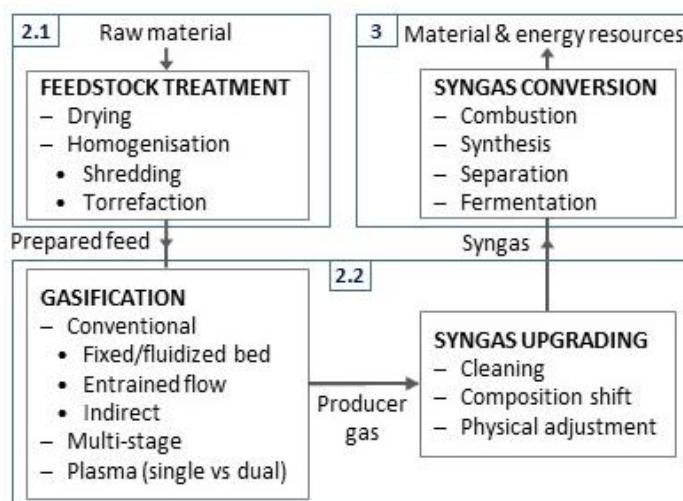


**Figure 2:** EU gross electricity generation by fuel; Fossil fuels (black full), nuclear (black dotted), natural gas (black dashed), hydro (grey full), wind (grey dotted), bioenergy (grey dashed), solar (black squared) and non-renewable waste (grey squared)<sup>9</sup>

Renewable electricity generation combined with electrification of our energy use, however, is not the sole solution for a sustainable society. Not only is the rate of change slow, but a large number of processes and product applications throughout all sectors (will – within the foreseeable future – continue to) rely on carbon-containing energy carriers and feedstock. On the short term, methane is one example of a carbon-containing energy-carrier that will still play an important role in the transition towards a fossil-free economy. Today, both in the energy use in the residential sector and in central electricity generation plants, natural gas still plays an important role. The gas supply is currently almost exclusively fossil-based, but has great potential for shifting a substantial part of our utility demand towards a CO<sub>2</sub>-neutral alternative, without the need for huge adaptations to existing infrastructure. This ambition to have the gas network undergo a similar transition towards renewables as the electricity mix has been formulated in the Green Gas Initiative,<sup>11</sup> in which seven independent gas infrastructure companies have committed themselves to achieve a 100% carbon-neutral gas supply in their transport infrastructure by 2050. Also on the longer term, for certain fields in the transport and industry sector, there are no foreseeable alternatives to carbon based energy-carriers like diesel for heavy-duty vehicles, jet fuel for aviation or certain feedstock for chemical synthesis. Therefore, CO<sub>2</sub>-neutral carbon sources will need to start replacing

the current fossil-based resources for these applications. Biomass and waste are two very abundant and accessible material streams that can provide a sustainable source of carbon. Biomass already plays an important role in making the society's energy supply more renewable and sustainable (provided that care is taken of all potential pollutants), contributing to all energy conversion sectors (electricity generation, transport and heating and cooling). However, the untapped potential of biomass and waste as low-carbon feedstocks is still huge. Moreover, there is an additional large reserve of waste material buried in over 500,000 landfills throughout Europe. In the context of Enhanced Landfill Mining,<sup>12</sup> landfills are no longer being considered as final disposal sites, but serve as temporary storage till further processing. Through appropriate conversion technologies (such as plasma gasification), the penetration of biomass and or waste-based products can achieve a much broader application range as material and energy resources in a sustainable society.

This paper focuses on the advanced conversion of any solid carbonaceous material (*i.e.* biomass and waste) into a wide array of energetic or chemical end applications. This is done through an intermediary energy-containing gaseous product, called syngas (mainly CO and H<sub>2</sub>) produced *via* the thermochemical process of gasification. The main parts of the process chain, as shown by the flowsheet in Figure 3, will be covered. Section 2 describes the feedstock treatment and waste conversion process into syngas *via* gasification. Section 3 elaborates on syngas conversion into chemicals, fuels and energy vectors. Finally Section 4 summarises the main conclusions. Plasma gasification can be identified as a key technology in the sustainable waste-to-resources process, as will be clear from Section 2, given the input specifications set by the downstream conversion technologies described in Section 3. This paper thus looks into a global system approach for the transition towards CO<sub>2</sub> neutral waste-to-resources, thereby stressing the strengths of plasma gasification.



**Figure 3:** Advanced waste-to-resources process flowsheet

## **From waste material to syngas**

In this section, general aspects about the pre-conditioning of the raw material and insights in the gasification process and the production of syngas are discussed.

### **Material input**

Raw material for waste gasification can originate from different sources: animal residue, agricultural residue, woody biomass (forestry residue and energy crops), municipal solid waste (MSW), industrial waste (IW), landfill waste, sewage sludge, etc. The pre-treatment of waste material, the process of converting MSW into refuse derived fuel (RDF), consists of: shredding, screening, sorting, drying and/or pelletisation in order to improve the handling characteristics and homogeneity of the material. These pre-processing steps of MSW are referred to as mechanical biological treatment (MBT). Metal recovery and drying of the material stream are generally the most common pre-treatment steps. Drying can be done either actively by using (excess) process heat or biologically by the reaction heat from aerobic bio-stabilisation of the biodegradable fraction. The main benefits of converting MSW to RDF are a higher calorific value (preferred by advanced Waste-to-Energy (WtE) technologies), more homogeneous physical and chemical composition, lower pollutant emissions, lower ash content, reduced excess air requirement during combustion and finally, easier storage, handling and transportation. MBT often requires large machines and a lot of energy, therefore, a trade-off between the increased costs of producing RDF from MSW and potential cost reductions in system design and operation needs to be found. The conversion of these pre-treated materials to a more manageable and versatile applicable intermediary gaseous product is accomplished by gasification.

### **The conversion process – (plasma) gasification**

**Gasification.** Gasification is the thermochemical conversion of solid, liquid, or gaseous carbonaceous material in an oxygen-controlled environment at increased temperatures (usually in the range of 500-1800°C). The carbon-rich material reacts through partial oxidation to a low-or medium-value synthesis gas (or syngas) in presence of an oxidant amount lower than that required for stoichiometric combustion. The oxygen required for the gasification process can be supplied as free oxygen (pure or as (enriched) air) or bound in the form of steam, carbon dioxide or a mixture of these gasifying agents. The resulting syngas consists mainly of CO, H<sub>2</sub> and contains varying amounts of H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub>, trace amounts of higher hydrocarbons such as ethane and propane and inert gases originating from the gasification agent. Besides the main gas components also a lot of unwanted gas species and other contaminants such as small char particles are formed during the gasification process. An overview of the different impurities that can be found in syngas and their potential

damaging impact on equipment and/or the environment is given in Table 1. An additional group of unwanted components in the syngas are tars. Tars are formed from condensable organic compounds which are insufficiently cracked during the gasification process. They are characterised by a high molecular weight and aromaticity, and can take the form of primary oxygenated products (*e.g.*, organic acids, aldehydes and ketones), heavier deoxygenated hydrocarbons and polycyclic aromatic hydrocarbons (*e.g.*, naphthalene). Tar is a toxic, sticky material that can condensate already at moderate temperatures, causing filter clogging, catalyst deactivation and fouling of cold spots and downstream equipment. Furthermore, as a by-product of the gasification process, it contains considerable amounts of energy lost to the desired syngas end purpose.

**Table 1:** List of syngas impurities<sup>13</sup>

Contaminants	Main species	Harmful impact	Cleaning measures
Particles	Ashes (< 1 µm - > 100 µm)	Fouling, corrosion, erosion, abrasion, sintering, slagging	Cyclone, filter, electrostatic precipitator (ESP), scrubbing,...
S-containing components	H <sub>2</sub> S, COS, CS <sub>2</sub> , S	Corrosion, air pollution (SO <sub>2</sub> ), catalyst poisoning	Adsorption, scrubbing,...
N-containing components	HCN, NH <sub>3</sub>	Corrosion, catalyst poisoning, air pollution (NOx)	Selective catalytic oxidation, thermal catalytic decomposition, adsorption, scrubbing,...
Halogens	HCl, HBr, HF	Fouling, corrosion	Adsorption, scrubbing,...
Alkali metals	Na, K	Fouling, corrosion, bed material defluidisation, catalyst poisoning	Condensation, adsorption, scrubbing,...
Trace metals	Hg, Fe, Ni	Air pollution	Activated carbon,...

The vast majority of all gasification units built to date were designed and optimised for the conversion of coal or petroleum residue (and biomass, to a lesser extent) into syngas for the production of electricity. The electricity generation is predominantly done through a combined cycle and through a boiler connected to a steam turbine in large-scale coal units and smaller-scale biomass units, respectively. In a gas boiler, the tars present in the syngas are burned and do not cause any problems for the downstream mechanical equipment. The decades long experience in (entrained-flow) coal gasification and the homogeneous nature of the material have led to syngas production with very low tar levels. Only in the last couple of decades has the well-established gasification process been reapplied to biomass waste (and MSW). Conversion of biomass/waste to energy vectors (using performant technologies) and material resources offers two big challenges:

- Heterogeneous composition, shape and size of biomass and waste material lead to much higher impurities and tar content;
- The tar tolerance of downstream conversion technologies is much lower and the overall syngas purity requirements are a lot more stringent than for syngas burning in a boiler.

Upgrading the syngas quality (by purification) is thus of crucial importance when starting from biomass or waste. Some of the different physical and chemical techniques that have been developed to clean the syngas from unwanted species are listed in Table 1. It remains a particularly difficult challenge to develop a feasible way to strongly reduce tar levels in syngas without compromising the gas quality. The typical level of tar concentrations in syngas ranges from 1 to 100 g/Nm<sup>3</sup>, depending on the configuration of the gasifier.<sup>14</sup> These are a couple of orders of magnitude higher than the tar tolerance levels for advanced syngas valorisation options.

Different techniques for tar abatement have been developed, which can be classified into primary and secondary methods. Primary or *in-situ* tar abatement aims at controlling either the gasifier configuration or the process parameters, however these techniques also directly affect other syngas parameters such as syngas yield, syngas composition and heating value. Therefore, secondary, or *ex-situ* tar abatement units, located downstream of the gasifier are preferred since they do not strongly affect other syngas quality indicators. Three main types of secondary methods exist: thermal, catalytic and plasma. Thermal units accomplish thermal decomposition of tars at elevated temperatures while catalytic units aim at accelerating the kinetics of tar removal. Plasma-based tar removal relies on the production of radicals that further react in the decomposition of large hydrocarbon structures of the tar components. Thermal plasmas combine the thermal and the plasma mechanisms, such that the high-temperature, reactive environment accelerates the kinetics and improves the thermal decomposition of hazardous organic compounds (such as tars) into desirable gas species.<sup>15</sup>

**Plasma gasification.** Plasma gasification is a type of gasification where the thermochemical conversion to syngas is combined with a thermal plasma. The configuration of a plasma gasification system is distinct to the function/emphasis of the plasma element to the gasification process. The configuration where the thermal plasma processing is physically separated from the gasification process is called a *dual-stage* or *two-stage plasma gasification* system. Alternatively (or additionally) to fulfilling the function of a syngas cleaning step, as described in below, the thermal plasma plume can also be directed to the residual solid fraction from the gasification process. The high-temperature plasma melts the inorganic residue of the treated material (ash and metals), which is then transformed into a dense, inert, non-leaching

(vitrified) slag, after quenching. This slag is more manageable than ash and can be further upcycled into useful by-products.<sup>16</sup> A good example of a dual-stage plasma gasification system is the Gasplasma<sup>®</sup> process by Advanced Plasma Power. It comprises two steps; firstly, in a fluidised bed gasifier VOCs and carbon are converted into a crude syngas using a fraction of the thermal energy of the waste and next, a plasma converter provides the high temperature environment for converting residual tars and chars, allowing further cleaning of the syngas and vitrification of the ash into a non-leaching slag.<sup>16</sup>

Besides breaking down the harmful tar components in the produced syngas, thermal plasma can also serve as the external heat source in an allothermal gasification process, offering a couple of additional advantages. The setup where the thermal plasma torch is directly incorporated in the gasification reactor and supplies the energy for the gasification reactions, is called *single-stage plasma gasification*. Since electricity is used as the energy source, instead of chemical reactions of the treated material and its devolatilisation products, heat supply is decoupled from process chemistry which increases process controllability and flexibility. Also the process temperature can be set independently from fluctuations in feed quality and supply of air/oxygen/steam required to gasify the feed.<sup>17</sup> At the elevated temperatures in the reactor volume, the inorganic constituents of the treated material can reach their melting point and can be reduced to a non-hazardous melt with a very low unburnt organic residue content. That is, however, not the primary goal of the plasma source in single-stage plasma gasification. A commercially proven example is the single-stage plasma gasification reactor developed by Westinghouse (Madison, USA), now AlterNRG.<sup>18</sup>

The major drawback of plasma gasification, in general, is the high energy cost for generating the plasma. Electricity is an expensive energy vector, turning economic considerations into the strongest barrier for using plasmas for waste treatment. Not only the electricity cost in the OPEX of plasma torches is significant, but also the replacement cost for the electrodes is considerable. Both single- and dual stage plasma gasification systems have other distinct benefits and disadvantages relative to each other.<sup>19</sup> For selecting the most optimal configuration, the characteristics of the waste stream (calorific content, amount of inorganic material and material flow rate) are among the most important parameters. Another crucial factor affecting the suitability of the selected plasma gasifier type is the desired end application of the produced syngas. The requirements of the syngas quality (syngas purity and syngas composition) vary for each syngas conversion technology.

## Syngas conversion

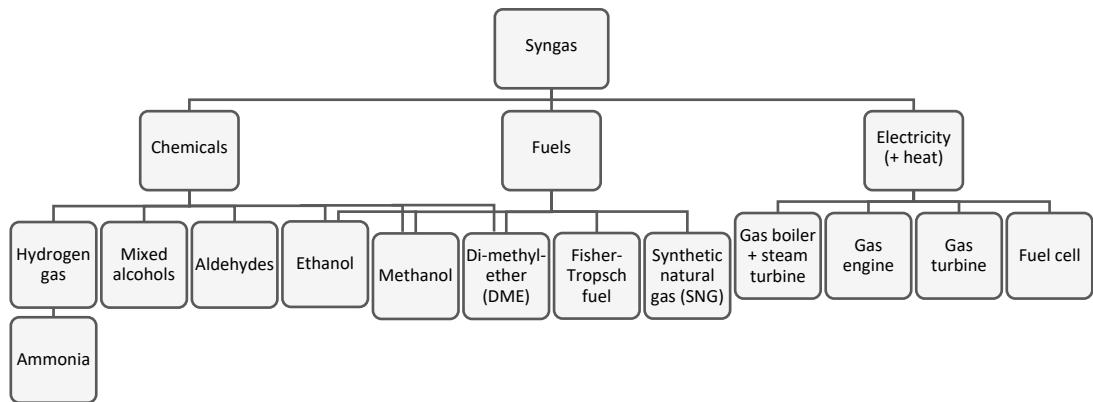


Figure 4: Overview of possible conversion pathways of syngas

### Energetic valorisation

Gasification systems intended for energetic valorisation of the produced syngas can be divided into *heat gasifiers* and *power gasifiers*, depending on the need for a syngas cleaning step in the process chain.<sup>20</sup> The approach of *heat gasifiers* involves direct burning of syngas in a boiler to feed an externally-fired steam cycle (or to use the thermal energy directly), including a typical post-combustion flue gas cleaning step. The combustion process poses no particular limitation on the level of undesired compounds and does not require prior syngas cleaning, except for the removal of coarse particulate matter. Because of its simplicity of operation, the heat gasifier configuration is applied in most commercial (small-scale) gasification facilities. In the public opinion, this Waste-to-Energy gasification approach is often labelled as “indirect combustion” and such gasification plants as “incinerators in disguise”, disfavouring public acceptance towards gasification.

However, thanks to the conversion of the solid waste material into syngas, its energetic content can be valorised to a greater extent by a broader range of more performant technologies than simply burning in a boiler. The gasification systems that tap into this potential, using more efficient electricity generating technologies, are called *power gasifiers*. In these configurations, a syngas clean-up is necessary to meet the specifications for impurity levels of high-efficiency, internally fired cycles (internal combustion engines and gas turbines) or fuel cells. These electricity generating devices are discussed in more detail in the following sections.

**Gas engine.** The conventional energy source in a gaseous-fuelled engine is methane. The quality of syngas as a fuel in internal combustion engines (ICE) is significantly poorer than gasoline and natural gas, especially because of the lower energy content.

Additionally, a number of syngas components (e.g. water vapour and hydrogen) cause challenges such as corrosion and reduced efficiencies, and a predisposition to pre-ignition, respectively. Therefore, the engines require some minor design modifications in order to be able to run on syngas. The quality of gas should be sufficiently high in terms of low tar and particulates content to maintain a consistent engine's operation and to provide an adequate durability of major engine components. The allowed particle and tar concentrations in syngas for satisfactory operation of the internal combustion engine is less than 100 mg/Nm<sup>3</sup> and 50 mg/Nm<sup>3</sup>, respectively.<sup>21</sup> Gas engines can also be operated in combined heat and power (CHP) mode by recuperating the sensible heat of the off-gases in a heat exchanger to generate pressurised steam or hot water. The Kymijärvi II gasification plant in Lahti (FI) is a great CHP example, supplying 50 MW<sub>el</sub> and 90 MW<sub>th</sub> (to district heating networks) from processing 250,000 tonnes/yr of solid recovered fuel (SRF).<sup>22</sup>

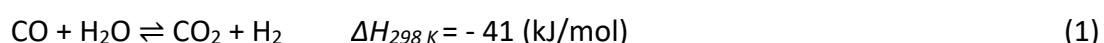
**Gas turbine.** Gas turbines consist of a compressor unit, a combustion chamber and a turbine. Pressurised air coming from the compressor is mixed with the fuel stream (typically natural gas), after which the mixture is ignited, resulting in a high-temperature, high pressure gas mixture. That mixture expands in a gas turbine, spinning a generator and producing electricity. Some key issues that need to be considered when using syngas rather than natural gas to fire a gas turbine are: flame stability issues, the level of water vapour, the lower calorific value and the higher corrosion potential.<sup>23</sup> The limitations on pollutants in the syngas are also more stringent than for gas engines. The particulate matter and tars cannot exceed 10 mg/Nm<sup>3</sup> and 5 mg/Nm<sup>3</sup>, respectively. Since syngas has a much lower LHV (4-14 MJ/Nm<sup>3</sup>) compared to natural gas (34-39 MJ/Nm<sup>3</sup>), higher mass and volume flow rates are required to generate the same power output. This has repercussions on the design of the gas turbine, namely the combustion chamber and the upstream equipment need to be adapted to these larger gas streams. Syngas-fuelled gas turbines are almost exclusively used in a combined cycle (CC) power block (consisting of one or more gas turbines and a steam turbine). The excess heat contained in the flue gases exiting the gas turbine(s) at high temperatures is captured, converted into steam, and sent to a steam turbine to produce additional electricity. Moreover, the system is referred to as *integrated gasification combined cycle (IGCC)* when the process streams are internally linked between the gasification process and the heat- and electricity generating unit, resulting in an increased energy efficiency of the system. The world's first integrated plasma gasification combined cycle was built at Teesside Valley (UK) by Air Products and AlterNRG with an installed gross power capacity of 50 MW fuelled by syngas produced from 950 tonnes per day of MSW. At the time of writing, the operations at the plant were (temporarily) suspended because of Air Products management's decision to refocus on the core activities of the company.

**Fuel cell.** Analogous to an IGCC power plant, *the integrated gasification fuel cell (IGFC)* cycle links a high-temperature type fuel cell (such as the solid oxide fuel cell (SOFC)) power generation unit to the gasification process. Fuel cells offer the ability to convert chemical energy directly into electrical energy with a very low environmental impact. A SOFC typically operates at higher temperatures than lower-temperature fuel cell types such as proton exchange membrane fuel cells or alkaline fuel cells. The latter fuel cell types require pure hydrogen as fuel, whereas the SOFCs can accept hydrogen, carbon monoxide, carbon dioxide, steam, and methane mixtures as fuel directly, because of their internal shift and reforming capabilities.<sup>24</sup> The waste heat from SOFC systems may be captured and reused, increasing the fuel utilisation ratio to as high as 80-85%.<sup>25</sup> Recent developments allow an integration of carbon capture & storage technology within IGCC and IGFC plants, which reduces the amount of CO<sub>2</sub> emitted to the atmosphere. The syngas must be pre-treated in order to reduce the impurities to a level that SOFCs are able to tolerate. These fuel cell purity requirements are dependent on electrode material, microstructure and operating conditions, but generally demand a practically particulate-free syngas with levels of tar lower than 1 mg/m<sup>3</sup>, of S-containing molecules lower than 1 ppm (as low as 60 ppb), of HCl lower than 100 ppm and of alkali compounds lower than a few ppm.<sup>26</sup>

### Chemical valorisation

The largest potential of converting waste material into an intermediary gas product *via* plasma gasification lies in the possibility of transforming the syngas into several different chemicals and fuels. Some of the most promising syngas-to-resources routes (see Figure 4) will be discussed in this section. More detailed information on the different syngas conversion paths and their corresponding syngas requirements can be found elsewhere.<sup>27,28</sup>

**Hydrogen Gas.** Depending on the material feed and the gasifying agent, the syngas leaving the gasification reactor can contain between 30 and 65 vol.% hydrogen gas. A gasification system aiming at producing hydrogen will have water vapour as (one of) the oxidising media (*i.e.* steam gasification) to maximise the production of hydrogen gas in the syngas composition. Similar to the steam methane reforming process, which is applied in 80-85% of the commercial hydrogen production plants, the production of pure hydrogen gas from syngas encompasses two major steps, downstream of the gasification unit; a water-gas shift (WGS) reaction and a gas separation step to isolate the hydrogen gas. The reaction mechanism of the WGS reaction is:



The WGS reaction generally proceeds in two parts with a high temperature (HTS) and low temperature water gas shift section (LTS), resulting in CO levels of 2-4 vol% and 0.2-0.5 vol%, respectively. The reaction is catalytically activated with a Fr/Cr catalyst between 350-500°C for the HTS and by a Cu/Zn catalyst around 150-300°C for the LTS. In both cases, the CO conversion increases with reaction temperature.

In the second step, the removal of CO<sub>2</sub> from the hydrogen rich H<sub>2</sub>/CO<sub>2</sub> gas mixture exiting the WGS reactor is most commonly done by the Rectisol process (absorption with cold methanol), by membrane separation or by adsorption. In the latter category, pressure swing adsorption (PSA) is widely used and can recover pure H<sub>2</sub> and pure CO<sub>2</sub> at high purity simultaneously, with high reliability and low capital cost.

The major consideration of H<sub>2</sub> production from syngas generated by biomass or waste gasification is that the amount of CO<sub>2</sub> emitted is larger than those from any other hydrogen production process. This puts an added emphasis on the need to develop carbon sequestration techniques that can handle large amounts of CO<sub>2</sub> before the widespread use of biomass and waste for H<sub>2</sub> production is implemented. While research on kinetic modelling<sup>29</sup> and the techno-economic feasibility<sup>30</sup> of biomass/waste gasification for hydrogen production is ongoing, no facilities have been erected yet. However, the gasification of heavy residue (1,650 tonnes/day) and subsequent H<sub>2</sub> production has been implemented by Lurgi and Air Liquide.<sup>31</sup>

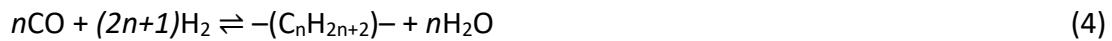
**Methanol.** The current methanol production is almost exclusively from syngas. The predominant catalytically-driven MeOH synthesis reactions with the main syngas components are:



The H<sub>2</sub>O by-product is recycled *via* the water-gas shift reaction (Equation 1). Combining the WGS reaction and the CO<sub>2</sub> hydrogenation reaction (Equation 3) gives the overall syngas-to-methanol reaction (Equation 2). In the forward direction, the reactions described by Equation 2 and 3 are exothermic and this heat of reaction should be efficiently removed to avoid overheating of the catalyst. The theoretical optimal stoichiometric number *S* (*i.e.* the ratio of (H<sub>2</sub>-CO<sub>2</sub>) over (CO+CO<sub>2</sub>)) for methanol formation is equal to or slightly above 2. The commercial methanol production in operation today is dominated by only a few processes (60% by Johnson Matthey and 27% by Lurgi)<sup>32</sup>, which all apply gas-phase methanol synthesis with copper-based (CuO/ZnO) catalysts, promoted by metal oxides (*e.g.* Al<sub>2</sub>O<sub>3</sub> or Cr<sub>2</sub>O<sub>3</sub>).

A relatively new technology for converting syngas to methanol is the liquid phase methanol (LPMEOH) process by Air Liquide.<sup>33</sup> In the LPMEOH reactor, the syngas is bubbled through an inert mineral oil, in which the catalyst is suspended in powder form. The main advantages of this process are efficient heat removal and temperature control by the mineral oil, a higher syngas conversion per pass than the gas-phase processes and the ability of converting low S-ratio syngas. Methanol is a very versatile molecule that can be reacted further to a wide range of derivatives (*e.g.* dimethyl ether (DME), formaldehyde, methyl tertiary butyl ether (MTBE), olefins, acetic acid, *etc.*). However, covering these processes and products does not fall within the scope of this paper. At present, almost all methanol synthesis is done with syngas produced from natural gas and only a small part from syngas produced by heavy residue/coal gasification. An innovative gasification-based technology has been developed by Enerkem, capable of converting waste to methanol. The gasification of the waste material is done in a bubbling fluidised bed reactor with oxygen and steam as gasification agents at 700-750°C. The company's first full-scale waste-to-biofuels and chemicals facility in Edmonton, Alberta (CA) produces 43,000 tonnes of methanol from 100,000 tonnes of RDF per year.<sup>34</sup>

**Fischer-Tropsch fuel.** The conversion of syngas produced from gasification of biomass and/or waste through the Fischer-Tropsch (FT) process has the ability to produce carbon-neutral and environmentally-friendly, clean liquid hydrocarbon fuels. The general reaction of the FT synthesis can be written as:



The heterogeneous catalytic process, typically operated at pressures between 25 and 40 bar, yields paraffins, olefins and oxygenated hydrocarbons with different carbon numbers. The choice between iron- or cobalt-based catalysts determines the type and length of the hydrocarbon chains. The FT process catalysed by cobalt takes place at temperatures between 220-250°C and yields a broad range of higher ( $\text{C}_{11+}$ ), waxy hydrocarbons because of the excellent CO hydrogenation activity of the cobalt-based catalysts. Fe-based catalysts, on the other hand, exhibit a selectivity towards lower olefins and require a higher temperature range (330-350°C). Syngas impurities (such as HCN, NH<sub>3</sub>, H<sub>2</sub>S, COS and tars) should be removed to concentrations (well) below 1ppm, because of the sensitivity of both catalyst types to poisoning. The synthetic crude oil obtained from the process can be further refined to transportation fuels (gasoline, diesel or jet fuel), petrochemicals, lubricants, *etc.*

The handful of commercial FT plants in the world use syngas produced by coal or from natural gas reforming. Their very large-scale (up to 4 million gallons of FT products/day) comes with huge challenges in terms of complexity and capital costs.

Consequently, over the past decade, the development of small-scale FT processes from carbon-neutral resources with inherent advantages compared to large-scale FT plants, such as modularity, reduced complexity, lower risk and smaller capital investment, has been triggered. A couple of companies with promising small-scale FT technologies, like Fulcrum Bioenergy and Velocys are looking to develop biomass/MSW-to-(jet)fuel plants in the near future (with biorefinery capacities of around 10-20 million gallons of biofuel/yr).<sup>35</sup> There is a vast interest in these developments, especially from airlines (including British Airways and Cathay Pacific Airways) who are looking for fuel alternatives to achieve the sector's target of 50% GHG reduction by 2050. Furthermore, the ambitious BioTfuel project has been proposed by Total, Thyssenkrupp and 4 other partners, aiming at transforming agricultural and forestry waste into 2<sup>nd</sup> generation biodiesel and biokerosene *via* torrefaction, gasification and FT synthesis, consecutively. The technical and economic feasibility of the process chain will be demonstrated by 2020 based on the results from two pilot units currently in operation in France; one in Venette for the upstream material processing and the other in Dunkirk for gasification and downstream syngas purification and conversion.<sup>36</sup>

**Ethanol.** The production of ethanol from syngas can be done catalytically or *via* a biochemical route. Even though the direct synthesis of syngas to EtOH or *via* methanol as an intermediate in the presence of catalysts is thermodynamically possible, the kinetics are too unfavourable for commercial operation. Efforts on the development and commercialisation of ethanol fermentation, on the other hand, are being intensified.

In this biochemical ethanol production path, clean, cooled syngas is converted into ethanol by acetogenic autotrophic micro-organisms under anaerobic conditions. The fermenter liquid collected from the reactor is then distilled and further cleaned to recover ethanol and the bottom fraction of the distillation is returned to the fermentation. This continuous process is operated at low temperature and pressure. More information on the enzymatic action of the microbes and the reaction mechanisms can be found in the review by Phillips *et al.*<sup>37</sup> This syngas valorisation scenario has been demonstrated at the pre-industrial-scale facility of Ineos Bio and New Planet BioEnergy in Vero Beach, Florida (US). The plant processes 300 dry tonnes per day (by 2 units) of vegetative, agriculture and yard waste into 8 million gallons/yr of cellulosic ethanol. Additionally, 6 MW gross power is generated with a steam turbine from the sensible heat of the syngas leaving the gasifier.<sup>38</sup> Another company that is bringing this technology to market is LanzaTech. Their proprietary microbes have the ability to consume hydrogen-free CO-only gas streams, making steel mill waste gases (which contributes to 5-7% of global CO<sub>2</sub> emissions) a very suitable feedstock. Besides ethanol, the company also targets the increased production of

chemical co-products, especially 2,3-butanediol, which can be converted to butadiene. After scale-up, from pilot-scale to 3 pre-commercial (100,000 gallon/yr.) demonstration plants (of which one still in operation), the construction of a commercial-scale facility in the port of Gent (BE) is underway. Upon completion of this Steelanol project by 2019, the steel waste gas stream of ArcelorMittal, mainly comprising of CO and CO<sub>2</sub> at 100,000 Nm<sup>3</sup>/h, will be processed into 80 million litres of ethanol/yr (about 20 million gallons/yr).<sup>39</sup>

**Bio-synthetic natural gas (bioSNG).** The synthesis of syngas to biomethane or bioSNG can deliver a sustainable alternative to natural gas. For bio-methane as the desired end product of the waste conversion process chain, syngas with a high methane content is advantageous. The gasification process and parameters (*e.g.* T < 900°C to limit CH<sub>4</sub> destruction) can be selected as such to accommodate this favoured syngas characteristic. Nevertheless, the major part of the CH<sub>4</sub> is synthesised from CO and CO<sub>2</sub> with H<sub>2</sub> *via* the methanation reactions:



These reactions are favoured at elevated pressures and low temperatures and are typically catalysed with nickel. They are highly exothermic; therefore, the process design needs to be adapted for heat removal. A comprehensive body of information on methanation fundamentals, concepts and reactor configurations can be found elsewhere.<sup>40</sup> A benchmark facility for SNG production following plasma gasification of biomass/waste has been realised by Advanced Plasma Power in Swindon (UK), which will be discussed elsewhere in this issue.<sup>41</sup> Two other interesting bioSNG production projects with syngas produced from biomass waste gasification are the commercial GoBiGas plant by Göteborg Energi in Göteborg (SE) and the pilot-scale GAYA plant by Engie in Saint Fons (FR) with outputs of 20 MW (from 32 MW wood pellets) and 100 kW of bio-methane, respectively.

**Mixed alcohols.** The mixed alcohols synthesis or higher alcohol synthesis (HAS) is very comparable to the Fischer-Tropsch process. FT-catalysts are often modified by adding alkali metals to promote the production of methanol, ethanol, propanol, butanols and some heavier alcohols. The main process differences are the required H<sub>2</sub>/CO ratio of 1.0-1.2, and the specific syngas requirements depending on the catalysts. The process of mixed alcohols production from syngas is gaining increased attention, but no industrial developments have been realised yet. The fuel additives market can be an interesting application for the HAS products. The company Standard Alcohol<sup>42</sup>, for example, has developed and is in the process of commercialising a promising octane-

enhancing solution, called i-Octane+®, produced from their patented Mixed Alcohols Technology™.

## Conclusions

In Europe, the transition towards a sustainable, carbon-neutral society has been initiated. With the goal of mitigating the detrimental effects of climate change, the EU is actively making efforts to decrease its greenhouse gas emissions, with success. The decrease in fossil fuel use and a shift to renewable electricity generation are positive developments towards a fossil-free future. However, in the coming decades, waste generation and increased demand for energy and resources following the sharply rising world population growth and increasing wealth will put even bigger burdens on the environment and the climate. In order to moderate this enormous threat, the development of disruptive, alternative technologies needs to be accelerated and expanded over all sectors of society. Biomass and waste can play an important role in this renewable revolution as abundant CO<sub>2</sub>-neutral resources for products and processes relying on carbon-containing energy carriers and feedstock. In this respect, gasification is a promising technology because of its ability to convert the solid waste material into an intermediary gaseous product, called syngas (mainly CO and H<sub>2</sub>), that can be used for a wide array of energetic or chemical end applications. The syngas processing technologies set stringent syngas specifications in terms of composition and impurity levels, making prior syngas cleaning of crucial importance in the process chain. The most difficult group of contaminants are tars. Nevertheless, the combination of thermal plasma with gasification can effectively crack tars, while offering several other process advantages. Therefore, plasma gasification is proposed as the thermochemical technology of choice to convert biomass and waste to ‘tar-free’ syngas for further processing.

This paper discusses plasma gasification technology and the downstream syngas valorisation routes for advanced conversion of biomass and waste to resources (chemicals, fuels, electricity and heat). The energetic valorisation of syngas is slowly evolving from burning the syngas in a boiler or a gas engine towards gas turbines and fuel cells. In addition to a more efficient electricity (and heat) generation, these technologies can also be integrated with the gasification process in a better way.

Besides converting the chemical energy of syngas to electricity, it can also be transformed into other energy carriers, such as (transportation) fuels and chemicals. The third Section of this paper presents the technology and most recent developments of hydrogen gas, methanol, Fischer-Tropsch fuel, ethanol, bioSNG, and mixed alcohols production form syngas. Most of these technologies have already been developed for syngas produced from coal and are now being adapted and

scaled-down for smaller syngas quantities produced from biomass or waste. A lot of interest is directed towards the “second generation” Fischer-Tropsch processes for producing jet fuel from biomass/waste. The majority of the valorisation routes for syngas from renewable resources have one or more demonstration or commercial facilities in operation with an outlook to several more in the near future. Only a hydrogen production facility from bio-based syngas still has to be developed.

Besides (academic) progress in modifying high performant electricity generating devices (especially gas turbines and fuel cells) to increase the energy conversion efficiency for syngas operation and optimising the selectivity and activity of catalysts, big advances are still to be made in syngas cleaning technologies. The conventional techniques for removing impurities from large quantities of syngas produced from coal are not (yet) adapted to smaller syngas flows produced from waste with a more complex mix of unwanted components. There is also a huge potential for (collaboration between) universities, research institutes and industry to bridge the gap between research innovations and market-ready technologies at industrial scale through thought-out scale-up with pilot and demonstration-scale units. With the current interest, invested effort and progress in the production and conversion of bio-based syngas, the supply of energy and material resources from biomass/waste promises to play an important role in the sustainable carbon-neutral future.

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# **ENERGETIC UTILISATION OF HIGH CALORIFIC RESIDUES FROM LANDFILL MINING**

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## **Introduction and explanation of terms**

Increasing substitution of fossil fuels like coal, crude oil and natural gas raises the demand for secondary raw materials (like plastics), meaning that the discovery of new potential raw material deposits is gaining significance for the economic sectors concerned. From a waste disposal point of view, the main focus here is on “urban mining”, *i.e.* exploiting anthropogenic deposits (such as cities) as raw material mines, and on “landfill mining”. Landfill mining involves the systematic excavation of previously dumped waste at landfill sites complying with applicable labour and neighbourhood protection requirements (fire and explosion hazards, for example). This can mean the remediation or securing of a site as well as mining of a whole landfill. While remediation or securing reduces the potential for hazards and pollutants of a landfill site to the protected goods, landfill mining involves processing the excavated waste for recycling or energy recovery. The non-recoverable fraction (*e.g.*, fine fraction) is compacted and returned to a landfill site, so that its total volume is considerably reduced.<sup>1</sup>

Arguments for past landfill mining projects included the extraction of compost or soil, gaining or reducing landfill volumes, the redevelopment of old sites, groundwater protection or need for industrial space.<sup>2-4</sup> However, the shift in waste management towards resource management has also made the recovery of potential secondary raw materials from waste and landfills increasingly important. In addition to ferrous and non-ferrous metals, secondary raw materials include especially plastics and other high-calorific fractions (paper, textiles *etc.*). Fossil fuels could be substituted by potential thermal utilisation of secondary raw materials, even in co-incineration plants, say, in cement plants. Emissions and costs (for transportation *etc.*) could be reduced or saved that way.

Regular landfill mining, however, entails many difficulties regarding location, technology, materials etc. The thorough analysis of a site is essential for assessing the yield of recyclable materials. Since usually only records and data on past compositions of waste and the like are available, drillings and prospecting, subsequent sorting and chemical analyses of the extracted materials are required to obtain more specific information on the landfill body. Investigations of this type are expensive, time-consuming and hard to carry out, though, and they will describe only a minor part of the materials deposited in the landfill so that the profound heterogeneity of waste material prevents a reliable assessment of the entire landfill.<sup>5</sup> The economic viability of a landfill mining operation, which depends on the amount of recyclable materials that can be recovered, requires a method to assess the potential gain in raw materials vs. the mining costs. Also, a mining project must comply with applicable legal regulations, although there are few laws that specifically regulate landfill mining.<sup>6</sup> Even more difficulties arise in the matters of sorting technology and recycling due to many years of deposition impairing the quality of recovered raw materials. The quality of high-calorific fractions in particular has to meet specific criteria, such as calorific value or the concentration of chlorine and heavy metals, to be utilised for energy recovery in Austrian co-incineration plants.

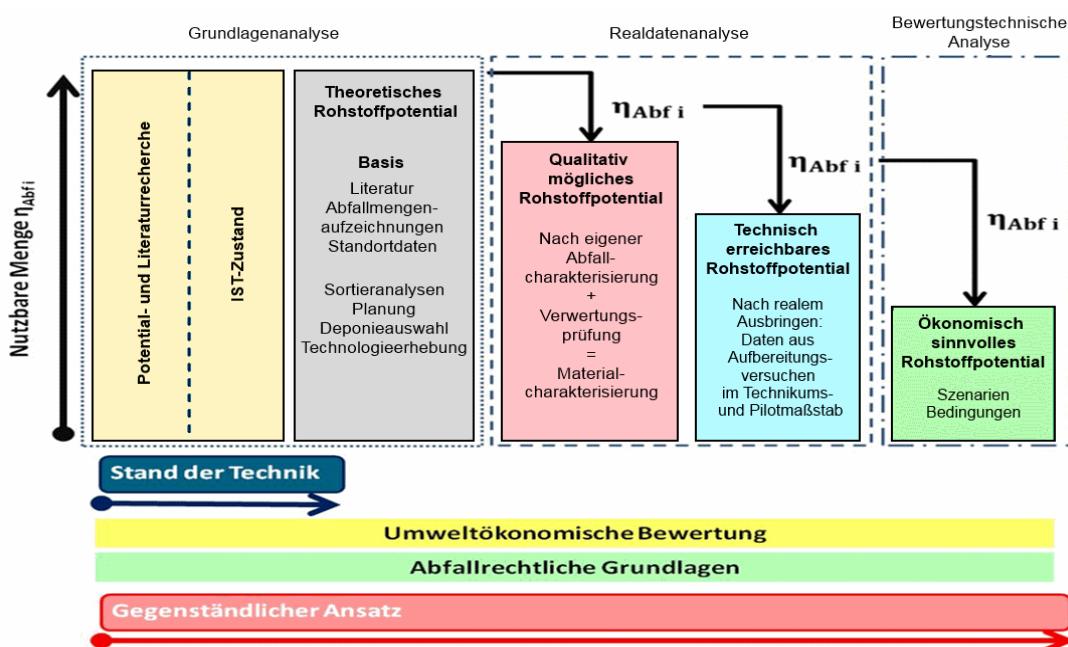
In addition to general descriptions, this article describes relevant results with regard to high-calorific residues from the “Landfill Mining Austria - Pilot Region Styria” project, LAMIS for short, in more detail. The project has been funded by the Austrian Research Promotion Agency (Forschungsfördergesellschaft, FFG). Both sites will be described that have been extensively investigated, and selected results will be presented, such as processing of the mined waste in mobile units.

## **LAMIS - Landfill Mining Austria - Pilot Region Styria<sup>6</sup>**

The LAMIS project has been initiated by the Chair of Waste Processing Technology and Waste Management at the Montanuniversitaet Leoben, jointly with various industrial partners and the Federal State of Styria, in response to the previously discussed tasks of landfill mining relating to the economic and ecological feasibility of the project and the development of basic data and approaches. The main objective of the project was the advancement and medium-term exploitation of findings from basic research in landfill mining to facilitate future applications in landfill mining. This project included establishing environmental and legal assessment methods for landfill mining projects, deriving appropriate evaluation tools and developing an economic model for decision-making. In summary, the following objectives have been achieved in this project:

- Obtaining information on the type, quantity and composition of deposited waste in Styrian landfills;
- investigating and presenting the theoretical potential of selected landfills in terms of raw materials;
- defining one or more locations suitable for mining;
- surveying established and proven technology and investigating its suitability for landfill mining;
- obtaining representative samples and characterising the deposited material in terms of quantity and quality;
- assessing the actual waste composition and its impact on sorting technology;
- illustrating the actually utilisable content and assessing the quantities and the quality of application;
- elaborating commercially viable recycling channels and illustrating potential customers and achievable revenues in one model;
- deriving principles and proposals for amending and modifying waste legislation from the results of these investigations, to facilitate the future utilisation of old landfills as resource deposits.

The project was carried out in three stages, as shown in Figure 1: elementary analysis, real data analysis and technical valuation analysis. Due to its geological, environmental and waste management conditions, *i.e.* its variety of waste treatment and landfill technologies, the Styrian region offers many opportunities (like the proximity of plants and technologies) needed to perform this extensive basic project.



**Figure 1:** Concept diagram of the Landfill Mining Austria - Pilot region Styria

The mass-waste landfills Hollabrunn (H) in Lower Austria and Allerheiligen im Mürztal (A) in Styria, selected as part of the LAMIS project, are described briefly in the following sub chapters.

### **Hollabrunn Landfill (Lower Austria)<sup>7</sup>**

The Hollabrunn landfill is a mass-waste landfill, approved by the water authorities in December 1982. This landfill site covers about 78,000 m<sup>2</sup>. It is divided into four sections. The total approved capacity is 950,000 m<sup>3</sup>, only 680,000 m<sup>3</sup> of which have been developed and filled. In May 2013, drilling was carried out on the VA02 backfill section in which waste has been deposited between 1990 and 2000. Additional drilling work was carried out in May/June 2014 on the VA03 backfill section of this landfill site (the 1990-2000 depositing period). The excavated material was transferred to the mobile processing test in which a high-calorific fraction could be produced. A detailed description of the mobile test and the sampling of the individual samples to be analysed is given below.

### **Allerheiligen im Mürztal landfill site (Styria)<sup>7</sup>**

This landfill was commissioned in 1979. The approved capacity is 543,200 m<sup>3</sup> on a deposit area of about 10 ha. The remaining capacity of the landfill was about 77,108 m<sup>3</sup> as of 1 January 2015. Until 2003, mainly mechanical-biologically (MB) pre-treated municipal waste and untreated bulky waste have been deposited on four filling sections. As part of the MB treatment, the municipal waste delivered has been crushed, ferrous metals have been sorted out, and screened (screen section 80 mm). The screen overflow has been brought straight back to the landfill, together with untreated bulky waste. The screen passage has been mixed with sewage sludge, biologically treated and finally deposited as MBA compost. For investigative purposes, material from sections 1 and 2 was excavated by means of prospecting (deposits from 1979 to 1988). Part of the waste was sorted by hand. The other part was used for the mobile processing test that also produced a high-calorific fraction. A description of the mobile test and the sampling of individual samples produced for chemical analysis is also given below.

## **Fundamentals of WtE**

As shown in Figure 2, WtE-plants can be divided into different systems:

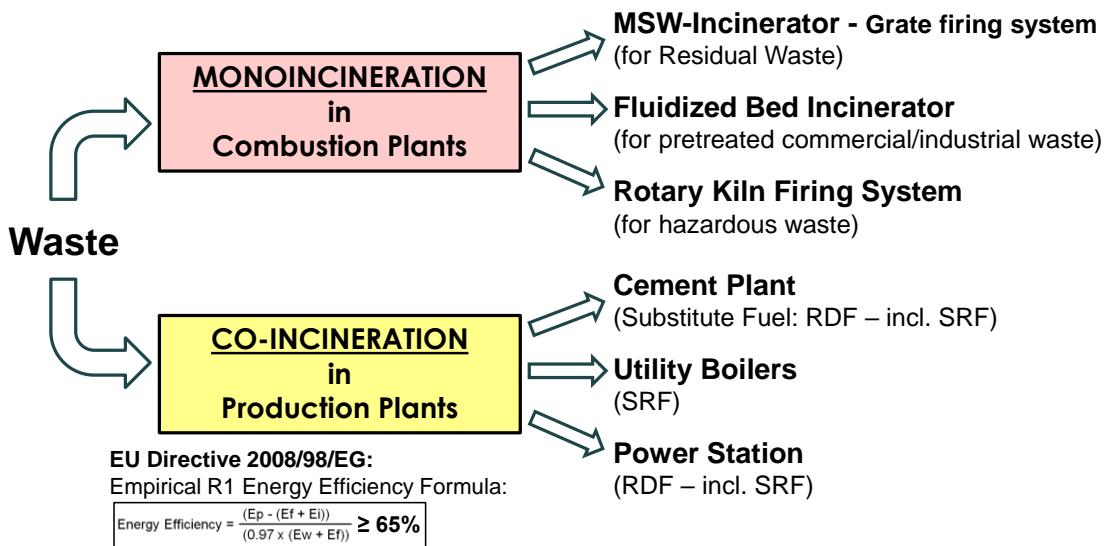


Figure 2: Mono-incineration and Co-incineration in WtE-systems<sup>13</sup>

In MONO-INCINERATION plants, different types of materials (household, commercial, municipal, industrial and hazardous wastes) are burnt directly (or after modest pretreatment only) in public interest and welfare. In CO-INCINERATION plants, substitute fuels (like RDF and SRF) are utilised to supply energy for a production process. The Input-quality of mixed Municipal Solid Waste (MSW) mainly depends on the origin (source) of generation, the Waste Management system applied (*i.e.*: collection system, waste separation, *etc.*) and the type of waste pre-treatment or processing done for material recycling and/or energy recovery.<sup>13</sup> For autonomous, self-supporting combustion without addition of external support fuel (*e.g.* coal, oil), a minimum net calorific value between  $H_u \geq 3$  [MJ/kgos] (*i.e.* for fluidised bed incinerator) and  $H_u \geq 5$  [MJ/kgos] (*i.e.* for grate-firing systems) is necessary. It also has to be mentioned, that waste is a “difficult fuel”, due to the presence of unwanted materials like chlorine that may cause corrosion of the WtE-plant.<sup>13</sup> Depending on local and regional requirements at the site of the WtE-plant, different strategies are applied for the recovery of energy from waste, like:

- Exclusive electric power generation;
- Exclusive heat generation;
- Exclusive production of process steam and;
- Combined heat & power generation (CHP) for district heating & cooling.<sup>13</sup>

Before a plant operator is ready to opt for (co-)incineration of waste fuel, the technologies that are applied have to be checked and fundamental conditions must be fulfilled:

- (inter)national legal compliance, but also legal validity of the operating license;

- a guarantee of supply and of sufficient quantities with the required chemical and physical quality of waste fuel;
- public acceptance for new and modern technological solutions and;
- no negative quality changes in the products allowed.<sup>13</sup>

### **Alternative WtE processes like Pyrolysis, Gasification etc.<sup>14</sup>**

Considering the worldwide number of installations as well as their capacity, the most dominating treatment method for waste is incineration. Currently, 225 million tonnes of waste are treated in 2,200 facilities. As confirmed by the scientific and practical international experience, waste incineration can be considered as the state of the art in the treatment of MIXED municipal waste. None of the so-called alternative processes (such as gasification and plasma) has proven comparable performance and flexibility under comparable conditions. Alternative thermal processes can only be economically successful under specific circumstances and requirements, which are: (1) Compliance with legal requirements (e.g. melting processes in Japan); (2) Achievement of specific product properties (e.g. vitrified slag, low contaminant content); and (3) Treatment of special fractions (e.g. highly toxic materials, materials containing chloride, fractions with very low calorific value like contaminated soils). There are currently no alternative thermal processes available that can be used to treat mixed municipal solid waste under comparable technical, economic and ecological conditions as is the case for waste incineration. Due to the higher complexity of alternative processes, this can also not be expected in the future. Therefore, treatment of mixed municipal solid waste should generally be reserved to the incineration processes developed and internationally approved for this application. Further detailed data and information is summarised in Quicker *et al.*<sup>14</sup>

## **Case Study**

This section discusses theoretical and practical investigations at the selected landfill sites in more detail.

### **Theoretical investigations**

**Energy potential of waste deposited in landfills.**<sup>6</sup> One objective of the landfill mining project was to investigate the option of energetic recovery of deposited waste. The first step was to assess the amount of plastic waste or other high-calorific fractions like paper, wood and textiles, that should be present in the landfill sites as part of an actual status survey and theoretical rating of potential resources.

**Identifying the deposited amounts (actual status survey).**<sup>6</sup> The first step in estimating the energetic potential of Styrian landfills was to determine the amount of waste per fraction. Ten bulk waste landfills were examined in total, selected by

volume, the expected potential raw materials and sufficient information on the deposit. In total, a theoretical amount of approx. 4,700,000 tonnes of potentially recyclable waste could be assessed. As shown in Figure 3, the content in the combustible fraction is approx. 65% or 3,050,000 tonnes. In relation to the total volume, approximately 31% or 1,480,000 tonnes are accounted for by the paper, cardboard and packaging fraction, approximately 14% or 660,000 tonnes by textiles and hygiene products, about 14% or 640,000 tonnes by plastics, about 4% or 200,000 tonnes by composites and about 2% or 70,000 tonnes by wood, leather and rubber. The inert fraction, consisting of the glass and metal-containing waste fractions, amounts to a total of about 13% or 640,000 tonnes. The largest amount of individual fractions is comprised of mineral waste, *i.e.* the fine fraction, with about 22% or 1,020,000 tonnes.

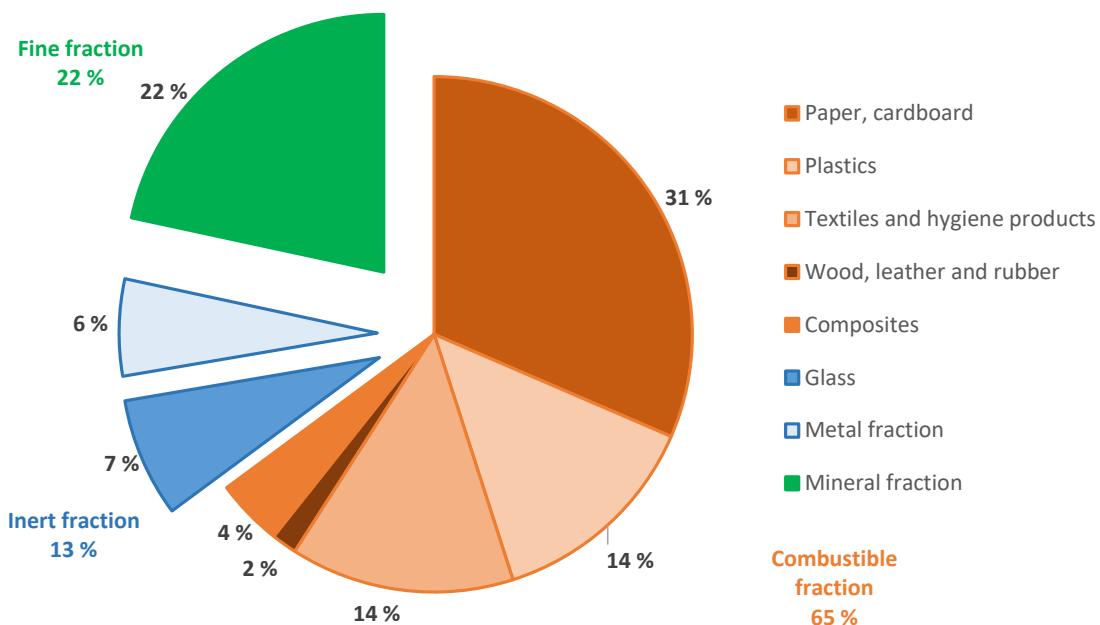
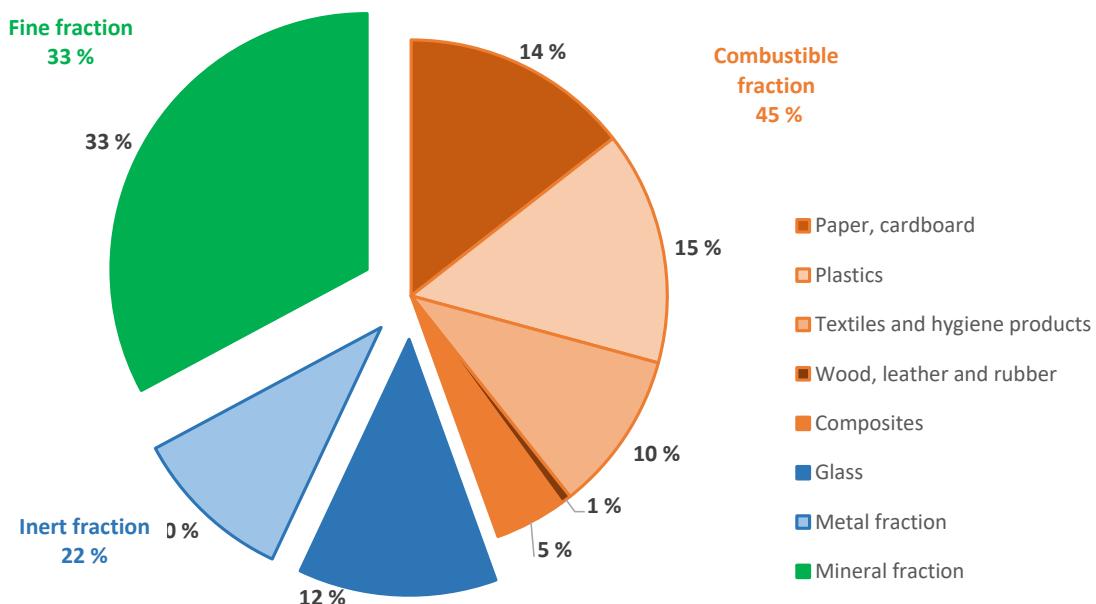


Figure 3: Distribution of the deposited fractions of selected Styrian mass-waste landfills

**Theoretical assessment of the potential raw materials of selected Styrian landfills.<sup>6</sup>** The assessment of the theoretical potential of raw materials - that theoretically available amount of recoverable material taking biochemical degradation processes into account, including the gas prognosis model of Tabasaran and Rettenberger<sup>8</sup> - resulted in an amount of about 3,910,000 tonnes of original substance (OS) of potential recyclables in the selected Styrian landfill sites. Taking the specific water content of the individual fractions into account, results in a total potential resource of around 2,750,000 tonnes relative to the dry content of the waste. As shown in Figure 4, the energetically recoverable potential raw material is approx. 45% or 1,220,000 tonnes, 15% of which are plastics - the largest share.

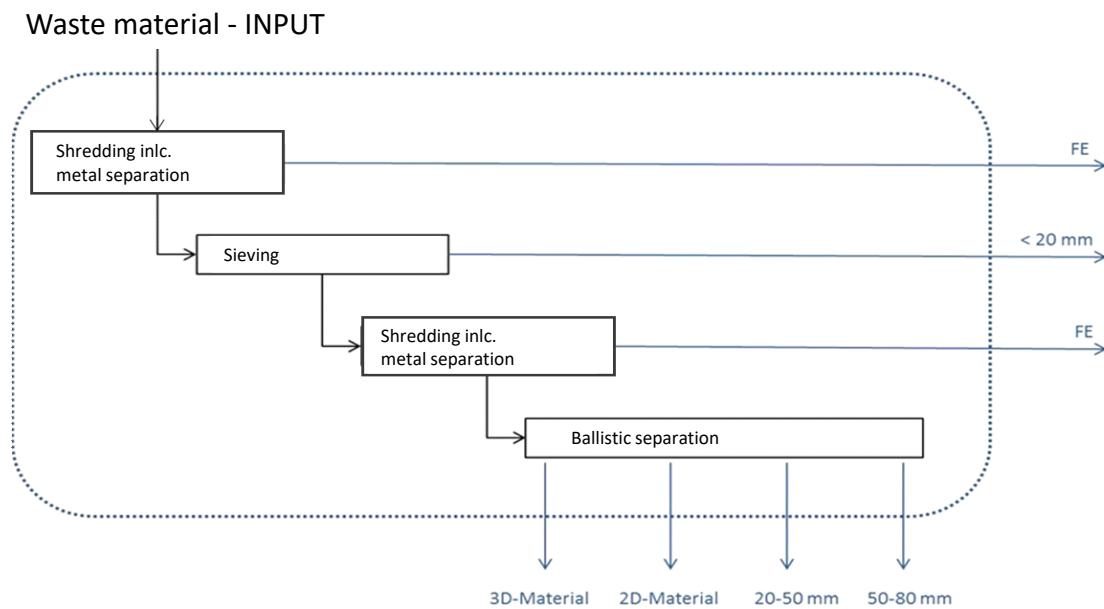


**Figure 4:** Allocation of the theoretical potential of raw material from selected Styrian mass-waste landfills

### Practical research - mobile processing test<sup>7</sup>

In addition to drilling, sampling and sorting for characterising the deposited material, a mobile processing test was performed with material extracted from VA03 at the Hollabrunn landfill site and from filling sections 1 and 2 of the Allerheiligen landfill site. In total 49 tonnes from Hollabrunn and 42 tonnes from Allerheiligen were fed to a mobile processing plant with single-shaft shredders, a drum screen (mesh size 20 mm) and a ballistic separator. The input materials were separately crushed and iron was removed by an overbelt magnet. The remaining waste flow was fed to the drum screen by a wheel loader so that fine fractions could be separated (approximately 59–62% by weight). The sieve overflow > 20 mm was another time crushed, metals were separated and then directly fed into the ballistic separator. The schematic diagram of the processing test is shown in Figure 5.

Due to the choice of processing steps, the excavated material could be divided into six fractions: iron, fine fraction (< 20 mm), 3D material, 2D material, 20-50 mm and 50-80 mm. The 2D material (about 6–13% by weight) consisted mainly of plastics, textiles and wood.



**Figure 5:** Diagram of a mobile processing test

## Results<sup>7</sup>

After completing the mobile test, four individual samples of 10 l (P1-P4) per landfill site were produced pursuant to ÖNORM S 2127<sup>9</sup> for chemically characterising the 2D material and the high-calorific fraction obtained. Chemical analyses of these samples resulted in the following (see Table 1).

**Table 1:** Analysis results of the high-calorific fraction of the Hollabrunn and Allerheiligen landfill sites obtained in the mobile processing test

Parameter	Unit	Hollabrunn				Allerheiligen			
		P1	P2	P3	P4	P1	P2	P3	P4
Heat value	MJ/kg DM	22,500	26,000	19,700	22,400	18,800	16,900	17,400	15,700
Antimony	mg/kg DM	17	11	9.3	22	17	19	26	250
Arsenic	mg/kg DM	4.1	6.2	7.6	7	17	22	13	16
Lead	mg/kg DM	200	440	120	230	510	540	830	700
Cadmium	mg/kg DM	3.1	5.1	14	14	4.7	10	30	10
Chrome	mg/kg DM	62	130	87	97	250	230	330	240
Cobalt	mg/kg DM	7.7	5.9	8.2	5.1	14	22	14	17
Nickel	mg/kg DM	24	36	74	26	65	97	65	94
Mercury	mg/kg DM	0.6	0.36	0.25	0.25	1.1	0.75	1.2	1.4

## Utilisation opportunities and limitations<sup>7</sup>

**Legal regulations applicable in Austria on the energy recovery of the high-calorific fraction in co-incineration plants.** The incineration of waste in co-incineration plants (meaning three types: cement plant, power plant and others, cf. Figure 2) is regulated by the Waste Incineration Regulation 2002 (BGBI. II No. 389/2002). Depending on the type of co-incineration plant, the AVV 2002 stipulates that different pollutant limits have to be observed with regard to the input material. These are shown in Table 2. Compliance with the limits is verified pursuant to the provisions of the Waste Incineration Regulation 2002. If more than five analysis results are available, the median or 80-percentile of these results shall be regarded as the assessment value. The limit value shall be deemed met if the assessment value does not exceed the limit value. If less than five analysis results are available, the arithmetic mean of these results shall be used as the assessment value. In this case, the limit value shall be deemed met if the assessment value does not exceed the limit value applicable to the median and if each individual measurement result complies with the limit value applicable to the 80 percentile.

**Table 2:** Pollutant limits for the use of waste in co-incineration plants (BGBI. II No. 389/2002)<sup>10</sup>

Parameter	Limits for co incineration plants [mg / MJ DM]					
	Cement plants		Power stations		Other facilities	
	Median	80s percentile	Median ≤ 15% *	80s percentile ≤ 15% *	Median	80s percentile
Antimony	7	10	7	10	7	10
Arsenic	2	3	2	3	1	1.5
Lead	20	36	15	27	15	27
Cadmium	0.23	0.46	0.17	0.34	0.17	0.34
Chrome	25	37	19	28	19	28
Cobalt	1.5	2.7	0.9	1.6	0.9	1.6
Nickel	10	18	7	12	7	12
Mercury	0.075	0.15	0.075	0.15	0.075	0.15

\* Percentage content of the fuel heat capacity from the incineration of waste in the total fuel heat capacity

**Utilisation of the high-calorific fraction in co-incineration plants.** The respective assessment values from the results of the analyses (see Table 1) were calculated separately for each landfill site pursuant to AVV 2002 for comparing the results of the 2D and high-calorific fractions obtained from the mobile processing tests. These are shown in Table 3.

The comparison of the limit values in Table 2 and the assessment values listed in Table 3 and Table 4 shows how the current legislation stipulates that neither the 2D or the high-calorific fraction from Hollabrunn nor the 2D fraction from Allerheiligen may be energetically utilised without additional processing, *i.e.* by feeding straight into a co-incineration plant. In the case of the Hollabrunn landfill site, an excess of the cadmium limit value can be observed regarding any utilisation in cement, power or other co-incineration plants. The high-calorific fraction from Allerheiligen also needs to take increased antimony, arsenic, lead and cobalt contents into account.

**Table 3:** Calorific value related values (mg/MJ DM) of the high calorific fraction from Hollabrunn (mobile processing test)

Parameter	P1	P2	P3	P4	Average
	mg/MJ DM				
Antimony	0.8	0.4	0.5	1.0	0.7
Arsenic	0.2	0.2	0.4	0.3	0.3
Lead	9	17	6	10	11
Cadmium	0.14	0.20	<b>0.71</b>	<b>0.63</b>	<b>0.42</b>
Chrome	3	5	4	4	4
Cobalt	0.3	0.2	0.4	0.2	0.3
Nickel	1	1	4	1	2
Mercury	0.030	0.010	0.010	0.010	0.015

Note: Bold numbers indicate excess of the limit values

**Table 4:** Calorific value related values (mg/MJ TS) of the high calorific fraction from Allerheiligen (mobile processing test)

Parameter	P1	P2	P3	P4	Average
	mg/MJ TS				
Antimony	0.9	1.1	1.5	15.9	4.9
Arsenic	0.9	1.3	0.8	1.0	1.0
Lead	<b>27</b>	<b>32</b>	<b>48</b>	<b>45</b>	<b>38</b>
Cadmium	0.25	<b>0.59</b>	<b>1.72</b>	<b>0.64</b>	<b>0.80</b>
Chrome	13	14	19	15	15
Cobalt	0.7	1.3	0.8	1.1	<b>1.0</b>
Nickel	3	6	4	6	5
Mercury	0.060	0.040	0.070	0.090	0.065

Note: Bold numbers indicate excess of the limit values

### Cleansing tests<sup>11</sup>

The surveys discussed above demonstrate that the heavy metal contents of the high-calorific fractions of the Hollabrunn and Allerheiligen landfills exceed the limit values

for energy recovery in Austrian co-incineration plants. It is assumed, however, that the elevated heavy metal contents can be traced back to impurities adhering to the fractions (defined as a fine fraction < 20 mm) and are not inherent to the high-calorific fraction proper. This assumption was confirmed by chemical analyses and cleansing tests on the fractions. The following questions are to be addressed:<sup>12</sup>

- How high is the content of (water-soluble) impurities/adhesions?
- How high is the heavy metal load in the uncleansed/cleansed state?
- Can heavy metal loads be reduced by removing impurities/adhesions?

Again, the individual or retained samples of the 2D or the high-calorific fraction (P1-P4) available for each incoming material were sampled for the cleansing tests and combined into a mixed sample. Each mixed sample was then subjected to two cleansing cycles. The cleansed material and the sludge were separated, dried, weighed and chemically analysed. In addition to the parameters of calorific value, TOC and TC, combustion-relevant parameters were determined (heavy metal contents, chlorine, sulphur, ash content and loss on ignition - see Table 5). The analytical methods discussed above were used for the analysis. Weighing the fractions obtained by cleansing showed that about 24% by weight of the high-calorific fraction (uncleansed) of Hollabrunn consist of impurities. In the case of the high-calorific fraction of the material from Allerheiligen, the content of impurities is about 44% by weight.<sup>12</sup> The lower content of impurities in the Hollabrunn sample is attributable to a lack of waste pre-treatment process before landfilling and as a consequence thereof the lower content on fine materials (*i.e.* particles).

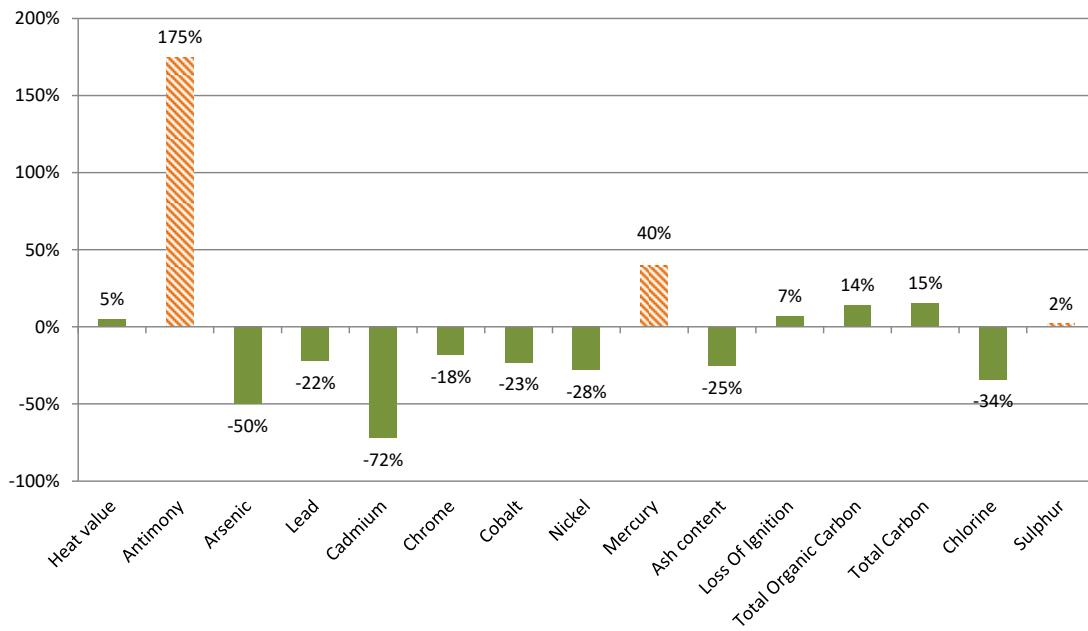
For assessing the effectiveness of cleansing with regard to reducing the heavy metal content, the results of the chemical analysis of the cleansed material are compared with those of the uncleansed mixed sample MP1-P4. The results of this comparison are shown in Figure 6 and Figure 7 for better overview. Adverse changes due to the cleansing process (like increasing the heavy metal content) are shown in dashed lines. The results for the sludge produced during cleansing are also shown in Table 5.

The results show that removing the impurities from the high-calorific fractions from Hollabrunn and Allerheiligen led to a gain in calorific value. The higher the gain is, the more the respective material was contaminated before cleansing (change to Allerheiligen > Hollabrunn). In addition, the ash content of the fractions could be reduced and, as a result, the material's loss on ignition increased. It is also evident that the cleansing process is essentially beneficial in terms of reducing heavy metal pollution. This can be observed most clearly when comparing the cleansed and uncleansed high-calorific fractions from Allerheiligen (*cf.* Figure 7). The adverse

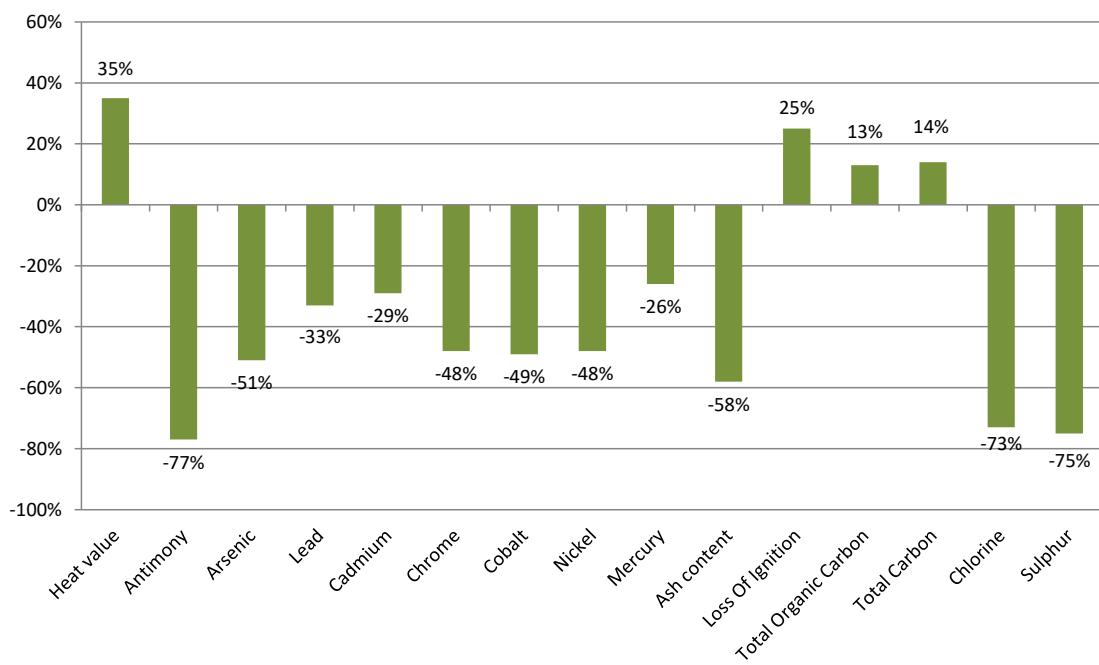
**Table 5:** Results of the cleansing test of the calorific fraction from Hollabrunn and Allerheiligen

Parameter	Unit	Hollabrunn			Allerheiligen		
		Cleansed sample	Sludge	Change	Cleansed sample	Sludge	Change
Mass amount		74.6%	24.3%	24.3%	55.3%	43.6%	43.6%
Heat value	MJ/kg DM	26,300	4,700	+ 5%	27,200	4,900	+ 35%
Antimony	mg/kg DM	33	14	+ 175%	15	22	- 77%
Arsenic	mg/kg DM	2.7	8.6	- 50%	6.9	29	- 51%
Lead	mg/kg DM	180	480	- 22%	380	1120	- 33%
Cadmium	mg/kg DM	3.4	3.5	- 72%	8.5	7.9	- 29%
Chrome	mg/kg DM	68	250	- 18%	130	430	- 48%
Cobalt	mg/kg DM	4.6	15	- 23%	7.6	36	- 49%
Nickel	mg/kg DM	28	79	- 28%	39	180	- 48%
Mercury	mg/kg DM	0.35	0.99	- 40%	0.89	2.2	- 26%
Ash content	%	16.2	64.74	- 25%	16.61	67.86	- 58%
Loss on ignition	%	81.5	27.5	+ 7%	80.7	27.2	+ 25%
TOC	%	56.5	32.6	+ 14%	52.3	32.5	+ 13%
TC	%	57	34.1	+ 15%	52.8	33.3	+ 14%
Chlorine	mg/kg DM	6,650	620	- 34%	4,070	810	- 73%
Sulphur	mg/kg DM	2,250	2,010	+ 2%	1,780	5,050	- 75%

N. 1: Strongly divergent results are due to the heterogeneity of the waste



**Figure 6:** Changes of the calorific fraction from Hollabrunn by the cleansing process, dashed: adverse effect



**Figure 7:** Changes of the calorific fraction from Allerheiligen by the cleansing process

effects (outliers) of the fraction from Hollabrunn (*cf.* Figure 6) for antimony and mercury can best be explained by the heterogeneity of the sampled materials and the associated problem of representative sampling. The assumption that heavy metals are mainly present in the impurities adhering to the material is generally confirmed. Wet screening therefore seems to be a sensible way of improving the quality of the resulting output flows.

## Conclusions

The results of the current paper indicate a high content of fine fraction of 59 – 62 wt% in landfilled waste. The coarse fraction, easy to separate by mechanical means, contains the high-calorific fraction that constitutes about 6–13 wt% of the total fraction. Applicable Austrian regulations do not permit energy recovery in co-incineration plants for the processed high-calorific fraction recovered from the two landfill sites discussed, but utilisation in mono-incineration plants (i. e. plants that are not subject to any statutory quality requirements for input materials) is possible. The results from the cleansing tests show that removing the impurities and fines from the high-calorific fractions raised the calorific value and reduced the ash content. In addition, the cleansing process reduced the concentration of heavy metals. Since the fine fraction is the main part of a landfill site, the main difficulty here is how to find appropriate disposal paths.

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# **THE TECHNO-ECONOMIC VIABILITY OF UPCYCLING RESIDUAL WASTE INTO ADVANCED BIOFUELS: A COMMERCIAL DEMONSTRATION PLANT CASE STUDY USING GASPLASMA® TECHNOLOGY TO CONVERT SYNGAS TO BioSNG**

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## **Introduction**

Advanced Plasma Power (APP) is collaborating with Cadent and Progressive Energy to demonstrate the technical and commercial feasibility of Bio-substitute natural gas (BioSNG) production from waste residues. The partners have constructed and operated a demonstration plant facility that has successfully shown BioSNG production. The results from this facility have validated the technical and commercial models of the process and enabled the development of the first commercial BioSNG plant which will deliver gas to grid in 2018.

The approach could help solve a major issue facing governments, energy suppliers, policy makers and consumer groups across the world: how to decarbonise (*i.e.* reduce the greenhouse gas emissions impact of) heat and heavy goods transport in a sustainable way through the development of technology that is commercially viable, affordable, and acceptable to consumers. It provides an economic and innovative route to decarbonise energy, while making the best use of the existing gas networks.

The commercial demonstration plant is based on the Gasplasma® technology, which combines a standard fluidised bed gasifier with a direct current plasma converter to produce high quality synthesis gas from waste. The Gasplasma® technology has a range of applications but the production of BioSNG is the first to be commercialised.

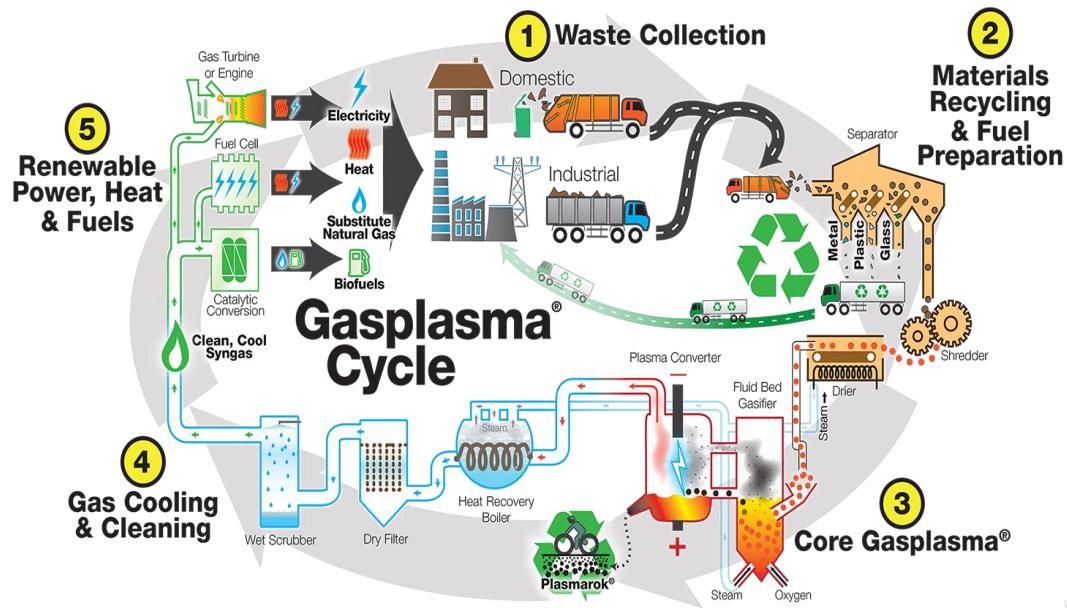


Figure 1: The Gasplasma® Cycle

The benefits from this process route include contributing to the acceleration of a low carbon economy, the decarbonisation of heat and transport, a marked reduction of waste volumes going to landfill, and a new pathway for valorising waste mined from landfill. The economic benefits include new investment opportunities, which will provide affordable energy for consumers and the possibility of increased local control over waste processing linked to green energy production.

## BioSNG Technology

BioSNG production comprises a five-stage process as shown in the following diagram:



Figure 2: The BioSNG Process

The stages are:

- Fuel Preparation:** Drying, shredding and removal of recyclates from feedstocks to produce a fuel that is compatible with the thermal treatment.
- Thermal Treatment:** Gasification or pyrolysis of the prepared feedstock to produce a synthesis gas that can be converted into biomethane.
- Cooling and Cleaning:** The synthesis gas contains contaminants such as tars, sulphur and chlorine compounds, and heavy metals that hinder the next stage. Techniques such as wet scrubbing, activated carbon filtration and other polishing media are used to remove these contaminants.

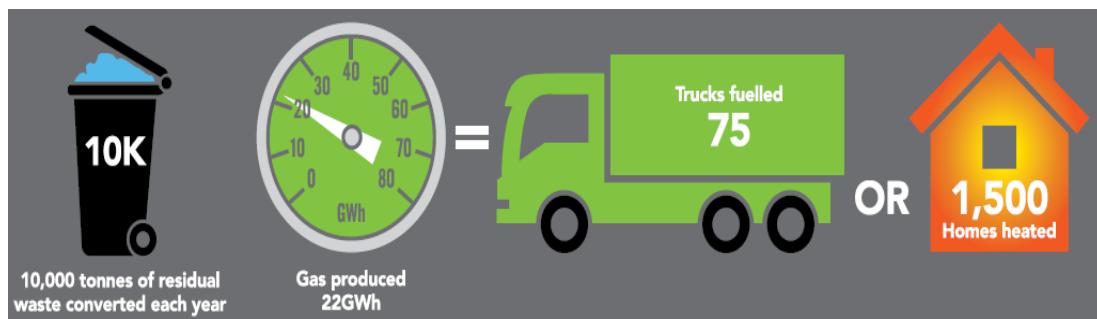
- **Gas Conversion:** A combination of catalysed reactions is used to convert the syngas to substitute natural gas (SNG).
- **Purification:** Carbon dioxide, hydrogen and other unwanted gases are removed from the product gas to give an SNG that meets grid or transport specifications.

All of these stages are established technologies with a large number of reference facilities but their combination is relatively novel. However, the challenges of decarbonising heat and transport have led to increased interest in the technology and pathway. The GoBiGas facility in Sweden? which was built by others and started operations in December 2015 and the current commercial plant being built by the project partners mentioned in this paper, and which will produce gas in 2018, are the first commercial facilities in the world.

Thermal technologies have demonstrated that they can utilise a wide range of feedstocks. Outotec, the gasifier supplier for the BioSNG commercial demonstration plant, has over 100 reference plants treating a wide variety of feedstocks including manure, paper sludge, wood waste, refuse derived fuel (RDF), sewage sludge, and agricultural residues. This flexibility is a key strength of the technology which makes it particularly suitable for processing wastes derived from Enhanced Landfill Mining (ELFM).

## Commercial BioSNG Demonstration Plant

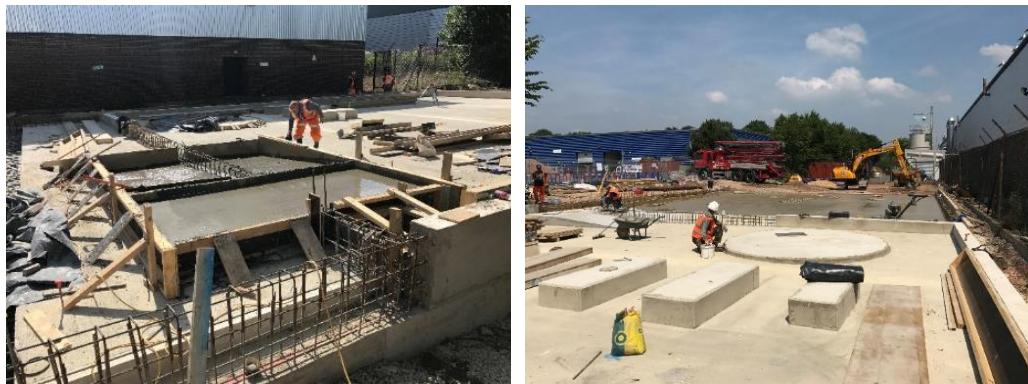
Advanced Plasma Power is constructing a plant that will convert 10,000 tonnes per annum of RDF into 22 GWh of green gas, enough to fuel 75 heavy goods vehicles or heat 1,500 homes.



**Figure 3:** BioSNG Commercial Demonstrator Statistics

The commercial plant will provide a reference facility for the BioSNG process that operates on a full-time basis in a fully commercial environment. It will give organisations the confidence to develop larger scale commercial facilities and will lead to the wide scale deployment of BioSNG technology.

Planning permission, an environmental permit, building control approval and landlord's consent for the facility have all been obtained. The facility has been independently reviewed to check that the process meets the International Sustainability and Carbon Certification standards for advanced biofuel production. The facility is being constructed in Swindon, UK. Civils work commenced at the start of 2017 and is now complete.



**Figure 4:** Civils work on the BioSNG facility, which is now complete

The procurement approach used for the facility is to manufacture equipment off-site as far as possible in order to minimise on-site integration work. The plant has been split into around ten major packages that have been manufactured in the UK, Spain, Italy and USA. All of these are now complete and are being shipped to and installed at the site in Swindon.



**Figure 5:** Methanation equipment and waste heat boiler being installed in Swindon



**Figure 6:** Plasma converter and gasifier undergoing factory acceptance tests

All equipment will arrive on site by the end of 2017 and piping and electrical integration should be completed by April 2018. Commissioning is expected to take around six months with the plant starting normal operations in September 2018. The first gas to grid is expected in June 2018. The waste for the facility will be collected from local households and processed by Thomas Crapper and Sons. The green gas produced by the facility will be shipped through the grid by Ceres Energy to transport customers such as Howard Tenens, who operate a compressed natural gas (CNG) filling station in Swindon.

Recruitment of the 20 staff members required to operate the plant has commenced and training will commence in February 2018. The plans and procedures for operating the facility have been drafted and are being reviewed by independent experts to ensure the plant is operated in accordance with the highest standards of safety. The overall cost of development, design, procurement, construction, commissioning and operational ramp-up of the facility is £30m (€34m). This will be met by an £11m grant from the UK's Department for Transport and £6m from Ofgem's Network Innovation Allowance with the balance coming from the project partners.

The plant is expected to cover its £4m per annum operating costs through payments for accepting waste; sales of gas and carbon dioxide; and support from the renewable transport fuel obligation, the UK's mechanism for implementing the requirements of the EU Renewable Fuels Directive. The key benefit of the facility is to provide a reference that will give funders, gas companies, engineering contractors and fleet operators with the confidence to invest in future large-scale facilities.

## Drivers for BioSNG Production

In 2014, heat and transport generated similar UK greenhouse gas emissions to electricity. However, emissions from electricity are falling rapidly due to the success of wind and solar power production. There has been very little progress on heat and transport to date and forecasts from the UK's Climate Change Committee show that expected emissions in 2030 are predicted to be similar to current levels.

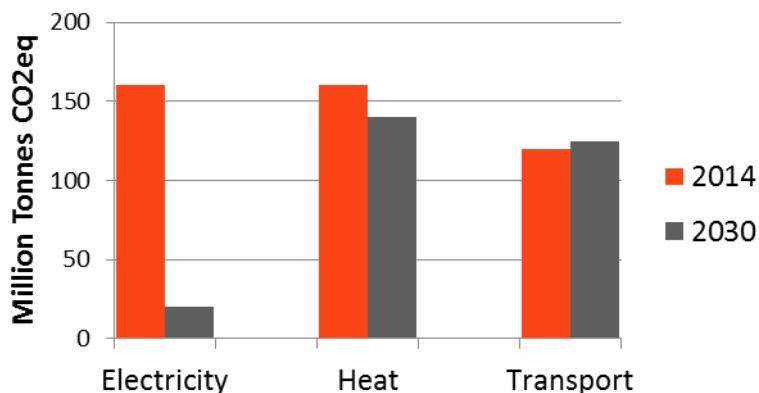
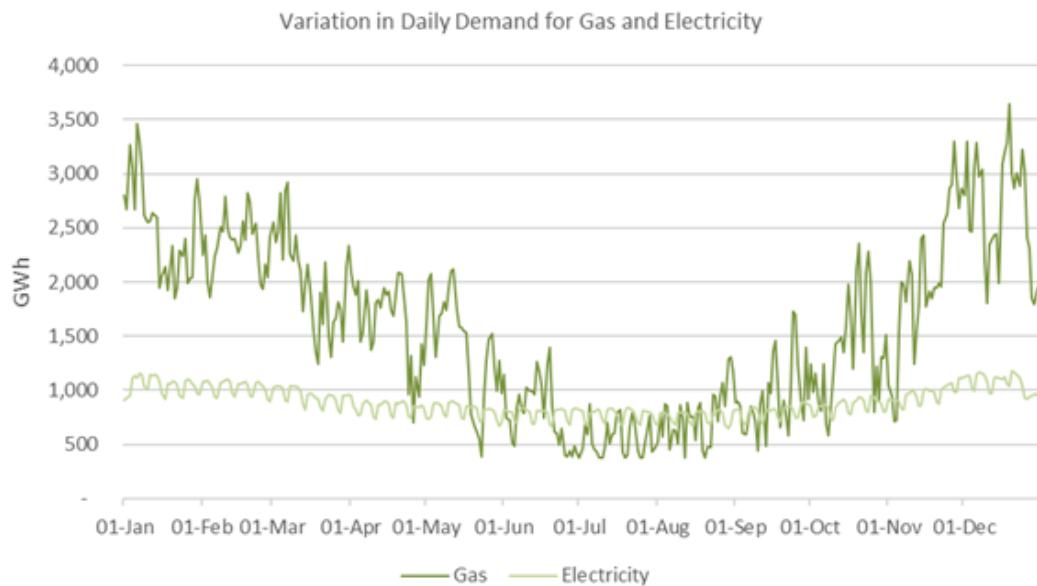


Figure 7: UK Climate Change Committee greenhouse gas emissions forecast

BioSNG has the following advantages over other routes for decarbonising heat:

- It does not require any changes to heating appliances or consumer behaviour. Gas customers are very satisfied with the performance of their heating systems. Work undertaken by Wales and West Utilities<sup>1</sup> shows that it is very challenging to persuade them to move to new solutions based on electric heating or heat networks.
- BioSNG is naturally stored within the gas network in order to smooth out the variability in demand for heating. The large variation in demand for heat, shown in the graph below, is very challenging for electric solutions to meet.
- The overall cost of using BioSNG to decarbonise heat is lower than other approaches. This is supported by work by KPM.<sup>2</sup>



**Figure 8:** Variations in daily gas and electric demand

For transport BioSNG offers the following benefits:

- Heavy goods vehicles and buses that can use gas as a fuel are available now. Scania, Iveco, Mercedes and Volvo all sell vehicles that can use BioSNG. Electrification of heavy goods vehicles will require major advances in battery technology.
- Currently the conversion of syngas to BioSNG is simpler and less expensive than the conversion to liquid fuels such as diesel.
- The gas grid provides a cost-effective network for delivery of BioSNG to transport users.
- BioSNG offers a low-cost route to decarbonising heat and transport that can address sectors that other solutions find challenging. It will play an important role in the UK's future energy mix.

## BioSNG Pilot Plant

Between 2014 and 2017 the project partners constructed and operated a small-scale pilot plant to demonstrate the commercial, technical and environmental feasibility of producing BioSNG from waste.



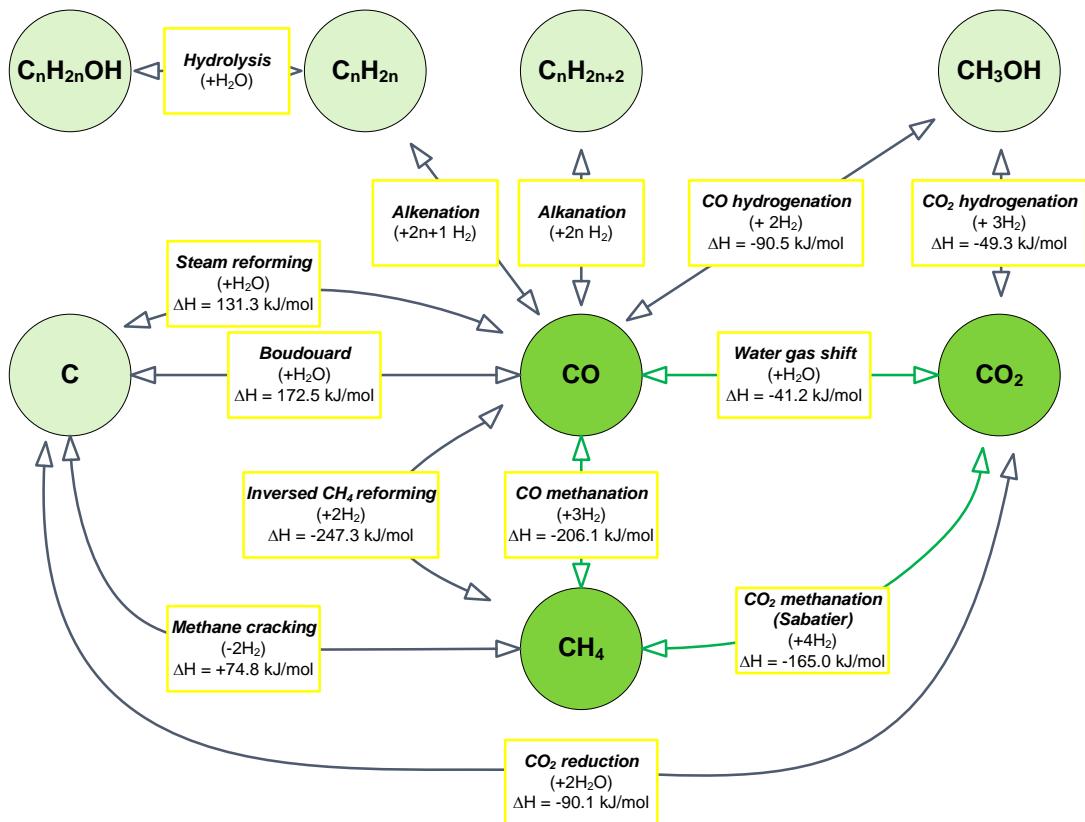
**Figure 9:** BioSNG Pilot Plant

The project produced the following important results:

- Experiments on the kinetics of the water gas shift and methanation reactions carried out in the pilot demonstration plant validated the process engineering models used to underpin the commercial design.
- Procedures and controls were developed to operate the plant.
- The solutions to design issues identified in the demonstration plant project were used in the commercial plant.
- The pilot plant tests provided confidence that contaminants in waste derived syngas could be removed and would not damage the sensitive methanation catalysts.

The methanation process comprises a complex system of reactions. Experiments in the pilot plant gave an insight on how these reactions work allowing the process to be optimised in the commercial plant.

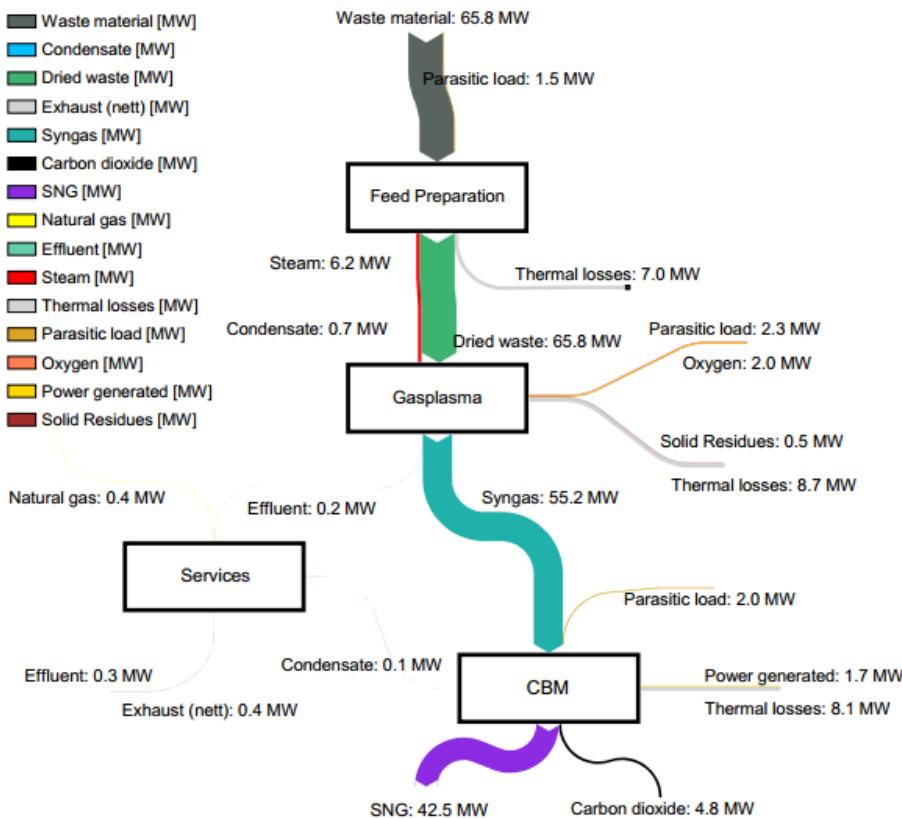
Operation of the demonstration plant has required development of a range of competencies within the operations team, which are directly transferable to a commercial plant. In particular, this has required development of detailed safety assessments and provided extensive operational experience with regard to handling combustible gases at high temperatures and pressures, as well as safe catalyst handling. This invaluable experience will form the basis for safe operation in commercial facilities.



**Figure 10:** Reactions taking place within the methanation system

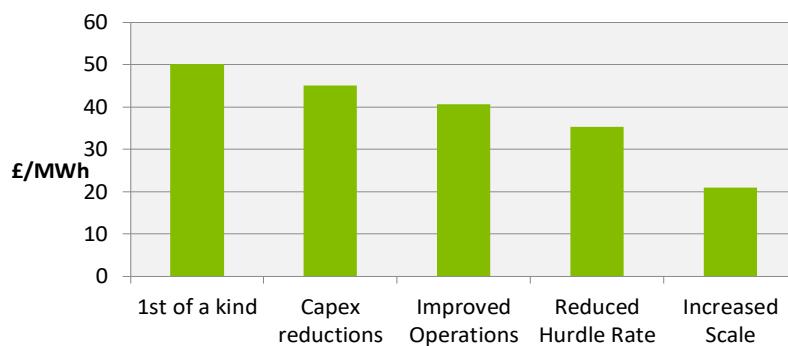
## Large-Scale Commercial Plant Engineering

A design for a large-scale commercial plant has been developed. This is based on the demonstration plant design and is informed by the results of experimental testing, an assessment of scale-up risk and engagement with suppliers. The team produced process flow diagrams for large-scale plants and then produced computer simulations of the process using the Aspen modelling software. The software was used to produce mass and energy balances and the information from these was used to engage with equipment suppliers to select equipment for each process step.



**Figure 11:** Energy Sankey for plant producing 315GWh of gas per annum

The results of the engineering design work were used to prepare financial models for large-scale facilities. The overall cost of a 315 GWh plant processing 100,000 tonnes of RDF per annum is expected to be around £100m including equipment, project development, design, construction and procurement. The cost of operating the plant is around £10m per annum including labour, power, consumables and maintenance. Models show that a first of a kind large-scale BioSNG plant processing RDF with a £60 gate fee has a levelised cost of gas of around £50/MWh, compared to current fossil gas prices of £15/MWh. As the technology matures the levelised cost will fall significantly until they are close to current fossil prices.



**Figure 12:** Projected levelised cost of BioSNG

It is important that support mechanisms are developed across the EU for low-carbon gases in order to allow the technology to overcome development hurdles and achieve its potential.

## Environmental Performance

The commercial plant design set out above can be used to calculate the greenhouse gas impact of BioSNG. Use of waste to produce BioSNG results in significant carbon savings over fossil natural gas; plants will produce BioSNG with GHG emissions 80% lower than fossil gas in the absence of carbon capture. If carbon capture is used and the impact of diverting waste from landfill is taken into account the saving could be as high as 264%, resulting in a GHG credit that can be used to offset GHG emissions from other activities. The basis for these figures is laid out in the emissions analysis below where the main areas of the process are considered and associated emissions highlighted. Waste contains a mix of fossil and biogenic carbon but the standard approach, as set out in the Renewable Energy Directive and other methodologies for GHG analysis, is to only consider the renewable component.

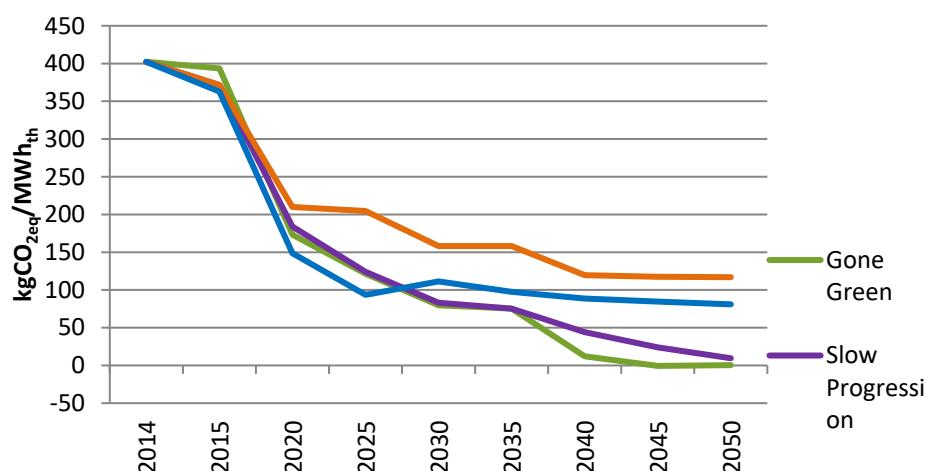
The waste used in these plants will be collected locally, typically from sites within a 10 km radius of the RDF processing plant, which will in turn be a short distance from (or collocated with) the BioSNG facility. Due to the short distances, the involved analysis has shown the impact of this feedstock transportation to be negligible, constituting less than 1% of the emissions from the process. The facilities under consideration are fuelled by RDF. Figures from existing RDF plants indicate electricity consumption of 0.42 MWh/tonne of wet RDF, resulting in 0.018 MWh electricity used per MWh of BioSNG (all figures stated using gross calorific value).

The counterfactual used for the waste handled in BioSNG plants is landfill. Landfilled biomass decomposes and emits methane; figures from the UK's Department for Farming and Rural Affairs estimate that each tonne of organic waste sent to landfill would release 350 kg CO<sub>2</sub>eq. Using this figure, we find that the BioSNG process saves 151 kg CO<sub>2</sub>eq/MWh of BioSNG produced. Emissions associated with construction and maintenance of BioSNG facilities need to be accounted for. Figures from a model produced by the NNFCC suggest that the lifetime contribution of these emissions equates to 15.9 kg/MWh of BioSNG. The BioSNG plant will generate some electricity from process heat but will require an additional electricity input of 0.127 MWh for each MWh of BioSNG produced. In addition, 0.011 MWh of natural gas is used in production of each MWh of BioSNG for the preheating of equipment.

The BioSNG process captures carbon dioxide at sufficient quality for sale to industry. If this is to be done, the CO<sub>2</sub> must be liquefied for temporary storage and transport.

In the production of each MWh of BioSNG, 290 kg CO<sub>2</sub> could be captured, with 0.078 MWh electricity used for liquefaction. Transporting the CO<sub>2</sub> to the end user would emit 6.8 kg CO<sub>2</sub>, assuming a distance of 250 km. The product (BioSNG) is then injected into the local gas grid, with negligible power required for this step. Since biomethane in use comprises biogenic carbon, emissions at the point of use are taken to be zero.

The overall emissions of the process depend strongly on the carbon intensity of the electricity used in the process. The National Grid Future Energy Scenario gives a forecast of the grid intensity of power under four different scenarios, as shown in the chart below. Even under the least aggressive assumptions, the carbon intensity of electricity is expected to fall to 204.5 kg CO<sub>2eq</sub>/MWh<sub>e</sub> by 2025, and this figure has been used to find a worst-case emissions figure for BioSNG. The “Gone Green”- scenario predicts a carbon intensity of 121.45 kg CO<sub>2eq</sub>/MWh<sub>e</sub> by 2025 and 79.85 kg CO<sub>2eq</sub>/MWh<sub>e</sub> by 2030, which has been used to provide less conservative estimates.



**Figure 13:** Forecast UK electricity carbon intensity

The table below summarises the emissions from the process under these various assumptions. All figures are given on a per MWh of BioSNG basis and the gas loads have been converted into CO<sub>2eq</sub> emissions using the EU grid mix value of 243 kg CO<sub>2eq</sub>/MWh. The results of the greenhouse gas analysis are shown in Table 1.

**Table 1:** BioSNG greenhouse gas emissions

	Electricity/gas consumption	Emissions (kg CO <sub>2</sub> eq) at kg CO <sub>2</sub> eq/MWh electricity		
		204.5	121.4	79.8
		MWh	Kg CO <sub>2</sub> eq/MWh BioSNG	
<b>Electricity</b>				
RDF production	0.018	3.7	2.2	1.5
SNG plant	0.127	26.0	15.4	10.2
CO <sub>2</sub> capture	0.078	15.8	9.4	6.2
<b>Gas</b>				
SNG plant	0.011	2.5	2.5	2.5
<b>Other</b>				
Construction & maintenance		15.9	15.9	15.9
Avoided landfill		(151)	(151)	(151)
CO <sub>2</sub> capture		(290)	(290)	(290)
CO <sub>2</sub> transport		6.8	6.8	6.8
<b>Absolute performance</b>				
With CO <sub>2</sub> capture and landfill credit		(370)	(389)	(398)
Without CO <sub>2</sub> capture, with landfill credit		(103)	(115)	(121)
Without CO <sub>2</sub> capture or landfill credit		48	36	30
<b>Comparison to fossil natural gas</b>				
With CO <sub>2</sub> capture and landfill credit		252%	260%	264%
Without CO <sub>2</sub> capture, with landfill credit		142%	147%	150%
Without CO <sub>2</sub> capture or landfill credit		80%	85%	88%

The calculations show that even at the worst expected GHG intensity of UK electricity, and ignoring the impact of diverting waste from landfill for carbon capture, BioSNG has a GHG intensity of 48 kg/MWh, which is 80% lower than fossil gas. Even larger savings are achieved if the waste used for BioSNG production is diverted from landfill or if the carbon dioxide produced in the process is sequestered.

## Conclusion

Currently, the primary pathway for energy recovery from residual waste is the production of electricity using incineration and steam turbines. However, other low carbon technologies such as wind and solar can produce renewable electricity more cost effectively than incinerating waste. Decarbonising heat and transport is a major

challenge in the next decade. Electrification will play an important role in both sectors but the variation in demand for heat and the challenges of electrifying heavy goods transport mean that fuels must be decarbonised as well. BioSNG provides an opportunity for decarbonising both heat and transport cost effectively and should be seen as one of the preferred routes for valorising residual waste.

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# CHARACTERISATION OF EXCAVATED PLASTICS FOR THERMOCHEMICAL UPCYCLING TO PLATFORM CHEMICALS AND LIQUID FUELS

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## Introduction

If the European Parliaments has its way, the concept of Enhanced Landfill Mining (ELFM) will be integrated into the EU Landfill Directive in the near future.<sup>1</sup> Landfilled waste will become a potentially valuable resource which is valorised as material (WtM) and energy (WtE).<sup>2</sup> In Europe, between 1995 and 2015, 5.25 billion tonnes of waste were deposited in landfills,<sup>3</sup> of which the plastic fraction represents between 5-25 wt% of the total landfilled waste.<sup>4,5,6</sup> Changes in physical and chemical properties of plastic waste during its storage in landfill have not been thoroughly studied, and further work is required to properly address this topic. This paper presents an early investigation on the degradation of plastics in landfills, focusing on the characterisation of excavated plastic waste from three different landfills in UK.

## Materials and methods

### Sample collection

A total of 8 excavated waste samples were collected from 3 different landfills located in the UK, at a depth ranging between 5 to 39 meters (Table 1). The excavated waste has been manually sorted and was divided in 10 fractions (Table 2).<sup>5,8</sup>

**Table 1:** Overview of excavated waste samples

Sample no.	1	2	3	4	5	6	7	8
Depth (m)	39.0	5.0	6.5	18.5	8.0	18.0	6.0	18.0
Quantity (g)	8,448	5,838	553	870	390	603	595	876

### Plastic characterisation

The excavated plastic samples were washed with cold water, air dried at room temperature and then weighed to calculate the percentage of impurities, such as soil and semi-degraded paper. The excavated plastic samples of approximately 4 x 4 cm were analysed by a visual-NIR spectrometer (ASD Inc Releases LabSpec 2500) with a

spectral range of 350-2500 nm and compared with fresh plastic spectra. The percentages for each plastic type identified were calculated. Similar plastic types were grouped based on their origin and depth. Samples 3, 5 and 7 were collected from the same landfill and depths between 6.0 and 8.0 m, and grouped by plastic type as Sample A. Similarly, samples 4, 6 and 8 were collected from the same landfill and depths between 18.0 and 18.5 m, and grouped by plastic type as Sample B. SEM-EDS (Environmental Scanning Electron Microscope Philips XL30 ESEM and Energy Dispersive Spectroscopy) was used to characterise the surface morphology and the chemical elements present in the surface of a representative plastic sample for each plastic type and to evaluate degradation and contamination levels. The ash C, H, N and metal content were determined following the British Standard method.<sup>9,10,11</sup>

## Results and discussion

### Excavated waste sample composition

Table 2 shows the percentage of each waste fraction found in the excavated waste samples. The largest fraction is represented by the soil with a range between 53 and 81 wt%, followed by plastic fraction ranging 5-26 wt%. The fraction 'Other' comprises mostly stones and unidentified materials. This distribution is consistent with previous studies which identified the fines fraction, which includes soil-type material as the major fraction in excavated waste followed by the plastic fraction.<sup>4,5</sup>

**Table 2:** Classification and quantification (in wt% as received) of waste fractions present in the excavated waste samples from landfill

Waste Fraction Sample no.	PI	P/C	M	G/C	T	W	S/F	B	WE	O
1	26	1	1	0	1	9	53	0	0	8
2	11	1	0	1	2	2	62	0	0	21
3	16	0	0	7	0	1	65	0	0	10
4	8	0	0	4	2	1	81	0	0	5
5	20	1	0	5	1	1	55	0	0	18
6	5	6	0	0	1	2	75	0	0	11
7	24	1	0	1	7	1	63	0	0	4
8	6	0	0	4	0	5	77	0	0	8

PI = plastic; P/C = Paper/cardboard; M = Metal; G/C = Glass/ceramic; T = Textile; W = Wood; S/F = Soil/fine fraction;

B = Batteries; WE = WEEE; O = Other.

### Excavated plastic waste characterisation

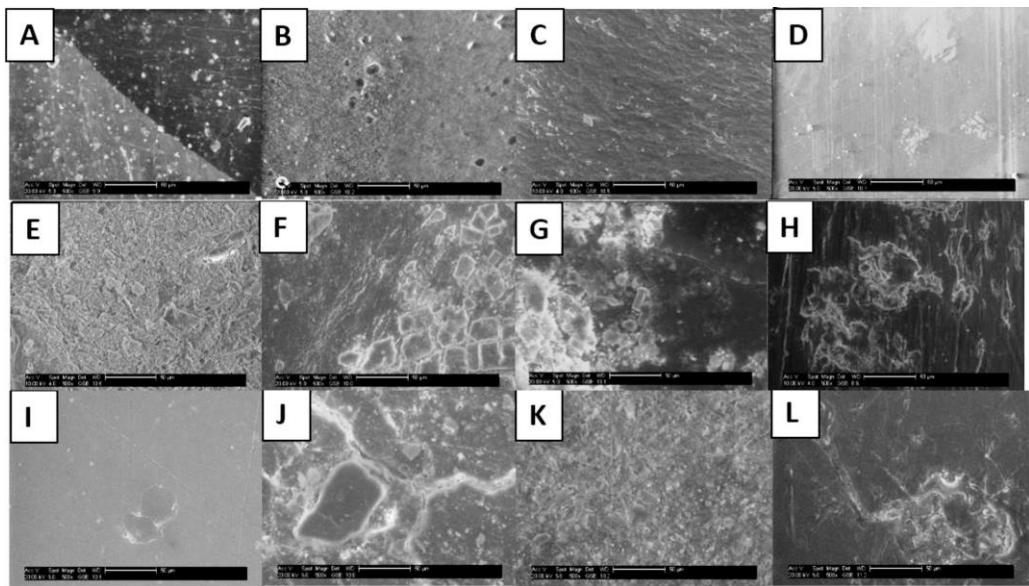
The percentage of impurities in excavated plastic ranges between 62 and 87 wt% mainly including soil, semi-degraded paper and moisture. Zhou *et al.*<sup>7</sup> observed similar results, with impurities ranging from 61.8 and 84.4 wt%. The results from NIR spectroscopy (Table 3) highlights that the main fraction of the municipal waste plastic is composed of thermoplastics (including PE, PET, PP, PVC, and PS), which is to be expected as thermoplastics represent 80 wt% of the plastic consumed worldwide.<sup>12,13,14</sup> PE is found as the predominant plastic type in all excavated waste samples (Table 3).

**Table 3:** Plastic types found in the excavated plastic waste, with wt% of total plastics shown

Sample no.	PE		PET		PP		PVC		PS		Rest	
	g	%	g	%	g	%	g	%	g	%	g	%
1	184.0	50.1	143.0	38.9	11.5	3.1	3.5	1.0	2.0	0.5	23.5	6.4
2	121.5	60.9	1.5	0.8	23.0	11.5	5.5	2.8	5.0	2.5	43.0	21.6
3	7.0	32.1	-	-	7.0	32.1	-	-	-	-	7.8	35.8
4	5.5	56.1	-	-	1.5	15.3	0.5	5.1	0.5	5.1	1.8	18.4
5	9.5	70.4	-	-	1.5	11.1	-	-	-	-	2.5	18.5
6	3.5	43.8	0.5	6.3	0.5	6.3	-	-	-	-	3.5	43.8
7	16.0	47.1	-	-	0.5	1.5	-	-	2.0	5.9	15.5	45.6
8	4.0	37.0	0.5	4.6	1.5	13.9	0.5	4.6	-	-	4.3	39.8

PE = polyethylene; PET = polyethylene terephthalate; PP = polypropylene; PVC = polyvinyl chloride; PS = polystyrene; Rest = other plastic types.

Figure 1 compares the surface of excavated plastic samples and the surface of fresh plastic waste of the same plastic type established by SEM-EDS. In general, the surfaces of fresh plastic waste (Figures 1A, 1B, 1D and 1I) appear more homogeneous than the surfaces of excavated plastic, which seem altered. Table 4 presents a description of the surface characteristics and level of imperfection which can be associated with the first visual effect of degradation.<sup>20</sup>



**Figure 1:** Surface images of fresh plastic waste (A, B, D, I) and excavated plastics (C, E, F, G, H, L, M, N) under 500x magnification. A: HDPE white carry bag; B: LDPE coloured packaging; C: Excavated PE (sample 1); D: PET; E: Excavated PE (sample 2); F: Excavated PE (sample B); G: Excavated PE (sample A); H: Excavated PET (sample 1); I: PP; J: Excavated PP (sample 1); K: Excavated PP (sample 2); L: Excavated PP (sample A)

**Table 4:** Surface characteristics and chemical elements detected by SEM-EDS (minimum concentration detected 0.08 wt%) of fresh and excavated samples

Sample	Figure	Surface texture	Surface degradation level	Main elements	Minor elements (< 5 wt%)	Trace elements (< 0.5 wt%)
HDPE	1A	F, AP	<b>Medium</b>	C, O, Ca		S, Cl
LDPE	1B	P	<b>Medium</b>	C, O, Ti	Al, Cl, Ba	Si, P, S, Cu
1 PE	1C	Fl, AP	<b>Medium</b>	C, O, Ca	Al, Si, Cl, K, Ti, Fe	Na, Mg, P, S, Cu, Zn
2 PE	1E	Fl, AP, Gr	<b>High</b>	C, O, Si, Ca	Al, K, Fe	Mg, P, S, Ti, Mn
A PE	1G	AP, Gr	<b>High</b>	C, O	Al, Si, Ca, Fe	Mg, P, S, K, Ti
B PE	1F	F, AP, Gr	<b>High</b>	C, O	Mg, Si, Ca	Al, P, S, Cl, Ti, Fe, Cu, Mo
PET	1D	S	<b>Low</b>	C, O		Al
1 PET	1H	G, AP, Gr	<b>High</b>	C, O	Al, Si, Ca, Fe	Mg, P, S, K, Ti
PP	1I	S	<b>Low</b>	C	Ca, Ti, Fe	Mg, Al, Si, Cl
1 PP	1J	F, AP, Gr	<b>High</b>	C, O	Si, Ca, Ti, Fe	Mg, Al, S, Cl, K, Zn
2 PP	1K	Fl, AP, Gr	<b>High</b>	C, O, Si, Ba	Al, S, K, Ca, Fe, Zn	Mg, P
A PP	1L	F, AP, Gr	<b>Medium</b>	C, O	Al, Si, Ca, Fe	Cl, K, Zr

F = fractures; AP = adhering parts; P = pits; Fl = flakes; G = grooves; Gr = granulates; S = smooth.

Calcium, which can be linked with the commonly used filler calcium carbonate ( $\text{CaCO}_3$ ),<sup>15, 16</sup> is present in fresh HDPE and all the excavated plastic samples. Other identified elements can be related to the use of additives in plastics, such as quartz ( $\text{SiO}_2$ ), wollastonite ( $\text{CaSiO}_3$ ), talc ( $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$ ), fire retardant  $\text{Mg}(\text{OH})_2$ , magnetite ( $\text{Fe}_3\text{O}_4$ ), titanium carbide (TiC), and pigment ( $\text{TiO}_2$ ).<sup>16, 17</sup> Ti and Al are Ziegler-Natta catalysts used to produce PP and PE.<sup>18</sup> The presence of Si and Al may be associated to impurities of soil which major constituents are  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . Indeed, these elements are detected in larger quantities in excavated plastics than in fresh plastic waste. This result agrees with Zhou *et al.* study.<sup>7</sup> The roughness of excavated plastic surface could be explained by the presence of these impurities in the excavated plastics even after washing. The ash content of excavated waste is found to be higher than fresh waste for PP and PET, while PE is found to generally follow an opposite trend (Table 5; the ash content of 1 PP, A PP and 2 PP are 18.9 wt%, 1.3 wt% and 13.3 wt% respectively, not shown in the table). The higher level of ash in fresh PE might be related to the high level of titanium present in the sample compared to the excavated PE waste.<sup>19</sup> The excavated plastic samples present a lower level of Ni, Pb, Cu, Cr, As compared to other studies.<sup>5,21</sup>

**Table 5:** Characteristics of excavated plastic waste and fresh plastic waste

	39 m		18 m	6-8 m	5 m	Fresh plastic waste		
	1 PE	1 PET	B PE	A PE	2 PE	PE	PP	PET
C (wt .% db)	79.6	62.6	80.8	83.2	83.8	72.9	84.2	62.3
N (wt .% db)	0.5	0.3	0.4	0.3	0.3	0.3	0.2	0.3
H (wt .% db)	13.1	5.0	13.3	13.7	13.9	11.9	13.6	4.9
Ash (wt .% db)	4.5	1.2	11.8	6.2	3.1	7.6	2.2	0.2
Hg (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
Cd (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
Tl (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
Sb (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
As (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
Cr (mg/kg)	2.2	7.9	1.4	2.0	<1	<1	1.6	4.4
Co (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
Cu (mg/kg)	5.9	13	6.8	7.4	10	11	4.8	12
Pb (mg/kg)	6.7	<1	2.0	1.9	5.8	1.1	5.1	3.7
Mn (mg/kg)	1.3	3.2	1.8	6.2	<1	4.9	2.7	1.1
Ni (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
Sn (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1
V (mg/kg)	<1	<1	<1	<1	<1	<1	<1	<1

db = dry basis.

## Conclusion

The analyses of excavated plastic waste highlight the presence of a larger quantity of impurities than those in fresh plastic waste probably due to soil impurities. The surface analysis indicates that the excavated PP and PET have degraded more than excavated PE. Excavated PP and PET show higher ash content than fresh PP and PET waste. Furthermore, the ash content of excavated PP reaches the maximum level in the sample from greater depth (39 m) compared to the shallow depth (6-8 m and 5 m). However, the ash content of excavated PE did not exhibit a clear trend which can be related to the difference in depth.

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# **THERMOCHEMICAL HEAT STORAGE DEVELOPMENT FOR 24/7 SOLAR-DRIVEN GASIFICATION OF REFUSE-DERIVED FUEL**

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## **Introduction**

The presence of roughly half a million landfills on the European territory<sup>1</sup> represents a serious environmental and health hazard but also an opportunity for energy recovery from refuse-derived fuel (RDF) extracted by landfill mining. Plasma-assisted gasification has been recognised as an energy-efficient technology to upcycle RDF into (i) high-value syngas and (ii) inorganic slag suitable as building material. The carbon footprint of this process can be decreased even further by utilisation of concentrated solar energy to preheat the gasifying agent (air or steam) to the required temperature ( $\sim 1,000^\circ\text{C}$ ). The 24/7 delivery of the constant-temperature gasifying agent can then be affected by integrating a thermal-energy storage (TES). A promising TES configuration for this purpose is a cascade of a sensible-heat storage (SHS) and a thermochemical storage (TCS).<sup>2</sup>

Although a SHS represented by a packed bed of high-thermal-capacity material allows for an efficient storage of heat, it suffers from a gradual decrease of the heat-transfer fluid (HTF) outflow temperature. The purpose of the TCS section, represented by a set of tubular packed-bed gas-solid reactors, is to keep this temperature constant *via* the controlled release of the energy stored in the chemical bonds of thermochemical storage materials. This controlled release of the reaction enthalpy is achieved by controlling the reaction kinetics *via* manipulating the partial pressure of the gaseous reactant within the TCS reactors.

This study focuses on (1) the selection of reversible gas-solid reaction systems that operate at the desired working temperature ( $\sim 1000^\circ\text{C}$ ), (2) the development of kinetic models for the selected materials to predict the dependence of the reaction rates on the partial pressure of the gaseous reactants, temperature, and conversion of the solid reactants, and (3) the development of a two-dimensional heat, mass and momentum transfer model of the TCS tubular packed-bed reactor.

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# **PYROLYSIS OF SOLID RECOVERED FUEL FROM LANDFILLED WASTE: GAS AND OIL PRODUCT COMPOSITION**

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## **Abstract**

A study has been conducted to examine the effect of different components in solid recovered fuel (SRF) on the pyrolysis performance and composition of pyrolysis products. The SRF samples were produced from fresh solid waste and excavated landfill waste. Pyrolysis was performed by heating up the sample from ambient temperature to 900°C at a heating rate of 25°C/min by using a nitrogen atmosphere. The results show that the gas product from pyrolysis of SRF landfill waste had significantly lower H<sub>2</sub>, CO, and CO<sub>2</sub> as compared to the case of SRF from fresh solid waste. Furthermore, the oil and wax product in the case of SRF from landfill was dominated by hydrocarbon compounds rather than oxygenated compounds as was found in the case of SRF from fresh waste.

## **Introduction**

It is estimated that there are no less than 150,000 to even 500,000 closed and active landfill sites in the EU-28 countries.<sup>1</sup> Unfortunately, nearly 90% of those landfill sites are non-sanitary landfills, which might lead to severe environmental problems.<sup>2</sup> Hence, the mining of landfills and the remediation of polluted land have been considered as essential measures for environmental protection in Europe.<sup>3</sup> Recently, Enhanced Landfill Mining (ELFM) has been considered as a potential solution for landfill remediation, through the adaptation of advanced waste sorting processes and thermochemical treatment processes to recover materials and energy from the landfilled waste.<sup>4</sup>

Municipal solid waste (MSW) originating from landfills has a different composition compared to the fresh MSW. It is reported that landfilled waste contains a higher fraction of fines, which is partially caused by the degradation of waste over time.<sup>5</sup> Moreover, it is found that the plastics and paper/cardboard fraction from landfills has higher ash content.<sup>5,6</sup> This might be due to the fact that those fractions have experienced long-term physicochemical reaction processes, which resulted in

significant amounts of impurities sticking to their surface.<sup>6</sup> Therefore, materials derived from ELF M might have different behaviour during the thermochemical conversion as compared to fresh MSW.

Pyrolysis (alternatively named devolatilisation) has been considered as a fundamental step in all main thermal conversion processes,<sup>7</sup> including gasification. Consequently, it is essential to understand the pyrolysis characteristics of MSW in adapting a thermochemical-based treatment. In this study, pyrolysis of solid recovered fuel (SRF) produced from MSW was performed to investigate the resulting gas composition and oil yield. The objective of the study was to understand the effect of differing SRF composition (from fresh waste and waste from landfill mining) on the pyrolysis performance and end products, and more particularly the gas and oil/wax composition.

## Materials and methods

### SRF samples

In this study, two SRF samples, SRF-1 and SRF-2, composing SRF derived from fresh solid waste and an SRF sample, SRF-LW, obtained from the excavation of landfill waste were used in the pyrolysis process. The fresh SRF samples were supplied by a commercial SRF producer (Shanks-Renewi, Belgium). The SRFs were produced through a series of operations including shredding, screening, sorting, and drying of commercial and industrial waste. Table 1 shows the composition of the SRF samples. The composition of SRF-1 and SRF-2 samples was obtained by manual sorting (handpicking). Meanwhile, the landfill waste composition was based on the previous report by Garcia Lopez *et al.*<sup>8</sup> The SRF-1 samples were obtained in a pelletised condition that consist of plastics, paper, wood, and a small fraction of textiles. On the other hand, SRF-2 samples consisted of a fluffy material that mainly comprises of shredded polyester sponge, paper, plastics, and textiles. The landfill sample was obtained from excavation waste at a landfill site in Halbenrain, Austria. The excavated waste was sorted and screened, which was then followed by size reduction step. The size reduction step consisted of hammer milling, disk milling, and a cryogenic cutting process of which the details can be found in Garcia Lopez *et al.*<sup>8</sup> The result of the size reduction process was a powder fraction, which consisted of mostly inert materials, and the SRF fraction (SRF-LW). Only the SRF fraction was used for the pyrolysis process. The amount of the powder fraction was relatively high (69 wt% of the total sample weight) due to the addition of soil that was detached from the waste surface during the milling and cutting process. SRF-LW has additional components to the main component (plastics, wood, paper, and textiles), as it also contains other combustible materials such as sanitary material, rubber, foam, nappies, sandpaper, electronic plates, etc.

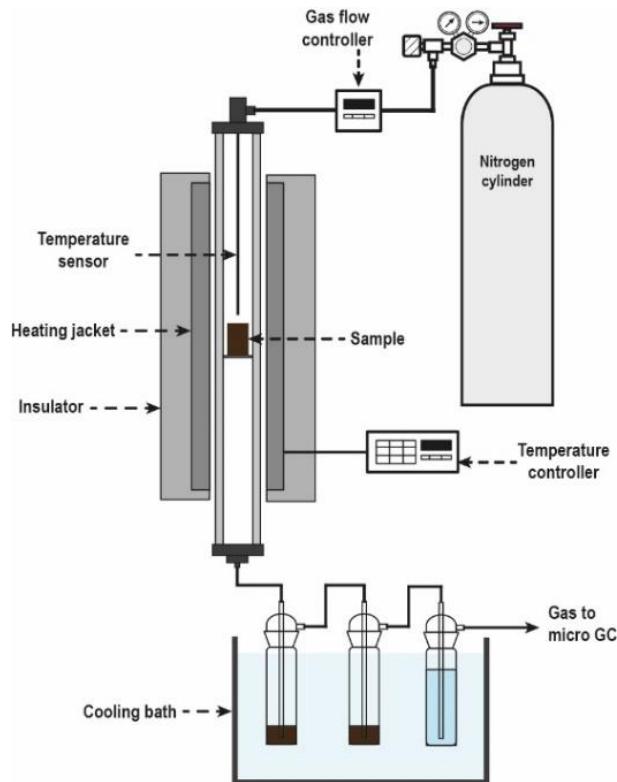
**Table 1:** Material composition of SRF samples

	SRF-1	SRF-2	SRF-LW <sup>*8</sup>
Component, wt%			
Plastics	34.92	23.55	21.46
Wood	15.83	3.03	11.90
Paper and cardboard	40.29	21.60	2.38
Textiles and fibres	8.96	13.02	0.94
Polyester sponge	-	38.80	-
Other combustible fraction	-	-	21.15
Metals			5.49
Inerts (soil, glass, etc.)			36.69

\*Composition before the sample was milling and cut, producing a fines and SRF fraction, of which only the SRF fraction was used in the present research.

### Pyrolysis experiment

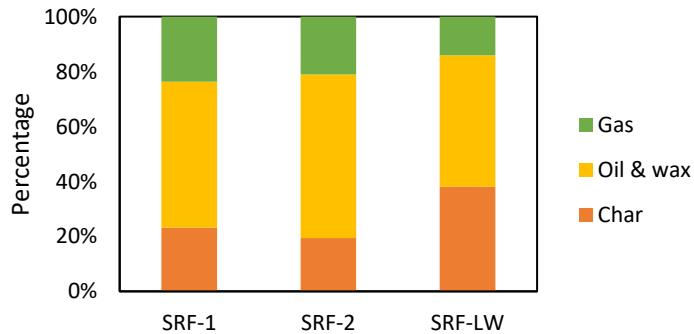
A fixed bed reactor was used to perform the pyrolysis process. The reactor consists of a metal tube, a thermocouple, an electric heater, a cooling bath, and a gas cleaning system as shown in Figure 1. For each experiment, approximately 10 g of sample was inserted in a metal basket and was then placed in the middle of the tube. To measure the temperature inside the tube, a thermocouple was put into the tube until its end was about 1 cm above the sample. Then, the reactor was heated up from ambient temperature to 900°C, using a heating rate of about 25°C/min and a nitrogen flow of 100 mL/min. The reactor was maintained at the target temperature for 1 h and subsequently cooled to ambient temperature. An on-line measurement of the gas composition was done using a micro gas chromatography (micro-GC) instrument using the procedure described in Evangelopoulos *et al.*<sup>9</sup> During the pyrolysis, oil and wax were collected through a washing bottle inside the cooling bath which was then analysed using a GC/MS analyser using the procedure described in Sophonrat *et al.*<sup>10</sup>



**Figure 1:** Schematic diagram of the pyrolysis reactor

## Results

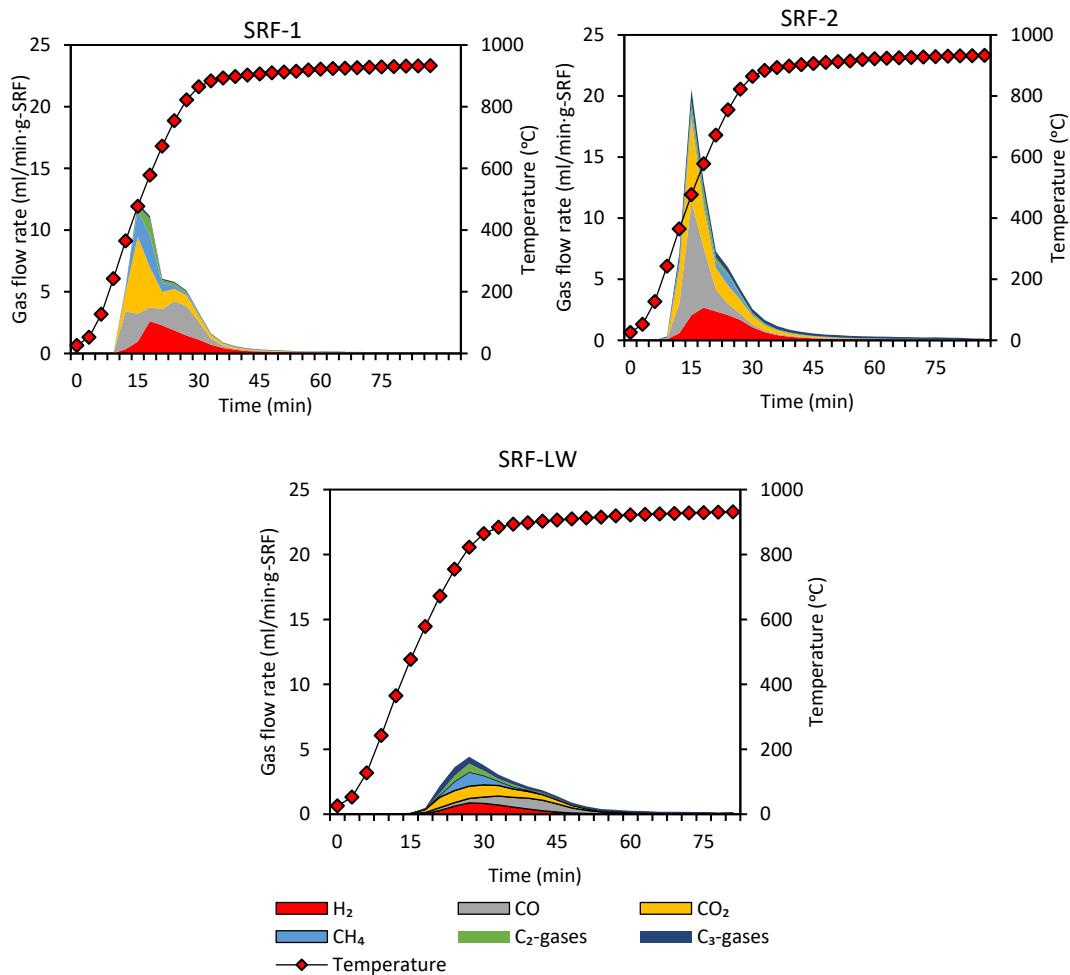
### Product yield distribution



**Figure 2:** Product yield distribution for all samples

Figure 2 shows the yield of the pyrolysis products for all samples. It can be seen that SRF-1 and SRF-2 samples have a yield of products with the highest fraction composed of the oil-wax mixture, which is common in case of pyrolysis of materials with high contents of plastic. Meanwhile, pyrolysis of SRF-LW produced a higher char fraction, which was mainly caused by high ash content of the SRF-LW sample.

## Gas composition

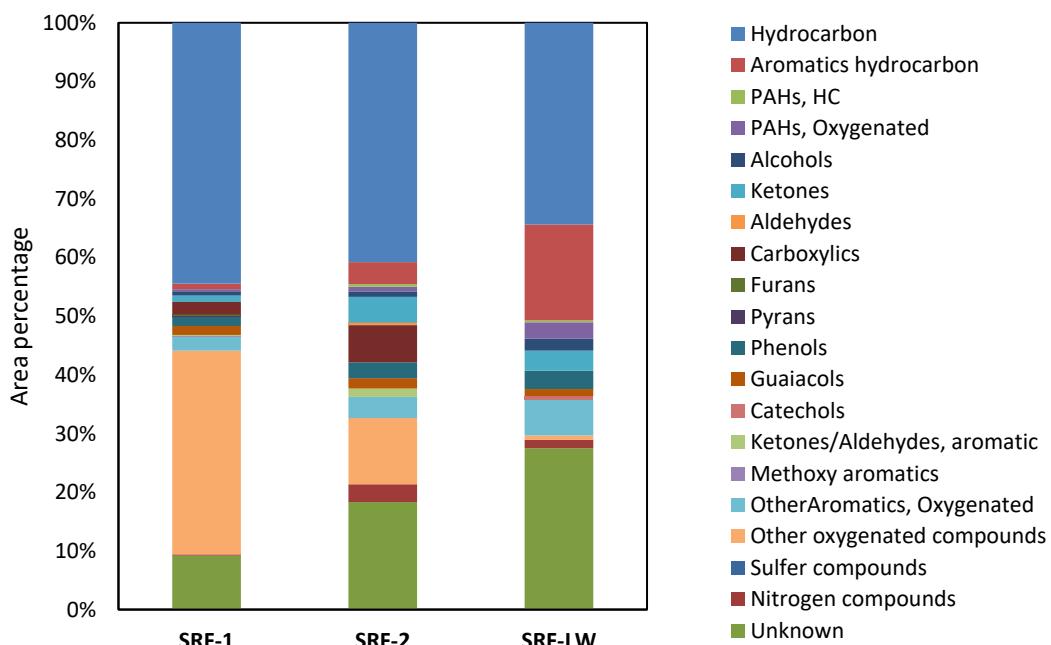


**Figure 3:** Gas product composition during pyrolysis

Figure 3 shows the gas composition during pyrolysis of the SRF samples. In the case of SRF-1, the total amount of the gas product was 165 mL/g-SRF being composed of 26 vol% H<sub>2</sub>, 13 vol% CH<sub>4</sub>, 31 vol% CO, and 30 vol% CO<sub>2</sub>. The CO production was observed to peak at two different temperatures, 365 and 820°C. The pelletisation of SRF-1 might be one of the reasons for the different peaks of CO. As a result of pelletisation, some materials trapped inside the pellets started to decompose and release gas in the later stage of pyrolysis. In the case of SRF-2, the total amount of the gas product was 206 ml/g-SRF being composed of 21 vol% H<sub>2</sub>, 5 vol% CH<sub>4</sub>, 30 vol% CO, and 28 vol% CO<sub>2</sub>. However, in contrast with the SRF-1 sample, there was only one peak for the CO production which occurred at the temperature of about 440°C. For both SRF-1 and SRF-2, the production of C<sub>2</sub>- and C<sub>3</sub>-hydrocarbon gases was significantly low. The gas produced from SRF-1 contained 5 vol% of C<sub>2</sub>-hydrocarbon and 3 vol% of C<sub>3</sub>-hydrocarbon gases, while the SRF-2 gas contained 5 vol% of C<sub>2</sub>-hydrocarbon and 11 vol% of C<sub>3</sub>-hydrocarbon gases.

In contrast with SRF from fresh waste, the pyrolysis of SRF-LW started to produce gas at a higher temperature. As can be seen in the figure, SRF-LW released the pyrolysis gas at around 450°C and peaked at approximately 800°C. In general, pyrolysis of SRF-LW produced significantly lower amounts of gas compared to SRF-1 and SRF-2 especially in terms of H<sub>2</sub>, CO, and CO<sub>2</sub>. This trend might be due to the lower content of light volatiles, *i.e.* volatiles which decompose in the temperature range of 250–350°C in the SRF-LW sample as a result of the devolatilisation occurring in the landfill site.<sup>11</sup> As a result, in percentage, the heavier gases (the C<sub>2</sub>-hydrocarbon and C<sub>3</sub>-hydrocarbon gas) were higher in concentration in case of SRF-LW (11 vol% and 23 vol% respectively).

### Oil-wax mixture composition



**Figure 4:** Composition of oil-wax mixture product from pyrolysis process

During the pyrolysis of SRF samples, the volatile content of the SRF was mostly converted into wax with a small fraction of heavy oil. This product is typically produced in a pyrolysis process of plastic-dominated feedstock when no catalysts are used. The composition of the oil-wax product from the pyrolysis of three SRF samples is shown in Figure 4. In the case of SRF-1, the oil-wax mixture composition is dominated by oxygenated compounds. This is because SRF-1 had a significant amount of wood, paper, and textiles which are the main source of oxygenated compounds in pyrolysis products. On the other hand, SRF-2 produces less oxygenated compounds as the hydrocarbon compounds dominate the oil-wax composition.

Furthermore, the oil-wax product from pyrolysis of RDF-LW consists of mainly hydrocarbon compounds (50.6 vol%), in which one third are aromatic hydrocarbons. The oxygenated compounds in the oil-wax mixture were significantly lower compared to other compounds.

## Conclusion

The results of this study show that the performance of pyrolysis was greatly affected by the SRF material composition. The gas product from pyrolysis of SRF derived from excavated landfill waste had significantly lower H<sub>2</sub>, CO, and CO<sub>2</sub> content compared to the SRF from fresh solid waste. This might be partly caused by the low light volatile content in landfilled waste. As a result, the volume percentage of C<sub>2</sub>- and C<sub>3</sub>-hydrocarbon gases in the gas product were relatively higher. In addition, the pyrolysis of landfilled waste produced gas at a higher temperature compared to the one from fresh waste. Furthermore, the oil and wax product in the case of SRF from landfill was dominated by hydrocarbon compounds rather than oxygenated compounds as was found in the case of SRFs from fresh waste. The phenomenon was due to the higher plastic and low biomass content in the landfill waste as compared to the SRF from fresh waste.

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# COLD PLASMAS FOR GASEOUS POLLUTANT CONTROL AS A BENCHMARK FOR THEIR USE IN TAR ABATEMENT IN SYNGAS

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## Introduction

Gasification is a key tool for the valorisation of carbon-rich materials, which includes the organic fraction of wastes found in landfills. Because of that, in Enhanced Landfill Mining (ELFM) the production of high-quality syngas is crucial from the energetic, environmental and economic point of view. Currently the syngas produced from waste and biomass is generally co-fired in boilers, but an improvement on its quality could allow to use it in more efficient combustion processes such as gas engines, gas turbines or fuel cells and even in organic synthesis processes such as Fischer-Tropsch. The most problematic barrier for producing high-quality syngas is the tar content.<sup>17</sup> Tars are condensable hydrocarbons generated as a by-product of gasification and are defined as all organic compounds with molecular weight greater than benzene.<sup>6</sup> The toxicity and condensation of tars cause lots of problems such as clogging in injectors, fouling in piping systems, and generation of additional waste streams reducing the operability of the processes and increasing dramatically maintenance costs.

## Tars, PAHs and VOCs

In this paper, a review is made on Polyaromatic Hydrocarbons (PAHs), Volatile Organic Compounds (VOCs) and tars. First of all, tars are all organic substances with a molecular weight higher than benzene.<sup>6</sup> Most of the time, the tars of interest are not the same in different studies, because tar composition changes along with process variables in gasification processes, reactor configurations and type of feedstock used. Although benzene is not by definition a tar, in numerous studies focused on tar abatement, benzene is considered as a major component in order to determine the tar removal performance. The second family of compounds, PAHs, refers to compounds consisting of only carbon and hydrogen atoms, and comprising two or more benzene rings bonded in linear, cluster, or angular arrangements.<sup>2,7</sup> They consist of at least two single or fused aromatic rings with a pair of carbon atoms shared between rings.

**Table 1:** Different molecules classified as VOCs, PAHs and tars

<b>Compound</b>	<b>VOC</b>	<b>PAH</b>	<b>Tar</b>	<b>Compound</b>	<b>VOC</b>	<b>PAH</b>	<b>Tar</b>
Benzo-pyrene		x	x	Indeno[1,2,3-cd]pyrene		x	x
Acenaphthylene		x	x	5-Methyl chrysene		x	x
Anthracene		x	x	Phenanthrene		x	x
Benz[a]anthracene		x	x	Pyrene		x	x
Benzo[b]anthracene		x	x	Acenaphthene	x	x	x
Benzo[b]fluoranthene		x	x	Naphthalene	x	x	x
Benzo[j]fluoranthene		x	x	Ethylbenzene	x		x
Benzo[k]fluoranthene		x	x	Toluol	x		x
Benzo[c]fluorene		x	x	MBK	x		x
Benzo[ghi]perylene		x	x	Pyridine	x		x
Chrysene		x	x	Phenols	x		x
Cyclopenta		x	x	Xylene	x		x
Cyclopenta[cd]pyrene		x	x	Toluene	x		x
Dibenz[a,h]anthracene		x	x	Hexanal	x		
Dibenzo[a,e]pyrene		x	x	Ethanol	x		
Dibenzo[a,h]pyrene		x	x	2-propanol	x		
Dibenzo[a,i]pyrene		x	x	Acetone	x		
Dibenzo[a,l]pyrene		x	x	Formadehyde	x		
Fluoranthene		x	x	Butane	x		
Fluorene		x	x	Propane	x		

Although there are many PAHs, most regulations, analyses, and data reports focus on only a limited number of PAHs, typically between 14 and 20 individual PAH compounds (*cf.* Table 1).<sup>1</sup> The most extensively studied PAHs among the presented ones are 7, 12-dimethylbenzo anthracene (DMBA) and benzo(a) pyrene (BaP).<sup>1,3</sup> The last family of compounds are the VOCs. The US Environmental Protection Agency (EPA) defines them as any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions.<sup>21</sup> However, the European Union uses other criteria in its definition, defining them as any organic compound having an initial boiling point less than or equal to 250°C measured at a standard atmospheric pressure of 101.3 kPa.<sup>9</sup> Even when both definitions of VOCs are based on a different criterion (photo-chemistry and boiling point), all have a general character of low boiling point, high vapour pressure and strong photo-reactivity. Practically all the compounds that fall into one definition, fulfil the criteria of the other one.

To summarise, the terms Polyaromatic Hydrocarbons (PAHs), Volatile Organic Compounds (VOCs) and tars, encompass families of compounds, comprising hundreds of different molecules. Some substances can be considered to belong just to one of these definitions, while others may belong to two or three families at the same time (*cf.* Table 1). The classification could appear ambiguous, especially since there is no consensus concerning the exact definition of PAHs, VOCs and tars. However, some common points of interest are defined. The most recent results of non-thermal plasma (NTP) techniques used for PAHs, VOCs and tar removal will be presented, underlying the remaining challenge of NTP for being used as a removal technique for tars.

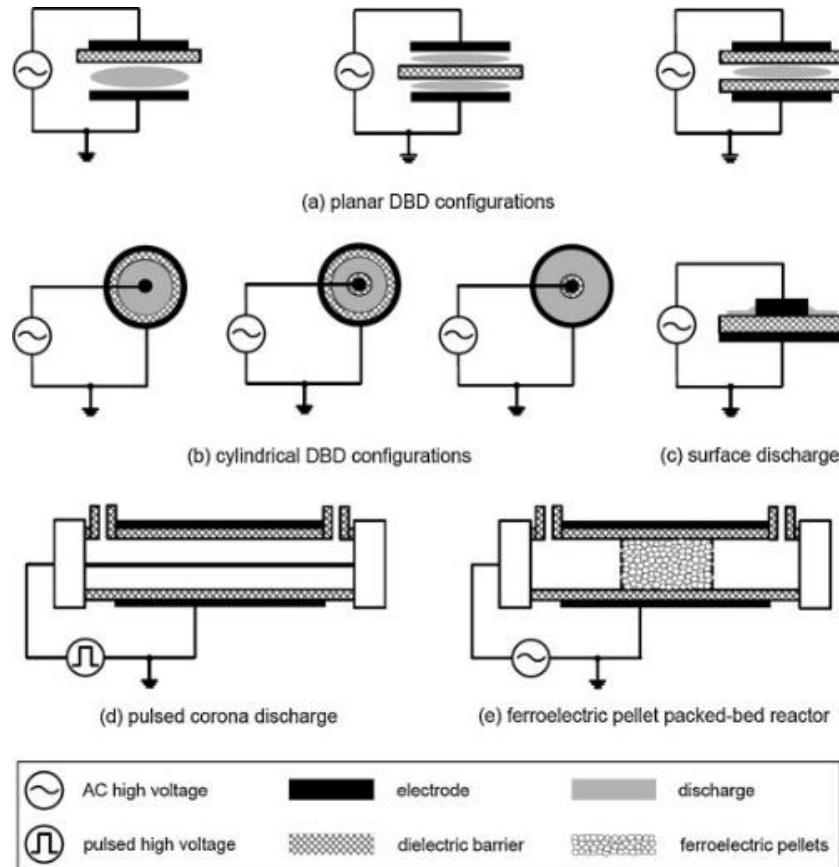
## Non-thermal plasma (NTP) technologies

There are two main NTP techniques for plasma removal of pollutants: Dielectric Barrier Discharge (DBD) and Corona. DBD plasma is built using an AC plasma source and a barrier discharge in one of the electrodes, while Corona uses a DC plasma source and a high-voltage pulse generation circuit (*cf.* Figure 1). When catalysts are added to these configurations, they can be attached in pellets forming a packed-bed, or as a powder in a thin layer coating one of the electrodes.<sup>22</sup> Cylindrical DBD configurations as well as pulsed corona discharges in VOCs removal have been demonstrated in numerous occasions in literature, especially with TCE<sup>8</sup>, benzene<sup>5,18,23</sup>, and toluene<sup>5,16,24,26</sup>, as well as for NOx and SOx.<sup>13,15</sup> On the other hand, the examples of NTP for PAHs removal are scarcer, but they tend to examine groups of PAHs rather than an individual PAH, usually including acenaphthene and anthracene.<sup>4,25</sup> The most recent research has been focused on combining NTP with biofilters<sup>19</sup> and catalysts.<sup>8</sup>

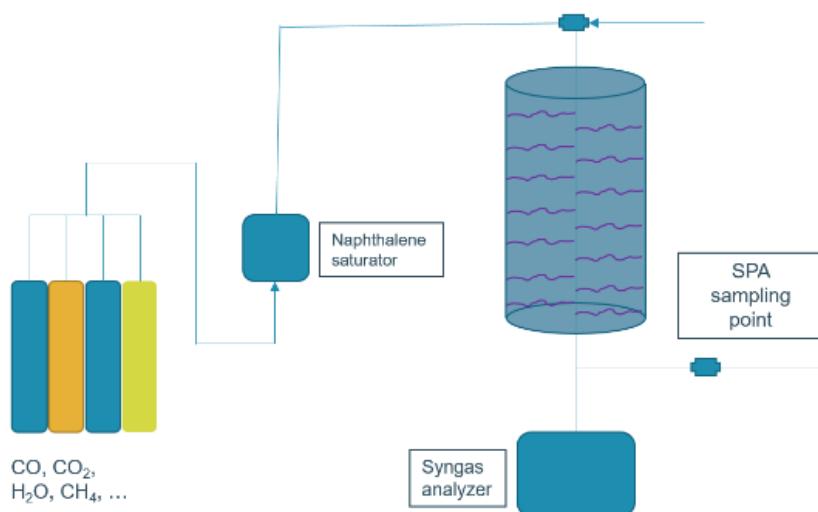
As it was already mentioned, some compounds are considered to belong to different families, like toluene that is a VOC and a tar. Toluene has been extensively studied using NTP removal technologies as a VOC<sup>5,16,24,26</sup>, but toluene is also removed using NTP, considering it as a model tar compound.<sup>10-12</sup> However, the conditions at which tar removal processes occur are very different compared to the ones for VOC removal. The same goes for naphthalene and benzene removal. Tar removal happens at gasification conditions, which means very high temperatures (usually above 800°C) and different atmospheres (including large amounts of CH<sub>4</sub>, CO, CO<sub>2</sub> and H<sub>2</sub>O). The difference in the process conditions does not allow to directly extrapolate results from one study to another, which poses the challenge of evaluating NTP technologies for VOCs and PAHs removal in gasification conditions that are more extreme.

The removal of heavy tars seems to be a second challenge with NTP technologies, because the compounds investigated in the literature are usually light compared with

many tar components that are problematic, like gravimetric tars. Two other factors that represent a challenge to adapt NTP technologies to tars are the concentrations of pollutants (that are much higher than the ones considered in PAHs and VOCs removal) and the very heterogeneous chemistry of tars (compared with the chemistry of VOCs and PAHs), which could affect the performance of NTP removal.



**Figure 1:** Different types of plasma configurations. Modified from Vandenbroucke *et al.*<sup>22</sup>



**Figure 2:** Corona plasma experimental setup

Due to the reasons given above, at KU Leuven a Corona Plasma unit able to reproduce the conditions at the exit of gasifiers has been built. The main idea is to evaluate if a corona plasma could be used in a secondary unit for tar removal just at the exit of the gasifier, and to evaluate the process parameters on which tars are better eliminated, focusing on an energy-efficient tar removal. The setup is presented in Figure 2. Model tar compounds will be used at the beginning, in a simple atmosphere increasing stepwise the complexity of the atmosphere and the tar composition in order to get an understanding of the influence of the different compounds on the plasma removal efficiency.

## Conclusion

PAH and VOCs are two families of compounds of special interest because of their toxicity and reactivity, and NTP techniques have been used to remove some compounds belonging to these families. The previous results with specific compounds, that also belong to the category of tars, show the potential of non-thermal plasmas for removing tar-like compounds. However, there must be studies more focused on removing such pollutants in real gasification conditions, on which tars are found, and which are completely different from the ones used for PAHs and VOCs removal. There are two main challenges for NTP technologies for tar removal. The first one is to remove tars under real gasification conditions, and the second one is to remove a broader range of compounds, going beyond the VOCs and the PAHs studied, focusing on high-molecular weight compounds. Technical aspects also play a role, especially the ones related with scalability and energy consumption. The scalability is crucial for gasification processes because the facilities intended to be used are large-scale and the concentration of the pollutants will thus be variable and much higher than the concentrations presented in toxicology and environmental studies. Secondly, the amount of energy used by the tar removal unit should be low enough to have a revenue in a gasification process.

Hence, VOCs and PAHs can be eliminated using NTP technologies, but at conditions which are drastically different from the ones presented in a gasifier. Although the results are promising, improved technologies should be built to evaluate if NTP could be a suitable tool to abate tars under gasification conditions. The evaluation should include also a broader range of compounds, going beyond the VOCs and PAHs already studied, keeping also an eye in the variation levels of the concentration.

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## Session 3

# Upcycling technologies for Enhanced Landfill Mining





# **VALORISATION OF MUNICIPAL SOLID WASTE INCINERATION RESIDUES IN CONCRETE PRODUCTS**

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## **Introduction**

Solid waste management in urban developed areas include collection, sorting, recycling of waste; the rest is incinerated. The incineration process, in addition to disinfection, reduces the volume of waste by 90% and 70% by weight.<sup>1</sup> The remaining residues are further sorted to separate ferrous and non-ferrous metals. Most of the incinerators used for incinerating municipal solid and non-hazardous wastes are of the grate furnace type, and the different fractions of ashes are named based on the location of collection and the size of the fraction. Bottom ashes, collected from the grates and bottom of the incinerator are classified as non-hazardous, and those that conform to environmental and technical specifications are mainly used as road subbase material, and for other construction applications. Air pollution control residues including fly ash collected from the flue gases are rendered hazardous due to their heavy metal and soluble salt content. The utilisation of residues helps to establish a circular economy, and saves landfill space and taxes and also reduces the need for mining of primary raw materials. Bottom ashes have potential to be utilised in a higher value application such as a cement replacement, as a cement raw meal additive, and as aggregates. However, certain properties of the material hinder their effective utilisation. On-going investigations explore different methods to beneficiate residues and make them usable for high value applications.

## **Physical, chemical and mineralogical characteristics**

The physical and chemical characteristics of the residues depend on the input material, type and process parameters of the incinerator in which they are produced. Municipal Solid Waste Incineration (MSWI) bottom ash have a dry density in the

range of 0.95- 1.75 g/cm<sup>3</sup>, while the density of MSWI fly ash varies between 1.3- 2.0 g/cm<sup>3</sup> and is increased by hydrothermal treatment, or sintering.<sup>2-5</sup> Bottom ash consists of irregularly shaped particles with a melt phase, which is composed of amorphous glass, and a quench phase, which contains hydrates and carbonates.<sup>6</sup> The main chemical constituents are calcium, silica, alumina and iron oxide, with other minor components. The relative proportions of the elements vary depending on the incinerator and sample taken, and also depending on the size fraction. The mineralogy of bottom ashes composes crystalline minerals such as quartz, calcite, gehlenite, hematite, magnetite, ingersonite, anorthite, anhydrite etc. as well as amorphous phases.<sup>6-9</sup>

## **MSWI ash as cement raw meal additive**

### **Principle**

Cement is manufactured by co-sintering various raw materials proportioned to achieve the required composition. The main chemical constituents are calcium-, silica-, aluminium- and iron oxide, which are supplied by minerals such as limestone, clay, shale, bauxite, etc. The proportioning is based on four main indices: lime saturation factor (LSF), silica ratio (SR), alumina ratio (AR) and hydraulic modulus (HM). The relative proportion of the final major phases alite, belite, aluminate and ferrite is based on the relative proportioning of the major oxides. Minor components such as sulphate, magnesium oxide, chloride, etc. also have a significant impact on the characteristics of the cement formed. MSWI residues have the same major chemical constituents as cement clinker and can thus be used as a corrective material along with other raw materials.

### **Obstacles**

#### **Presence of chlorides/alkalis/sulphates**

MSWI residues contain considerable amounts of chlorides, alkalis, and sulphates compared to other conventional raw material sources. Chlorides, being volatile, are mostly present in the air pollution control residue fraction. The chloride content in cement is limited, mainly due to its effect in acceleration of corrosion of reinforcements in concrete. Furthermore, the presence of high amounts of chlorides also has different implications on the clinkering process. Chlorides are volatile and are displaced to cooler regions in the kiln, precipitate and form kiln rings and cause clogging of the kiln. Alkalies and sulphates have a combined effect. Alkalies and sulphates separately, with little presence of the other, are volatile, thus evaporate and condense in cooler parts, also forming kiln rings. When occurring together, they form alkali sulphates which reduce the viscosity of the melt, which is a favourable condition for more alite formation. Alkali sulphates precipitate in clinker as minerals

such as arcanite, aphthalite, thenardite *etc.* An excess of alkalis will increase the viscosity and reduce the alite content, while forming orthorhombic C<sub>3</sub>A, which causes faster setting of the cement. Highly soluble alkalis in the final cement have the effect of increased early age strength and reduced later age strength. Excess sulphate results in formation of calcium langebeinite.<sup>10,11</sup> The effect of sulphates is also related to the content of magnesium oxide (MgO). A high SO<sub>3</sub>/MgO ratio hinders the formation of alite.<sup>12</sup>

### **Presence of heavy metals**

Certain finer fractions of MSWI residues contain heavy metals, which have specific effects on the cement clinker. The incorporation of heavy metal ions in clinker minerals is favourable from an environmental point of view, if these metals are effectively immobilised. The effect on the quality of cement also has to be considered. A high copper content reduces the formation of alite, and increases the presence of belite and free lime. Zinc affects the formation of aluminate (C<sub>3</sub>A) by formation of Ca<sub>6</sub>Zn<sub>3</sub>Al<sub>4</sub>O<sub>15</sub>. Nickel and tin are not incorporated into the main cement phases, but lead to the formation of additional phases such as MgNiO<sub>2</sub>, Ca<sub>2</sub>SnO<sub>4</sub> *etc.* Because of this, threshold limits are set for different heavy metals in clinker, being 0.35%, 0.5%, 0.7% and 1% for Cu, Zn, Ni and Sn, respectively. The belite phase is rarely affected by the presence of trace elements.<sup>13</sup>

### **Research and real applications**

Various investigations have been conducted with the aim of utilising MSWI residues as raw meal additive (Table 1). Ecocement, which is a commercially produced cement containing MSWI residues is also described.

**Table 1:** Research and actual applications of MSWI residues used as cement raw meal additive

Kikuchi 2001 <sup>14</sup>	MSWI ash was used as a raw material for cement production with up to 40 wt% addition in the raw meal. Most of the chlorine content in ash was immobilised during the clinkering process.
Shih <i>et al.</i> 2003 <sup>15</sup>	MSWI ash was subjected to sieving, grinding and magnetic separation treatments and was used as cement raw meal additive, with and without conditioning for lime saturation factor (LSF) and hydraulic modulus (HM). The compressive strengths of specimens were comparable to that of samples containing cement produced with a conventional raw meal.
Krammart & Tangtermsirikul 2004 <sup>16</sup>	MSWI ash was used as a cement raw meal replacement at levels of 5 wt% and 10 wt%. This adjustment resulted in reduction of alite formation. Compensating for LSF and HM could solve this problem.
Eco cement <sup>17</sup>	In Japan, cement incorporating MSWI residues, along with limestone and fly ash has been successfully and commercially produced under the name eco-cement since the year 2001. The clinkering process is optimised to ensure technical quality and to comply to environmental criteria such as leaching of heavy metals, dioxin formation, etc.

## MSWI ash as Supplementary Cementitious Material (SCM)

### Principle

Supplementary Cementitious materials (SCMs) are inorganic materials that, when used in conjunction with Portland cement, contribute to the properties of the hardened concrete through chemical reaction, e.g. through hydraulic or pozzolanic activity.<sup>18</sup> The most used SCMs are fly ash from thermal power plants, blast furnace slag and silica fume.<sup>19</sup> These materials are used as cement replacements, thus saving clinker, which has a high carbon and energy footprint. MSWI residues have a composition suitable to be used as an SCM, except for the presence of some trace substances that can have a negative effect, which is discussed below.

### Obstacles

#### Presence of metallic aluminium

Metallic aluminium with origin of various sources like aluminium foils, wraps, cans etc. is present in waste residues. After various processing steps such as burning, washing, sorting etc. very little metallic aluminium remains in the residues, the content is in the range of 0-4%.<sup>20</sup> For use as SCM, the residue is ground to a fine powder, which increases the surface area of aluminium particles. When mixed with cement, the alkalis in cement accelerate the reaction between aluminium particles and water resulting in the rapid generation of hydrogen gas. Hydrogen gets

incorporated into the cement matrix, increases the porosity and permeability thus reducing strength, workability and durability of the resulting concrete.<sup>21</sup>

### **Presence of chlorides**

Chlorides are present in bottom ash fractions in the range of 0.2-5 wt% and in air pollution control (APC) residues in the range of 0.5-15 wt%.<sup>22</sup> Free chlorides present in MSWI ash get released into the pore solution and cause pitting corrosion of reinforcement, which affects the durability to a great deal.

### **Retarding effect of zinc**

Zinc contents in certain MSWI residues are higher compared to conventional cement, which has the effect of retarding the hydration of cement. In the presence of zinc, calcium zincate is precipitated and forms a layer on the surface of alite preventing its dissolution.<sup>23</sup>

### **Research**

Various investigations, as given in Table 2, have been carried out on the utilisation of MSWI residues as SCM after subjecting it to various beneficiation techniques to improve its potential. Some studies were executed with milled MSW incineration bottom ash and fly ash, and in some cases MSW incineration fly ash was sintered and milled prior to utilisation.

**Table 2:** Research carried out in view of utilisation of MSWI residues as SCMs

Carbone <i>et al.</i> 1989 <sup>24</sup>	The use of milled MSW incineration bottom ash, MSW incineration fly ash and a mixture of both as cement replacement up to 30 wt% was investigated. It was found that the combination with cement immobilised toxic elements, and the compressive strength results qualified the material to be used for the construction of load bearing walls.
Wang <i>et al.</i> 2001 <sup>25</sup>	MSWI fly ash was molten to form a glassy material, which was ground and used as pozzolanic addition. The early age strength decreased at increasing cement replacement, but the strength improved at later ages up to 20% replacement. Leached constituents were below standard limits.
Remond <i>et al.</i> 2002 <sup>26</sup>	MSWI fly ash was used as a cement replacement and resulted in increased setting times, an increase in strength up to 10% replacement, and a decrease in workability.
Lin <i>et al.</i> 2003 <sup>27</sup>	Molten MSWI fly ash was used as a pozzolanic addition with alite and hydration characteristics were investigated.
Bertolini <i>et al.</i> 2004	MSWI bottom ash and MSWI fly ash were used as cement replacement. Bottom ash was subjected to a wet grinding process to prevent the hydrogen production of elemental aluminium and fly ash was washed to minimise the chloride content. Wet ground bottom ash at 30% replacement increased the strength about 30% compared to a control mix with 0% replacement.

Aubert <i>et al.</i> 2004 <sup>28</sup>	MSWI fly ash concrete subjected to the Revasol treatment process was used as a cement replacement at levels of 12.5% and 50%. The treated fly ash behaved like inert sand and resulted in a reduction of compressive strength.
Lin 2005 <sup>29</sup>	MSWI fly ash slag was used as a cement replacement. There was no reduction in strength up to 10% replacement. Replacement by fly ash slag resulted in an increase of initial and final setting times.
Aubert <i>et al.</i> 2006 & 2007 <sup>8,30</sup>	MSWI fly ash was treated with two processes, one being the conventional Revasol process including washing, phosphation and calcination, and a second process where the washing step was modified with sodium carbonate solution to hydrolyse metallic aluminium and zinc. The modification of the process resulted in a considerable stabilisation of Cr, Se and Sb. The second process proved very effective in improving the quality as a pozzolanic material (the ash showed considerable pozzolanic reaction).
Polettini <i>et al.</i> 2005 <sup>3</sup>	Activators such as sodium silicate, sodium hydroxide, sodium sulphate and calcium chloride were added to activate the pozzolanic reaction of bottom ash. Na-based activators were not effective, but the addition of 2% calcium chloride increased the mechanical strength of concrete.

## MSWI ash as aggregates in concrete

### Principle

The granulate and sand fractions of MSWI residues can be used as aggregates in concrete. MSWI fly ash, which is powder inherently, can be solidified by sintering, or using binders like cement or lime and can subsequently be used as aggregates.

### Obstacles

#### Amorphous silica

A large portion of MSWI bottom ash is composed of broken glass, which is chemically amorphous silica. This reacts with alkali hydroxides in cement forming a gel, which swells by absorbing moisture, and causes differential stresses in concrete causing spalling and cracking.

#### Presence of metallic Al

The presence of metallic Al can be detrimental also when the ash is used as an aggregate; it reacts with water in the presence of alkalis in cement generating hydrogen resulting in a strength decreases of the concrete.

## Research and real applications

**Table 3:** Research carried out in view of MSWI ash used as aggregates in concrete

Pera <i>et al.</i> 1997 <sup>31</sup>	MSWI ash was used as an alternative aggregate. Bottom ash was pre-treated with sodium hydroxide solution for 15 days to prevent the reaction of elemental Al with alkalis in cement. A 28% decrease in 28-days strength is reported with 50% replacement of gravel by bottom ash aggregates, and 32% decrease with 100% replacement.
Collivignarelli and Sorlini 2002 <sup>32</sup>	MSWI fly ash was milled, washed and stabilised using a cement-lime process, and was subsequently used as recycled aggregate in concrete. The concrete showed 40-50% reduction in compressive strength. The leaching values conforming to the standard values.
Müller and Rubner 2006 <sup>33</sup>	MSWI bottom ash was used as aggregate in concrete, and the release of hydrogen gas resulting from the presence of elemental aluminium and alkali silica reaction due to high bottle glass content in ash were identified as major problems with respect to utilisation. Microstructural analysis showed that a large portion of the alkali silica gel formed was accommodated in macro-pores due to hydrogen release.
Ferraris <i>et al.</i> 2009 <sup>34</sup>	MSWI bottom ash was vitrified and used as filler, sand and aggregate in concrete. The addition of 20% filler did not reduce the compressive strength of the mortar. Vitrified bottom ash (VBA) was considered to be unsuitable to be used as sand fraction due to poor cohesion between the glass surface and cement paste. The complete replacement of gravel by VBA decreased the compressive strength by 10%, and there was no considerable decrease of strength with up to 50% replacement.
Chen <i>et al.</i> 2010 <sup>35</sup>	Synthetic light weight aggregates were manufactured with MSWI fly ash and reservoir sediments. The use of MSWI ashes was limited to a replacement of 30% due to the low content of SiO <sub>2</sub> as required for optimum expansion.
Saikia <i>et al.</i> 2015 <sup>36</sup>	The effect of heat treatment at about 675°C and chemical treatment with Na <sub>2</sub> CO <sub>3</sub> solution were investigated for MSWI bottom ash to be used as a fine aggregate.
Van den Heede <i>et al.</i> 2016 <sup>37</sup>	Pre-treated MSWI bottom ash was used as aggregate in non-reinforced concrete blocks. Crushing operations to eliminate the porous fraction, reactive washing with 1 M NaOH and pre-wetting of ashes was performed before the casting of elements.

## Beneficiation techniques

### For metallic aluminium

Metallic aluminium is currently removed from residues by techniques such as eddy current separation, magnetic density separation, shaking table, jig head separation,

etc. However, after execution of these separation techniques small quantities of metallic aluminium remain in the residues, and separation might not be economical from a metal recovery point of view, but the quality of concrete can be affected. In such a situation, the most economical preventive treatment is to facilitate the reaction of aluminium with water prior to its utilisation. The hydrogen gas released could be collected and used for the generation of electricity, which improves the economy of the plant. Various parameters that affect the reaction kinetics are fineness of ash, alkalinity of solution, temperature and agitation of the solution.<sup>38,39</sup> The higher the fineness, the larger the surface area of aluminium particles and thus the faster the reaction will occur. An increased alkalinity facilitates faster corrosion of the alumina layer on the surface of aluminium particles and results in faster reaction. Alkalinity of the system could be increased by addition of alkalis such as sodium hydroxide. Even though alkalis are costly, since they are not utilised in the reaction, they remain in solution, enabling reuse of the solution.<sup>40</sup> Temperature also increases the rate of reaction. Agitation of solution facilitates diffusion of hydrolysis products away from aluminium particles and thus accelerates the process.<sup>41</sup>

### **For chlorides/sulphates/alkalis**

Due to the high solubility of chlorides, alkalis and sulphates, the most commonly used technique for their removal is washing with water. A drawback of this procedure is secondary pollution of water. A possibility is to use waste water streams to remove chlorides without additional consequences. Washing with water containing calcium hydroxide has been investigated to remove other chlorides except calcium chloride, and proved to be effective for use of the ash as raw material for cement kilns.<sup>42</sup>

### **For heavy metals**

Phosphation is the most used method at present for stabilising heavy metals. The heavy metals are converted into their insoluble phosphate form in apatite group minerals, which thus prevents their leaching to groundwater.<sup>43</sup> Washing is also effective, but leads to secondary pollution of water.<sup>44</sup> Another class of processing methods is the solidification of ash by various methods such as binder stabilisation, hydrothermal treatment, sintering, etc. Cement is the most commonly used binder, ensuring heavy metal encapsulation in various hydrates formed, preventing heavy metal leaching. During hydrothermal treatment the solubility of heavy metals increases, making it possible to transfer them to the liquid phase allowing separation from the solid phase.<sup>45</sup> Washing with sulphide rich effluent also proved to be an effective technique in immobilising heavy metals in insoluble sulphides.<sup>46</sup> Carbonation is effective in encapsulating heavy metals when the ash is not ground prior to utilisation. Stack gas from incinerators rich in CO<sub>2</sub> can be utilised.<sup>47</sup> Electrodialytic remediation is another technique which was investigated to remove

heavy metals by suspending fly ash in an aqueous solution, after which metal ions are separated from slurry using ion exchange membranes.<sup>48</sup>

## Conclusions

Three routes for the valorisation of MSWI residues were assessed. Each of the routes allows to come a step closer to a circular economy. Various options for beneficiation are available. A barrier for effective utilisation is the need for economic and technical optimisation of the techniques described. The processes can be optimised by linking “all the loose ends” in the process. For example, hydrogen generated by beneficiation of aluminium can be utilised for energy generation, CO<sub>2</sub> from the stack gas can be utilised for the carbonation of ash, the residual heat from stack gas can be used for accelerating the reaction of aluminium, washing water can be given the required residence time to facilitate aluminium reaction, etc. Some success stories like the development of ecocement already prove the effective deployment of certain technologies.

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# **POSSIBILITIES TO TRANSFORM (LANDFILLED) URBAN SOLID WASTE AND INDUSTRIAL RESIDUES TOWARDS NEW MATERIALS**

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## **Abstract**

Substantial amounts of Fe-rich resources are available worldwide, whereas residues, such as bauxite residue (red mud), slags from non-ferrous metallurgy, as well as Fe-rich urban solid wastes, are typically stockpiled in the order of million tonnes per year. In some cases, these materials are used in applications, for example, in clay-based ceramics, as a raw material for cement clinker or as aggregates in concrete. Yet, these applications are of low added value and do not absorb the total volumes available. An alternative approach is presented herein. Three different processes are discussed, where the Fe-rich residue is converted into a binder for building materials and construction. All proposed processes can incorporate high volumes of residues and offer resilience by being able to control fluctuations in the incoming streams of raw materials. In the first process, the end material is a sulfo-ferroaluminate-belite cement. In the second process, the end material is an inorganic polymer, that is also used as a binder. Finally, in the last approach, the end material is an alkali-activated binder, with a small content of Ordinary Portland Cement in the mix design. The conclusion is that pragmatic solutions can be implemented.

## **Introduction**

In the European Union (EU), environment is a topic high on the agenda. On a governance level, there are three Directorate General (DGs), one on Climate Change, one on Energy and one on Environment.<sup>1</sup> Next to these, there is the European Environment Agency (EEA), that assists in developing, adopting, implementing and evaluating environmental policy.<sup>2</sup> In practice, the EU is supporting actions for “resource efficiency”, that concerns the use of resources in a more sustainable way, and creates the tools and framework for a 2050 low-carbon economy<sup>3</sup> with intermediate targets set for 2020, 2030 and 2050.<sup>4</sup> In fact, climate is one of the 10 priorities for the European Commission.<sup>5</sup>

Implementing these actions, a new mindset that goes beyond CO<sub>2</sub> emissions is needed, and indeed, this is acknowledged. For instance, a plethora of initiatives has been launched, involving industry, public services, academia, and NGOs, such as the European Innovation Partnership (EIP) on Raw Materials<sup>6</sup>, prioritised in the European Commissions' new Circular Economy Action plan.<sup>7</sup> The latter is a clear, specific and visionary plan that aspires to facilitate the transition to a more circular economy, where: "*the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimised*". Most importantly, this transition is seen as an opportunity for innovation and growth, and not only as a contribution to the agenda on climate. For instance, it is expected that: "*The circular economy will boost the EU's competitiveness by protecting businesses against scarcity of resources and volatile prices, helping to create new business opportunities and innovative, more efficient ways of producing and consuming. It will create local jobs at all skills levels and opportunities for social integration and cohesion.*"

Within this wider framework, where both the political and ideological constituents are present, the management of municipal solid wastes is also evolving as a concept. Probably one of the frontrunners of the innovations-to-come, is the NEW-MINE project.<sup>8</sup> The project trains early-stage researchers in two pillars, technological innovation, and multi-criteria assessments. The technological innovation follows a value-chain approach, from advanced landfill exploration, mechanical processing, plasma/solar/hybrid thermochemical conversion, up to upcycling. The multi-criteria assessment methods on the other hand allow comparing combined resource-recovery/remediation Enhanced Landfill Mining methods with the "Do-Nothing", "Classic remediation" and "Classic landfill mining with (co-)incineration" scenarios. A notion that concerns both pillars, however, is that of resilience. In simple terms, the technological innovation should lead to processes that can accommodate fluctuations in the characteristics of the incoming streams of residues. Similarly, the multi-criteria assessment protocols should recognise the importance of such process adaptability. Without pre-treatment processing, it would be naive to expect consistency in the incoming stream of landfilled residues. On the other end, it would be more than reasonable to expect consistency in the behaviour and performance of the materials made thereof.

Considering the above, we propose three processes herein that have in-built resilience, and in addition, are more sustainable than comparable industrial processes of today. These processes could in principle deliver end-products of consistent quality, even if there is fluctuation in the characteristics of the incoming streams of raw materials. The first two processes take place at high temperature, the third at low temperature. High-temperature processing provides extra degrees of freedom, in the sense it can be seen conceptually as a beneficiation process: volatile

elements can be removed and the final microstructure can be designed (most often) by thermodynamic calculations beforehand. The low-temperature process involves carefully selected additives that could adjust the performance towards the desired direction. Due to space restrictions, the works presented herein cover primarily the ones where the authors were involved. It is obvious that there have been important contributions in the domain by other research groups; this will be included in a full review article on the topic.

## Calcium sulfo-ferroaluminate-belite cements

### Motivation and background information

In the area of cement, there is intense research on developing alternative clinkers to the one of Ordinary Portland Cement (OPC) formulations.<sup>9</sup> The available work in the area is immense and there are different strategies and cementitious systems suggested. Focus is placed herein on the calcium sulfo-ferroaluminate (CSFA)-belite cements (aka belite-ye'elimit-ferrite binders), a compositional group of cements close to calcium sulfoaluminate cements CSA<sup>b</sup>. CSA cements contain calcium sulfoaluminate, aka ye'elimit or "Klein's compound" ( $C_4A_3\hat{S}$ ) as a major constituent (30–70 wt%), whereas CSFA cements contain  $C_4A_3\hat{S}$  and ferrite ( $C_6A_{3x}F_x$ ;  $1 \leq x \leq 2$ ). Both types of cements accommodate also a substantial amount of  $C_2S$  phase. The production process requires few modifications in the raw meal and firing conditions comparable to OPC. Significant benefits can be derived from the lower energy consumption during production (clinkering temperature between 1250 and 1350°C) and the reduced CO<sub>2</sub> emissions per mass of clinker produced. In addition, due to their low porosity and ability of ettringite ( $Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 32H_2O$ ) and AFm phases to bind heavy metals, CS(F)A cements and their blends with Portland cement are of interest in the field of hazardous waste encapsulation.

From an ELF M perspective, these cements are more attractive than OPC: the chemistry of the raw meal is much wider, with a lower content of CaO, and they also contain SO<sub>3</sub>-phases. Thus, a higher content of residues (or residues only) can be used as raw materials. Considering that and the lower firing temperature, it would be even conceivable to produce such clinkers on the landfill-mining site. Nonetheless, these cements can be produced at an existing cement plant and this is perhaps a more pragmatic step forward.

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<sup>b</sup> The cement nomenclature is used in the text, *i.e.* C = CaO, S = SiO<sub>2</sub>,  $\hat{S}$  = SO<sub>3</sub>, A = Al<sub>2</sub>O<sub>3</sub>, F = Fe<sub>2</sub>O<sub>3</sub>, H = H<sub>2</sub>O.

## Selected published work

One of the first works in the area was by Singh<sup>10</sup> who investigated three series of cements, namely: (a) aluminoferrite ( $C_4AF$ )-belite ( $\beta-C_2S$ ) using lime, bauxite residue (BR) and fly ash; (b) aluminoferrite-ferrite ( $C_2F$ )-aluminates ( $C_3A$  and  $C_{12}A_7$ ) utilising lime, BR and bauxite; and (c) sulfoaluminate ( $C_4A_3\bar{S}$ )-aluminoferrite-ferrite using lime, BR, bauxite and gypsum (terminology is reproduced as in original work). The BR content in the raw meals reached up to 50 wt%. The obtained results indicated that it was feasible to produce cements possessing 28 days strengths comparable to that of ordinary Portland cement (OPC). In a relevant work by the same authors,<sup>11</sup> cements were made by using lime, gypsum, BR and bauxite, where BR varied between 0 and 50 wt%. This work aimed at the synthesis of the calcium sulfoaluminate ( $C_4(A,F)_3\bar{S}$ ) phase, which exhibits high early and ultimate strengths. Cements with high strengths, similar to OPC, were obtained for firing at 1300°C. It was found that the presence of titania in  $C_4A_3\bar{S}$  increases the strength development of cement paste, lowers the dehydration temperature of monosulfate hydrate and effects the morphological structure of the hydrates.

Almost 10 years later, Vangelatos *et al.*<sup>12</sup> prepared  $C_2S$ -rich cements as well as  $C_2S$ -rich cements with calcium sulfoaluminate. Three different types of cement were prepared, one belite active (BC) and two belite-sulfoaluminoferrite activated cements (BSFC1 and BSFC2). The compressive strengths developed after 28 days of curing were 53.7, 43.7 and 34.2 MPa for BC, BSFC1, and BSFC2 respectively. BC has long setting time and workability, whereas the cements with the sulphur compounds set faster, as a result of the hydration reaction of the Klein compound. In the same year, the same group designed three calcium sulfoaluminate-ferrite cements, with variable levels of  $C_4A_3\bar{S}$ ,  $C_4AF$  and  $C_2S$ .<sup>13</sup> The authors used lime, BR, spent bed ash, pulverised coal combustion (PCC) fly ash and bauxite. After 1 day the strength was about 17.2 MPa and eventually increased to 34.5 MPa after 56 days. The work in the domain of CSA cements continues and iron/BR are still of interest. For example, Senf *et al.*<sup>14</sup> made sulfobelite clinkers with 30–70 wt%  $C_2S$ , 20–60 wt%  $C_4A_3\bar{S}$  and 10–25 wt%  $C_4AF$ , using BR as source of iron and aluminium, whereas Cuberos *et al.*<sup>15</sup> doped the  $C_2S$  phase with  $B_2O_3$ , in order to increase reactivity in a Fe-rich belite-sulfoaluminate cement. More recently, Fortes *et al.*<sup>16</sup> used limestone, gypsum, BR and clay, and investigated the impact of  $Al_2O_3/Fe_2O_3$  ratio in the mix design. Cements containing more than 10.5 wt% of BR achieved mechanical strength comparable to Portland cements after 7 and 28 days of curing.

In an industrial level, Lafarge<sup>17</sup> has been experimenting with clinker compositions containing  $\alpha-C_2S$ ,  $C_4A_3\bar{S}$  and  $C_2A_xF_{(1-x)}$  solid solution as the three principal phases. According to the company, such “BCSAF” clinkers can produce cements with similar performance to Portland cements (OPCs) while in principle being manufactured in

conventional Portland cement plants with the emission of 20–30% less CO<sub>2</sub> than the equivalent OPCs. Lafarge has adopted the name “Aether™” for cements produced using this technology.

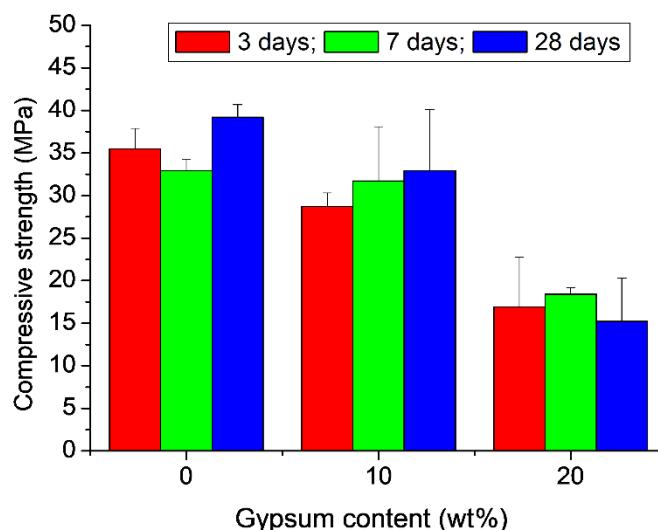
### Recent and upcoming work

In this work,<sup>18</sup> clinkers were made with BR and other oxides, Table 1. After preliminary experiments, firing took place at 1300°C, equilibrated for 2 h at maximum temperature, followed by rapid cooling using pressurised air. After milling, the clinker was mixed with different amounts of gypsum (0, 10 and 20 wt%) and mortars were prepared according to EN 196-1.

**Table 1:** Mix design composition

Component	BR	CaSO <sub>4</sub> · 2H <sub>2</sub> O	CaCO <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>
Wt%	36.4	13.0	43.9	6.7

The main phases in the clinker were a Fe-rich ferrite (C<sub>6</sub>AF<sub>2</sub>, 40 wt%), ye'elimitite (C<sub>4</sub>A<sub>3</sub>S; approx. 25 wt%) and β-C<sub>2</sub>S (approx. 10 wt%). The compressive strength results after 3, 7 and 28 days of cement mortars made with different amounts of gypsum addition are given in Figure 1. In summary, when no gypsum was added, the obtained mechanical properties were similar to OPC CEMIII 52.5R at 3 d and comparable to OPC CEMIII 42.5R at 28 d of hydration. Mortars with 10 wt% gypsum and 2 min mixing time presented 3 d strength comparable to OPC CEMIII 52.5 and 28 d strength comparable to OPC CEMIII 42.5R. Ettringite was the main hydration product in presence of gypsum. Ferrite was still detected in all samples at 28 d of hydration. The results are promising and there is a number of realistic actions to be explored that can further improve the performance of the mortars.



**Figure 1:** Compressive strength results for mortars with different gypsum additions and 3 minutes mixing

The work currently continues, and additives, as well as other process parameters, are being evaluated.

## Fe-rich alkali activated binders and inorganic polymers

### Background information and motivation

The term alkali-activated cements is applied to an extensive range of formulations. The classification of alkali-activated cements can be based on the nature of the solid precursors, *i.e.* glassy, amorphous (like metakaolin) or crystalline, on the chemistry of the solid precursors, *i.e.* alkaline binding systems  $\text{Me}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$  and “alkali–alkaline-earth” binding systems  $\text{Me}_2\text{O}-\text{MO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$  (where  $\text{Me}=\text{Na}, \text{K}, \dots$  and  $\text{M}=\text{Ca}, \text{Mg}, \dots$ ), on the origin of solid precursors, *i.e.* slag-based, fly ash-based, OPC-based *etc.*, or the nature of the resulting binding phase, *i.e.* C-(A)-S-H and/or N-A-S-(H).<sup>19</sup>

From an ELF perspective, alkali-activated cements are an attractive pathway to pursue as these binders do not necessitate usually a high-temperature processing step for the synthesis of the solid reactants or precursors. In most cases, alkali-activated cements are developed with by-products and residues, and in fact, these materials constitute the actual reactive components. This, however, does not compromise the properties obtained. In many cases, mechanical performance exceeds that of OPC binders today or new properties are attained, *e.g.* fire resistance. An overview was recently published.<sup>20</sup>

### Selected published work

Reports on Fe-rich OPC-free formulations can be clustered according to the kind of precursor. In the first group, the Fe-rich precursor is of analytical grade, and emphasis is placed on the atomic structure obtained. Bell and Kriven<sup>21</sup> synthesised Fe geopolymers from synthetic  $\text{Fe}_2\text{O}_3 \cdot 2\text{SiO}_2$  powder and potassium silicate solution to produce  $\text{K}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 13\text{H}_2\text{O}$ , but the resulting material was water-soluble and rubbery, requiring nearly one year to harden. In the second group, the Fe-phase is present in ores or minerals. Lemougna *et al.*<sup>22</sup> investigated the role of iron in the formation of IP from volcanic ashes. Using  $^{57}\text{Fe}$  Mössbauer spectroscopy, they identified both ferrous and ferric sites in the ashes, arising from the presence of both amorphous and crystalline (ferroan) forsterite, and augite. Obonyo *et al.*<sup>23</sup> used Fe-rich laterites. The results (good mechanical properties, stability in water) indicated effective transformation and endurance of the newly formed products.

In the third group, Fe-phases are present in residues, that are metallurgical slags or resemble them. Four subgroups can be identified depending on the precursor: Fe-Mg

slags, Fe-Ni slags, secondary copper slags, and lead slags and secondary lead slags.<sup>24-27</sup>

### Recent and upcoming work

In an extensive scanning of residues, it was found that the chemistry and mineralogy of Fe-silicate slag has a profound influence on its reactivity for inorganic polymer synthesis and the properties of synthesised mortars.<sup>28</sup> More specifically, the reactivity can be boosted drastically by water quenching of the slag after the metallurgical process, increasing the amorphous fraction.<sup>29</sup> Such mortars have compressive strengths exceeding those of OPC. The final Fe-rich IP was stipulated to contain Fe<sup>3+</sup> even though most Fe-rich precursors contain Fe<sup>2+</sup>. Interestingly, recent results have shown that having Fe<sup>2+</sup> in the precursor slag is actually preferred over Fe<sup>3+</sup>, leading to faster reaction kinetics and higher compressive strengths (unpublished data). The mechanism of formation at the nano-scale was revealed by *ex situ* Mössbauer spectroscopy and *in situ* X-ray pair distribution function analysis and consists of 3 stages: dissolution of the precursor, formation of a Fe<sup>2+</sup> silicate, in which Fe is homogeneously distributed in the silicate network and where the oxidation to Fe<sup>3+</sup> which leads to clustering of the Fe species on the nanoscale. The strength is mainly controlled by the Fe/Ca molar ratio of the slag, while the kinetics are largely controlled by the SiO<sub>2</sub>/Na<sub>2</sub>O molar ratio of the silicate solution. The latter leads to the ability to decouple workability and mechanical performance and flexibly change them independently, which is a key benefit with respect to OPC. More on the role and fate of Fe can be found in a recent publication.<sup>30</sup>

The work in the area continues, and two new domains are currently explored. In the first pillar, residues are thermally transformed into known-to-perform-well slag precursors. Assuming that this milestone is reached, then the know-how from the work on fayalitic slags can be leveraged and both the microstructure and the properties can be tailored to a great extent. An example in that area has been already presented recently<sup>31</sup> and the work continues.<sup>32</sup> In the second pillar, a range of slags are systematically studied in order to correlate structure of the glass and properties of the inorganic polymer.<sup>33</sup> This know-how will allow to go back to the metallurgical plant and design a reactive slag precursor early on. This optimised material will require less activating solution downstream, thus, the whole synthesis process becomes more sustainable.

## **Hybrid cements**

### **Background information and motivation**

This family of binders, often called hybrid or blended cements, could incorporate a high content of industrial residues and needs only a small content (*i.e.* max 30 wt%) of OPC. From an ELMF perspective, hybrid cements can be seen as the middle path between new and OPC clinker formulations on one hand, and inorganic polymers and geopolymers on the other. They are in fact an alkali-activated system, but unlike the ones described above, there is OPC in the formulation. As a result, hybrid cements can be seen as the next “pragmatic” step.

### **Selected published work**

The work pursued so far was mainly focused on alkali-activated blast furnace slag, as high calcium source, and on metakaolin, fly ash, *etc.* as low-calcium sources. Incinerator ashes and blast furnace slag, due to their mineralogical and chemical composition, were found less responsive to alkaline activation than fly ash and hence they required a clinker content of at least 40 wt% to obtain acceptable strength values.<sup>34</sup>

In these systems, both the residue and the activators employed are crucial factors.<sup>35</sup> For instance, in OPC, the phases prevailing are C-S-H and CH, at a slightly alkaline activating environment. In the hybrid cements, where only a fraction is OPC and the most abundant source are the Si,Ca,Al,Fe-rich by-products, additional phases or hybrid phases could form. In most of these hybrid systems, the activator is typically NaOH solely but a combination of Na-silicates (*i.e.* water glass) could also be used;<sup>36</sup> therefore, Na could replace Ca and if Al is present, it could convert from traditional poorly-crystalline C-S-H, into gels like N-A-S-H or (N,C)-A-S-H. For the (N,C)-A-S-H to occur, high Ca and low Al need to be present. The (N,C)-A-S-H formation is due to the similar ionic radius and electronegative potential of Na and Ca ions.<sup>37</sup> These phases need typically higher alkali concentrations.

### **Recent and upcoming work**

The use of BR slurry as an activator in a hybrid system was explored in this work.<sup>38</sup> The strong alkaline nature of the slurry, which is considered as a major barrier for most valorisation routes, is beneficial in this approach, where it is used as single source of water and alkalis to activate a hybrid cementitious precursor blend. Moreover, the fineness of the solid fraction of the slurry is expected to improve the particle packing, enabling reduction of the water content and thus of the final system porosity. Experimentally, ≥ 33 wt% of BR slurry, was homogenised and subsequently mixed with either non-ferrous metallurgy slag or ground granulated blast furnace slag (GGBFS), ≤ 10 wt% of Ordinary Portland Cement (OPC) and minor additives; Table 3

report the chemicals of the raw materials (mineralogical analysis can be retrieved in cited work). For the synthesis of the samples, the raw materials were mixed as presented in Table 4, and the resulting pastes were cured at ambient conditions. Satisfactory mechanical properties were reached, exceeding 35 MPa already after 3 d of curing at room temperature, Figure 2. The results are promising, also considering that the slag mix can be potentially replaced by a thermally processed BR, thus leading to a maximisation of total BR content in the newly formed binder.

**Table 2:** Chemical composition of the base raw materials (XRF)

	<b>FeO<sub>x</sub></b>	<b>SiO<sub>2</sub></b>	<b>CaO</b>	<b>Al<sub>2</sub>O<sub>3</sub></b>	<b>MgO</b>	<b>(K,Na)<sub>2</sub>O</b>	<b>TiO<sub>2</sub></b>	<b>SO<sub>3</sub></b>	<b>LOI</b>
NFMS	43.3 <sup>(1)</sup>	35.2	11.7	4.9	2.7	0.5	0.5	-	-
GGBFS	0.6 <sup>(1)</sup>	33.1	38.2	13.7	8.2	0.8	1.1	2.0	-
CEMI 52.5 N	4.9 <sup>(2)</sup>	20.7	64.2	3.5	0.9	0.6	0.2	2.3	1.4
Dried BR	43.6 <sup>(2)</sup>	11.7	5.5	19.3	0.1	8.8 Na <sub>2</sub> O 0.1 K <sub>2</sub> O	9.1	0.6	9.5

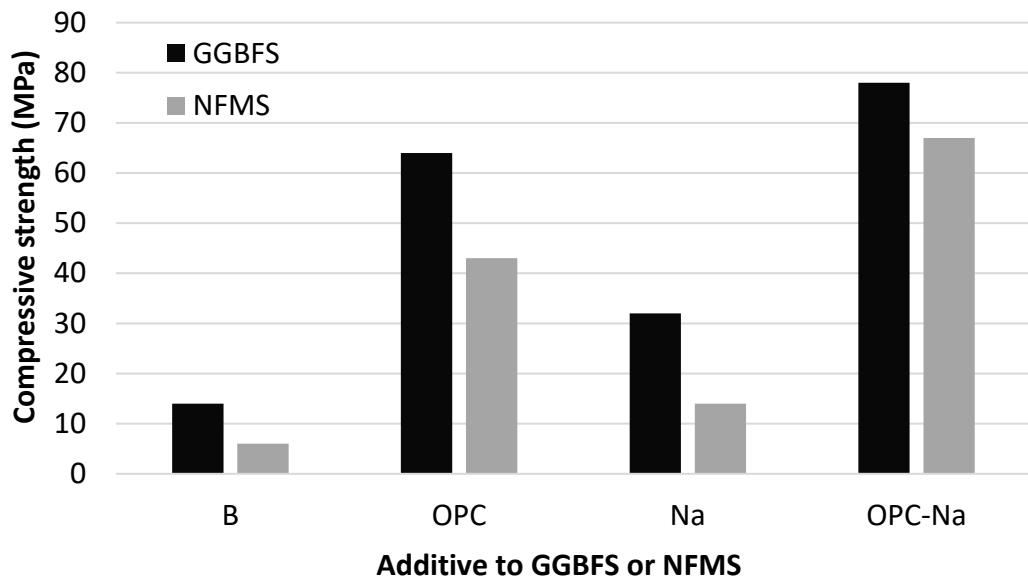
<sup>(1)</sup> calculated as FeO, <sup>(2)</sup> calculated as Fe<sub>2</sub>O<sub>3</sub>

**Table 3:** Composition of the pastes in kg/m<sup>3</sup>t; he wt% are indicated in brackets

<b>Sample</b>	<b>BR slurry</b>	<b>GGBFS</b>	<b>NFMS</b>	<b>CEM I</b>	<b>NaOH</b>	<b>CaSO<sub>4</sub>·0.5H<sub>2</sub>O</b>	<b>plasticiser</b>
GGBFS-B	1000 (41)	1400 (58)	-	-	-	12 (0.5)	20 (0.8)
GGBFS-OPC	1000 (41)	1200 (49)	-	200 (8.2)	-	12 (0.5)	32 (1.3)
GGBFS-Na	1000 (40)	1400 (56)	-	-	20 (0.8)	12 (0.5)	48 (1.9)
GGBFS-OPC-Na	1000 (40)	1200 (49)	-	200 (8.1)	20 (0.8)	12 (0.5)	40 (1.6)
NFMS-B	1000 (33)	-	2000 (66)	-	-	12 (0.4)	20 (0.7)
NFMS-OPC	1000 (33)	-	1800 (59)	200 (6.6)	-	12 (0.4)	32 (1.1)
NFMS-Na	1000 (32)	-	2000 (65)	-	20 (0.6)	12 (0.4)	48 (1.6)
NFMS-OPC-Na	1000 (33)	-	1800 (59)	200 (6.5)	20 (0.7)	12 (0.4)	40 (1.3)

NFMS = Non-ferrous metallurgy slag

The work in the domain continues and we will be reporting soon on a range of residues relevant for Flanders.



**Figure 2:** Compressive strength after 28 days of mortars prepared, respecting a paste/sand ratio of 1

## Conclusions

Urban solid wastes, produced now or mined from landfill sites, can be processed towards new materials of added-value. Three processes were presented herein, where this was exemplified. The characteristic of these processes is that they have in-built stepwise control options, thus could accommodate fluctuations in the quality of the incoming streams without that affecting the properties of the end-product. These end-products are all binders, with a range of properties and envisaged applications. For instance, they could substitute OPC but they could also deliver unpreceded properties, including ultra-high strength and fire-resistance.

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# **RECYCLING OF INORGANIC WASTE IN MONOLITHIC AND CELLULAR GLASS-BASED MATERIALS FOR STRUCTURAL AND FUNCTIONAL APPLICATIONS**

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## **Introduction**

Any form of management of inorganic waste, from landfill disposal to recovery, implies a stabilisation step applied through several chemical and physical processes, including vitrification. The most common applications of this technology concern waste from metallurgical industrial processes, from the demolition of buildings and civil infrastructures, or from combustion processes, particularly from municipal solid waste (MSW) incineration.<sup>1</sup>

Vitrification generally consists of the dissolution of metal oxides from hazardous waste in molten glass, at high temperatures; the metal ions are then “frozen” into the vitreous structure following the cooling of the melt. Waste-derived glasses offer high chemical stability, in a vast range of compositions, with the only constraint of adequate content of SiO<sub>2</sub>, essential for glass formation.<sup>1,2</sup> This requirement is generally fulfilled by mixing waste with minerals or glass cullet from recycling operations or even by considering waste mixtures. In some cases, the stabilisation does not rely on the dissolution of waste, but simply on the thermal destruction, by high temperature processing: as an example, for asbestos-containing waste (not containing heavy metal oxides), vitrification is recommended essentially for the dismantling of the characteristic hazardous fibrous structure.<sup>1</sup>

In general, vitrification compares poorly with other management options, if followed simply by landfilling. Direct landfilling, backfilling in salt mines, neutralisation of waste acid, use as filler material in asphalt, etc. may be more convenient for energy consumption and air emissions.<sup>3</sup> The cost/benefits balance may be improved if an extra revenue is achieved, by use of waste-derived glasses as raw material for high-value products.<sup>1</sup> These products (mostly) consist of monolithic glass-ceramics for structural applications, as an alternative to natural stones or ceramic tiles, or foams (*e.g.* cellular glass-ceramics) for thermal and acoustic insulation.

Both classes of glass-based products actually depend on the application of a secondary thermal treatment, implying extra costs. Again, the cost/benefits balance may be adjusted favourably, typically by: (i) engineering the conversion process from waste-glass to products thermal treatment; (ii) integrating the processing of glass-based products in whole ‘waste management chain’. As reported Gomez *et al.*,<sup>4</sup> waste-glass may correspond to the final output of plasma heating of waste, providing both gasification of organics, by pyrolysis (thermal treatment in non-oxidative atmosphere), and metal separation upon melting (under reducing conditions). Avoiding landfill charges combined with the energy production from waste-derived gas ('syngas'), the recovery of metals together and the added value from glass products, improves the commercial viability of the approach.

The integration is essential for Enhanced Landfill Mining approaches, and constitutes the basis of the current MSCA-ETN NEW-MINE European project.<sup>5</sup> The present paper aims at providing an up-to-date overview of the technology of glass-based products as an effective solution for the upcycling of the inorganic residue from thermochemical conversion of landfill wastes. The added value will be put in correlation with both structural and functional properties.

## Inorganic waste as raw materials for glass-based products

Inorganic residues, in the view of conversion into glass-based products, can be divided according to the content of glass formers, notably silica. In fact, silica-rich waste materials can be vitrified by themselves or with limited quantities of additives, such as recycled glasses. Silica-poor wastes, on the contrary, cannot lead to glass-ceramics or glass-foams, without additional raw materials; however, silica-poor wastes may have a significant impact on the functionalities of the final products.<sup>1</sup>

Ashes from different combustion processes represent a fundamental example of silica-rich waste.<sup>6</sup> Coal fly ashes (FA) from thermal power plants vary their composition as function of the type of coal used, the combustion conditions or the provenance, as shown in Table 1.<sup>7</sup> Molten coal fly ashes may form glass directly, but more commonly some additional oxides are added to lower the viscosity, from minerals or from glass cullet.<sup>8,9</sup>

Ashes from incineration of municipal solid waste (MSW) should be considered as belonging to two distinct categories: (a) MSW incinerator bottom ashes (BA); (b) MSW incinerator fly ashes. Bottom ashes (consisting of glass, magnetic metals, minerals, synthetic ceramics, paramagnetic metals and unburned organic matter) are known to be poorly hazardous, especially in form of coarse particles.<sup>10</sup> On the contrary, MSWI fly ashes constitute a significant form of hazardous waste, since they

contain dioxins or furans, to be destroyed, as well as leachable heavy metals (Cd, Cr, Cu, Pb), to be immobilised.<sup>11</sup>

The high temperatures required by vitrification cause the destruction of organics,<sup>1,2</sup> but gaseous emissions must be verified in terms of chlorine and volatile heavy metal oxides. Preliminary treatments (washing, mixing with additives) are feasible, but they may determine a new disposal problem.<sup>2</sup> Ashes actually derive from any process for energy recovery, reduction of waste volume and destruction of possible organic pollutants. The ashes produced vary in their composition according to the different waste incinerated. Rice husk ash, produced in biomass power plants that use rice husk as fuel, has been used as a silica precursor since it contains around 85–90% of amorphous or crystalline silica depending on the combustion conditions.<sup>2</sup> Sewage sludge fly ash, paper sludge ash, oil-shale ash or meat and bone meal ashes feature are interesting since they contain significant amounts of other glass forming oxides, such as P<sub>2</sub>O<sub>5</sub>.<sup>2</sup>

The most significant production of iron-rich wastes derives from the iron and steel industry. Blast furnace (BF) slag is undoubtedly easier to process than other slags, due to the high contents of silica and alumina, usually accompanied by CaO and, in a lower amount, MgO, as reported in Table 1. However, being a well-known pozzolanic material, BF slag is often reused for non-glass-based products, such as concrete and geopolymers.<sup>2</sup> Other slags, such as basic oxygen furnace slag (BOF) and electric arc furnace (EAF) slag, dust from an electrostatic precipitators, on the contrary, may find applications only after composition correction and vitrification.<sup>1</sup> Finally, iron-rich waste arise also from non-ferrous metallurgy processes (separation of copper from ores, zinc hydrometallurgy, aluminium extraction aluminium hydroxide, in turn deriving from bauxite after separation of the well-known ‘red mud’), each leading to specific waste compositions.<sup>2</sup>

Plasma heating of waste from excavated landfills yields, besides syngas from anaerobic gasification of organics, a solid residue falling in an intermediate position between silica-rich waste and iron-rich waste,<sup>12,13</sup> as shown by Table 1. However, the addition of low cost additives (such as recycled glasses, mine tailings) and conditioning treatments, notably pyrometallurgical processes – for the separation of valuable metals –, may make the chemical composition closer to the ranges for the most established waste-derived glass-ceramics (Slagstitals, see later) and favour the manufacturing of chemically stable, dense or porous products.

**Table 1:** Typical chemical compositions of selected waste and commercial waste-derived glass-ceramics (Slagsitalls) - adapted from the literature<sup>1,2,7</sup>

Oxide	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	MgO	Fe <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	Others (main)
<b>Coal FA</b>	18.1 -75.6	7.6 -55.5	0.8 -37.8	3.5 -9.0	3.1 -9.9	0.2 -2.6	0.6 -2.4	2.5 -18.2 SO <sub>3</sub>
<b>MSWI FA</b>	7.3 -27.5	3.2 -11.0	16.6 -19.5	2.6 -3.1	1.4 -5.0	13.1	11.2	9.8 SO <sub>3</sub>
<b>MSWI BA</b>	30.3 -47.4	9.9 -13.0	18.8 -23.1	2.8 -2.9	4.3 -10.2	1.9 -4.5	0.9 -1.0	1.2 -1.9 P <sub>2</sub> O <sub>5</sub>
<b>MBM *</b>	2.3	0.2	46.4	1.3	8.7	8.7	3.5	34 P <sub>2</sub> O <sub>5</sub>
<b>Sewage ash</b>	39.5	17.2	7.2	2.1	11.1	1.2	2.7	1.9 P <sub>2</sub> O <sub>5</sub>
<b>Oil shale ash</b>	31.9 -34.7	9.1 -9.4	27.6 -27.7	3.4 -5.9	3.8 -4.4	0.2 -0.3	4.2 -7.4	
<b>Rice husk ash</b>	90.7	0.06	1.2	0.8	0.3		1.6	3.6 P <sub>2</sub> O <sub>5</sub>
<b>BF slag</b>	34.4 -37.0	14.5 -14.8	26.6 -41.7	6.5 -6.7	0.3 -0.6	0.2 -1.4	0.4 -0.7	
<b>BOF slag</b>	10.3 -13.7	1.1 -3.9	38.7 -40.4	7.4 -8.2	11.2 -12.9			2.0 P <sub>2</sub> O <sub>5</sub>
<b>EAF dust</b>	4.4 -5.9	0.7 -1.5	7.5 -20.7	5.2 -9.6	24.3 -52.8	0.9 -6.6	1.0 -1.8	1.1 - 15.9 Cr <sub>2</sub> O <sub>3</sub>
<b>Cu extraction waste</b>	24.8 -24.9	0.8 -0.9	0.6 -0.8	0.3 -0.5	67.6 -67.7			7.6 -13.8 ZnO
<b>Red mud</b>	7.8	17.1	11.7	0.6	44.1	3.2	0.1	
<b>Plasmastone</b>	26.2-42.2	6.7-17.3	14.3-26.6	1.9-4.0	11.9-27.3	0.5-4.2	0.4-1.3	1-1.7 TiO <sub>2</sub>
<b>Soda-lime glass cullet (SL)</b>	71.6	1.0	9.0	3.9	0.1	13.5	0.4	
<b>Boro-alumino silicate glass cullet (BS)*</b>	72.0	7.0	1.0			6.0	2.0	12.0 B <sub>2</sub> O <sub>3</sub>
<b>Slagsitalls</b>	49.0 - 63.0	5.4 -10.7	22.9 - 29.6	1.3 - 12.0	0.1 - 10.0	2.6 -5.0		5.0-10.0 P <sub>2</sub> O <sub>5</sub> 3.0-6.0 TiO <sub>2</sub>

\* MBM=meat and bone meal ash; \*\* from discarded pharmaceutical vials

## Monolithic glass-ceramics

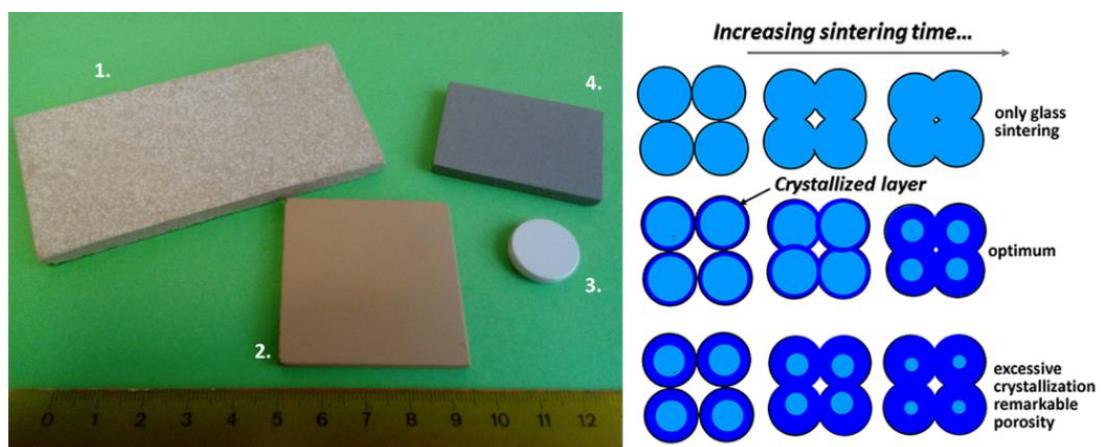
Selected glass compositions may lead to controlled crystallisation, with formation of the so-called glass-ceramics, by a double step heat treatment. A glass component (shaped into the desired form) is heated first to the temperature of maximum nucleation and then to the temperature of maximum crystal growth (slightly higher than the previous one), with a holding time at each temperature, before cooling. Discovered in the late 1950s, the technology has been applied to waste-derived glasses since the early 1960s.<sup>7</sup> As a consequence, the manufacturing of glass-ceramics must be considered as the most established valorisation way for inorganic waste, supported by an extremely vast literature, and by extensive industrial production, under trade names such as "Slagsitalls" and "Slagceram".<sup>2,7</sup>

Sheeted and pressed Slagsitalls have been produced for the last 50 years in more than twenty billion square meters and used in construction, chemical, mining and other branches of industry. The base glasses for both Slagsitalls and Slagceram products belong to the systems  $\text{CaO}\text{-}\text{Al}_2\text{O}_3\text{-}\text{SiO}_2$  (CAS) and  $\text{CaO}\text{-}\text{MgO}\text{-}\text{Al}_2\text{O}_3\text{-}\text{SiO}_2$  (CMAS) (see Table 1), and are obtained from slags of ferrous and non-ferrous metallurgy, ashes and waste of mining and chemical industries, with minor compositional adjustments with glass-forming oxides.<sup>1,2</sup>

Quite constant glass compositions may be achieved adjusting the ratios between different wastes, when variations in the composition of a single component occur. In any case, changes in the overall glass composition are tolerated, considering the nature of the crystal phases developed, *i.e.* calcium silicates and alumino-silicates, forming a number of solid solutions (wollastonite,  $\text{CaO}\cdot\text{SiO}_2$ ; anorthite,  $\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot2\text{SiO}_2$ ; gehlenite,  $2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{SiO}_2$  etc.).<sup>2</sup> The high percentage of crystals, distributed uniformly in the whole volume, with sizes varying from 0.1 to 1 mm, leads to good mechanical strength and excellent abrasion resistance, coupled with good chemical durability.

A key feature of waste-derived glasses, on the contrary, is the availability of nucleating agents, such as iron oxides. The crystallisation of iron-rich glasses begins with the separation of small magnetite ( $\text{Fe}_3\text{O}_4$ ) crystals, but the surface oxidation of  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$  may cause the formation of hematite ( $\text{Fe}_2\text{O}_3$ ), thus decreasing the crystallisation degree. Operating with Fe-rich waste glasses, usually dark and exhibiting poor thermal conductivity by radiation, has some significant drawbacks. The removal of gas bubbles from the glass melt requires high temperatures and long holding times (refining step). Many pores in the base glass, frozen upon crystallisation, strongly limit the mechanical properties of the final glass-ceramics. In

addition, waste-derived glass-ceramics are generally aesthetically poorer than natural stones and traditional ceramics.<sup>1,2</sup>



**Figure 1:** Examples of waste-derived sintered glass-ceramics (Slagsitall-type composition): 1. starting from coarse glass granules; 2. starting from fine glass powders ( $<50\text{ }\mu\text{m}$ ); 3. starting from fine glass powders sintered after mixing with zircon white pigment; 4. material from direct sintering of a soda-lime glass/MSWI BA mixture (left); mechanism of simultaneous sintering and crystallisation (right)

The sinter-crystallisation process, consisting of the viscous flow sintering of glass frits with concurrent crystallisation, provides valid solutions for the above-mentioned drawbacks. Originally applied for the first time during the 1970s, for the manufacturing of marble-like tiles (used in the building industry), the process has been progressively transferred to the valorisation of waste glasses.<sup>1</sup> When applying the sintering route, there is no need to refine the melt before casting into a frit, thus reducing cost and gaseous emissions. In fact, the vitrification may be applied in small plants and in particularly short times, favouring the immobilisation of components that could vapourise with longer heat treatments. The ground glass powder is later pressed and heated to a certain temperature, at which viscous flow and crystallisation occur simultaneously. The crystallisation, generally starting at the contact points between adjacent glass granules<sup>14</sup>, gives a pleasant visual appearance to the products (see Figure 1, left part). More significantly, a relatively high degree of crystallisation may be achieved in very short times, the surface of glass being a preferred site for nucleation. In some cases, the sintering may be performed with very fast heating rates (even by direct insertion of glass powder compacts in furnaces set at the sintering temperature), thus configuring a fast sinter-crystallisation.<sup>15</sup>

The sinter-crystallisation process relies on a delicate balance between viscous flow sintering and surface crystallisation. As shown by Figure 1 (right), if the crystallisation at the glass surfaces is too intensive, the densification may be incomplete; on the contrary, for a glass not prone to surface crystallisation, the viscous flow sintering

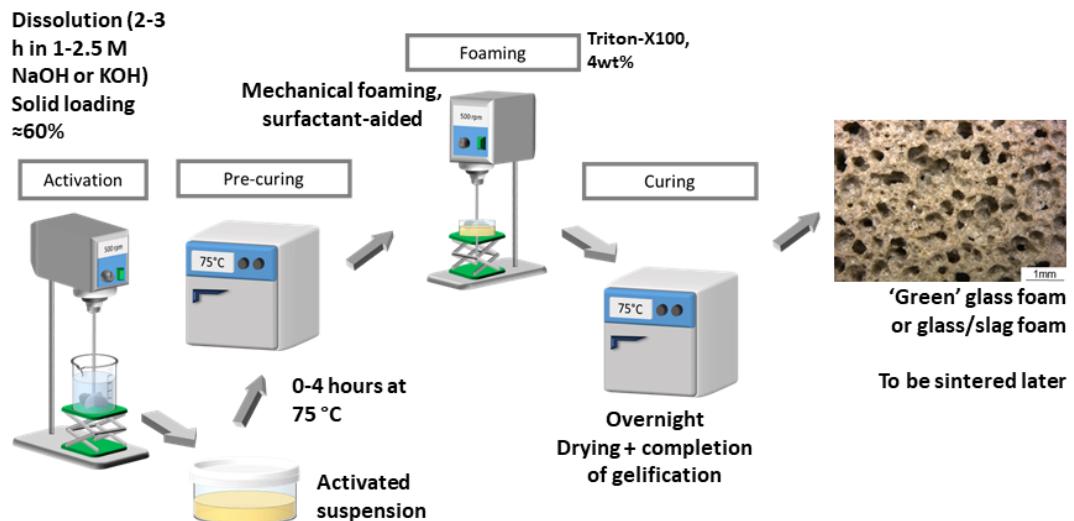
predominates, with the formation of a sintered glass body. An optimum balance may be obtained by engineering the glass composition (Slagsitalls formulations provide a good reference), but also by adopting a hybrid approach, implying the use of mixtures of a glass particularly sensitive to surface nucleation with a glass not prone to crystallisation (*e.g.* waste-derived glass combined with soda-lime glass).<sup>2</sup>

## Cellular glass-ceramics

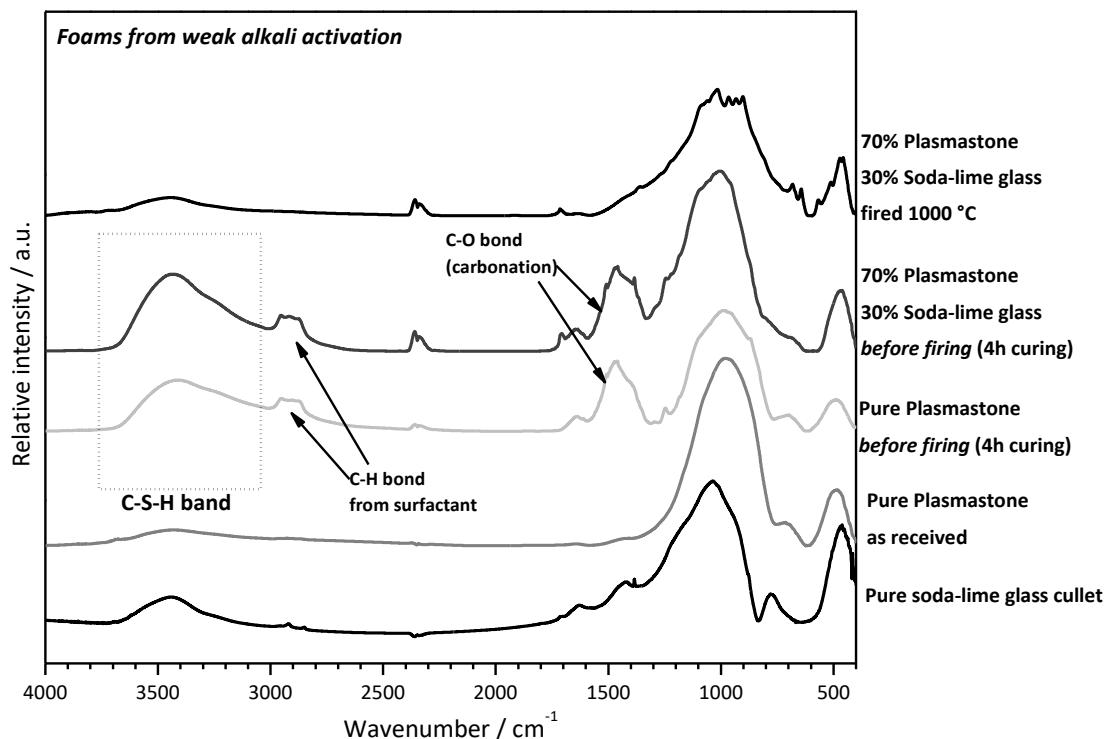
Cellular glasses generally offer high surface area, high permeability, low density, low specific heat, high thermal and acoustic insulation and high chemical resistance.<sup>16</sup> If mostly closed-celled, they can be termed as “foams”. In most cases, glass-based foams represent a further variant of glass sintering. If sinter-crystallised glass-ceramics depend on a delicate balance between viscous flow sintering and crystallisation, glass foams rely on a similarly delicate balance between viscous flow sintering and gas evolution. Crystallisation may occur as well.<sup>2</sup>

The gas evolution depends on oxidation or decomposition reactions of additives mixed with glass powders.<sup>16</sup> Oxidation reactions cause the release of CO<sub>x</sub> gas (carbon monoxide or carbon dioxide) from C-containing compounds, *e.g.* carbon black, graphite, SiC, organic substances, reacting with oxygen from the atmosphere. Decomposition reactions are those provided by carbonates (mainly Na- and Ca-carbonates) or sulfates, leading to the release of CO<sub>2</sub> or SO<sub>x</sub>; a special variant comes from oxides of metals undergoing transition from high to low valence state and releasing oxygen gas (*e.g.* MnO<sub>2</sub> being transformed into MnO). Oxidation and decomposition may even overlap, with nitrides, transformed into oxides with release of nitrogen.<sup>16</sup>

Foaming additives, such as SiC, may be quite expensive and have a negative impact on the overall cost/benefit balance. Improvements are expected from the adoption of a new method – developed recently –<sup>17</sup>, based on alkali activation, as shown by Figure 2. Soda-lime glass suspensions, in weakly alkaline aqueous solutions (2.5 M NaOH, or KOH), undergo progressive gelification at low temperature (80°C). Before complete hardening, an extensive foaming may be achieved by vigorous mechanical stirring, with the help of a surfactant. The hardening to the formation of hydrated calcium silicate compounds (C-S-H), in analogy with conventional Portland cement.



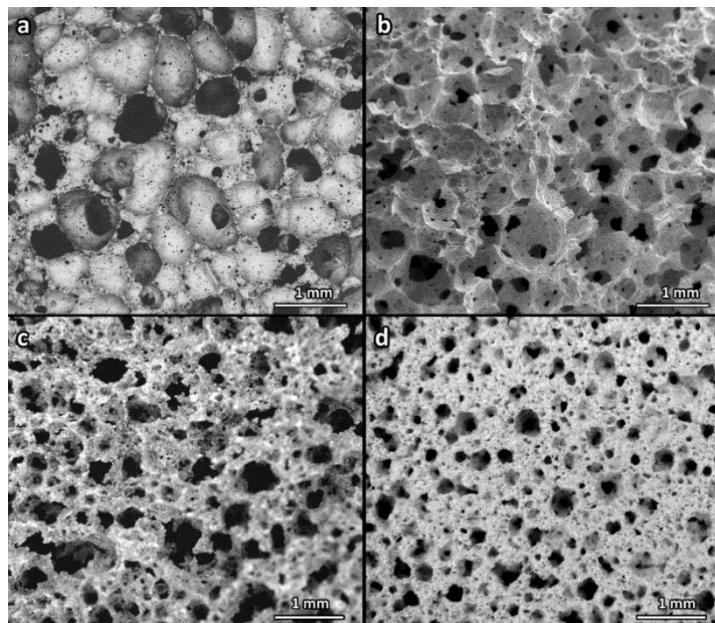
**Figure 2:** Schematic representation of the manufacturing of glass-based foams according to “weak alkali activation” (before sintering)



**Figure 3:** FTIR spectra of selected waste glasses before and after weak alkali activation/gelification/mechanical foaming

As shown by the FTIR spectra in Figure 3, plasmastone, owing to its high CaO content, exhibits a well visible absorption band centred at about  $3400\text{ cm}^{-1}$ . The band is even enhanced when the waste-derived glass is considered after mixing with soda-lime glass (also rich in CaO). The band, not visible in the as-received conditions, disappears

after firing above 700°C. The water release associated with the decomposition of hydrated compounds is thought to contribute to the cellular structure (“secondary foaming”), upon firing. A slight contribution could actually come also from CO<sub>2</sub> release (the formation of carbonates is testified by the peak at 1400 cm<sup>-1</sup>). The surfactant, visible from peaks attributable to vibrations of C-H bonds (C-H<sub>2</sub> stretch at about 2800 cm<sup>-1</sup>), does not provide any contribution, upon firing, being completely decomposed below 400°C.<sup>71</sup>



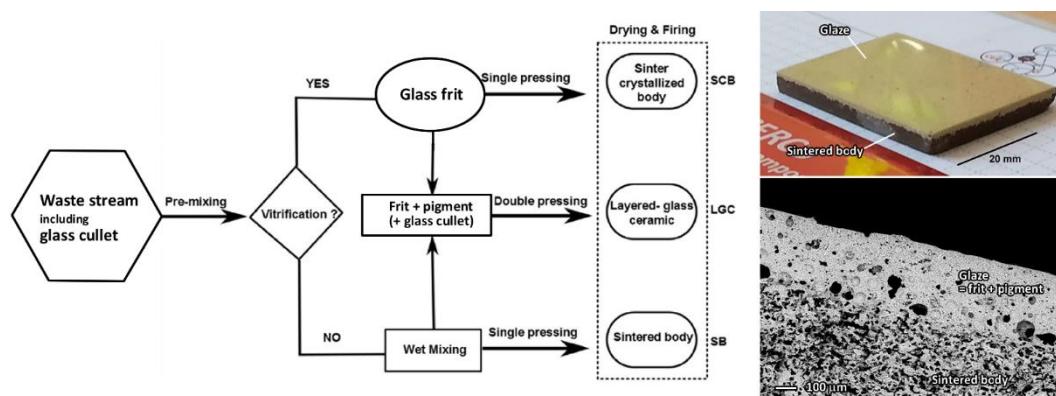
**Figure 4:** Example of glass-based foams resulting from weak alkali activation/gelification/mechanical foaming/sintering: a) soda-lime glass (3 h dissolution in 2.5 M NaOH solution; 4 h at 75°C; foaming with 4% Triton X-100 surfactant; firing at 700°C, 1 h); b) Ca-Mg silicate bio-glass (dissolution in 1 M NaOH; foaming with surfactant; firing at 900°C, 1 h); c) plasmastone 70%-soda-lime glass 30% (dissolution in 2.5 NaOH/KOH solution; foaming with surfactant; firing at 900°C, 1 h); d) glass from vitrification of MSWI BA (dissolution in 2.5 NaOH solution; 1 h at 75°C; foaming with surfactant; firing at 900°C, 1 h)

For soda-lime glass, the sintering step, aimed at stabilising the cellular structures, may be performed just at 700°C, *i.e.* at a much lower temperature than those required by foaming with C-containing additives (well above 850°C). A typical microstructure is shown in Figure 4a. The approach is so flexible that it can be applied, besides pure soda-lime glass, to (CaO-rich) bioglasses (Figure 4b)<sup>18</sup>, mixtures of soda-lime and iron-rich slag from copper metallurgy, Plasmastone (pure and with addition of soda-lime glass, Figure 4c) and glass from the melting of MSWI bottom ash (Figure 4d). The extensive crystallisation upon firing (*e.g.* occurring from glass-slag interaction) is not an issue, since it may freeze the open-celled morphology of the starting alkali-activated, foamed glass suspensions, leading to materials not simply

suitable for thermal and acoustic insulation, but also as scaffolds for tissue engineering, catalytic supports and filters.

## Direct sintering and Layered glass-ceramics

Glass-ceramics from direct sintering rely on the formation of silicate and alumino-silicate crystals, similar to those produced by crystallisation of waste glasses, by interaction of recycled glasses with inorganic waste, upon sintering. This fact supports the use of the term “glass-ceramic”, despite the absence of any melting step.<sup>2</sup> The direct sintering is advantageous for reducing the volatilisation of some pollutants; on the other hand, the products lack homogeneity, so that some pollutants could remain concentrated in some areas. The leachability of sintered residues could be in any case lower than that of untreated waste (Zacco *et al.* specifically mention the viability of direct sintering of incinerator residues).<sup>11</sup>



**Figure 5:** Schematic representation to different approaches to waste-derived glass-ceramics, with overall appearance (top right) and typical cross-section detail (bottom right) of a layered glass-ceramic tile

Layered glass-ceramics (LGCs), shown in Figure 5, object of more recent investigations, may be seen as an evolution of directly sintered glass-ceramics. They refer to a specific market need, in the field of building materials, *i.e.* that for lightweight tiles, with low water absorption (below 2%, for optimised frost resistance), to be placed vertically. Anchored to metal frames, in turn fixed on main building walls, these tiles constitute the so-called ventilated façades. The air gap between the tiles and the wall contributes positively to the thermal insulation (minimising thermal losses, in winter, and minimising overheating, in summer). In layered glass-ceramics, a single-step treatment causes the direct sintering of a base body formed by a glass/waste mixture and the sinter-crystallisation of a glaze, obtained from a glass in turn derived from the same starting materials.<sup>2</sup> The high residual porosity (in the order of 30-35%), the high water absorption, the poor visual appearance and the limited chemical homogeneity of the base body are not

significant issues. In fact, mechanical strength, colour and stabilisation of pollutants depend on the much denser glaze (the glazed side is that to be exposed to the environment). Strength, colour and shrinkage of the glaze can be adjusted by using additives, like pigments and other glasses. Vitrification of waste is reputed to be sustainable, since it is applied only to a limited amount of starting materials; the single firing reduces the costs associated to the deposition of a glaze.

**Table 2:** Strength-density correlations for selected glass-ceramic foams

Formulation	Sintering T (°C)	Total porosity (vol.%)	Shape factor ( $\phi$ )	Compressive strength, $\sigma_{cr}$ (MPa)	Calculated strength, $\sigma_{fs}$ (MPa)
SL glass foam, amorphous (Fig. 4a)	700	86	0.8	$3.2 \pm 0.5$	89.7
Bioglass CEL2, crystallised (4b)	900	75	1	$2.4 \pm 0.2$	102.9
Plasmastone/SL glass 70-30, crystallised (4c)	1000	80	1	$1.4 \pm 0.1$	78.2
Plasmastone/BS glass 70-30, crystallised	1000	75	1	$2.2 \pm 0.3$	88.0
Vitrified BA, crystallised (4d)	900	81	1	$6.2 \pm 0.7$	374.3
Soda-lime glass + Cu slag (6c)	900	82	0.8	$1.3 \pm 0.1$	30.0

## Structural and functional properties

Most of glass-ceramic foams exhibit a quite favourable compromise between thermal conductivity (good if low) and strength (good if high). The strength of glass-based foams can be actually tuned according to cell morphology and crystallisation. In general, the crushing strength of a cellular material depends on the bending strength of the solid, with a scaling factor. This factor is a function of the relative density ( $\rho_r$ , ratio between density of the porous body and density of the solid phase, or “true density”), according to the well-known Ashby’s model:<sup>2</sup>

$$\sigma_{cr} = \sigma_{fs} \cdot [0.2 \cdot \varphi \cdot \rho_r^{1.5} + (1-\varphi) \cdot \rho_r] \quad (1)$$

Where  $\varphi$  defines the fraction of solid at the cell edges (1- $\varphi$  represents the fraction of solid at the cell faces),  $\sigma_{cr}$  is the compressive strength and  $\sigma_{fs}$  is the bending strength of the solid phase. A closed-cell morphology corresponds to significant contribution from the linear term, absent for open-celled foams (or “sponges”, with  $\varphi = 1$ ).

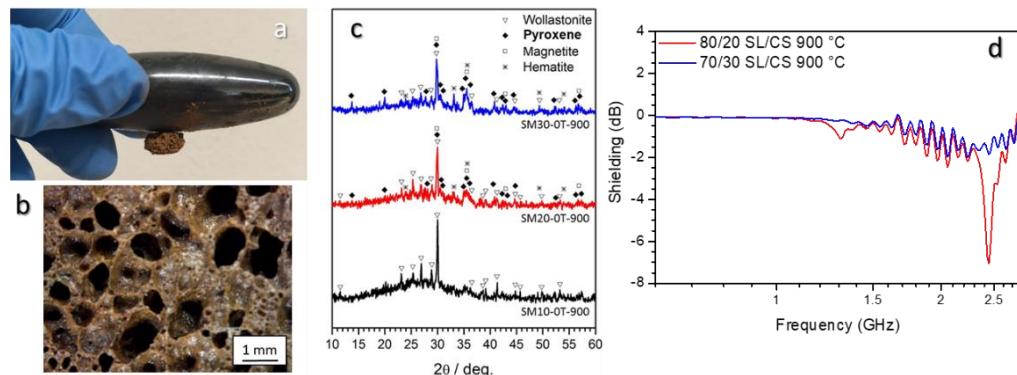
Table 2 reports some estimations of the bending strength of the solid phase for the foams shown in Figure 4, based on  $\varphi$  values of at least 0.8. Any glass-based cellular

material, in fact, is not “ideally closed-celled”, in its mechanical behaviour; membranes between adjacent cells (visible in Figure 4a, for soda-lime glass foams) do not collaborate in full, for the presence of pores, so that a good fitting of data is given by relatively high  $\varphi$  values. The effect of partial crystallisation on the crushing strength of glass-ceramic is not straightforward. On the one hand, it may increase the bending strength of the solid phase (visible from CEL2 and vitrified BA); on the other hand, the crystallisation may increase strongly the apparent viscosity of the glass, limiting any reshaping of pores upon firing and leading to poorly homogeneous materials. The structural disuniformity (see the foam from plasmastone/glass mixture, Figure 4c) may compromise the reinforcing effect. Finally, as brittle materials, porous glass-ceramics are subjected to a size effect, so that beyond differences in the distribution of solid phase between edges and faces, the strength increases with decreasing cell size (see the foam from vitrified BA, Figure 4d, exhibiting a particularly remarkable compressive strength).

Some crystal phases do not affect the strength, but are interesting for the functional properties. In particular, iron-rich phases, such as magnetite ( $Fe_3O_4$ ) and other ferrites (oxides with the general formula  $M^{2+}O \cdot Fe_2O_3$ ), are well known for their ferri-magnetic behaviour, that could be tuned by changing composition, processing temperature, annealing time, particle size (for frit-derived glass-ceramics), heating and cooling rates. As an example, Francis studied the annealing of a glass, from the melting of furnace slag and flue dust, for 2 h at 800 to 1000°C, and found that saturation magnetisation decreases as a consequence of the transformation of the magnetic species into non-magnetic phases.<sup>19</sup>

The ferri-magnetism implies the dissipation of electromagnetic energy, owing to magnetisation hysteresis, that could be exploited in many applications. As an example, Ponsot *et al.* obtained ferrimagnetic glass-ceramics, from the sintering of borosilicate waste glass with iron-rich slags (from copper and lead metallurgy), that could reach high temperatures (exceeding 300°C) after the application of an alternating magnetic field for very limited times (60 s).<sup>20</sup> The glass-ceramics could configure innovative heating elements (for cooking tops), considering the resistance to thermal shock (due the low expansion coefficient of the borosilicate glass matrix) and the chemical stability (confirmed by cytotoxicity studies). Further studies, *e.g.* in the field of electromagnetic shielding, are currently in progress on foams from alkali activation/gel casting/firing based on plasmastone-based foams, sintered at low temperature (800°C, Figure 6a) and mixtures of soda-lime glass and Cu metallurgy slag (see Table 1, Figure 6b). In particular, Cu slag leads to glass-ceramic foams owing to interaction between constituents, in turn causing the precipitation of Ca-Fe silicate (pyroxene) and iron oxides, in form of magnetite and hematite (Figure 6c), upon firing at 900°C. For an optimum slag content of 20 wt% the glass-ceramics exhibit some

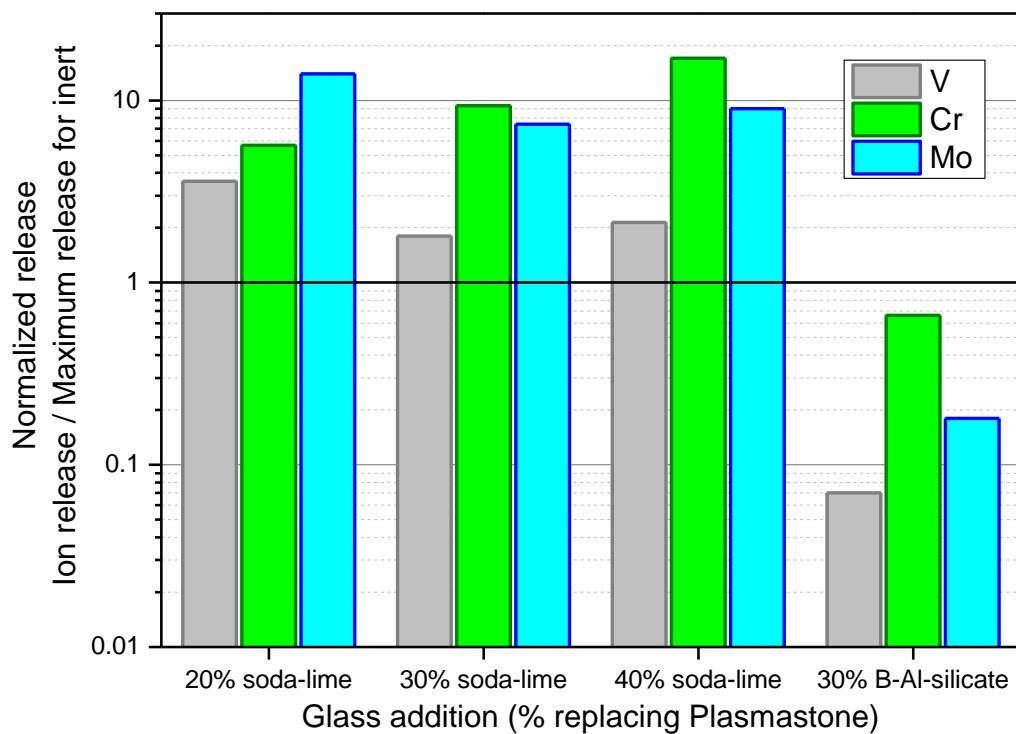
potential in electromagnetic shielding, owing to the observed absorption band at 2.4 GHz (Figure 6d); the obtained glass-ceramics could find a valuable application, despite the relatively low strength (see Table 2).



**Figure 6:** Obtainment of ferri-magnetic glass-ceramics: a) magnetic behaviour of plasmastone-based foam sintered at 800°C; b) microstructure of a foam from soda-lime glass and Cu slag (20%), obtained by alkali activation/gel casting, fired at 900°C; c) crystal phases as a function of Cu slag content; d) electro-magnetic shielding tests on selected foams

Any valorisation option has no actual sense if the developed materials do not exhibit an absolute stabilisation of pollutants from the adopted waste. The reference to a standard composition, provided by Slagsitalls (already recognised as stable materials), is specifically intended to optimise the chemical durability. The leaching performances of glass-ceramics, in fact, may be hard to predict, with some ions embedded in the crystal phases or in the residual glass phase. The previously mentioned “hybrid” approach may be helpful if a waste-derived glass is already available and remelting would not be possible and/or convenient. Glass from dismantled pharmaceutical vials (see Table 1), as an example, may be considered as an additive for plasmastone-based foams obtained by weak alkali activation/gelcasting. The practical absence of CaO determines some difficulties in the low temperature hardening (the amount of C-S-H developed is attributable only to plasmastone dissolution; 30% recycled glass means a reduction of 30% of the phase responsible for the hardening), but the chemical durability is much higher than that exhibited by foams with soda-lime glass as additive. Figure 7, in particular, shows the release of selected heavy metals (V, Cr, Mo), upon leaching tests, normalised on the thresholds for class D (=inert) materials, according to the Austrian Recycling Building Materials Ordinance.<sup>21</sup> Contrary to soda-lime glass-containing foams, the foams from the use of pharmaceutical glass can be considered as perfectly “safe”: V and Mo are nearly one order of magnitude below the threshold; Cr remains closer to the threshold, but more than one order of magnitude below compared to the leaching of materials deriving from soda-lime glass. The durability is favourably

affected by the overall reduction of alkali and by the enhancement of oxides with a stabilising action, such as  $B_2O_3$  and  $Al_2O_3$ .



**Figure 7:** Leaching of selected heavy metals from glass-ceramic foams (according to Austrian Recycling Building Materials Ordinance) derived from plasmastone/recycled glass mixtures

## Concluding remarks

The continuously increasing production of hazardous and toxic wastes undoubtedly favour the manufacturing of both monolithic and cellular glass-based materials, by application of viscous flow sintering. The extra costs for these treatments may be limited by a careful engineering of chemical compositions and well compensated by integrating the processing of glass-based products in a comprehensive “waste management chain”, according to which the starting glasses are not the only result of waste stabilisation, but are available as side products of gasification/metal extraction operations. The mixing of waste-derived glasses with recycled glasses generally provides some control on viscous flow sintering, crystallisation and chemical durability even *a posteriori*, *i.e.* not operating on the starting formulations. Finally, chemical components that could represent an issue for the overall processing of glass-ceramics, such as iron oxides, may actually be turned into an opportunity for extending the functionalities of the final products.

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# **PILOT ON INNOVATIVE SEPARATION AND VALORISATION TECHNIQUES IN CASE OF ELFM**

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## **Abstract**

This article describes the sampling and laboratory phase of a pilot project on innovative separation and valorisation techniques on landfill material. Based on the results of the sampling and laboratory phase, a full-scale pilot test will be carried out. The general objectives of the project are to determine the different fractions of waste, to optimise the separation, to separate the more valuable materials, to determine the purity of the different fractions and to determine the valorisation possibilities. The innovative character of the project is situated in the objective to combine technologies used in the processing of shredder waste and technologies used for the recycling of contaminated soils and debris. The materials used for the pilot come from a historical landfill with municipal household waste.

## **Introduction**

The Public Waste Agency of Flanders (OVAM) aims to further elaborate knowledge on innovative separation and valorisation techniques in Flanders based on the memorandum of Sustainable Resource Management of Landfills, which has been approved by the Flemish Government on October 16, 2015. This concept, also described as Enhanced Landfill Management & Mining (ELFM<sup>2</sup>), aims at a sustainable long-term management of (mostly former) landfills, including interim use, and the valorisation of its content and surface.

Traditionally, techniques such as sieving, crushing, hydrocyclones and magnet bands are used in an attempt to separate landfill material. In this project more innovative techniques will be looked at, of which an example would be eddy current separators, which are used in the shredder waste industry.

## **Methodology**

### **Case Study**

The chosen landfill for the project is a landfill situated in the municipality of Kruibeke - Antwerp, Belgium. This landfill is the ideal case because this is a non-active, closed landfill with a diversity of materials (municipal waste, industrial waste and construction materials). Besides the possible reuse of material (Waste-to-Material), the location also offers opportunities for sustainable redevelopment of the area (Waste-to-Land) and the elaboration of social added value. Therefore close communication and cooperation with the municipality is carried out.

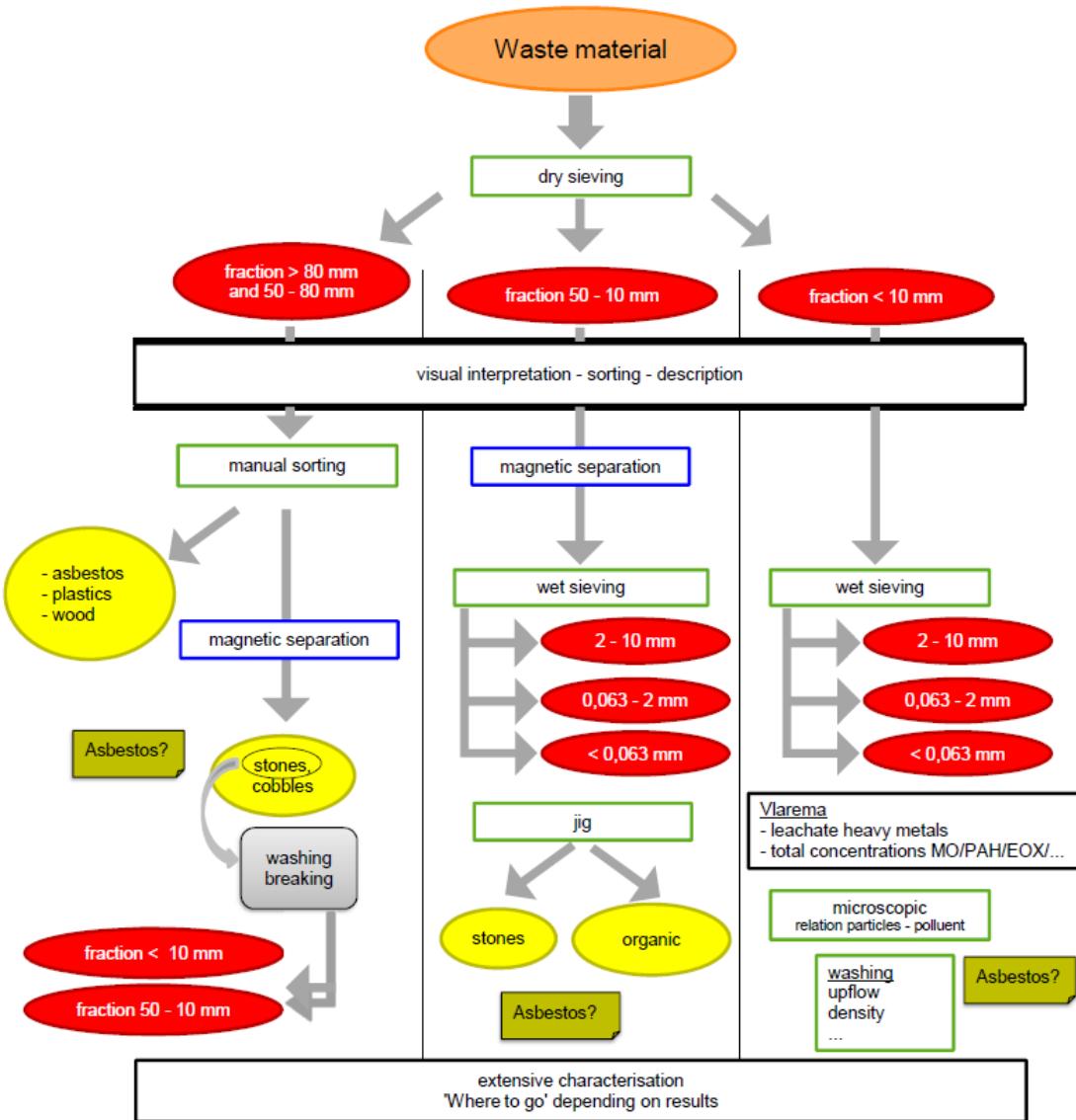
The total area of the landfill is approximately 4,000 m<sup>2</sup> with a total volume of approximately 10,000 m<sup>3</sup>. The landfill was used from 1960 until 1980. The pilot project consists of three phases: sampling, laboratory tests and pilot test. The first phase took place on June 16, 2017. A total of 195.40 tonnes of waste material was sampled for laboratory testing. The material was taken from five different locations in order to have a representative diversity of materials. At every sampling location a pit was dug until the original soil was encountered. The main findings of the sampling phase are the large presence of glass and stone material.

### **Laboratory characterisation set-up**

The purpose of the laboratory tests is an extensive characterisation of the waste material. Based on the characterisation, several separation techniques can be proposed and tested on a laboratory scale. Figure 1 shows the initial lab test flow diagram. During the laboratory tests this flow diagram needs to be adapted depending on the findings in every step. In a first step, the material is sieved to four different fractions. A sample of the biggest fraction is sorted out manually to evaluate the materials in this fraction. The fraction 10–50 mm goes through a wet sieving process which results in three different fractions: fines, sand and gravel. The different fractions are sorted out manually. This fraction is also separated in a jig, to separate the stone material from the organic material. The smallest fraction, 0-10 mm, is separated in a wet sieving process as well. Depending on the analysis results, the fraction is investigated under a microscope, to see the relation between the particles and pollutant.

### **Results**

All landfill material has first been dry screened with a vibratory screen in order to remove the > 50 mm oversize. This fraction was further split in a 50-80 mm fraction and a > 80 mm fraction. The remaining 0-50 mm fraction was dry screened by means of a drum screen, with a mesh size of 10 mm. The various fractions can be seen in Figure 2. The distribution of these fractions can be found in Table 1.



**Figure 1:** Lab testing flow diagram

**Table 1:** Mass balance after dry screening step

	< 10 mm	10–50 mm	50–80 mm	> 80 mm
<b>Mass (tonne)</b>	107.40	53.90	20.10	14.00
<b>Percentage of total</b>	55.0%	27.6%	10.3%	7.2%

Visually, the fraction 0–10 mm looks very homogeneous, almost soil-like. Some glass and wood fragments can be distinguished, but are fairly rare. The 10–50 mm fraction visually contains a lot of glass, wood, plastic etc. As the material is moist, also cohesive lumps formed of finer material are present in this fraction. This will be later confirmed in the particle size distribution. The 50–80 mm fraction seems to contain

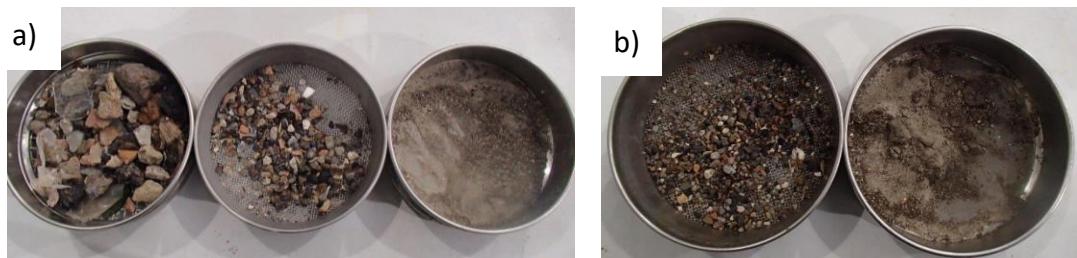
less glass, and much more bricks, along with lumps of finer material. Finally, the > 80 mm fraction contains mainly concrete, wood and plastics.



**Figure 2:** Various fractions generated during dry screening, with a) fraction > 80 mm, b) fraction 50-80 mm, c) fraction 10-50 mm and d) 0-10 mm

### Characterisation results

The 0–10 mm and the 10–50 mm fractions were sampled for further characterisation in DEME's Research lab. For both fractions a simplified particle size distribution (PSD) was made based on wet screening, and a classification was done on the coarser fractions from the 10 – 50 mm fraction. Table 2 shows the PSD for the 0–10 mm and the 10–50 mm fractions. The PSD for the 50–80 mm and > 80 mm fractions were estimated on a visual basis. It is clear that the 0–10 mm fraction mainly consists of very fine material: about 64.6% are fines (clay and silt, finer than 63 µm), 28.8% sand, and only 6.5% between 2 and 10 mm. As visually perceived, the 10–50 mm fraction indeed contains a lot of fine material: only 57% is really coarser than 10 mm (not shown in the table), the rest consists of fine gravel, sands and fines. The various fractions generated from the PSD analyses are shown in Figure 3.



**Figure 3:** Fractions washed out of the screen fractions 10–50 mm (a) and 0–10 mm (b). At the left the coarse gravel (> 10 mm), fine gravel (2–10 mm) and sand (0.063–2 mm) fractions are shown. On the right the fine gravel (2–10 mm) and sand (0.063–2 mm) fractions are shown.

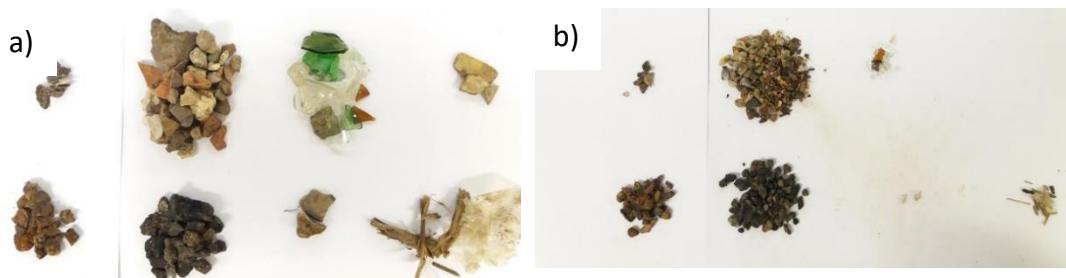
In Table 2 an overall mass balance is calculated. This shows that about 40% of the landfill material consists of fines, 22% sand, and 38% gravels (or coarse material). Two fractions obtained from the wet PSD testing on the 10–50 mm fraction were dried and characterised by means of manual sorting. This was done on the 2–10 mm fraction and on the 10–50 mm fraction. Table 3 shows the results. It can be seen that mainly the coarse gravel (> 10 mm), apart from stones (brick, concrete, pebbles), contains large amounts of glass and clinker. The finer gravel (2–10 mm) contains less glass, but higher amounts of iron(oxide) and clinker. The clinker was identified based on its colour; a loss-on-ignition test confirmed the material is partially coal. In the coarse gravel some sheets were found which are potentially asbestos containing. Pictures of the manual sorting can be seen in Figure 4.

**Table 2:** Overview of the split based on dry screening and (wet) particle size distribution

				Particle size distribution			Fraction distribution (ton dry matter)		
	Mass wet (tonne)	DMC	Mass dry (tonne)	< 63 µm	0.063–2 mm	> 2 mm	< 63 µm	0.063–2 mm	> 2 mm
							39.7%	22.3%	37.9%
Input	195.4		168.0				66.8	37.5	63.6
< 10 mm	107.4	82%	88.1	64.6%	28.8%	6.5%	56.9	25.4	5.7
10–50 mm	53.9	90%	48.5	15.2%	14.9%	69.9%	7.4	7.2	33.9
50–80 mm	20.1	90%	18.1	10%	20%	70%	1.8	3.6	12.7
> 80 mm	14.0	95%	13.3	5%	10%	85%	0.7	1.3	11.3

**Table 3:** Results of manual sorting on the fractions obtained from the 10-50 mm fraction; the percentages in the last column are calculated based on the results of the particle size distribution

	10 - 50 mm	2 – 10 mm	2 – 50 mm
	wt%	wt%	wt%
stones	50.9%	56.7%	51.9%
glass	18.3%	4.2%	15.8%
sheet	1.9%	0.0%	1.6%
iron(oxide)	5.6%	13.9%	7.1%
clinker	20.7%	24.2%	21.4%
bone	1.3%	0.1%	1.1%
organic	0.4%	0.0%	0.3%
non-defined	0.8%	1.0%	0.8%



**Figure 4:** Results of manual sorting from 10–50 mm fraction, with a) manual sorting of > 10 mm fraction, and b) manual sorting of 2–10 mm fraction

## Conclusion and discussion

It can be concluded that about 40% of the landfill material consists of fines, 22% sand fraction, and 38% gravel fraction (included very coarse oversize material). The fines and sand are potentially reusable, but chemical analyses are not yet ready. The gravel fraction contains a lot of gravel, clinker, and iron(oxide), and potentially some asbestos, and, therefore, the gravel should be considered of poor quality and hard to put on the market for recycling. Further steps in the project consist of separation tests on lab scale, followed by a full-scale pilot test. The separation steps to be taken will depend on the final results of the characterisation. The aim is to find the best possible combination of separation techniques, based on existing technologies of different industries, such as separation techniques used in the processing of shredder waste and the treatment of contaminated soils and debris.

# METALLURGICAL CONCEPTS FOR RECYCLING OF BOTTOM ASHES FROM MUNICIPAL WASTE INCINERATORS

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## Abstract

In several European countries, incineration remains the main means of municipal solid waste (MSW) processing.<sup>1</sup> With pre-processing prior to incineration, inorganics and metal fractions are recovered by mechanical separation. However, there remains around 7% of metals mixed with inorganics and combustion residues which collect in the bottom of incineration furnaces. For Germany alone, bottom ash represents almost 4.8 million tonnes a year.<sup>9</sup> Currently, bottom ash is re-used in road works; however, the contained metals may cause damage to vehicles.<sup>8</sup> In recent years, scientists are looking at these materials as a precursor to produce Inorganic Polymers (IPs) that could be used to create eco-friendly and sustainable construction materials.<sup>7</sup> In this study, a robust characterisation analysis was undertaken with the objective of defining the most attractive strategies for pre-treating the ash fractions. Mechanical separation, leaching and pyrometallurgical treatment of the different ash fractions was also evaluated to maximise metal recovery. Finally, the inorganic phase produced as result of pyrometallurgical treatments was analysed and studied as a suitable inorganic polymer precursor.

## Introduction

Landfills are still the main disposal systems for Municipal Solid Waste (MSW). With more than 500,000 Landfills in Europe, this kind of disposal represents a serious environmental risk due to hazardous compounds. Several European countries turn to incineration as a way to valorise MSW as an energy source.<sup>1,3</sup> Incinerated residues represent 30% of the original MSW, where bottom ashes are the main residues.<sup>2,3</sup> Around 20 million tonnes of MSW incineration bottom ash (MSWI BA) is produced every year in Europe.<sup>1,3</sup> The use these ashes for construction materials after metal extraction becomes an economical route to exploit.<sup>4,5</sup> However, the presence of heavy metals and a wide range of complex compounds is the real limitation to use MSWI BA as a promising raw material.<sup>4,6</sup> This paper describes a combination of different approaches to recover almost all the valuable elements contained in MSWI Bottom ash as well as how to transform a complex and hazardous material into a safe

and stable vitrified slag that could be used as precursor for cements, inorganic polymers, ceramics, etc.<sup>7</sup>

## Methodology

In order to evaluate the quality and proportion of the metals inside MSWI BA, four different strategies were carried out (Figure 1). In all of them, an electrical arc furnace was used to melt the BA at the end. In strategies 2, 3 and 4, metals were recovered by mechanical separation. The last strategy introduces a second step of mechanical treatment to clean the metals, and a hydrometallurgical treatment to extract valuable metals from the finest BA fraction.

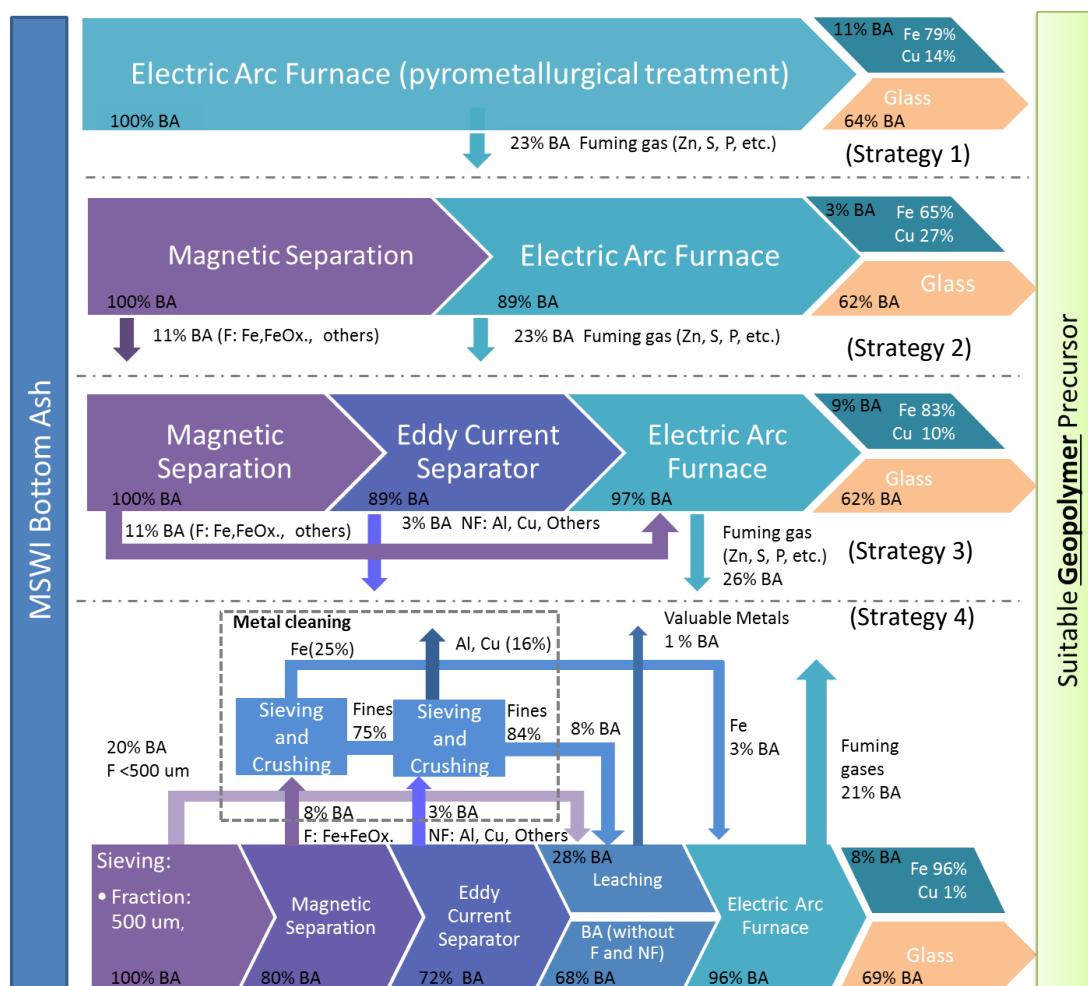


Figure 1: Strategies to valorise MSWI Bottom ash

## Sample preparation

For this study, 100 kg of wet MSWI BA with metals, provided by the company AVR in Netherlands, were consumed. BA was first dried at 200°C for 24 hours. Sieves between 45 µm and 10 mm, a jaw crusher and planetary ball mills were used to create

fractions for analysing. A magnet was used to hand-recover all BA magnetic particles. This method is more efficient than the traditional suspension-magnet-separator<sup>8</sup> used by industry. Non-ferrous-metals (NF-metals) were collected using an eddy-current-separator (ECS). A Jaw crusher was used to separate the fractions obtained by mechanical separation into metals and non-metals. Sifting these fractions, a clean stream of metal was obtained.

### **Chemical Analysis**

PANanalytical WDXRF spectrometer was used for the analysis of the final vitrified slag and bottom ash fractions; and a Portable XRF analyser (Thermo Fisher NITON XL3t 600) was used for metals and the fraction used for the leaching experiments. A PANanalytical X'Pert<sup>3</sup> x-ray diffractometer and HighScore software were employed for the mineralogical analyses. The mineralogical detection was made following the method of C. Kirby and J. Rimstidt.<sup>9</sup>

### **Leaching**

Three different solutions were performed to examine the yield of recovery of different elements present in the BA fraction < 500 µm. One using sulphuric acid with concentrations of 1 M, 2 M and 4 M; and the others with nitric and chlorhydric acid with a concentration 4 M in order to compare the performance of the acids. Tests were conducted at 50°C using a liquid-to-solid ratio (l/s) of 20 during 2 hours.

### **Pyrometallurgical treatment**

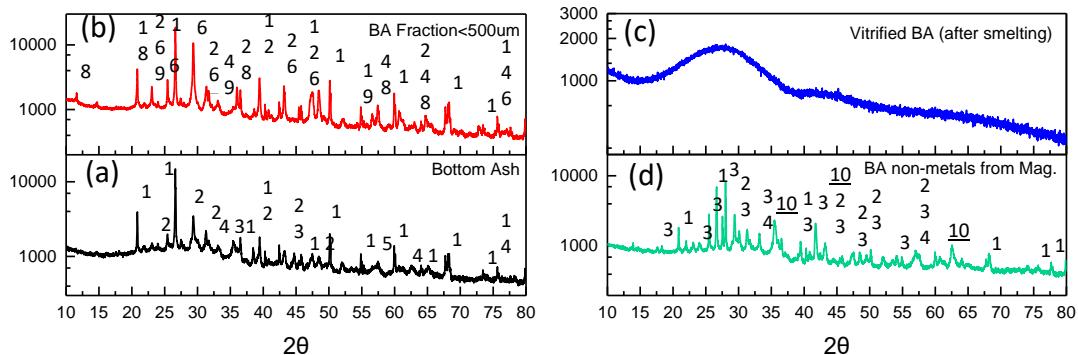
For this study a lab-scale electric arc furnace (EAF) operating in single-phase alternating current mode was used. This furnace uses a graphite electrode of 50 mm at the top and on the base the contra-electrode serving as a crucible. The graphite crucible with 150 mm diameter and 220 mm height could carry up to 3 kg of BA. The power of the furnace was set in order to maintain a temperature of around 1400-1500°C.

### **Inorganic polymer preparation**

Vitrified slag after smelting was cooled down under air inside a metallic bucket coated with ZrO<sub>2</sub>. The slag was first milled for 10 hours in an Attritor mill to obtain a specific surface of 4200 g.cm<sup>-2</sup> (EN196-6) and then mixed with three different NaOH solutions using concentrations of 3 M, 6 M and 9 M. The liquid-to-solid ratio was 0.35. Finally, each mixture was poured into 2 x 2 x 8 cm<sup>3</sup> steel moulds, wrapped in plastic foil and then and then cured at 20°C for 45 days. Compressive strength tests were performed based on EN196-1.<sup>6</sup>

## Results

MSWI BA has a large amount of different compounds. XRD analyses reveal the presence of large quantities of carbonates and sulphates. Comparing XRF analysis (Table 1a) with these XRD profiles (Figure 2a and 2b), both elements represent 4.5 wt% and 2.2 wt%, respectively. The presence of these elements is higher in the finest fraction (BA < 500 $\mu$ m) where, for example, carbon represents 13 wt%, being present almost completely in Ca-carbonate. These phases are the most significant after amorphous phases and quartz (~65 wt%).



**Figure 2:** XRD profiles: (a) MSWI BA, (b) MSWI BA fraction <500 $\mu$ m, (c) Vitrified slag after MSWI BA smelting and (d) non-metallic fraction after cleaning metals. (1) quartz, (2) calcite, (3) magnetite, (4) hematite, (5) aluminium, (6) anhydrite, (7) halite, (8) gypsum, (9) perovskite, (10) cuprospinel

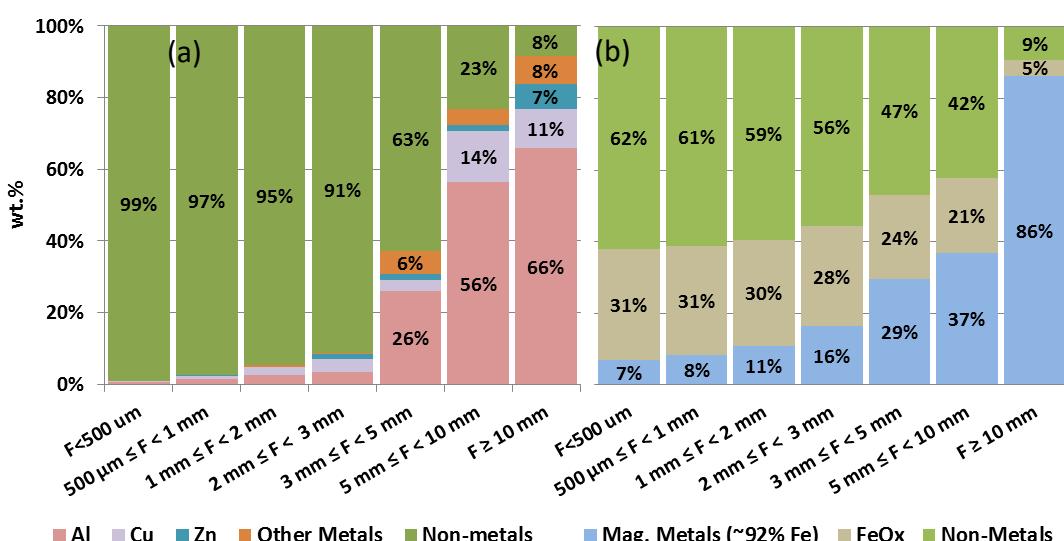
**Table 1:** XRF analysis of MSWI BA

(a) MSWI BA (wt%)									
Fraction	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	Fe <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	C	S
MSWI BA	39.7	16.1	8.6	4	9	1.8	0.8	4.7	0.8
BA<500 $\mu$ m	19.4	26	7.3	0.6	5	1.7	1.1	13.1	1.3
(b) Trace element composition of MSWI BA fractions (ppm).									
Fractions	Zn	Cu	Pb	Cr	Sn	Co	Ag		
Non-metals from mag. sep.	5400	2090	930	1310	340	430	130		
Non-metals from ECS	3262	5986	842	382	319	0	20		
BA fraction<500 $\mu$ m	11670	2650	2340	550	290	0	0		
(c) Results of smelting MSWI BA in an EAF (wt%)									
Metal	Fe	Cu	Si	P	Cr	Mn	Ni	Co	Sn
Strategy 1	79.0	14.5	1.2	1.6	0.71	0.32	0.39	0.22	0.34
Strategy 2	65.10	26.70	1.30	1.90	1.50	0.92	0.70	0.50	0.27
Strategy 3	81.20	12.60	1.40	1.67	0.48	0.21	0.53	0.61	0.22
Vitrified slag	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	Fe <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>
Strategy 1	49.3	20.5	18.7	4.5	0.1	2.6	0.71	1.1	0.05

MSW is always first incinerated and then quenched in water.<sup>3</sup> These two processes have a strong influence on the metal quality. Ferrous metals are partially oxidised during the incineration and then corroded in contact with wet ashes (alkaline medium). Non-ferrous-metals such as aluminium, zinc, lead or tin are molten first and partially oxidised. Other metals such as copper do not suffer major changes in the BA.

The elements recovered by magnetic separation were between 8 and 10 wt% of the BA. Several reviews expose that ferrous metals represent between 7 and 10 wt% of BA<sup>3,10,11</sup> but no description is made about the quality of these metals. After mechanical cleaning of the magnetics, ferrous metals represent just 24 wt% of this fraction (3 wt% of BA). In the magnetic fraction there are almost 30 wt% of iron oxides (Figure 3b) nevertheless on average, there are 10 wt% of iron oxides spread in the ashes (Table 1a). XRD profile of Figure 2d shows that the half of these oxides are magnetite (created during the incineration) and the other part, hematite (produced by corrosion).

In the case of separation by eddy currents, recovered elements represent 3 wt% of BA but after mechanical cleaning, NF-metals depict 18 wt% of this fraction (0.6 wt% of BA). ECS works well for particles larger than 5 mm (Figure 3a). Aluminium represents 70% of metals separated by ECS but has a poor quality because it was molten and strongly polluted during the incineration.



**Figure 3:** Mechanical separation: (a) eddy-current-separator and (b) magnetic separation

### Pyrometallurgical treatment

Smelting BA has several advantages, such as the reduction of all iron oxides using the carbon present in these ashes (~ 5 wt%), re-melting the metals and transforming all the inorganic compounds into a vitrified slag (see Figure 5). After smelting, the iron

recovered was 9 wt% of BA against 3 wt% obtained after mechanical cleaning (Figure 1-strategy 4). At high temperature, almost all heavy metals leave the slag and can be recovered in the fly ash.

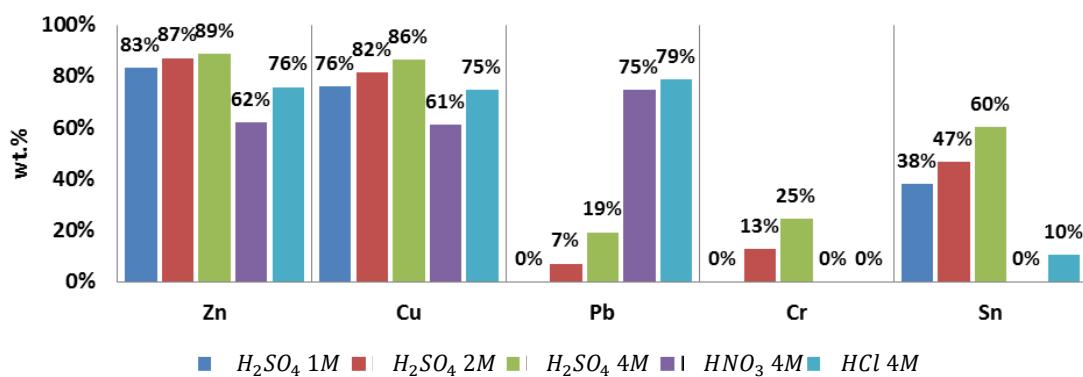


**Figure 4:** Final products after pyrometallurgical treatment of MSWI BA

Copper is one the most difficult elements to extract from bottom ash. Regarding the result of strategy 1 (Figure 1) there is between 1 and 1.5 wt% of copper in the bottom ash. By ECS only a fifth part was extracted. The magnetic and the finest fraction of bottom ash also contain copper (Table 1b and Figure 1 - strategy 2/3). Except for the proportion of aluminium oxide that is reduced by 10 percent in vitrified slag produced in the strategies 3 and 4 (aluminium recovered with ECS), the slag composition remains practically unchanged.

### Leaching experiments

The non-metallic-fractions recovered after mechanical cleaning show the presence of copper, zinc, lead and silver. The elements in Table 1b represent a potential source of valuable metals that can be recovered by hydrometallurgy.



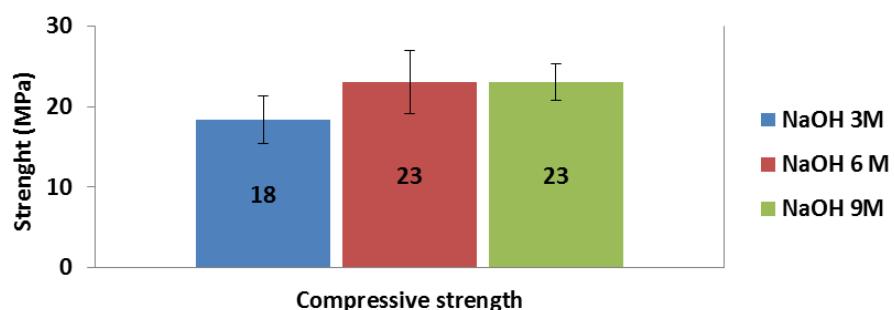
**Figure 5:** Extraction Yield for of valuable elements present in the MSWI BA

Results of leaching experiment for the finest BA fraction are shown in Figure 5. Solutions containing sulphuric acid seem to be effective to extract the majority of

valuable elements from BA, except lead where nitric acid was more effective. No major differences were observed between sulphuric acid concentrations of 2 M and 4 M.

### Inorganic polymers

The XRD profile in Figure 2c revealed that vitrified slags had a fully amorphous structure. During the preparation of inorganic polymer pastes, the mixing glass/alkali-solution produced gas bubbles altering the quality. Small metallic particles at the interface metal/slag are the origin of this defect. The results are exposed in Figure 6. Inorganic polymer pastes produced from vitrified slags (Figure 4), carried out with very slow cooling, solidified well after 45 days. Even if the quality was not excellent due to the pollution with metals and alkali solutions still need to be optimised, these IPs produced from MSWI BA are a promising solution to recycle MSWI.



**Figure 6:** Mechanical properties of inorganic polymers produced from MSWI BA

### Conclusions

MSWI Bottom ash produced in moving grate incinerators contains a wide amount of species that could be avoided using other technologies such as gasifiers.<sup>3</sup> For this reason, it is usual to find unburned plastics, papers, textile, but also hazardous compounds such as asbestos or fiberglass which only can be destroyed at high temperatures. The finest BA fraction also contains large amounts of heavy metals. These metals could be extracted using strong leaching solution, nevertheless always a small amount of these remain in the ashes.

Eddy current separators are efficient to extract metals larger than 5 mm but below this size the efficiency falls.<sup>10</sup> The proportion of elements extracted using magnets and ECS are in the same order that those reported in other reviews.<sup>8,9,11</sup> However, after a second step of mechanical cleaning, the metals recovered were a quarter of these fractions. Examining the mass balance of the different processes carried out, it can be concluded that less than 20 wt% of non-ferrous metals are extracted by traditional separation techniques.

It was demonstrated that pyrometallurgical treatments effectively upgrade BA. In addition, the large content of commercial glass inside BA allows an amorphous structure after smelting. The composition and structure of the vitrified slag can be employed to produce inorganic polymers and some types of glass-ceramics. For these applications, it will be decisive to avoid any trace of metals, and if it is desired to increase reactivity, and thus the conversion of BA to slags followed by quenching is favoured.

## Acknowledgments

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# INFLUENCE OF MICROSTRUCTURE ON MECHANICAL STRENGTH OF ALKALI-ACTIVATED Fe-Si-Ca RICH MATERIALS

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## Introduction

Enhanced Landfill Mining is a novel integrated waste management concept seeking the recovery of valuable resources from landfill sites. In the ELFm concept, the maximisation of valorisation of individual material streams is considered as critical for environmental sustainability and economic viability of the concept. The gasification and vitrification of refuse derived fuel (RDF) derived from ELFm is expected to generate significant volumes of Fe-Si-Ca rich residues<sup>1,2</sup> of which the use as inorganic polymers (IP) precursors has been identified as a promising valorisation route.<sup>3,4</sup>

The use of these residues, commonly termed plasmastone as an IP precursor is incipient<sup>5</sup> and suggested applications include – among others - pavers<sup>3</sup>, mortars<sup>4</sup> and insulating building materials.<sup>6</sup> Aiming to contribute to the design and conceptual development of novel value-added plasmastone-based products, the present work aspires to identify the effect of different processing parameters on the synthesis of such IP binders. A Design of Experiments (DoE) methodology was used to evaluate the effect of three main compositional factors, their interaction, and the system responses.

## Experimental

A “Two-Level-Full-Factorial” design with a central point was employed in order to assess the influence of three variables (solid-to-liquid ratio, K<sub>2</sub>O/SiO<sub>2</sub> molar oxide ratio of mixture (solids and activating solution) and the KOH solution molarity) on IP properties. Their minimum and maximum values and the description of the experimental design are given in Table 1. A synthetic glass (further termed as PS) was used as IP precursor and its detailed production process can be found elsewhere.<sup>3</sup>

The glass was dried, homogenised and milled to a Blaine surface of approximately 360 m<sup>2</sup>/kg; and is composed of (in wt%) SiO<sub>2</sub> 35.1, CaO 22.9, Fe<sub>2</sub>O<sub>3</sub> 22.8, Al<sub>2</sub>O<sub>3</sub> 16.1, MgO 1.4, K<sub>2</sub>O 0.6, TiO<sub>2</sub> 0.6, Na<sub>2</sub>O 0.3, Mn<sub>2</sub>O<sub>3</sub> 0.1, SO<sub>3</sub> 0.1 and 1.9% loss on ignition (LOI). Commercially available Si and Si-Al rich powdered material were used as admixtures, at levels not exceeding 10 wt%. The use of M-silicates, where M is Na and/or K, was avoided to reduce IPs production cost.<sup>7</sup> Potassium hydroxide solutions were used to provide the alkaline medium and demineralised water was added to achieve the pre-defined S/L ratio. In PS3 and PS8 samples additional 7.69 g/kg<sub>slurry</sub> of demineralised water was provided to achieve the required flowability to allow proper casting of the samples. The mixture followed the procedure described elsewhere,<sup>8</sup> but mixing speed was increased to 140 rpm. The slurries were cast into 4x4x16 cm<sup>3</sup> moulds and cured for 24 h at 20 °C and 95% RH. Afterwards, the samples were demoulded and kept at room conditions (20 °C and 65% RH).

X-ray fluorescence was used to determine the chemical composition of the raw materials. The IPs' mineralogical composition was assessed by X-ray diffraction. Scanning electron microscopy equipped with energy dispersive X-ray spectrometry was used to evaluate IPs microstructure. Archimedes method was employed to evaluate the IP water absorption. Open porosity was estimated as described in literature<sup>8</sup> while IPs' apparent density was determined by the relation between the weight and volume of each sample. The flexural and compressive strength of the cured IP samples were determined according to the EN196-1:2016. The experimental error was assessed by testing two samples for each formulation and curing age that were produced independently one from the other.

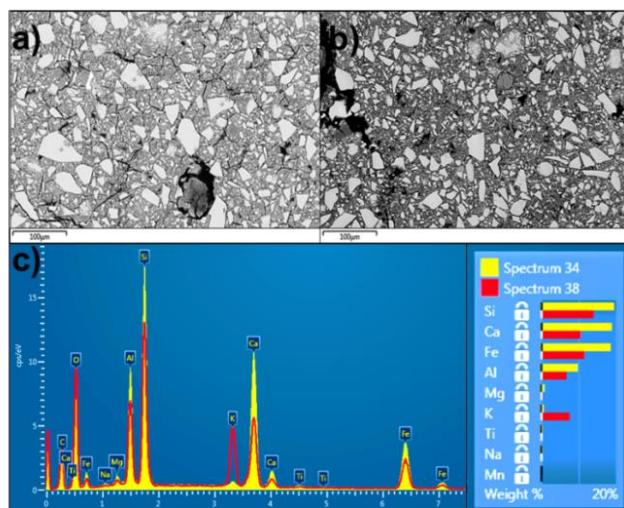
**Table 1:** DoE experimental plan

Code	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9
S/L	2.50		2.90		2.70	2.50		2.90	
K <sub>2</sub> O/SiO <sub>2</sub>	0.200	0.170	0.200	0.170	0.185	0.200	0.170	0.200	0.170
KOH mol/L		14			12		10		

## Results and discussion

Figure 1a and 1b show representative SEM micrographs of samples after 28 days of curing. Unreacted particles showed that precursors' complete dissolution did not occur. The high content of solid precursors limited dissolution, but all samples exhibited a homogeneous matrix where undissolved particles act as small-sized aggregates. The K<sub>2</sub>O/SiO<sub>2</sub> molar oxide ratio seemed to affect the degree of dissolution while the change in KOH molarity induced less pronounced microstructural changes. Comparing samples with similar S/L and KOH molarity, e.g. PS1 and PS2 (Figure 1), suggests that as the K<sub>2</sub>O/SiO<sub>2</sub> molar oxide ratio decreases, the content of unreacted

particles rises. Still, quantitative analysis is needed to describe the impact of the investigated compositional factors on precursors' degree of dissolution. EDS analyses revealed a binder phase predominantly composed of Si, Al, Fe, Ca and K, while undissolved particle spectra were in line with PS chemical composition. Elemental mapping did not suggest crystalline precipitations, in line with XRD data and SEM observations. The XRD patterns of the IP revealed their amorphous nature, with only one low-intensity crystalline diffraction peak identified as calcite (diffraction patterns not shown here for sake of brevity).



**Figure 1:** SEM micrographs of sample PS1 (a) and PS2 (b) and representative EDS spectra from sample PS1 where spectrum #34 shows PS unreactive particles and spectrum #38 the binder (c).

Spherical large size pores were observed and can be attributed to entrapped air during mixing; no correlation was found between their amount and size and the studied compositional parameters. Length and size of micro-cracks seem to be governed by the K<sub>2</sub>O/SiO<sub>2</sub> molar ratio. Three simultaneous effects may contribute to such behaviour: (i) crack development and propagation being limited by the presence of undissolved particles which was incremented by lowering the K<sub>2</sub>O/SiO<sub>2</sub> molar ratio<sup>4</sup>; (ii) a delay effect on elasticity development, as higher H<sub>2</sub>O/K<sub>2</sub>O ratios<sup>9</sup> decrease the rate of IP binder formation, resulting in lower autogenous shrinkage and (iii) lower polymerisation degree resulting in less intensive exothermic reaction, hence decreasing the internal temperature during the polycondensation process.<sup>3</sup> Nonetheless, such pores and micro-cracks did not have a significant influence on the overall open porosity and water absorption capacity of the IPs, suggesting their closed nature and low connectivity. Still, S/L seems to determine density and open porosity, whereas increasing the K<sub>2</sub>O/SiO<sub>2</sub> ratio contributes to further densification. Rising the K<sub>2</sub>O/SiO<sub>2</sub> ratio maximises the binder formation, leading to a more homogenous binder matrix. Regardless of the beneficial effect of limiting crack formation, samples PS3 and PS8 showed the lowest water absorption and open

porosity values. The KOH molarity impact can also be seen, and samples produced with 10 M KOH solution are slightly less porous than their 14 M KOH counterparts. In fact, by combining high *S/L* and K<sub>2</sub>O/SiO<sub>2</sub> ratios and using 10 M KOH solution the highest density was achieved ( $2.30 \pm 0.02 \text{ g/cm}^3$ ).

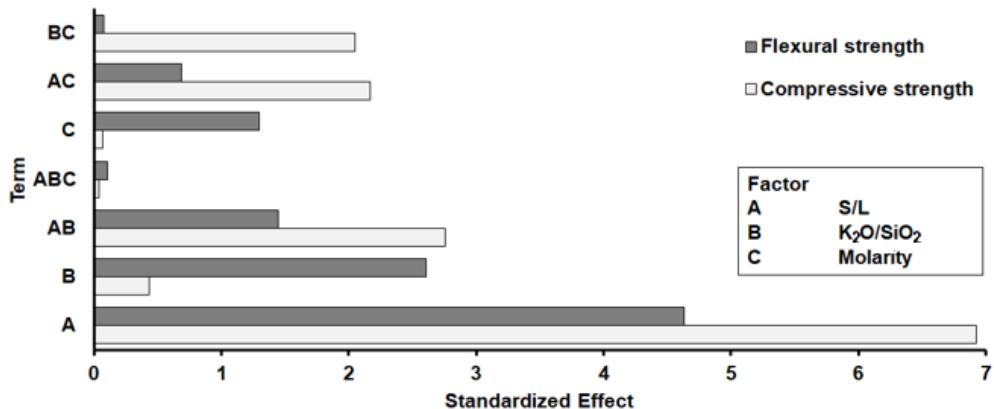
**Table 2:** IPs apparent density, open porosity, water absorption, flexural and compressive strength and corresponding standard deviations after 28 days of curing

Code	Apparent density (g/cm <sup>3</sup> )	Open porosity (%)	Water absorption (%)	Flexural strength (MPa)	Compressive strength (MPa)
PS1	2.21±0.00	2.27±0.07	1.04±0.03	2.8±0.0	88.2±0.4
PS2	2.13±0.01	2.99±0.16	1.41±0.07	2.2±0.3	76.1±1.5
PS3	2.29±0.04	0.93±0.01	0.41±0.01	5.1±0.2	94.2±0.0
PS4	2.27±0.01	1.50±0.02	0.67±0.01	3.3±0.9	93.8±6.2
PS5	2.21±0.01	1.34±0.18	0.61±0.08	3.3±0.1	94.6±2.4
PS6	2.20±0.01	1.55±0.39	0.71±0.18	3.0±0.3	78.9±3.4
PS7	2.13±0.01	2.10±0.07	0.99±0.04	2.5±0.7	75.0±1.6
PS8	2.30±0.02	0.68±0.18	0.29±0.09	6.0±1.5	93.6±0.1
PS9	2.25±0.01	1.16±0.09	0.52±0.04	4.2±0.1	105.5±5.2

IPs mechanical properties were measured after 7 and 28 days of curing and the highest mechanical performances were achieved with samples produced with *S/L* = 2.90, namely samples PS3, 4, 8 and 9 (Table 2). Flexural strength diminishes over time, while the compressive strength exhibits the opposite trend (only 28<sup>th</sup> day data shown here for sake of brevity). As previously reported,<sup>8</sup> the polymerisation reactions are not concluded after 7 days of curing and the on-going reorganisation of the structure leads to an increase of compressive strength over time. Nonetheless, the increase of rigidity of highly cross-linked structures can lead to poor flexural performances. In fact, a reduction of IP flexural strength over time was observed in all samples (ranging from 14.8 to 46.0%). The different relative influence of each compositional parameter and their synergistic effects on strength development can be depicted through its standardised effect, shown in Figure 2, while the flexural and compressive responses are shown in Figure 3.

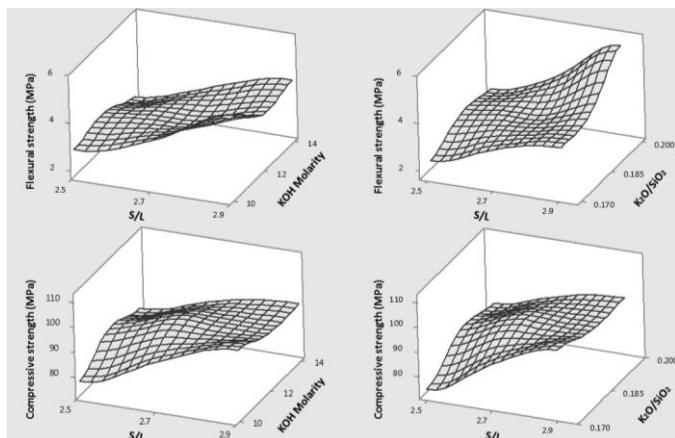
In general, decreasing the *S/L* ratio is detrimental to strength development and its dominant character affects both flexural and compressive strength. KOH molarity assumes a significant role regarding the flexural strength development while its synergistic effects with *S/L* and K<sub>2</sub>O/SiO<sub>2</sub> has a significant impact on compressive strength (Figure 2). In high *S/L* formulations, rising K<sub>2</sub>O/SiO<sub>2</sub> molar ratio promoted better flexural strengths, whereas in samples prepared with lower *S/L* ratio no significant changes occurred. Compressive strength was particularly enhanced when

$K_2O/SiO_2$  ratio was raised in formulations prepared with  $S/L = 2.50$ , but no evident beneficial effect can be seen in higher  $S/L$  ratios (Figure 3).



**Figure 2:** Standardised effect of compositional parameters on flexural and compressive strength after 28 days of curing

In IP synthesis, compositional and processing parameters are often considered individually underestimating their combined effects. The results presented herein confirmed the relevancy of synergic effects on IPs properties (as identifiable in Figure 2) and corroborate the necessity for more elaborative models, integrating not only singular compositional parameters but also their combined effects. These subjects will be addressed by the authors in future works.



**Figure 3:** Influence of compositional parameters and their synergistic effects on IPs flexural and compressive strength after 28 days of curing

## Conclusions

In the present work, Fe-Si-Ca rich inorganic polymeric binders (IPs) were synthesised with high contents of Fe-Si-Ca rich residues (86.7 wt%), no Na,K-silicate solutions and low curing temperature (20°C). Results showed that IP properties can be controlled by proper mix design. Solid-to-liquid and  $K_2O/SiO_2$  ratios were found to be the main

governing factors, whereas the influence of KOH molarity was less significant for the investigated IP properties. The produced IPs presented low open porosity (< 3.0%) and water absorption (< 1.41%), and considerable flexural (up to 6 MPa) and compressive strength (up to 105.5 MPa) after 28 days of curing. Further research should be conducted to assess the influence of other compositional (*e.g.* SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>/(Al<sub>2</sub>O<sub>3</sub>+Fe<sub>2</sub>O<sub>3</sub>)) and processing factors (*e.g.* mixing, curing conditions). The results herein constitute the first contribution towards a model where Fe-Si-Ca-rich IP binder properties can be predicted and tailored by adjusting the mix design while suppressing the production cost. This approach will ultimately make these materials more attractive for real-life applications, and by doing so, facilitates the transition to a circular economy.

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# DEVELOPMENT AND CHARACTERISATION OF DENSE WASTE-DERIVED GLASS-CERAMICS

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## Introduction

Landfilling of waste has been employed for centuries as a low-cost manner for managing waste, which can provoke known serious issues to environment and society such as long-term methane emissions and local pollution issues.<sup>1</sup> Enhanced Landfill Mining (ELFM) has a potential to be a solution not only for the management of existing landfills, but also for current problems related to the limited availability of resources and energy production. *Ex situ* ELFM consists of excavating landfills and seeks maximum resources recovery in an efficient way. In addition, the fraction of waste that cannot be recovered can be used to generate energy by employing clean technologies such as plasma gasification.<sup>2</sup> During this process, a vitrified residue named plasmastone is generated, which can then be upcycled for developing building materials such as inorganic polymer binder.<sup>2,3</sup> Plasmastone can contain a high content of iron oxide which aids in the nucleation and crystallisation of glass during sintering.<sup>4</sup> Therefore, this glassy material could also be applied in the development of glass-ceramic materials without adding a nucleating agent by sintering with concurrent crystallisation (sinter-crystallisation).<sup>5</sup> However, as plasmastone is easily crystallised, its densification can be hindered due to an increase of the apparent viscosity of the glass caused by the formation of crystals during firing.<sup>6</sup> An option to produce dense glass-ceramics made with a glass sensitive to crystallisation is to introduce another glass that is hardly crystallised and can be easily densified by viscous flow, such as soda-lime glass (SLG).<sup>7</sup> Based on this, this paper reports the production, characterisation and environmental impact assessment of dense glass-ceramics made with a mixture of fine powders of plasmastone, recycled SLG and kaolin clay by cold pressing and sinter-crystallisation to be employed as tiles.

## Materials and Methods

Plasmastone (particle size < 75 µm) was provided by Scanarc (Sweden) with the following main composition: SiO<sub>2</sub>: 37.3 (wt%); CaO: 22.9; Fe<sub>2</sub>O<sub>3</sub>: 20.9; Al<sub>2</sub>O<sub>3</sub>: 12.8;

MgO: 2.4 and Na<sub>2</sub>O: 1.1. In addition, this material also contained metals like Cu (7124 ppm), Cr (406 ppm) and Ni (203 ppm), which exceed the Austrian limit values to be used as secondary resource in building materials. SLG (mean particle size of 30 µm) was provided by the company SASIL SpA (Italy). SLG, a fine powder, composes the residual waste glass fraction obtained after colour selection and removal of metallic and polymeric residues in glass recycling.<sup>8</sup> The main composition of this glass was SiO<sub>2</sub>: 71.9 (wt%); Na<sub>2</sub>O: 14.3; CaO: 7.5; MgO: 4.0; Al<sub>2</sub>O<sub>3</sub>: 1.2.<sup>9</sup> Sintered plasmastone derived glass-ceramics were obtained by uniaxially pressing a fine mixture of powders of 45 wt% plasmastone/45 wt% SLG/10 wt% white kaolin clay at 50 MPa in a steel die of squared section (50 mm). The green tile was dried overnight at 75°C and fired at 1000°C for 30 min with heating and cooling rates of approximately 40°C/min.

The mineralogical composition of powdered glass-ceramics was determined by X-Ray diffraction (XRD) (Bruker D8 Advance, Germany). The density was measured according to the Archimedes' method and water absorption according to the boiling method. The dynamic elastic modulus was measured using non-destructive dynamic resonance (E). Vickers microhardness was measured applying a load of 9.8 N and porosity was determined using the software ImageJ on micrographs obtained by scanning electron microscopy.

A four-point bending test (32 mm outer span, 8 mm inner span) was performed using an Instron 1121 UTS instrument (Instron, USA) on 15 specimens (35.1 ± 1 mm X 3.5 ± 0.2 mm X 3.1 ± 0.1 mm) with cross-head speed of 1 mm/min. Weibull statistics was applied according to Barsoum,<sup>10</sup> obtaining the Weibull modulus (*m*) and the characteristic strength ( $\sigma_0^{4pt}$ ). The equivalent strength for three-point configuration was estimated by using scaling equations based on Weibull modulus and under the hypothesis of flaws happening with a volume (*Vf*) or surface (*Sf*) distribution.<sup>11</sup>

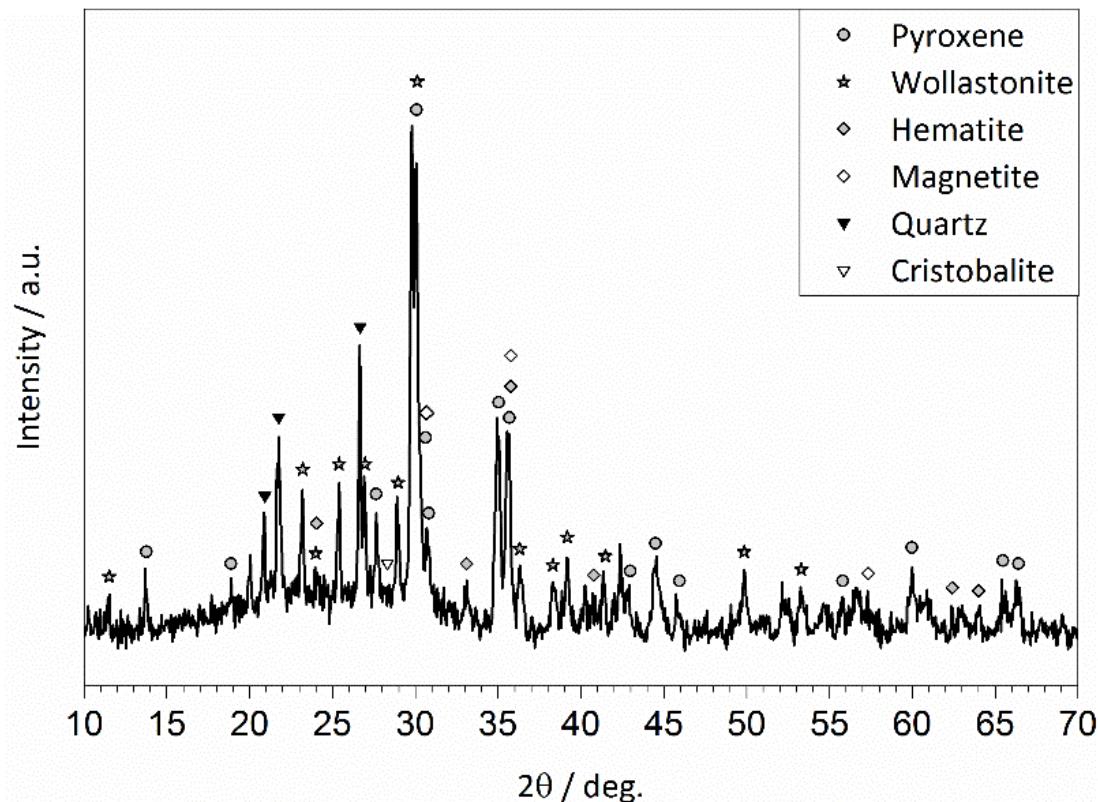
Leaching tests were performed following the ÖNORM EN 12457-4 (waste) with a liquid (distilled water) to solid ratio of 10. A commercial tile of "Ceramiche di Sassuolo" (Gruppo B II b) was used as control, as the use of recycled materials is only allowed as it can be proved that the environmental impact of the recycled product is not worse than that of a competing product from primary raw materials, according to Austrian Waste Management 2002. Inductively coupled plasma mass spectrometry and ion chromatography were used to measure the contents of heavy metals in the leachates and the Austrian Recycling Building Materials Ordinance was used as a reference.

The sample was analysed for distribution of main and trace elements using microprobe analysis (Jeol JXA 8200 Superprobe) after polishing the materials using 1 µm-sized diamond suspension and diamond spray followed by coating with a fine

layer of carbon. Main and trace elements were measured in five points of each phase. These phases have been previously found in the XRD pattern and then identified by EDS.

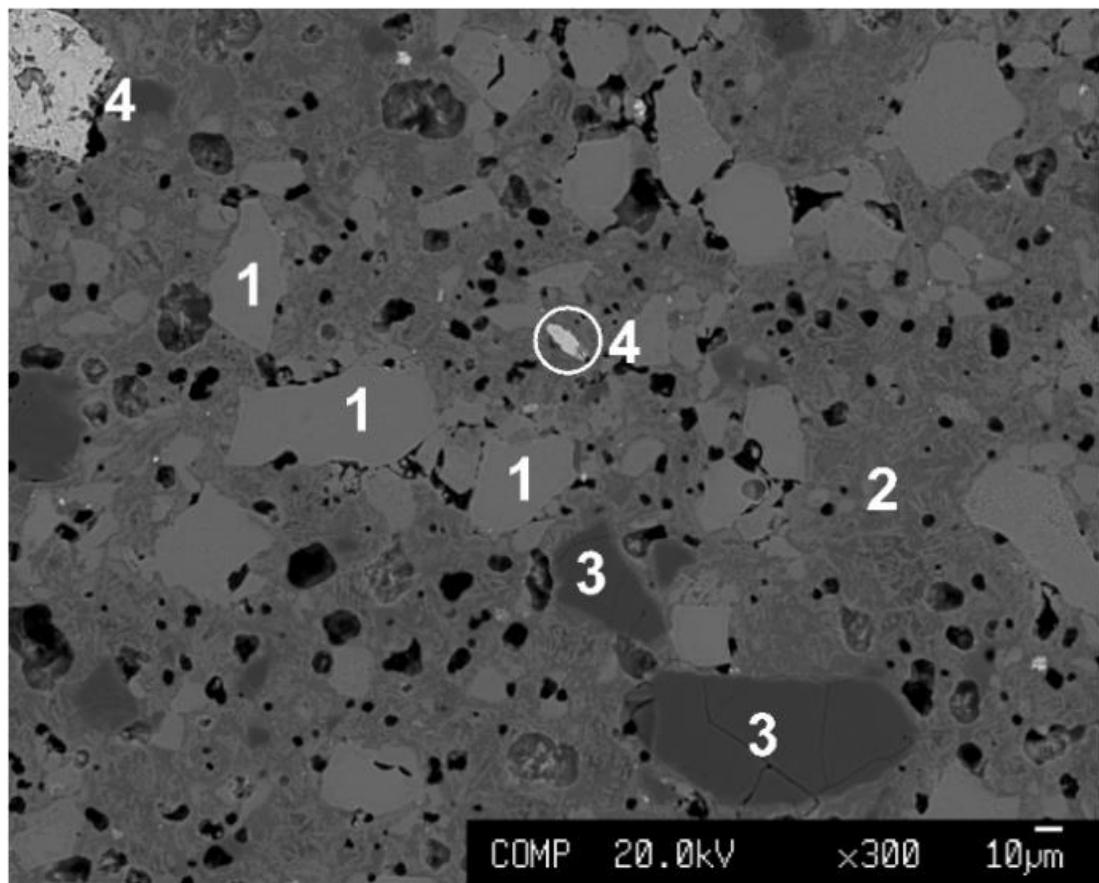
## Results and Discussion

XRD analysis (Figure 1) reveals that presence of the following phases in plasmastone-derived glass-ceramics: Fe rich silicate (hedenbergite,  $\text{Ca}(\text{Fe}_{0.821}\text{Al}_{0.179})(\text{SiAl}_{0.822}\text{Fe}_{0.178}\text{O}_6)$  PDF no. 78-1546), wollastonite ( $\text{CaSiO}_3$  PDF no. 84-0655), hematite ( $\text{Fe}_2\text{O}_3$  PDF no. 89-2810), magnetite ( $\text{Fe}_3\text{O}_4$  PDF no. 89-0691), quartz ( $\text{SiO}_2$  PDF no. 83-0539) and cristobalite ( $\text{SiO}_2$  PDF no. 89-3607). The silica phases are originated from kaolin clay.



**Figure 1:** XRD pattern of dense plasmastone based glass-ceramic

The results from XRD are consistent with the micrograph (Figure 2) which shows the crystalline phases embedded in residual glassy phase, which helps in sealing the iron silicate rich zones. In addition, silicon oxide and iron oxide phases can be identified as well as a closed porosity, similar to industrial tiles.



**Figure 2:** Micrograph of dense glass-ceramic: 1) iron silicate rich zone; 2) glass/wollastonite zone; 3) silica; 4) iron oxide

The mechanical properties of the glass-ceramic (Table 1) are in the same range as the mechanical properties of commercially available material: the elastic modulus is comparable to the one measured for a commercial porcelain stoneware,<sup>12</sup> while the microhardness is similar to other waste-derived glass-ceramics.<sup>13,14</sup> The equivalent strength  $\sigma_{eq}^{3pt}$  in a three-point configuration of a sample with standard geometry (cross-section of 3 mm x 4 mm and loading span of 40 mm) was calculated as 76 MPa. In addition, the equivalent strength for bigger tiles  $\sigma_{eq}^L$  (cross-section of 8 mm x 300 mm and loading span of 300 mm) exceeded the lower strength limit (35 MPa) for materials to be applied as tiles (Bla group).<sup>15</sup>

**Table 1:** Physical and mechanical properties of the dense sample

Water absorption (%)	Density (g/cm <sup>3</sup> )	Porosity (%)	<i>E</i> (GPa)	<i>m</i>	Strength (MPa)			<i>H<sub>v</sub></i> (GPa)
					$\sigma_0^{4pt}$	$\sigma_{eq}^{3pt}$	$\sigma_{eq}^L$	
0.65 ± 0.12	2.52 ± 0.01	5	76.79 ± 2.5	11	69.8	76.6 <sup>Vf</sup>	39.3 <sup>Vf</sup>	5.3 ± 0.04
						76.4 <sup>Sf</sup>	43.1 <sup>Sf</sup>	

Leaching tests (Table 2) shows that the samples are within the Austrian regulation for classes U-A and U-B with respect to leachability, despite the fact that the total contents of Cu, Cr and Ni exceeded the Austrian limit values for recycled building materials. U-A and U-B refer to quality classes for recycled construction materials used in unbound or (hydraulically/bituminously) bound applications as aggregate. On the other hand, the sample cannot be classified as D (which is relevant for slags), due to the quantity of Mo leached. However, it should be noted that even the control sample cannot be classified as D due to leaching of Co and W.

**Table 2:** Results of the leaching test of dense materials (mg/kg DM)

	<b>U-A</b>	<b>U-B</b>	<b>D</b>	<b>Control</b>	<b>Sample</b>
Cr	0.6	1.0	0.3	0.017	0.088
Cu	1.0	2.0		0.19	0.33
Ni	0.4	0.6		0.042	0.019
Cl	800	1000		5.9	3.4
SO <sub>4</sub>	2500	6000		19	32
Ba			20	0.029	0.13
Cd			0.04	0.001	0.0015
Co			1	2.9	0.018
Mo			0.5	0.12	1.5
Tl			0.1	<0.0010	0.0041
V			1	0.26	0.064
W			1.5	2.8	0.18
F			10	4.2	2.6

Low leaching of heavy metals can be explained by the incorporation of heavy elements in stable mineral phases, as indicated by electron microprobe analyses (Table 3). They show that Cu is mainly bound in Fe oxide, Cr in iron silicate rich zones, whereas Zn and Ba are evenly distributed among iron silicate rich zones and glass/wollastonite zones (due to the resolution of the microprobe, it was not possible to perform the quantitative analysis separately in these phases). Mo, which is the only problematic element with respect to leaching, is mainly distributed among the glass/wollastonite zone. It is possible that the higher leaching of Mo is caused by dissolution of residual glassy phase: one of the reactions that occur when SLG is exposed to water is ion exchange reaction. In this class of reaction, protons or others cations replace Na (or other modifiers cations), which can cause the enhancement the pH of the solution, favouring network dissolution.<sup>16</sup> If indeed the glassy phase is dissolved, then other pollutants bond to it should also have been leached. However, Cu is present in a high quantity in glassy phase/wollastonite and its leaching is very low. One hypothesis is that Cu may be only bond to wollastonite, which apparently is

not dissolved. Another hypothesis could be that Cu is indeed leached, but then a copper zinc silicate is precipitated which is not dissolved. This assumption comes from the identification of these silicates in others plasmastone based glass-ceramics developed by the group.

**Table 3:** Results of the microprobe analysis

Phase	Mo (%)	Fe (%)	Cu (%)	Ba (%)	Zn (%)	V (%)	Cr (%)
Iron silicate zone	0.01	13.3	0.20	0.03	0.06	0.04	0.13
Silica	0.01	0.18	0.01	0.00	0.00	0.00	0.00
Glass/ wollastonite zone	0.03	3.50	0.25	0.03	0.05	0.01	0.03
Iron Oxides	0.00	62.1	0.41	0.00	0.03	0.02	0.10

## Conclusion

We may conclude that dense plasmastone derived glass-ceramics were successfully produced by sinter-crystallisation. The glass-ceramics present low water absorption and mechanical properties comparable to those of commercial ceramic tiles and natural stones. Concurrently, heavy metal leaching experiments indicated that the glass-ceramic have low leachability when compared to commercial ceramic tiles. However, Mo leaching was above Austrian regulation values. Separation of metals should thus be considered in the ELFM value chain prior to or during plasmastone production before its use in glass-ceramics.

## Acknowledgement

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# DIELECTRIC PROPERTIES MEASUREMENTS OF MUNICIPAL SOLID WASTE INCINERATOR BOTTOM ASH AT HIGH TEMPERATURES

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## Introduction

Along with recycling and landfilling, incineration is an established management strategy, allowing to recover energy while at the same time reducing the waste volume. Incineration, however, leads to the generation of municipal solid waste incinerator (MSWI) bottom ash (BA) as a major solid by-product. Bottom ash is either used in road construction or is disposed in landfills. With the aim of exploring the reuse potential of BA, the elemental composition, mineralogy, and leaching behaviour have been thoroughly studied. The dielectric properties of BA at elevated temperatures were measured as microwave thermal processing is aimed for, allowing the production of highly vitrified slag, which will be used as precursor for the synthesis of inorganic polymers.

The design of microwave processing requires knowledge of the dielectric properties of materials, since this property determines the response of being subjected to a microwave field. In general terms, the dielectric properties determine the ability of the material to absorb microwave energy and convert it into heat. These properties mainly depend on the frequency, temperature, nature, moisture content and particle size of the material. In this study, a dual single-mode microwave applicator was used both to heat the material and dynamically characterise its dielectric properties in a wide range of temperatures.<sup>1</sup>

## Materials and methods

### Background theory

In simple terms, the dielectric properties (also known as permittivity) can provide information on how the material interacts with the applied electric field. In scientific terms, the dielectric permittivity (Equation 1) is the macroscopic expression of the polarisation of solid particles, which can also include the ionic atmosphere and

double layers around the particles.<sup>2</sup> It is a complex function, composed of a real and imaginary part. The real part, the dielectric constant ( $\epsilon'$ ), reflects the ability of the material to be polarised under the induced electric field. The most essential factor that determines the ability of the material to convert the absorbed power into heat is the dielectric loss factor,  $\epsilon''$  (the imaginary part).

$$\epsilon = \epsilon' - j\epsilon'' \quad (1)$$

where  $\epsilon$  is the complex dielectric permittivity,  $\epsilon'$  and  $\epsilon''$  are the dielectric constant and loss factor respectively.

## Sample preparation

Wet MSWI BA samples were received from an incineration plant in the Netherlands. X-ray fluorescence data, presented in Table 1, show that the chemical composition predominantly consists of SiO<sub>2</sub> followed by CaO, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> and minor quantities of Na<sub>2</sub>O and MgO. Specific BA specimens were used to examine the influence of the particle size on the dielectric properties. The aim of these measurements was the dielectric characterisation of the BA and the determination of the best BA processing parameters for electromagnetic heating.

Initially, in the pursuit of obtaining the optimal BA particle size distribution, the dielectric properties of a “fine” and “coarse” grade were measured. Both samples were oven-dried at 105°C to remove moisture. The “fine BA” was initially disk milled (Fritsch Pulverisette 13) followed by attritor milling (Wiener 1S) for 8 h. The “coarse BA” was obtained by disk milling (Fritsch Pulverisette 13) only. The particle size distribution was measured by a laser diffraction particle size analyser (Beckman Coulter LS13 320). The  $D_{50}$  of the fine and coarse BA was 7.63 and 809 µm, respectively. All dielectric properties were measured on loose powder under a continuous nitrogen gas flow.

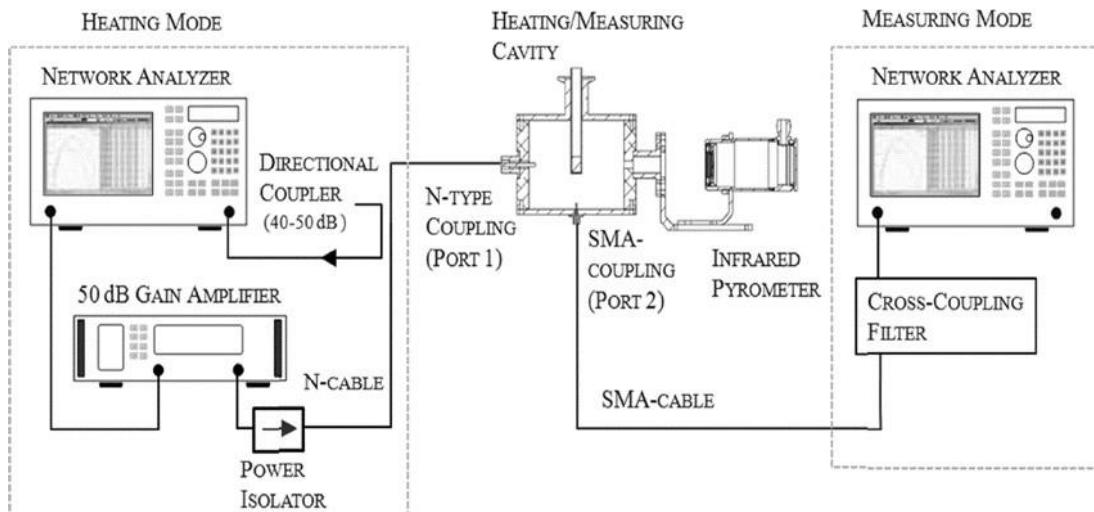
**Table 1:** Normalised chemical composition of BA, based on XRF data (error of semi-quantitative analysis: 10%)

Component	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	MgO	Others
Wt%	54	15	11	8	4	2	<1

## Measurement set-up

The microwave cavity that was used for the dielectric measurements is illustrated in Figure 1 and has been designed to have a high power dominant mode for heating the material and a second mode to measure the dielectric properties. The  $TE_{111}$  mode is

used for heating and it has been designed to resonate near the ISM (Industrial, Scientific, Medical) frequency of 2.45 GHz, more precisely in the bandwidth of 2.2–2.6 GHz. The  $TM_{010}$  mode provides a larger frequency shift between 1.9 and 2.2 GHz and is used for measuring the dielectric properties. Different resonant frequencies have been selected to avoid interference of the two signals. The signal source for the heating mode is produced by a Vector Network Analyser (VNA) connected to an amplifier. The VNA delivers an output of 0 dBm (1 mW) up to 50dB (140 W) using an amplifier. A second VNA is used for the measuring mode.



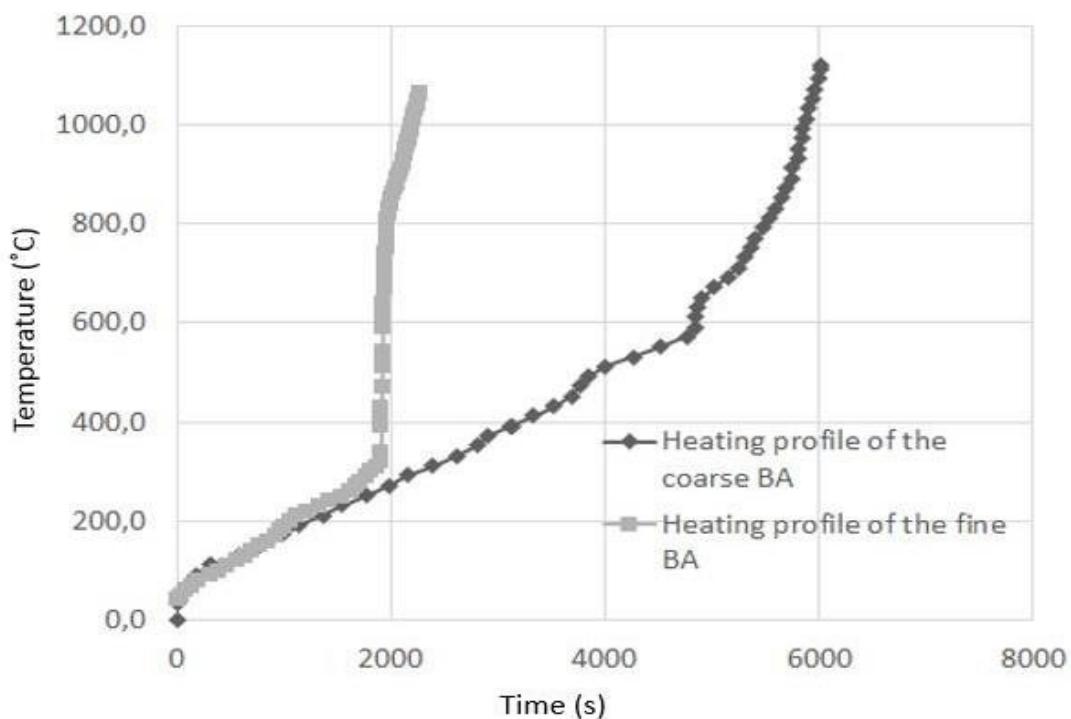
**Figure 1:** Schematic of the equipment to determine microwave-matter interactions. Modified from from Garcia-Banos *et al.*<sup>3</sup>

## Results and discussion

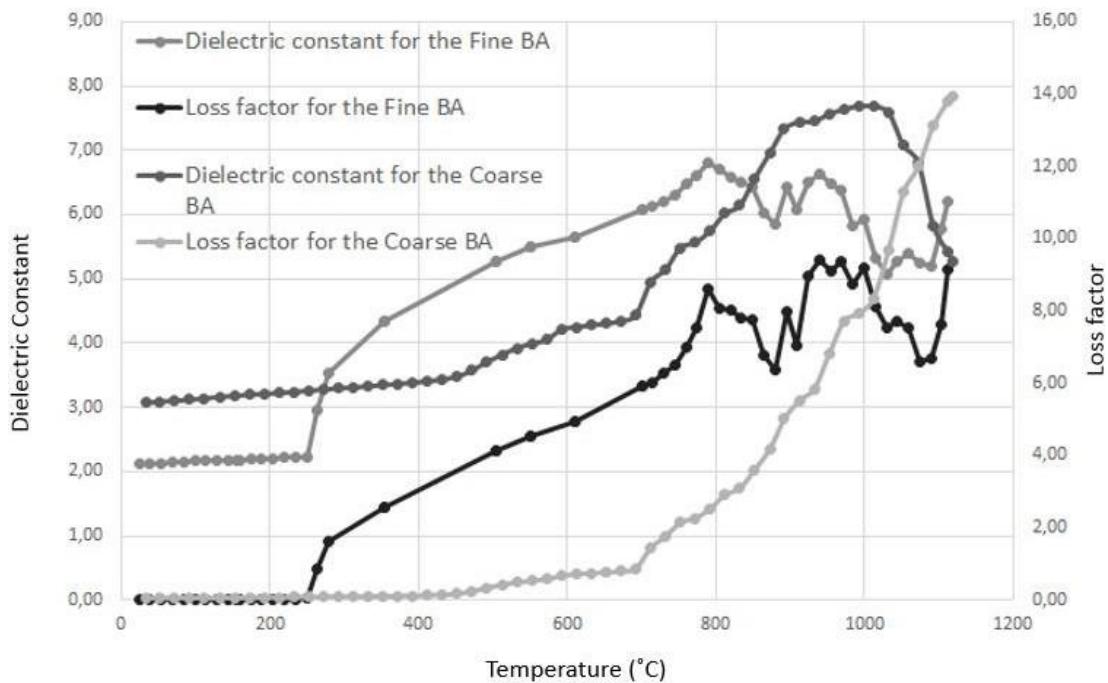
### Effect of particle size on dielectric properties

In order to examine how the BA material responds under the microwave energy, it is essential to know the heating profile and the dielectric properties. Figure 2 presents the heating profile of the fine and coarse BA under an applied power of 140 W, whereas Figure 3 depicts the measured values of the dielectric properties for both materials from room temperature up to approximately 1100°C. In Figure 3, the dielectric constant of the fine BA was higher than for the coarse BA in the 280–850°C range, as it is also depicted in the loss factor. Probably, the small particle size of the fine BA and the respective high specific surface area result in an enhanced polarisation of the induced electric charges. The fine BA powders showed accelerated heating around 250°C, accompanied by a strong increase  $\epsilon'$  and  $\epsilon''$ , whereas this was delayed up to 700°C for the coarse BA powder. However, for temperatures below 280°C and above 850°C, the dielectric constant of the coarse BA was higher than for the fine BA. The reason behind it needs further investigation. Although there are not so many studies on the effect of particle size on dielectric properties, some

researchers have investigated this correlation for polymers and ceramic composites. Q.G. Chi *et al.*<sup>4</sup> studied the effect of the particle size on the dielectric properties of ceramics and concluded that the dielectric constant of the ceramic powders decreased with increasing ceramic particle size. Hsing-I-Hsiang<sup>5</sup> studied the effect of the BaTiO<sub>3</sub> powder size on the dielectric properties of BaTiO<sub>3</sub>/polyvinylidene fluoride composites at different frequencies. At frequencies > 100 KHz, the dielectric constant of the composites increased with decreasing BaTiO<sub>3</sub> particle size. On-going work focuses on conventional thermal analysis to assess the phase transformations and elucidate how these are reflected in the material dielectric response at microwave frequencies. Simultaneously, in-depth investigation of the BA microstructure will give a better understanding of the interplay between the dielectric properties and the constituent phases.



**Figure 2:** Heating profile of the fine and coarse BA under 140W input power



**Figure 3:** Dielectric properties of the fine and coarse BA during heating to 1100°C under 140W input power

## Conclusions

Dynamic dielectric characterisation of BA was performed during microwave heating up to 1100°C and revealed the dielectric response of two different BA particle sizes in an electromagnetic field. The comparison shows that the finer BA material has a higher heating rate above 250°C, due to a higher dielectric constant as well as loss factor, allowing a more efficient microwave heating process.

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# FUNCTIONALISED ACTIVATED CARBON FOR THE ADSORPTION OF RARE-EARTH ELEMENTS FROM AQUEOUS SOLUTIONS

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## Abstract

The Flemish Strategic Initiative Materials (SIM) “MaRes” programme is about recycling of “Materials from solid and liquid industrial process Residues”, and aims at creating and demonstrating an operational, flexible toolbox of different concentration, extraction and valorisation technologies. Within the “Get-A-Met” project, part of the SIM MaRes programme, a ‘Groundbreaking Extraction Technology for critical Metals and Metalloids from industrial waste waters’ is developed through an electrometallurgical approach. The core technology is capacitive electroprecipitation, which involves the development of a gas-diffusion electrode material from activated carbon. This is combined with advanced speciation knowledge, pre-treatment with membrane electrolysis and surface-functionalised carbon materials, to achieve high selectivity and performance. In this paper, we discuss the functionalisation of AC with the chelating agent ethylenediamine tetraacetic acid for the selective adsorption of rare-earth elements from aqueous solutions.

## Introduction

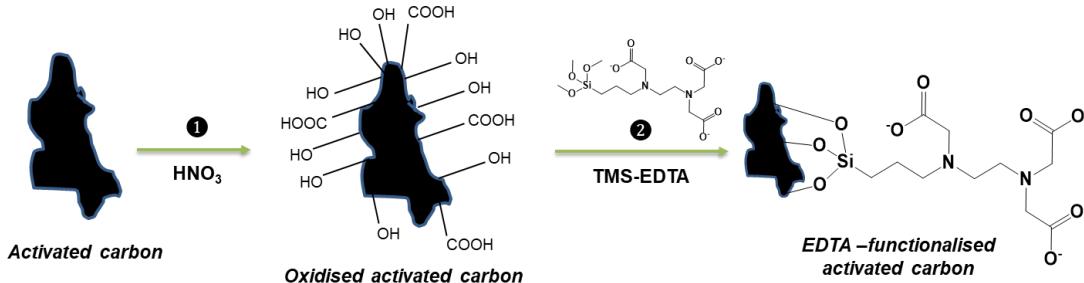
Waste water is generated by a variety of industrial activities. Contamination of waste water with rare earths creates a serious threat to environment and human health because of their toxicity, non-biodegradability and accumulation in living organisms.<sup>1</sup> Moreover, since rare earths (and other critical metals) are required for a wide range of high-technological applications, research is becoming more and more focused on the selective recovery of these elements. This might allow turning (landfill disposal) costs into revenues. Among many techniques attempted to recover valuable metals from dilute waste waters, adsorption is generally considered the preferred technology, due to its combined simplicity, effectiveness and low cost.<sup>2</sup> Like many adsorbent materials, activated carbon (AC) is unlimitedly available, environmentally friendly and cheap.<sup>3</sup> AC has also interesting properties, such as a high specific surface area, a well-developed porous structure and tuneable surface chemistry.<sup>4</sup> In addition, AC is characterised by a high chemical resistance and conductive behaviour, so it can be used in a wide range of chemical environments, temperatures and pressures, in

different kinds of (electrochemical) processes.<sup>5</sup> It has been reported that surface functionalisation with ethylenediamine tetraacetic acid (EDTA) results in materials with a high selectivity for and amongst rare-earth elements (REEs) by the formation of stable coordination complexes.<sup>6</sup>

In this work, AC was oxidised to incorporate oxygen groups over the carbon matrix. These allowed subsequent functionalisation with the chelating agent EDTA on the AC surface. The obtained materials were extensively characterised by FTIR and Raman spectroscopy, TGA, N<sub>2</sub> physisorption, SEM and the Boehm titration method, the latter being used to determine the amount and type of oxygen functional groups present in carbon samples. Then, the adsorption of REEs from aqueous solutions with EDTA-functionalised AC was examined. Kinetic and thermodynamic adsorption data were fitted with common adsorption models. EDTA-AC appeared to have a high selectivity for the rare earths, so this adsorbent material could be used as well to separate these valuable metals from other metals (present, for instance, in electronic waste). Finally, it was shown that the functionalised AC sample was well reusable. Hereby, it was demonstrated that EDTA-functionalised AC is highly suitable for the selective recovery of REEs from waste water.

## Experimental

Oxidation of AC powder (Norit SX1G, 5 g) was done with concentrated HNO<sub>3</sub> (15 M, 50 mL). The reaction mixture was refluxed at 85°C for 6 h. Note that the combination of fine AC powder (with a high specific surface area) and strong acids or oxidising agents can be explosive. The residue was filtered, washed several times with deionised water until neutral pH and dried under vacuum at 50°C. The optimised immobilisation of *N*-(3-trimethoxysilyl)propyl]ethylenediamine triacetic acid (TMS-EDTA) over oxidised AC was performed in a solvent mixture of isopropanol and water.<sup>7</sup> AC (1 g) was added to an isopropanol–water mixture (85:15 volume ratio) and the pH was adjusted to a value of 4 to 5 with HCl. The mixture was ultrasonicated for 2 h to get a uniform dispersion. Then, the beaker was set in stirring mode and TMS-EDTA (5 mL) was added dropwise to the solution. Acetic acid (1 mL) was added to the solution to increase the amount of condensation reactions between the –OH groups of AC and the hydrolysed silanol groups in TMS-EDTA. The reaction mixture was stirred for 24 h at room temperature. After functionalisation, the particles were filtrated and washed with water and acetone. Finally, the EDTA-functionalised AC particles (EDTA-AC) were dried under vacuum at 50°C. The overall synthesis procedure of EDTA-AC is depicted in Figure 1.



**Figure 1:** Schematic diagram for the synthesis of EDTA-functionalised AC

In adsorption experiments, functionalised particles (20 mg) were added to a rare-earth solution (10 mL). Unless stated otherwise, a 1 mM Nd(III) solution was used. The adsorption experiments were maintained for 4 h by shaking the solutions at 250 rpm and 20°C. After adsorption, the solid AC particles were separated from the liquid by centrifugation. Aqueous metal concentrations were analysed by TXRF. The equilibrium adsorption capacity ( $q_e$ ) was then calculated by Equation 1:

$$q_e = \frac{V(C_0 - C_e)}{M} \quad (1)$$

where  $C_0$  and  $C_e$  are the initial and equilibrium concentration ( $\text{mg L}^{-1}$ ) of the metal ion in solution,  $V$  the aqueous volume (L) and  $M$  the mass of the adsorbent (g).

## Results and discussion

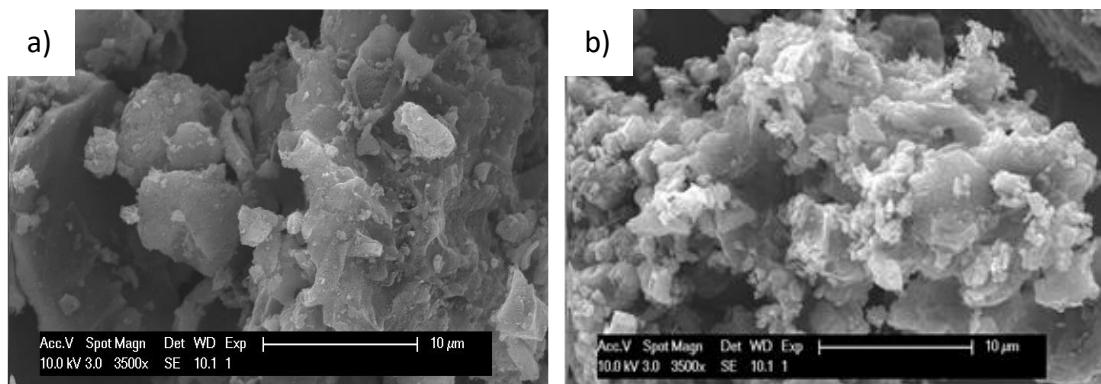
### Synthesis and characterisation

Oxygen surface groups on AC were identified and quantified by the Boehm titration method. For the subsequent functionalisation step, especially the amount of –OH (phenolic) groups was targeted, being 117, 252 and 981  $\mu\text{mol g}^{-1}$  for  $\text{HNO}_3$  concentrations of 5, 10 and 15 M, respectively. Since the highest number of phenolic groups was created through oxidation with 15 M  $\text{HNO}_3$ , this oxidation treatment was used for the preparation of AC particles for further functionalisation with EDTA.

FTIR measurements were performed to identify the surface functional groups in the synthesised materials. Immobilisation of EDTA was evident from the peaks at 1350 and 1600  $\text{cm}^{-1}$ , which can be attributed to, respectively, symmetrical and asymmetrical stretching modes of carboxylate groups. The intense peak around 1100  $\text{cm}^{-1}$  originated from the stretching vibration of Si-O bonds.

Measurement of the particle size distribution elucidated an increase in the particle size when going from oxidised AC to functionalised AC, up to a maximum value of 18.50  $\mu\text{m}$  for the 90% smallest particles. This can be explained by the immobilisation

of EDTA-groups on the AC particles. SEM analysis of EDTA-AC revealed particles of varying size and no distinct morphology (Figure 2). The functionalised particles showed some aggregation and coating of lighter particles over the carbon particles. Evidently, these originate from the immobilisation of the EDTA-ligand on the AC support through silica linkers, as originating from TMS-EDTA. Textural properties of AC materials were thoroughly examined by N<sub>2</sub> physisorption measurements. EDTA-functionalised AC had a specific surface area of 741 m<sup>2</sup> g<sup>-1</sup>, a total pore volume of 0.41 cm<sup>3</sup> g<sup>-1</sup> and an average pore diameter of 1.54 nm.



**Figure 2:** SEM-image of Norit AC (a) and EDTA-AC (b)

From CHN analysis, the incorporation of oxygen and nitrogen atoms in the respective materials became clear. From the mass percentages given in Table 1, the amount of functionalisation could be calculated to be 264 mg g<sup>-1</sup> of TMS-EDTA per gram of AC. Together with the data from TGA measurements, these results showed that the oxidation and the functionalisation procedure proceeded successfully.

**Table 1:** Elemental analysis of the adsorbent materials

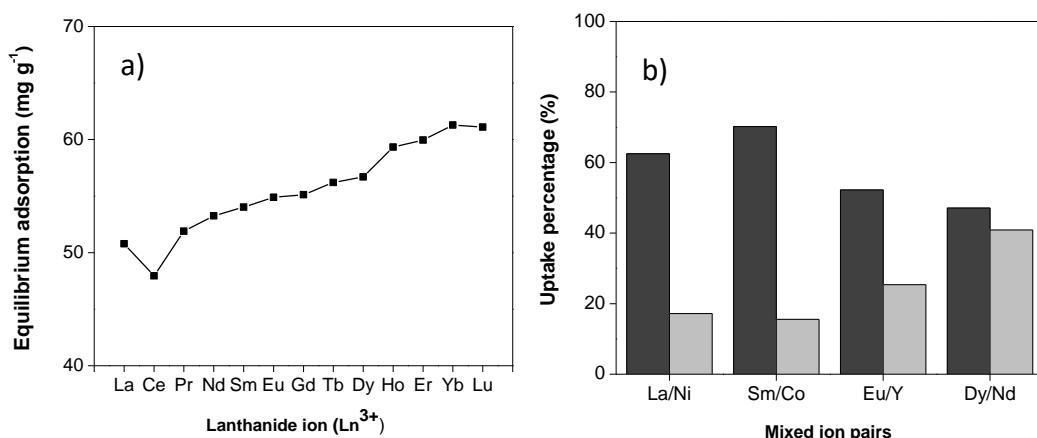
Adsorbent	C (wt%)	H (wt%)	N (wt%)	O (wt%)
Norit AC	91.70	0.87	0.57	6.86
Oxidised AC	74.59	1.18	0.52	23.71
EDTA-AC	65.64	2.08	1.60	30.68

### Adsorption performance

Adsorption isotherms were constructed for AC, oxidised AC and EDTA-AC by varying the Nd(III) concentration (10 to 300 mg L<sup>-1</sup>) and fitting with the Langmuir and Freundlich adsorption models. The maximum adsorption capacity of EDTA-AC was determined to be 71.42 mg g<sup>-1</sup>, whereas a value of only 19.08 mg g<sup>-1</sup> was derived for the original AC. From these results, we can conclude that the immobilisation of EDTA over AC significantly enhanced the adsorption capacity for Nd(III). Kinetic adsorption data were modelled with the pseudo-second order rate equation. Nd(III) was

completely removed from the aqueous solution within 15 min of contact time. The rapid adsorption may be attributed to the textural properties of EDTA-AC. The amount of Nd(III) adsorption increased sigmoidally with an increasing pH, until a maximal plateau value was obtained around pH 5. This can be explained by (de)protonation of the functional groups immobilised on the AC surface. In addition, increasing temperatures resulted in enhanced Nd(III) adsorption. Thermodynamic data were modelled with the Van 't Hoff equation. Since reusability plays a vital role in bulk-scale production processes, regeneration of the adsorbent was tested over five consecutive adsorption-desorption cycles. The adsorption efficiency remained 90% after the fifth regeneration cycle, revealing the potential of EDTA-AC for industrial applications.

Affinity for and selectivity between REEs was investigated for EDTA-functionalised AC (Figure 3). High adsorption values were observed for all lanthanide ions. Moreover, adsorption increased gradually with the atomic mass of the respective lanthanide ions, probably a consequence of the "*lanthanide contraction*".<sup>8</sup> These differences in selectivity between distinct rare-earth ions may eventually be exploited to separate them from each other. Adsorption tests were as well performed from binary mixtures of several metal-ion pairs: La(III)/Ni(II), Sm(III)/Co(II), Eu(III)/Y(III) and Dy(III)/Nd(III). These were chosen because of their occurrence in End-of-Life waste sources, like batteries, magnets and lamp phosphors.<sup>9</sup> The adsorption of La(III), Sm(III), Eu(III) and Dy(III) were found to be higher than that of Ni(II), Co(II), Y(III) and Nd(III), respectively. From the considerable differences in uptake percentage (up to a difference of 70 to 17% for the Sm(III)/Co(II) pair), the separation capability of this low-cost EDTA-AC adsorbent material becomes evident.



**Figure 3:** EDTA-AC equilibrium adsorption capacity from single-element lanthanide solutions (a) and equimolar, binary metal-pair mixtures (b)

## Conclusions

By immobilisation of the chelating agent EDTA on AC, an adsorbent material with an excellent capability of recovering REEs from aqueous solutions was obtained. Characterisation of the functionalised AC particles elucidated a high specific surface area ( $740\text{ m}^2\text{ g}^{-1}$ ) and micropores with a volume of  $0.41\text{ cm}^3\text{ g}^{-1}$ , enabling a high accessibility of the functional groups and avoiding any kind of diffusion problem. The amount of functionalisation was determined to be  $264\text{ mg g}^{-1}$ . Adsorption was fast: equilibrium was reached within 15 min. The adsorption capacity of EDTA-AC was found to be  $71.42\text{ mg g}^{-1}$ , which was almost 4 times higher than that of pure AC. A high selectivity was achieved towards the (heavier) REEs. Separations were studied for the binary mixtures La(III)/Ni(II), Sm(III)/Co(II), Eu(III)/Y(III) and Dy(III)/Nd(III), all commonly present in electronic waste. The regeneration efficiency remained higher than 90% after five consecutive adsorption-desorption cycles. Because the EDTA-functionalised AC is cheap, easily synthesised, chemically stable and highly efficient, application can be found for the recovery of REEs from industrial waste water streams.

## Acknowledgements

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# **EIT RAWMATERIALS ZeroWaste CLUSTER NETWORKS OF INFRASTRUCTURE: OFFERING RESEARCH AND PILOT INFRASTRUCTURE IN A ZeroWaste METALLURGICAL TOOLBOX**

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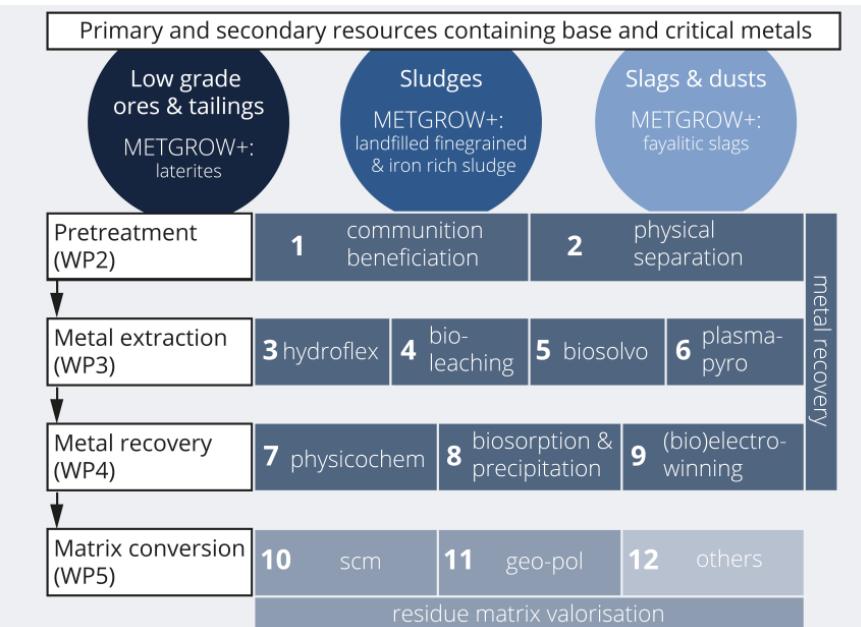
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## **Introduction: the ZeroWaste metallurgical toolbox**

Complex low-grade industrial residues and wastes can be considered as an important source for metallic and mineral raw materials, of which the primary sources are often lacking in Europe. These streams can include mine tailings, bottom and fly ashes from incineration processes, metallurgical slags and dusts. These secondary products often contain relatively low concentrations of metals, but due to the vast volumes in which they are produced, they can present a significant value in terms of raw materials. Very often, these side products are landfilled, and thus causing a significant cost and environmental burden. In order to extract value from these secondary streams and (landfilled) stocks, an integrated metallurgical ZeroWaste approach is needed. This approach integrates different types of extractive metallurgy (hydro-, pyro-, solvo-, electro- and biometallurgy), together with pre-treatment and valorisation of the remaining mineral matrix, *e.g.*, as added-value binders or cementitious products for the construction industry. This zero-waste toolbox allows for designing flexible flow sheets in order to design a treatment train for specific streams, optimised both in terms of material recovery as well as economic feasibility and environmental impact.

The top-class European research institutes Ghent University, KU Leuven, VITO (Belgium) and VTT (Finland) have joined forces, based on complementarities in expertise, to bring this concept of the “ZeroWaste metallurgical toolbox” to a next level. This has resulted in a number of joint initiatives: technology development projects (*e.g.* the Flemish research programme MaRes within SIM-Flanders,

<http://www.sim-flanders.be/research-program/mares>), design of a decision-support framework (e.g. the H2020 project METGROW+, <http://metgrowplus.eu/>; Figure 1) and a virtual pool of research and pilot infrastructure.



**Figure 1:** The zero-waste metallurgical toolbox in the Horizon 2020 project METGROW+

## EIT RawMaterials

EIT RawMaterials brings together about 120 European partners (Figure 2) from the three different sides of the knowledge triangle (universities, research institutes and companies) to tackle Europe's scarcity in metallic and mineral raw materials. It is the biggest community ever built in Europe to tackle raw materials challenges. EIT Raw Materials therefore funds matchmaking, innovation, education and business projects in exploration, mining, recycling, substitution and circular economy. EIT Raw Materials disposes of an annual budget of earmarked Horizon 2020 funds of 30 to 80 M€ between 2016 and 2022 for these different project types. More info can be found on <http://www.eitrawmaterials.eu>.

A specific project type are the so-called Networks of Infrastructure (Nol). A Nol is typically an accelerator aiming at mapping services to provide overview and access to facilities and expertise in a specific field in the raw materials sector, available within the EIT RawMaterials consortium. A Nol presents a virtual pool of infrastructure, a so-called 'virtual laboratory'. These services include pilot plants, process, analytical and modeling infrastructure. One network typically consists of 5-15 partners (industry, research and universities) and is coordinated by a single-point-of-contact (SPOC), located at one of the partners.

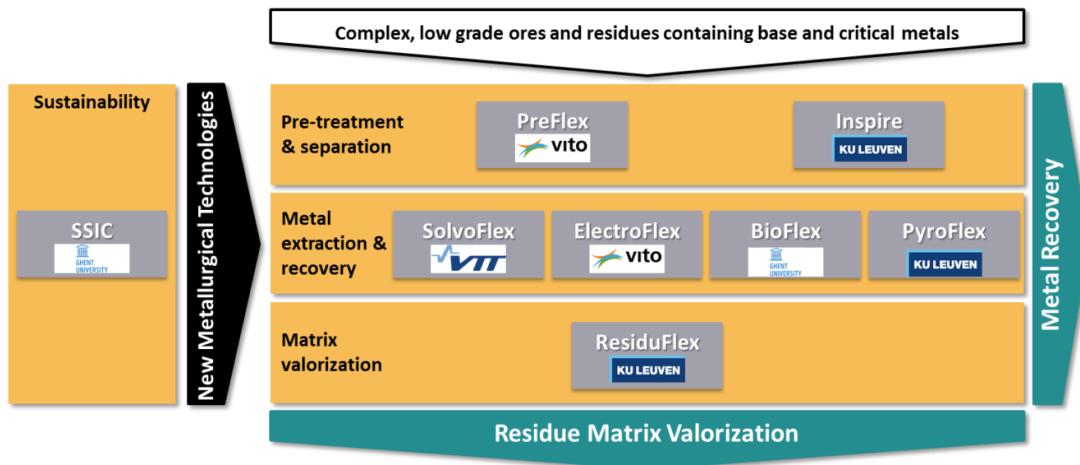


**Figure 2:** EIT RawMaterials partnership

## The Zero-Waste cluster

Ghent University, KU Leuven, VITO and VTT are coordinating a number of Nols in specific building blocks of the ZeroWaste metallurgical toolbox, each requiring very specific infrastructure and expertise. The Nol PreFlex (on pretreatment and physical separation, coordinated by VITO) and Inspire (on intensified separation, KU Leuven) are the Nol in the pretreatment step of the ZeroWaste toolbox. The metal extraction and recovery infrastructure is covered by the Nol SolvoFlex (VTT), PyroFlex (KU Leuven), BioFlex (Ghent University) and ElectroFlex (VITO), on solvo-, hydro-, pyro-, bio- and electrometallurgy respectively. Matrix valorisation infrastructure is brought together by ResiduFlex (KU Leuven). The Sustainability Support and Information Centre (SSIC, Ghent University) groups the necessary expertise in sustainability assessment, needed to assess the economic feasibility and environmental impact of new ZeroWaste processes. These eight individual Nol have decided to join forces into the ZeroWaste Nol cluster (Figure 3). This clustering is evident because of the complementarities in infrastructure and expertise and creates benefits in terms of more effective communication and dissemination and a harmonised way to approach potential customers.

### EIT RawMaterials ZeroWaste Cluster



**Figure 3:** The EIT Raw Materials ZeroWaste cluster of Networks of Infrastructure

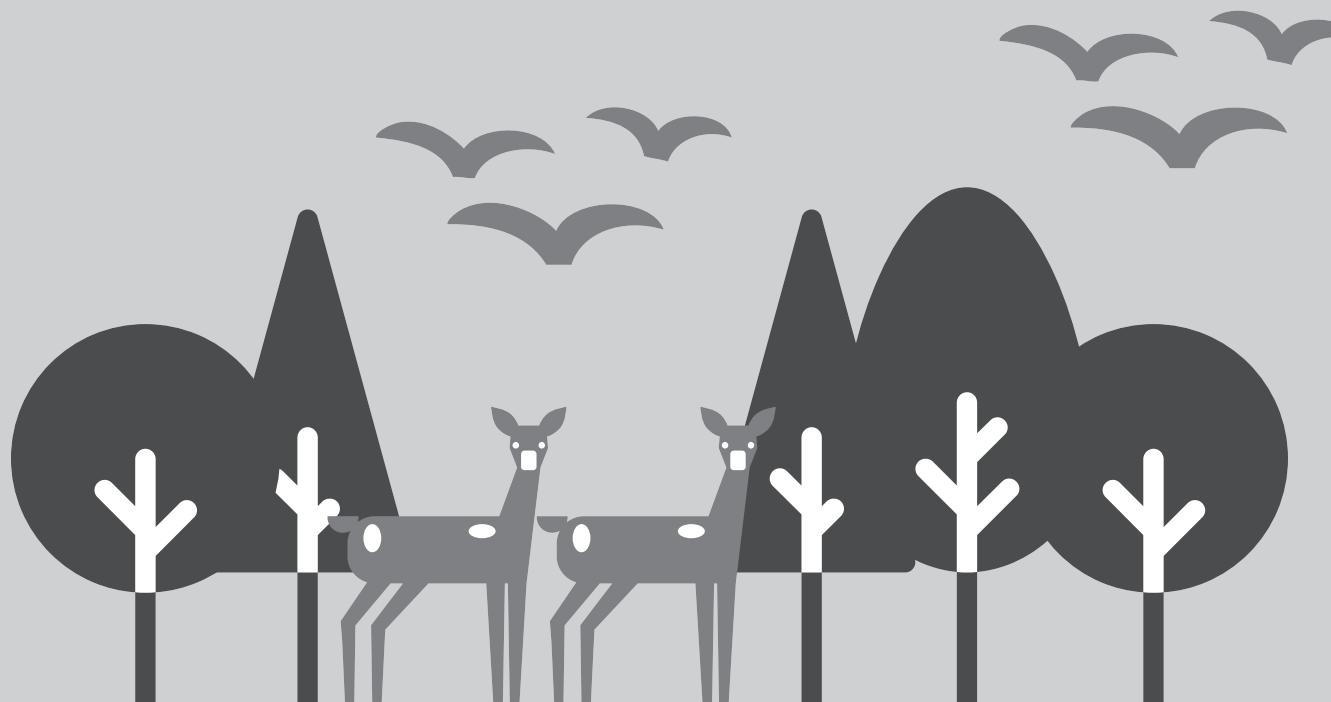
The ZeroWaste cluster has a joined website (<https://www.zerowastecluster.eu>), with links to pages of the individual networks. Dissemination material (posters, leaflets, social media accounts) are developed jointly. Customers of the different networks are guided to the requested infrastructure by a web-based platform, guiding the customer to the parties able to the specific infrastructure he/she needs. This is a much more user-friendly approach compared to presenting the customer a list of all available infrastructure within the network. Due to the different types of infrastructure within the different networks of the Zero-Waste Cluster, each Nol has a different webtool. However, the architecture of the different webtools is very similar, which will allow for an easy integration in the future. The Nol webtool serves as a matchmaking and brokerage platform, but leaves the customer free choice between all parties able to fulfill the request. All Nol partners that are able to handle a specific request are invited to make an offer. It is up to the customer to choose the best value of these offers. The webtool will follow up whether a match has been successful and if it has led to a dedicated project.

## The ZeroWaste cluster and Enhanced Landfill Mining

The ZeroWaste cluster could provide a powerful tool in Enhanced Landfill Mining. Industrial landfills (tailings, slacks, bottom and fly ashes, ...) often require a combination of metallurgical technologies to unlock their secondary raw material potential. The ZeroWaste cluster could offer powerful (web)tools to guide researchers and technology developers to the infrastructure they need to optimally extract the value of the materials present in these landfills. The Nol coordinators have a more detailed knowledge about the specific building blocks of the ZeroWaste toolbox and about the infrastructure present in Europe at different scales. They can assist customers in their requests for infrastructure.

## Session 4

# Multi-criteria assessment for Enhanced Landfill Mining





# **HOW TO EVALUATE (ENHANCED) LANDFILL MINING: A CRITICAL REVIEW OF RECENT ENVIRONMENTAL AND ECONOMIC ASSESSMENTS**

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## **Introduction**

Landfill mining has been proclaimed as an alternative strategy to address unwanted impacts of waste deposits.<sup>1,2</sup> In real-life projects, such excavation and processing of deposited waste has mainly been used to facilitate traditional objectives such as remediation, land reclamation or creation of landfill airspace.<sup>3</sup> A key target of recent landfill mining research is, however, to go beyond this type of local motives and enhance the recovery of materials and energy resources by developing advanced processing technologies.<sup>4,5</sup> Although such an ambitious approach clearly displays a wider societal potential, it also adds complexity to the implementation and assessment of pros and cons of landfill mining.

Recent reviews display multiple challenges for sound implementation of landfill mining in terms of further development of know-how and technology as well as a better understanding of influencing policy and market conditions.<sup>3,5</sup> In essence, the field suffers from a deficit in knowledge about how resource recovery from landfills could be executed cost-efficiently together with clear societal benefits. An important barrier for the development of the area is the so far often speculative nature of research using models with a wide range of real-life assumptions. Besides a few, often small-scale pilot trials, there is a general lack of empirical knowledge regarding real-life implications and consequences of landfill mining implementation. However, also the mere complexity of such resource recovery initiatives contributes to this situation. For instance, the economic and environmental impacts of landfill mining are influenced by a large number of site-specific, technical, organisational, policy and market factors and conditions.<sup>6</sup> Understanding how all these influencing elements interact and jointly contribute to the outcome is indeed a challenging endeavour.

For any emerging concept, systems analysis methods could be useful for assessing the potential and feasibility of various solutions, and for guiding knowledge and technology development towards critical factors for implementation.<sup>7</sup> Initially, however, the usefulness of applying such assessment frameworks is often restricted due to several unresolved empirical and methodological challenges.<sup>8</sup> When it comes to landfill mining, quite a few economic and environmental assessments have been conducted during recent years but there is not yet any systematic synthesis of this body of knowledge. It is thus useful to review the main findings of these studies, the consistency of their applied methodologies and to what extent they have contributed to the further development of the field.

### **Aim and scope of the study**

This study involves a review of recent economic and environmental assessments of landfill mining. By analysing their main contributions and weaknesses, our aim is to provide guidance on how such assessment frameworks could be further developed and used to better support knowledge and technology development within the area. The review is structured according to the following research questions:

- What can we learn from the conducted assessments about critical factors and conditions for implementation and performance of landfill mining?
- How have the assessments been realised in terms of methodological choices and principles and which are the implications on their validity and usefulness?
- Which are the key empirical and methodological challenges for assessment of landfill mining and how could these challenges be addressed in future research?

The selected literature targets research in which the full value-chain of landfill mining has been assessed in specific case studies, *i.e.* LFM scenarios. In order to avoid too much overlap with previous reviews within the field, only assessments published after 2010 were included. In the first step of the review, we focused on the empirical findings of the different case studies by simply summarising their main results with special emphasis on identifying re-occurring critical factors for performance. The second part of the review is more analytical. Here, we used state-of-the-art knowledge from systems analysis theory to assess strengths and weaknesses of the methodologies applied in the assessments. This benchmarking exercise was primarily conducted to specify the validity and usefulness of the obtained results and structured according to key elements of any economic and environmental assessment, *i.e.* modelling principles, scenario development and procedures for handling of parameter data. Finally, our findings were put in relation to previous research on conditions for implementation of emerging concepts such as landfill mining. This concluding discussion targets the usefulness of systems analysis as a learning tool for guiding the further development of emerging concepts and

highlights key empirical and methodological challenges to be addressed in future research.

## **Characteristics and main results of the reviewed economic and environmental assessments**

In total, 12 articles published during the period 2013-2017 were selected for review. Five focus on economic assessments,<sup>9-13</sup> two focus on environmental impacts<sup>14,15</sup> while the rest involve studies addressing both topics<sup>16-20</sup> (Table 1). Most of the studied landfills are municipal solid waste (MSW) deposits, which could be regarded as small to medium sized in a European context, *i.e.* containing 0.1 to 2 million tonnes of deposited mass. Worth noting is that one of the large-sized deposits, the REMO landfill in Belgium, with about 16 million tonnes of waste, has been the case for several of the reviewed assessments.<sup>16,18,20</sup> Virtually all of the studies include somewhat of a reference case displaying “business-as-usual” if the landfill in question is not to be mined. This reference serves as a benchmark to which the environmental impacts and economics of landfill mining are contrasted. “Do-nothing” (implying no further actions or costs) or “final closure and aftercare” represent the two most common reference cases.

The lack of knowledge and experience from full-scale projects is apparent, meaning that most of the studies involve *ex ante* assessments of landfill mining scenarios developed from expert judgements or, less commonly, small-scale pilot trials. Only one of the studies is an *ex post* assessment of a realised, full-scale landfill mining project.<sup>10</sup> When it comes to the material processing schemes, the assessments are quite evenly distributed between scenarios based on mobile separation units<sup>9,10,13,15,19</sup> and more advanced sorting plants.<sup>12,14,16-18,20</sup> The subsequent treatment and recovery of separated energy carriers and materials often follows state-of-the-art waste management practices in the different countries. However, for waste-to-energy, some main differences can be found among the studies in terms of employed technologies (*i.e.* waste incineration and plasma gasification) and the organisation of related costs and benefits (*i.e.* project internal and external thermal treatment of refuse-derived-fuel, RDF).

### **Important processes for economic and environmental performance**

The results from the economic assessments imply that the choice between project internal or external thermal treatment of extracted RDF has overarching implications on cost and benefit profiles. In projects where such fuel is sent to external waste-to-energy plants, process-related (*e.g.* labour, energy, auxiliary materials and maintenance of employed processing lines) and material flow-related (*e.g.* gate fees, disposal costs and transports of extracted materials) cash flows are reported as the

main expenditures. Also in projects involving internal thermal treatment, these main processes remain significant but capital investments and operational expenditures related to the (new) waste-to-energy plant then typically dominate the cost profile.

Regardless of employed waste-to-energy (WtE) approaches, the total project cost of the different cases is virtually always significantly higher than anticipated revenues for separated materials and energy resources.<sup>12,13,17–20</sup> Here, a fundamental problem is that in most current markets only a small share of the processed resources will generate any significant income (*i.e.* metals) while the remains will involve low revenues (*e.g.* aggregates) or, even worse, disposal costs (*e.g.* gate fees for RDF, disposal of fines and mixed residues). This market situation is also why some studies conclude that the employment of more advanced and thereby expensive material separation plants do not pay-off financially. Indeed, approaches that involve internal thermal treatment of RDF extend the material-flow related revenues beyond sales of metals to also including income from generated heat and/or electricity. However, such increased revenue streams are typically followed and surpassed by a massive need for financial investments and/or increased operational costs. Several studies therefore conclude that the cost-efficiency of internal thermal treatment approaches relies on governmental support in terms of, for instance, green energy certificates<sup>11,16–18,21</sup> and/or investment subsidies.

Despite previous reviews of landfill mining that stress the importance of indirect benefits in terms of reclaimed land, landfill airspace or avoided closure and aftercare, the conditions for such benchmarking costs and revenues are often poorly described in the assessments or not even accounted for. When properly included, their importance ranges from insignificant to being the main economic driver dependent on case specific settings. Given the above-described markets for secondary resources, it is, however, clear that identifying landfills related to (extraordinary) high indirect benefits or alternative costs is an essential step in developing cost-efficient landfill mining operations.<sup>11,16,18</sup>

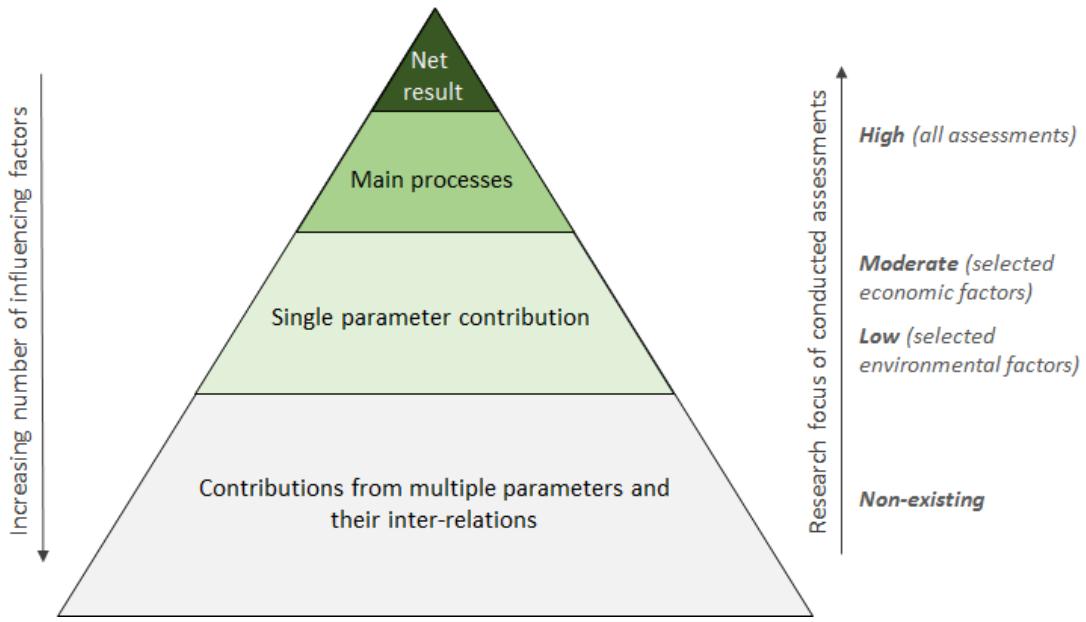
**Table 1: General description of reviewed articles. For the net results, only climate impacts are presented for the environmental assessments.**

Publication & topic	Type of landfill, size & location	Type of assessment	Reference case	LFM processing technology	Treatment of energy resources and materials & reclaimed land/landfill airspace	Main costs for LFM scenarios in descending order of magnitude	Main benefits for LFM scenarios in descending order of magnitude	Net outcome
Färdigerd et al., 2013 <i>Environment</i>	MSW landfill, 1 Mt, SWE	Ex ante	Solely remediation of landfill, no existing LFG collection	Different scenario for mobile & advanced separation units	WtE: RDF recovery by incineration WtM: metals, aggregates, plastics (adv. separation) Land/airspace: N/A	Incineration of plastics	Air/soil: heat, plastics & metals production	LFM better than remediation
Van Passel et al., 2013 <i>Economic</i>	REMO MSW/IW landfill, 16 Mt, BEL	Ex ante (extrapolated from pilot trial)	Do nothing, existing LFG collection & utilization	Advanced separation plant WtE: internal RDF recovery by Gas Plasma WtM: fines, aggregates, metals Re-landfilling: N/A Land/airspace: land (but value not accounted for)	CAPEx / OPEX of WtE Material processing & separation Contingency (mixed) Excavation	Incineration	Electricity sales Green energy certificates Mixed material sales	LFM potentially profitable given non-conventional conditions
Jain et al., 2014 <i>Environment</i>	Typical MSW landfill, 1 Mt, US	Ex ante extrapolated from other full-scale LFM projects)	(i) do nothing, no existing LFG collection, (ii) Relocats, LFG collection & utilization	Mobile separation unit WtM: metals soils Re-landfilling: Ash from incineration Land/airspace: N/A	Incineration	Avoided: Metals production, coal for electricity	Env: LFM better than alternatives	
Danthurebandara et al., 2015a <i>Environment/Economic</i>	MSW open dump site, 1 Mt, LKA	Ex ante	Do nothing, no existing LFG collection	Advanced separation plant WtE: (i) RDF to cement industry or (ii) RDF to incineration WtM: fines, metals, glass/aggregates, Glass Land/airspace: hazardous & mixed residues	Env: (i) Transportation, (ii) RDF to incineration Incineration Eco: transportation	Env: Avoided: (i) coal combustion, (ii) electricity, metal production Eco: (i) RDF selling price, (ii) Electricity revenues	Env: LFM beneficial Eco: LFM non-profitable	
Danthurebandara et al., 2015b <i>Environment/Economic</i>	REMO MSW/IW landfill, 16 Mt, BEL	Ex ante (extrapolated from pilot trial)	Do nothing, existing LFG collection & utilization	Advanced separation plant WtE: internal RDF recovery by Gas Plasma WtM: fines, aggregates, metals, glass Re-landfilling: Solid waste Land/airspace: land	Env: Thermal treatment Eco: Operation costs WtE, Investment WtE	Env: Electricity revenues, LFM support, Green energy fraction	Env: LFM non-beneficial Eco: Not explicitly stated	
Färdigerd et al., 2015 <i>Economic</i>	Typical MSW landfill, 0.1 Mt, SWE	Ex ante	Solely remediation of landfill, no existing LFG collection	Mobile separation unit WtM: metals, aggregates, fines Land/airspace: land (small amount reclaim)	Landfill tax for landfill (if applicable) OPEX (heat/electricity sales (internal RDF recovery)) WtE (internal RDF recovery) Material sales (metals) Land reclamation	LFM cost-efficient to solely remediation under certain rare conditions		
Wintersteller et al., 2015 <i>Environment/Economic</i>	REMO MSW/IW landfill, 16 Mt, BEL	Ex ante (extrapolated from pilot trial)	Landfill closure & aftercare, existing LFG collection & utilization	Advanced separation plant WtE: internal RDF recovery by Gas Plasma/Incineration WtM: metals, aggregates, fines Re-landfilling: fines and mixed residues Land/airspace: land (but value not accounted for)	Env: WtE emissions Eco: CAPEx of WtE, Material processing and separation; Excavation and storage Fuel, labor & maintenance	Env: net addition of climate emissions Eco: Electricity sales, avoided closure & aftercare, material sales (metals)		
Wagner and Raymond, 2015 <i>Economic</i>	Ecomaine ash landfill, 0.7 Mt, US	Ex post (assessment of real project)	Do nothing	Mobile separation unit WtM: metals Land/airspace: landfill airspace (small amount reclaim)	Excavation & processing equipment Fuel, labor & maintenance	Env: Landfill airspace (due to metal recovery)	LFM profitable	
Zhou et al., 2015 <i>Economic</i>	Yinchuan MSW landfill, 1.5 Mt, CN	Ex ante	Only landfill aftercare	N/A assumes 100% separation efficiency WtM: metals, soil-type fertilizer, aggregates, glass Land/airspace: land or landfill airspace	Excavation & hauling equipment Material processing & separation Transport	Env: Landfill airspace (due to metal recovery) WtE: external RDF recovery by incineration WtM: metals, aggregates, glass Land/airspace: land	LFM potentially profitable under non-conventional conditions	
Wolfberger et al., 2016 <i>Economic</i>	Typical MSW landfill, 0.7 Mt, AT	Ex ante	Do nothing	Mobile separation unit WtM: metals, aggregates Land/airspace: not accounted for	Gate fees & disposal (incl. transport) Material processing and separation	Material sales (metals)	LFM not profitable	
Hermann et al., 2016 <i>Economic</i>	Styria MSW landfill, 0.7 Mt, AT	Ex ante	Landfill closure & aftercare	Mobile separation unit WtE: external RDF recovery by incineration WtM: metals Land/airspace: land	Gate fees & disposal Material processing & separation	Land reclamation Material sales (metals)	LFM not profitable	
Kieckhäfer et al., 2017 <i>Economic</i>	Pohle Heide MSW Landfill, 2.6 Mt, DF	Ex ante (extrapolated from pilot trial)	Landfill closure & aftercare	Different scenarios for mobile & advanced separation units WtE: external RDF recovery by incineration WtM: metals, aggregates, plastic (adv. separation) Land/airspace: land or landfill airspace	Gate fees & disposal (incl. Transport) Material processing & separation Capital investments	Land reclamation New landfill airspace Material sales	LFM not profitable	

When it comes to environmental assessments, the only impact that has been comprehensively studied in the reviewed literature is climate impact. The reported results are somewhat opposing, where some studies conclude that landfill mining would lead to reduced climate impacts,<sup>14,15,17</sup> while others have found that such projects would instead result in net contributions to global warming.<sup>18,20</sup> In essence, these reported variations of the climate impact rely on to what extent landfill mining contributes to avoided emissions from long-term landfill gas generation and replaced energy generation and material production. This is, in turn, influenced by a wide range of inter-related parameters ranging from landfill-specific factors (e.g. material composition, landfill gas potential and treatment), over project settings (e.g. efficiency of selected material processing technologies) and system conditions (e.g. assumptions about avoided primary material and energy production) to modelling choices (e.g. applied landfill gas and carbon footprint models and procedures for accounting of biogenic emissions from thermal treatment processes). Many of these potentially important parameters and conditions are, however, not clearly described and/or elaborated in the reviewed studies, making comparisons and valuations of the validity of the results difficult. Nevertheless, reduced landfill gas impacts and metal recovery often seem to constitute key processes for avoided climate emissions, while waste-to-energy processes could be significant both in terms of added and avoided emissions.

### **Applied procedures for assessing critical factors for performance**

A general feature of the reviewed cases is a lack of systematic and fine-grained assessments of what actually builds up the economic and environmental performance of landfill mining. Instead, emphasis is rather on assessing the overall potential and feasibility of engaging in such projects, Figure 1. This means that when it comes to critical factors for performance, the results merely highlight main process steps (e.g. material processing and separation, waste-to-material and waste-to-energy), while contributions of underlying factors in terms of the numerous model parameters that build up each of these processes largely remain unknown, or at least implicit. The identification of critical factors is further complicated by a low level of transparency regarding project-specific conditions and different manners for how the subsequent processes of landfill mining and their constituents have been aggregated.



**Figure 1:** Critical factors for performance of landfill mining could be assessed on different levels, ranging from just identifying main process steps as important to specifying the contributions of multiple and inter-related model parameters

Admittedly, several studies include some sort of sensitivity analysis of a few, selected single model parameters. This is especially so when it comes to economics and one of the most common type of parameters assessed are market prices for metals,<sup>9,19</sup> generated electricity<sup>18</sup> and reclaimed land or landfill airspace.<sup>12</sup> These parameters are, however, not necessarily identified as critical in the studies but the sensitivity assessments rather elaborate on at what realistic or unrealistic (future) revenue streams landfill mining could approach break-even. Another type of even less frequently occurring sensitivity analysis aims to identify important performance drivers. Such assessments often take a closer look at the contribution from selected, single model parameters related to the efficiency of e.g. material separation<sup>9</sup> and waste-to-energy processes.<sup>16-18</sup>

Although such variations of one, selected parameter at a time within a certain value range could provide useful insights, it is also insufficient for developing a sound understanding of the economic and environmental principles of landfill mining.<sup>22</sup> Apart from being arbitrarily determined, the applied value ranges for the parameters are often very narrow – something that directly influence the result of the sensitivity analysis, *i.e.* the importance of a parameter. However, what is more important is that the performance of landfill mining is virtually always influenced by several hundred of such model parameters. Many of these parameters are strongly inter-related throughout the landfill mining value-chain, meaning that their real criticality depends

on downstream and upstream parameter values and is thus a matter of such combination effects rather than the possible variation of a single model parameter.

## **Implications of applied methodological choices and principles**

Virtually all of the reviewed studies constitute *ex ante* assessments, meaning that they aim to forecast economic and/or environmental outcomes of engaging in future landfill mining projects. Although forecasts are inherently uncertain, they are nowadays common practice not the least within the financial world. However, the fact that landfill mining is yet an unconventional practice makes these *ex ante* assessments particularly challenging. In contrast to established practices, such emerging concepts suffer from lack of knowledge, practical experience and records of accomplishment. This epistemological deficit has several potential methodological implications on the design, execution, analysis and presentation of the obtained results. Here, we will discuss some examples of such challenges and, in particular, how they have been dealt with in the reviewed assessments.

### **Procedures for scenario development**

From systems analysis theory, we know that the scenario(s) under consideration constitute the foundation of any assessment. Apart from determining spatial and temporal boundaries, such “models” specify the included processes and how their interactions, together with system boundary conditions (*e.g.* policy and markets), affect relevant material, energy, economic and environmental flows. In this section, we will focus on how the reviewed assessments have dealt with three fundamental parts of such scenarios along the landfill mining value chain: (1) selection of landfills and reference cases (*i.e.* BAU if landfill mining is not realised), (2) choice of material processing and treatment schemes and (3) assumptions about resource quality and accessible markets for extracted materials and energy resources.

(1) When it comes to the studied landfills, they seem to have been more or less “randomly picked” at least in terms of their resource potential and suitability for landfill mining. Such an understanding is further strengthened by the fact that none of the reviewed studies reflect on the question if the studied deposit is to be considered as a particularly good, bad or moderate case for landfill mining. Typically, the studied landfills seem to involve heterogenic and low-grade MSW deposits and the related reference cases imply low-to-moderate landfill management costs and impacts. The absence of explicit discussions about the importance of such site-specific settings makes it hard to fully understand the implications of the results from the different case studies. This is especially so given that landfill material compositions, costs and environmental impacts of landfill management options,

values of reclaimed land or landfill airspace, and so on, could vary widely between different cases and regions.

(2) While most landfill mining scenarios seem to involve similar core process steps, significant differences can be found in the type and advancement of employed technologies for material separation. Here, the cases display a quite wide spectrum of equipment ranging from simple or standard mobile units to highly advanced processing plants. There are, however, several issues related to how this very central part of landfill mining scenarios are dealt with in the conducted assessments. To start with, most of the studies only assess one landfill mining scenario involving a specific material separation scheme, and they often do so without providing any clear criteria for why this particular processing line was selected. How was the separation scheme developed, based on what knowledge, empirical evidence and specifications of requirements? Are there any alternatives that potentially could be more suitable and/or cost-effective in this particular case? Instead, selected separation schemes are more or less taken for granted and only dealt with on a very general level, often by referring to industry expertise/estimates or some previous, small-scale trials. This lack of description of the constituents, capabilities and limitations of selected processing lines makes it difficult to evaluate their actual validity and suitability for landfill mining.

A similar situation exists for the selection of thermal treatment methods where especially knowledge in terms of possibilities and limitations of using emerging technologies such as plasma gasification for treatment of RDF retrieved from landfills are poorly described. In some studies, this general lack of transparency regarding the selected material separation and treatment schemes is explained by confidentiality reasons but equally important is probably the low level of knowledge and practical experience of processing previously deposited materials. The employed separation and treatment schemes could, therefore, merely be considered as conceptual and largely reliant on experiences from adjacent fields of knowledge.

(3) It is a well-known fact that beneficial implementation of landfill mining relies on the fact that the excavated masses can be separated out and then recovered or at least disposed of in some affordable and environmentally just way. Material outputs and their anticipated marketability, therefore, constitute a key issue of any landfill mining scenario. However, given the absence of real-life projects, we know very little about what quantities of different materials and energy resources that can be produced from the full-scale processing of deposited waste and even less about at what quality levels. Still, only a few studies discuss the important issue of resource quality while the rest seem to assume that the exhumed resources such as waste fuel, aggregates and various metals will be readily accepted by existing material and

energy markets. Such an assumption is by no means straightforward and, if not true, this will have significant implications on the economic (*e.g.* revenues, disposal costs, amount of reclaimed land or landfill airspace) and environmental (*e.g.* impacts of disposal, type and extent of avoided primary production) outcome. Worth noting is that the marketability of the extracted resources is not just a matter of their intrinsic quality. Knowledge of existing market structures, competition, policy measures and supply and demand dynamics are equally important for facilitating sound estimates on viable recovery routes. For instance, it is largely unclear if recyclers and incinerators are willing or even have the capacity to accept supplementary resources extracted from landfills, which by the way also compete with more high-quality materials obtained from source separation programmes.

### **Empirical support and handling of parameter data**

In order to specify the material and energy flows and related economic and environmental implications of the developed landfill mining scenarios, different types of data need to be collected and introduced into the assessment model in terms of numerous input parameters. Typically, these input parameters are represented as one single, estimated value in the reviewed assessments. This practice of neglecting the likely event of parameter variation constitutes an important weakness of the studies, which could be used as an argument to undermine the validity of the results. Even in well-established practices, stochastic variations of such parameters often occur due to, for instance, changing conditions in various processes and markets. Just this kind of “naturally” occurring variations could have significant impacts on plausible net outcomes of a process, investment or industrial project. However, when it comes to landfill mining, also epistemological uncertainties come into play, meaning that the possible ranges for parameter variation are much larger due to an incomplete or inaccurate scientific understanding of the studied processes. If fully taken into account, such stochastic and epistemological parameter distributions would in many cases have major implications on what actually could be said about the net economic and environmental outcome of landfill mining. Typically, the result would then not constitute a single (and implicitly highly uncertain) value but rather display a wide range of plausible outcomes – ranges that very well could include both positive and negative net results.<sup>23</sup>

When it comes to the empirical data used in the reviewed studies, there is a general tendency that both its quality and relation to the specific project gradually decreases along the landfill mining value chain. The used landfill material composition, for instance, often originate from specific data obtained from waste sampling and characterisation of the deposit in question. Still, common practice to use an average composition could be questioned given the largely heterogenic nature of such

deposits and that the assessed waste samples at best only covers a minor share of the landfill body.

When it comes to the subsequent processes of landfill mining in terms of excavation, handling and temporary storage of masses, material separation and treatment and recovery of materials and energy resources, the applied data primarily originates from adjacent knowledge fields. Typically, experiences from the processing, treatment, disposal and recovery of other, conventional types of waste such as fresh MSW serve as a foundation for specifying material and energy flows as well as related economic costs and revenues and environmental impacts. When it comes to environmental assessments, for instance, the environmental impact parameters are to a high degree based on generic processes from LCI databases – processes that often have little to do with the specific landfill mining project.<sup>18,14,15,17</sup> For any emerging concept, such a practice is more or less unavoidable. However, the main concern is the lack of discussions about to what extent such empirical data or industry estimates from adjacent fields are applicable to the specific processes of landfill mining. The scarcity of uncertainty analysis in the reviewed assessments makes this important issue even more implicit. Moreover, temporal dynamics such as effects of technology learning are rarely accounted for and, as a result, the uncertainty range for economic and environmental performance is further increased.

To take another example, several studies use extremely high efficiencies of employed separation technologies,<sup>11,16-18</sup> which in practice means that 80-90% of the different deposited materials and energy resources in the landfills are assumed extractable. Such assumptions are often combined with quite optimistic estimates regarding the obtained resource quality, economic value and potential for environmental savings due to substitution of primary production. Although maybe applicable to the processing and recovery of some conventional wastes, there is an obvious risk that this transfer of (unconditioned) knowledge from adjacent fields might result in overestimating both the economic and environmental potential of landfill mining. Admittedly, there are also a few exceptional studies using more conservative data regarding these aspects, thereby acknowledging the often inevitable degradation of materials situated in landfills and the practical difficulties of processing previously deposited masses. These studies are commonly related to specific pilot trials and material characterisation efforts.

### **Applied modelling principles for economics and environmental impacts**

Although some of the economic assessments focus on direct costs and benefits,<sup>9,10</sup> the most common metric used to study the profitability of Landfill mining is the Net Present Value (NPV).<sup>11-13,16-20</sup> Such capital budgeting is frequently used in many lines of business to evaluate whether or not it is worthwhile to invest in a project. In

principle, the NPV indicates the potential profit of a landfill mining project by subtracting the investment costs from the total sum of cash flows during a pre-determined time. In contrast to direct costs and benefits, the NPV is sensitive to when different cash flows occur and the time value of money is accounted for by a discount rate incorporating inflation, investment risks and rates of return into the assessment.<sup>25</sup> From a practical point of view, this means that the present value of money is lower the farther we go in the future and the higher the selected discount rate is. For long-term projects such as landfill mining, this way of budgeting is somewhat challenging given that large up-front investments need to be done while many of the revenue cash flows will come in small portions distributed over the years (*e.g.* electricity and material sales), or only materialise in a distant future (*e.g.* avoided landfill aftercare and reclaimed land). There are, however, different private and public views on to what extent the value of money should be downplayed by time and among the reviewed assessments the applied discount rates range within the interval of 0-15% - something that obviously has significant effects on the obtained results.

Virtually all of the economic assessments are performed from the perspective of one single (private) actor in terms of the landfill owner or project manager. However, several studies also underline the key challenge that many of the proclaimed benefits of landfill mining currently only materialise on the societal level. A few assessments, therefore, include some environmental economics principles, for instance, by inserting a monetary value on avoided climate impacts (inverted carbon tax) and renewable energy (green energy certificates).<sup>11,16-18,21</sup> However, when it comes to broader socio-economic values such as nature restoration, employment, local health and material autonomy issues our knowledge is still largely limited. Admittedly, some studies discuss or even semi-quantify some potential societal benefits but real-life projects would presumably generate several socio-economic consequences, both in terms of benefits and costs.

Just as for the economic modelling, the environmental evaluations rely on assumptions and simplifications in order to be able to assess the complex systems at hand. In an ideal life cycle assessment (LCA), all relevant environmental impacts arising from the emissions and resource extractions from the processes within the studied system should be evaluated. Several of the articles study multiple environmental impact categories but there is very little argumentation to clarify the selection of categories and to explain the consequences of such choices.<sup>17,18,24</sup> Furthermore, for systems which are mainly based on *ex ante* modelling it is hard to get specific data that covers a multitude of impacts. This means that for the studies that present highly local environmental impacts such as toxicity, generic data from commercial databases is used with little to no connection to the actual site and the

specific toxicity problems. In most cases a discussion on the relevance of the results to the studied scenarios is lacking.

All of the studies show the impact on climate change for the studied scenarios. These impacts can mainly be attributed to various energy processes throughout the whole chain of landfill mining activities. Normally these emissions are divided into climate gases of fossil or biogenic origin. The biogenic emissions have historically often been regarded as carbon neutral when biomass has been used as some kind of biofuel. Recently, this neutrality has been put into question on the account that added focus should be on changes in carbon stocks, rather than just on sequestration and release of carbon dioxide.<sup>26</sup> In the case of ELFM this means that biomass-based waste in the landfills could be regarded as a carbon sink and when excavated and then used in a waste-to-energy facility the ensuing emissions should be taken into account and be assessed alongside the waste of fossil origin. Only one of the environmental assessments actually includes these emissions although one other article mentions the concept but does not include it.<sup>14,20</sup> If the modelling principle of counting biogenic emissions from waste-to-energy practices is included, the climate change impact will be substantially influenced.

## Concluding discussion

Although conducted assessments have provided valuable knowledge on the potential of landfill mining, the usefulness of applying systems analysis in such an early phase of conceptual development have only been partly explored. In essence, there is a need for more exploratory studies focusing on learning and guiding research towards key challenges and potentials rather than assessments aiming to obtain an accurate result for a specific landfill mining scenario.<sup>8</sup> Given current deficits in knowledge and real-life experiences, such attempts to forecast the net outcome of landfill mining will most likely be wrong anyway, displaying a high risk of either overestimating or discriminating the potential at a too early stage of development.<sup>7</sup>

More research is required in order to develop detailed guidelines on how to perform exploratory studies of emerging concepts such as landfill mining. However, a few tentative principles could be outlined. To start with, the usefulness of such *ex ante* assessments rely on the recognition of large uncertainties, both on the scenario and parameter levels.<sup>8</sup> From a learning perspective, such uncertainties should be made explicit, brought to the forefront of analysis and also be allowed to expand to identify essential as well as potentially promising paths of development. When it comes to landfill mining, this means that assessment of several possible scenarios is advisable to identify implications of e.g. different site-specific settings, processing lines and technology choices and policy and market conditions.<sup>6,20,23</sup> Even in specific case

studies, such an openness to different alternatives and conditions could be useful given the often early stage of development. The fact that many landfill mining projects first will be implemented in the future also implies a need to include temporal dynamics into these scenarios, e.g. various effects of technology learning, gradually changing policy and market environments and upscaling of technologies.<sup>7</sup>

A key feature of exploratory assessments is the use of advanced approaches to model uncertainties.<sup>6</sup> This is fundamental because it makes it possible to accurately display and internalise the level of uncertainty of the results.<sup>20,22,23</sup> The use of more advanced approaches such as global sensitivity analysis also enables fine-grained assessments of critical factors for performance, specifying contributions of multiple model parameters as well as their combination effects.<sup>6</sup> Such detailed knowledge on the importance and relations of different factors and conditions occurring on the site, project and system levels is a necessity for developing tailored landfill prospecting methods, blueprints and specifications of requirements for landfill mining processing schemes as well as support for in policy and decision making.

The realisation of such assessments of what actually builds up the performance of landfill mining scenarios relies on the provision and collection of corresponding data displaying possible ranges of variation for model parameters.<sup>6,22</sup> In an early phase of development, such data collection obviously needs to be based on laboratory tests, expert judgements and knowledge from adjacent fields.<sup>8</sup> In practice, this means that most model parameters will initially be associated with large uncertainty ranges,<sup>9,23</sup> which then gradually could be narrowed down in tandem with real-life initiatives such as pilot trials and eventually full-scale projects. A key challenge here is that most landfill mining processes are currently treated as “black-boxes”. In order to facilitate identification of critical factors and potentials for improvement, these boxes need to be unlocked and their various process parameters fully incorporated into the assessment frameworks.

This review has also illuminated some inconsistencies when it comes to applied modelling principles for profitability and climate impacts. In order to facilitate comparison, synthesis and thus a common knowledge building within the area, it might be fruitful to discuss and streamline what models and metrics to use for assessing performance of landfill mining.<sup>3</sup> Although somewhat theoretical, such methodological research is of utmost importance for the development of the area, given that certain modelling choices (e.g. selected discount rates, investment models, procedures for accounted biogenic climate emissions, and so on) could potentially have a significant impact on the motives for landfill mining projects. In order to better support decision-making, this research must also address challenges related to the need for broader assessment frameworks that includes global to local environmental

impacts as well as socio-economic consequences of such landfill mining.<sup>3,5,16</sup> Again, such a challenging research endeavour should initially be guided by a will to learn and better understand various cause-effect relationships rather than attempting to obtain an accurate result, simply because we are not yet in the position of being able to provide such findings and claims.

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# DEVELOPMENT OF AN EARLY WARNING SYSTEM FOR THE CLOSING THE CIRCLE PROJECT AT THE REMO LANDFILL SITE

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## Introduction

During the “Closing the Circle” Enhanced Landfill Mining project of Group Machiels in Belgium, an environment, safety and health monitoring system will be set up to secure the health of the employees and the surrounding inhabitants of the Remo landfill site. This monitoring system consists of a flexible toolbox of instruments to monitor the public health impact of landfill mining operations. Depending on the phase of the CtC project, different tools will be used, e.g. air quality monitoring, effect-oriented measurements, human biomonitoring, ecosurveillance etc. This paper discusses the set-up of an Early Warning System (EWS) to monitor emissions and provide early warning detection of increased emissions of odour and fine dust. The target is to establish a real-time monitoring system, which can automatically alert Remo when odour or dust nuisance might occur, so that immediate corrective actions can be taken on site.

## Approach

The EWS consists of an odour monitoring system with electronic noses (eNoses) and PM monitoring with continuous dust monitoring and off-line dust characterisation. Pilot measurements were carried out to validate the instrumental setup.

An eNose is an instrument comprising an array of non-specific gas sensors. The eNose responds when it is exposed to oxidising or reducing gas mixtures. When all the sensor responses are put together, they form a pattern or fingerprint, which is typical for the gas/odour presented to the array. As the sensors are non-specific, the eNoses have to be trained to recognise specific gases/odours and to determine the specific fingerprints. Training of eNoses is done by linking other information about the gas/odour situation during the recording of the eNose data. This training can be done by investigating time and place correlations between eNose recordings and human odour perceptions in the field, or by means of dynamic olfactometry. An eNose

network consists of several eNoses that are on-line connected to a remote computer system *via* a wireless data communication link. Software on the remote computer interprets the signals of the remote eNoses in real time.

The sensor box for dust measurements consists of semi-automatic reference monitors (Partisol Plus, Thermo Scientific) for filter sampling (24 h samples) according to EN 12341 and on-line optical dust samplers (Grimm 1.108 dust monitor), which simultaneously determine the mass concentrations for different dust fractions (TSP, PM<sub>10</sub>, PM<sub>2.5</sub>).

From June 27<sup>th</sup> to July 6<sup>th</sup> 2017 a measurement campaign was carried out to collect odour and dust data and to derive alert levels, which indicate when odour or dust nuisance might occur. During this campaign the relevant ELFM activities (excavation, transport and storage) were simulated. The eNose and PM measurements were performed during representative ELFM operations as a function of the distance to these activities.

## Odour

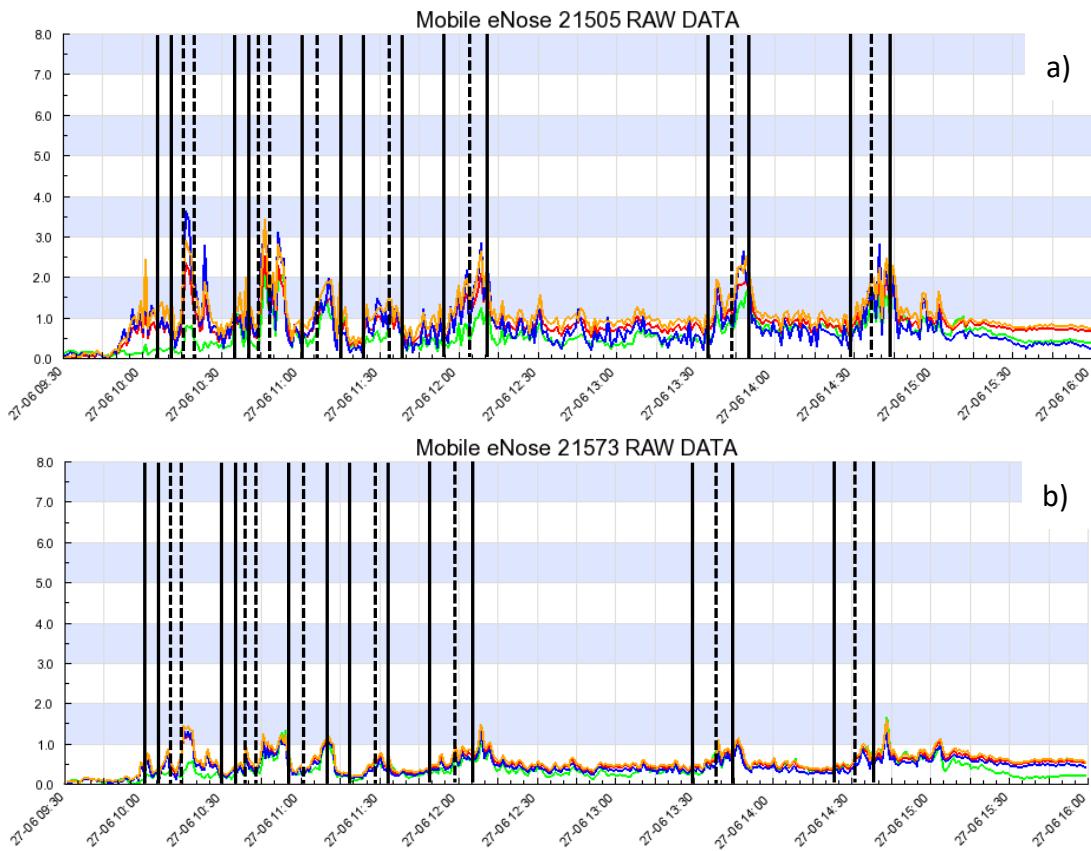
### Excavation activities

At the excavation sites, one eNose was placed upwind of the excavation pit and four to five eNoses were placed at different distances (from about 10 to 50 metres) downwind the excavation pit (Figure 1). Additionally two eNoses were used to perform mobile measurements. Similar set-ups were installed at 4 different excavation sites. The excavation activities (excavation and loading of the dumper, and “stirring” in the excavation pit) were logged. To simultaneously link the eNose readings to information about the odour situation, eNose measurements and human odour perceptions were performed at different locations and times.



**Figure 1:** Set-up of the eNose network at an excavation pit with one upwind eNose and four downwind eNoses

An example of the results of the eNose measurements is shown in Figure 2. The eNoses used consist of four different sensors; the readings of each sensor are indicated in different colours.



**Figure 2:** eNose readings of two eNoses at 10 m (a) and 40 m (b) of the excavation pit (the black lines and dashed lines indicate the start and end times of the excavation activities (loading of the dumper truck + stirring))

During the excavation activities increased eNose readings were observed. The measurement values decrease with distance to the excavation pit. During the field measurements, some weak and moderate odours were perceived. Based on the results of the simultaneous eNose and human odour measurements specific alert levels were derived that indicate from which eNose readings odour perception can occur.

### Transport and storage

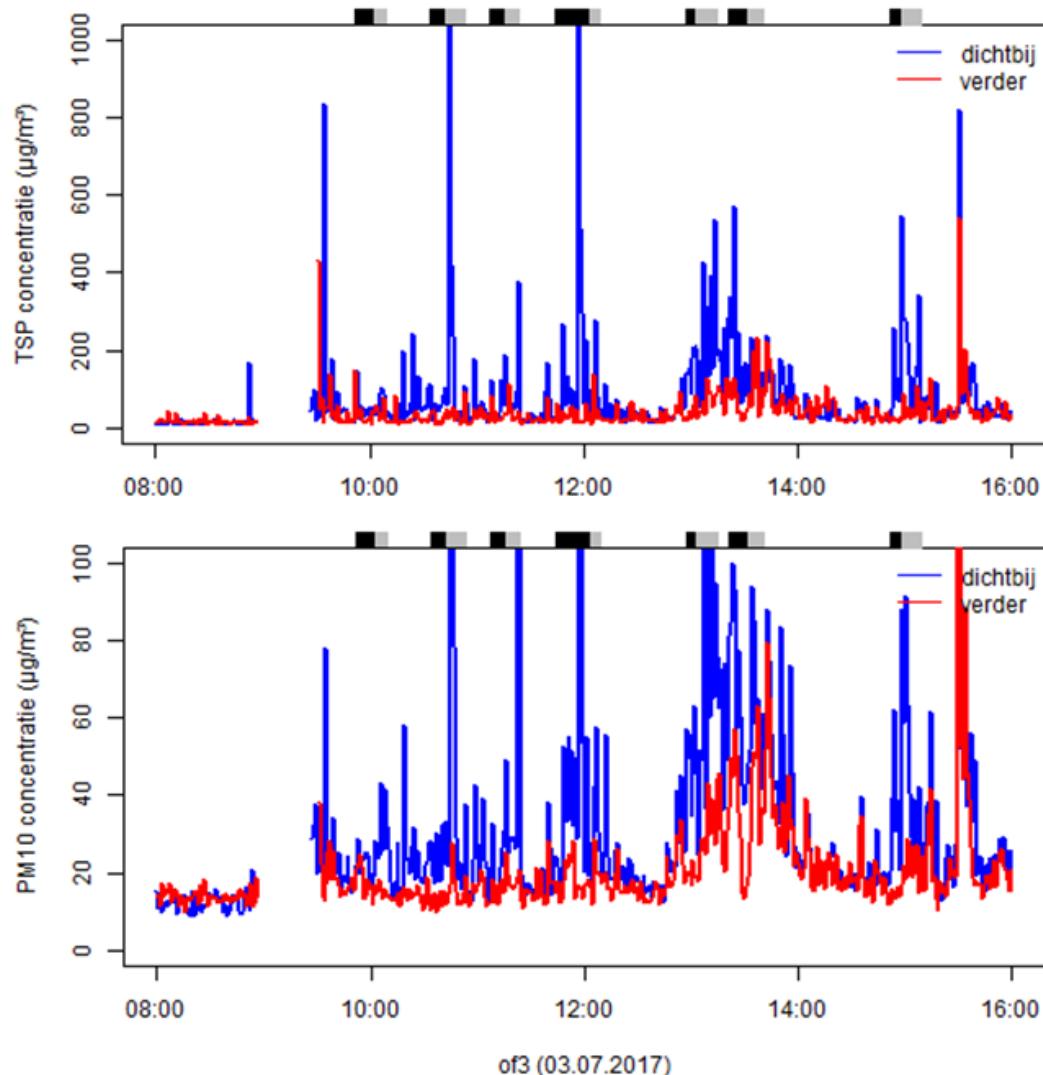
During the transport with the dumper trucks, the unloading of the dumper trucks as well as during the storage of the material, very limited odour emissions were recorded by the eNoses as well as by the human observations.

## Dust

The reason for focussing on TSP and PM<sub>10</sub> dust fractions, is justified by the typical diameter distribution that was found at the landfill site. About 30% of the total (TSP) dust is smaller than 10 µm (*i.e.* belongs to the PM<sub>10</sub>-category) and about 10% of the total dust is smaller than 2.5 µm (*i.e.* belongs to the PM<sub>2.5</sub>-category).

## Excavation activities

At the excavation sites, two monitors were placed in the downwind direction of the excavation pit (5 m and 20 m). The excavation activities were logged. The measurement series from 3/07/2017 at one of the sites is shown in Figure 3.



**Figure 3:** Dust concentration (TSP and PM<sub>10</sub>) during excavation in the near vicinity (5 m, blue line) and a bit further (20 m, red line) from the pit. The activity of the crane is indicated at the top of the plots. Dark grey periods indicate excavation and loading activities, light grey indicates stirring.

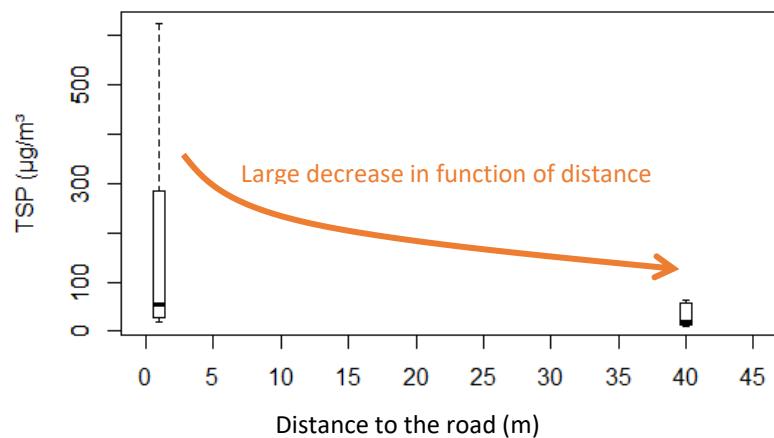
Increased dust concentrations in relation to the activities are observed. Peak-concentration of PM<sub>10</sub> can be as high as several hundreds of  $\mu\text{g}/\text{m}^3$ . The peaks are short in time and background concentrations are reached within minutes after the excavation activity. The average PM<sub>10</sub> dust concentration over longer periods did generally not exceed the limit value of 50  $\mu\text{g}/\text{m}^3$  for ambient air.

## Transport

Whirling dust from transportation over dusty roads, in this case from the excavation site to the temporal storage site, may result in significant dust emissions, especially during dry conditions. Dust emission reduction techniques like wetting of the roads could be applied to better control these emissions. A monitoring set-up was elaborated to get insight into the effect of wetting of the road and reduced dust emission from transport under these conditions. Again, one monitor was placed nearby the road (2 m) and the other at larger distance (45 m). The reduction of the dust concentration after wetting is high. The dust concentration near the road is more than 50 times lower, both for TSP and PM<sub>10</sub>. Further away from the road the concentration was 10 times lower after wetting the road (Table 1). The dust concentration resulting from dust emissions from the road due to transport decreases significantly with distance (Figure 4).

**Table 1:** Dust concentration (TSP) before and after wetting of the transport road

	Close	Distance
<b>PM<sub>10</sub> (<math>\mu\text{g}/\text{m}^3</math>)</b>		
Before wetting	1,900	157
After wetting	33	16
<b>TSP (<math>\mu\text{g}/\text{m}^3</math>)</b>		
Before wetting	6,800	386
After wetting	97	24



**Figure 4:** The dust concentration (TSP) decreases significantly with distance from the road.

## Temporary storage

At the Remo temporary storage site, dust peak concentrations were observed at passage or unloading of the dumper (Figure 5). Very limited dust emissions occur from the temporary storage, as could be observed during inactivity (lunch period).

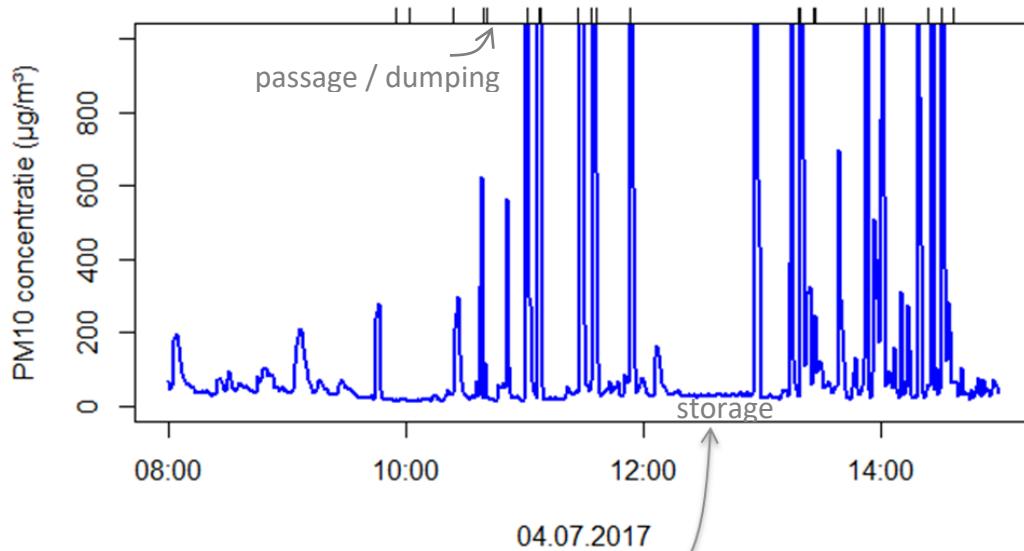


Figure 5: The dust concentration (PM10) at the temporary storage

## Conclusions

The results of a first measurement campaign demonstrate the eNose's and PM sensors' potential as an on-line tool for continuously monitoring odour and dust emissions during the different ELFM activities. The most relevant odour emissions originate during excavation activities; relevant dust emissions come from transport over dusty roads and from excavation. Based on the results of the eNose and dust measurements specific alert levels were derived. During the next measurement campaign, the alert levels will be fine-tuned. In the end the EWS will allow:

- Warning at an early stage for increased odour and PM emissions so necessary measures on site can be taken;
- Source characterisation (different landfill operations, incineration, waste processing, transport);
- Differentiation of landfill-related impacts from regional background concentrations and other local pollution sources;
- Communication of monitoring data to surrounding communities.

# INTEGRATING LANDFILLED MATERIAL STOCKS INTO MODERN RESOURCE CLASSIFICATION FRAMEWORKS

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## Introduction

As an integral part of holistic resource planning strategies, the efficient use of resources, including urban mining, recycling and re-use, as well as the management of waste, has gained increasing importance in Europe.<sup>1</sup> Already in the 1960s, Jane Jacobs acknowledged the resource potential of cities and predicted a transition from geogenic to urban mines.<sup>2</sup> More recently, various authors, such as Johansson, Krook<sup>3</sup>, Sverdrup, Ragnarsdottir<sup>4</sup> or Weber<sup>5</sup> have pleaded for establishing a link between mining geogenic materials and mining anthropogenic resources. Several studies<sup>6,7,8</sup> conclude that anthropogenic deposits, such as landfills, old buildings and hibernating infrastructure, are comparable in size to the remaining natural stocks of certain metals. And also the mineral grade of exploitable anthropogenic stocks was found to be similar to virgin material deposits.<sup>9</sup>

Some studies<sup>10,11,12</sup> compare potential extraction projects from different types of anthropogenic resource deposits, *e.g.* recovering copper from hibernating infrastructure in different cities. Some studies also try to map anthropogenic resources and/or related recovery projects into existing primary resource classification frameworks. Lederer *et al.*<sup>13</sup> evaluate the mining potential of different anthropogenic phosphorus stocks in Austria. Fellner *et al.*<sup>14</sup> investigate the economic viability to recover zinc from different solid residues of waste incineration. Both use the McKelvey diagram<sup>15</sup> to identify that part of the entire resource potential that can be economically extracted under current conditions. Mueller *et al.*<sup>16</sup> classify different types of waste electrical and electronic equipment containing rare earth elements under the United Nations Framework Classification for Resources (UNFC)<sup>17</sup>, mainly focusing on the knowledge on the deposit's composition.

While there are some first attempts to classify diverse anthropogenic resource stocks under primary resource classification frameworks, for landfill mining the main focus of research projects so far has been on characterising a specific landfill's composition and on evaluating its resource potential.<sup>6,18-22</sup> Several studies also assessed the environmental and economic performance of landfill mining.<sup>23,24-31</sup> Landfill mining can either represent a push or a pull situation.<sup>32</sup> Some landfill mining projects were carried out with a major focus on resource and energy recovery.<sup>32,34,35</sup> In this case, mining an old landfill requires positive socioeconomic prospects either for a private investor or a public entity (pull situation). A private investor is only interested in direct financial effects, unless non-monetary effects are monetised in the form of subsidies.<sup>36</sup> A public entity is expected to include long-term societal and environmental effects<sup>37</sup> in the evaluation, such as the elimination of a source of local soil and water pollution,<sup>6</sup> the avoidance of long-term landfill emissions,<sup>38</sup> the public's perception,<sup>39</sup> the creation of new jobs<sup>25</sup> and the potentially increasing value of surrounding land,<sup>40</sup> after mining the landfill. Most of the early landfill mining projects were largely driven by local pollution issues or by the need for new landfill capacities, where authorities obliged the former landfill operator to act (push situation), rather than by recovering landfilled materials as secondary resources.<sup>19,36,41,42</sup> Nowadays, in many densely populated regions in Europe, such as Flanders, the key drivers of landfill mining are rising land prices and the need for new clean land.<sup>43</sup>

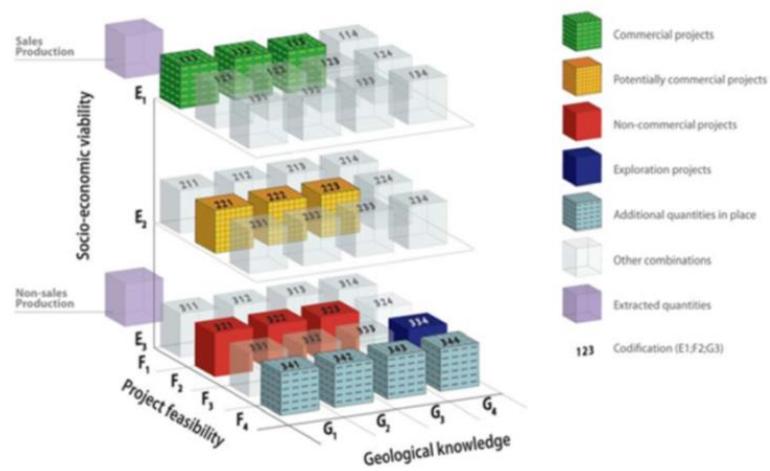
## Objectives

The aim of this paper is to summarise the work that has been done so far on the integration of landfilled materials stocks into modern resource classification frameworks. Subsequently, state-of-the-art research is presented by showing a concrete example of resource classification applied to a planned landfill mining project in Flanders.

## Integration of landfilled materials stocks into modern resource classification frameworks – the journey so far

The purpose of modern primary resource classification systems is to help managing scarce commodities by categorising resource deposits and by making potential resource extraction projects comparable for involved stakeholders. Governments, industry, investors and regulators require a comprehensive understanding for assessing the availability of primary resources at the level of individual mining projects as well as at national and global scales. As the mining industry has become more and more a global business, starting from the 1990s on, there have been increased efforts to harmonise existing national classification codes to create transparency and comparability in the reporting of primary raw materials.<sup>17,44</sup> The

United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC) was therefore initiated by the United Nations Economic Commission for Europe (UNECE).<sup>45</sup> In 2017 it was renamed into “United Nations Framework Classification for Resources”.<sup>46</sup> The process of creating official guidelines to fit anthropogenic resources into UNFC has been initiated at the 6<sup>th</sup> session of the UNECE Expert Group on Resource Classification (EGRC) and is still on-going.<sup>47-50</sup> Under UNFC, mining projects are classified on the basis of three fundamental criteria displayed on three different axes, namely “socioeconomic viability” (E1 – E3), “field project status and technical feasibility” (F1 – F4) and “knowledge on composition and extractable material content” (G1 – G4), with E1F1G1 being the best category (cf. Figure 1).<sup>17</sup> Combinations of these criteria create a three-dimensional system.



**Figure 1:** United Nations Framework Classification for Resources (UNFC); reproduced courtesy of the United Nations Economic Commission for Europe

Wintersteller and Laner<sup>29</sup> used the United Nations Framework Classification for Resources (UNFC) to classify recovered materials from a historic landfill site in Belgium. Since UNFC just like all the other resource classification codes, serves for classification means only and does not provide specific guidelines for assessing a mining project, a first operative evaluation procedure was established.

The focus of the evaluation was set on how different technological options impact the project’s economics. Four scenarios have been investigated, representing different alternatives for the combustible waste fraction’s thermal treatment and for specific stakeholder interests (public vs. private perspective). The main drivers of the economic performance are parameters linked to the thermal treatment of the combustible waste fraction as well as to the sales of recovered metals. As none of the scenarios was found to be economically viable, cut-off prices were calculated for key parameters, to determine under which conditions an anthropogenic deposit has

reasonable prospects for future economic extraction, and so to decide whether it can be labelled a “resource” or not. Based on required future price increases for non-ferrous metals and/or electricity to make the project economically viable, the scenarios resulted in different final resource classifications under UNFC.<sup>29</sup> In continuation of that first study, Krüse<sup>51</sup> mapped different landfill mining scenarios for the Hechingen landfill in Germany within the three dimensions of UNFC, comparing different project set-up options for the excavated combustible waste fraction (on-site vs. off-site incineration), to find out how the project’s economic performance is impacted. Also the perspectives of a private investor vs. a public entity were compared. To broaden the classification scope to other types of anthropogenic resources, the ECLAR methodology for the evaluation (E) and classification (CL) of anthropogenic resources was developed by Winterstetter<sup>52</sup> and then applied to case studies for landfill mining (obsolete stocks), recycling of obsolete personal computers (waste flows) and recovering materials from in-use wind turbines magnets (in-use stocks).<sup>32</sup>

In Flanders there are more than 2,000 landfills; the majority of these is no longer operational.<sup>43</sup> To assess these landfills’ contamination risks and their respective resource potential, the Public Waste Agency of Flanders (OVAM) – in charge of preparing waste and soil policies – developed the FLAMENCO model (Flanders Landfill Mining, Challenges and Opportunities) as a decision support tool. The model is based on a multi-criteria analysis using specific weighing factors.<sup>53</sup> Based on this work, OVAM is currently prospecting the resource and land recovery potential of selected historic landfills. The ECLAR methodology in line with UNFC helps to systematically decide, whether these sites are to be mined or not and under which framework conditions, by considering each landfill’s specific characteristics.<sup>54</sup>

While OVAM has done some fundamental work related to landfill mining in Flanders so far, further landfill mining projects are about to be realised in close cooperation with local authorities. For this purpose, old landfills are continuously inventorised and integrated with the spatial model of Flanders. Besides, OVAM pursues different projects, such as the EU Interreg Project COCOON to improve the legal framework conditions for landfill mining<sup>55</sup> or the EU Interreg Project RAWFILL promoting the standardisation of enhanced landfill inventories in North-West Europe.<sup>56</sup> On a European level, the European Enhanced Landfill Mining Consortium (EURELCO), founded in 2013, aims to further develop the knowledge on the EU’s 500,000+ landfills, which can potentially provide for a substantial part of the EU’s material, energy and land needs.<sup>57</sup>

## **Operative evaluation procedure: ECLAR methodology for the Evaluation (E) and Classification (CL) of Anthropogenic Resources (AR)**

To facilitate the integration of anthropogenic resources into UNFC, which was originally designed for primary resources, the ECLAR methodology for the Evaluation (E) and Classification (CL) of Anthropogenic resources (AR) was developed.<sup>52</sup> It comprises an operative evaluation procedure as well as a set of specifications to classify recovered materials from old landfills and other types of anthropogenic deposits.<sup>32,52,58</sup> The evaluation is built on a spreadsheet tool that allows analysing the effect of changes in various conditions (e.g. land prices, metal prices, sorting efficiencies) on the economics of a landfill mining project. To decide whether to start actual mining activities or not, the stages “(pre-) prospection”, “exploration” and “evaluation” have to be run through. Details can be found in Winterstetter & Wille<sup>54</sup> and Winterstetter & Laner<sup>32</sup>. After screening existing databases and selecting a specific deposit for potential mining, three key aspects – as used under the three dimensions of UNFC<sup>17</sup> – need to be considered (cf. Table 1).

1. The knowledge on composition, contamination level, share of recoverable resources /land from a recovery project is expressed as the level of certainty on the G-Axis. Depending on whether the level of confidence is high, medium, low or whether knowledge on the minable content is practically not existing the deposit is graded with G1 to G4.<sup>52</sup>
2. The technical feasibility of a mining operation (F-Axis) is indicated by the use of fully mature technologies and on-going activities including all required licenses (F1). One or several of those criteria being unfulfilled results in the lower categories F2 – F4.<sup>52</sup>
3. In the evaluation phase the project’s socioeconomic viability is analysed (E-Axis) via a Discounted Cash Flow (DCF) Analysis. Modifying factors such as legal, environmental, socioeconomic, political, marketing, transportation and technological factors are considered.<sup>59</sup> A positive Net Present Value (NPV) results automatically in E1. In case of a negative NPV, cut-off values for key parameters decide, whether there are reasonable prospects for future economic extraction (E2) or not (E3). Concluding the evaluation stage allows for a decision, whether the project shall be developed for exploitation, delayed, studied further or abandoned.<sup>52</sup>

For the classification of landfill mining projects, the preconditions (push vs. pull) (A) set the initial framework conditions for all further steps. With respect to influencing factors, a distinction should be made between parameters related to the specific site (B) (e.g. landfill's composition, land prices), the project (C) (e.g. selected technologies)

**Table 1:** Resource classification process for potential landfill-mining projects<sup>based on 52:54</sup>

Systemic factors	<ul style="list-style-type: none"> <li>• Markets for secondary products</li> <li>• Commodity prices world market</li> <li>• Regional land prices</li> <li>• ...</li> </ul>		
Phases	Goal (UNFC axes)	Influencing factors	Methods for decision foundation
1. Pre-Prospection/ Mapping	Selection of a landfill to be mined	A) Preconditions a) Availability status Obsolete stock b) Mining condition • Pull: Landfill can be mined • Push: Materials must be extracted due to system constraints	Analysis & evaluation of reports/data bases on anthropogenic deposits: Macro scale MFA and/or FLAMINCO model
2. Prospection	Identify the landfill's resource potential & contamination level (G-Axis)	B) Site specific parameters a) Type & Location b) Volume c) Composition	Detailed investigation of the deposit (e.g. log books, sampling, waste analysis)
3. Exploration/Surveying of a specific landfill	Gain knowledge on the landfill's share of extractable & potentially usable materials/recoverable land (G-Axis) Check technical feasibility & Project status (F-Axis)	C) Project specific parameters a) Technology maturity & different options of project set-ups for extraction & processing with specific recovery efficiencies b) Project status (public perception, licenses etc.)	Micro scale MFA Technology assessment Policy framework analysis Stakeholder analysis
4. Evaluation	Socioeconomic viability of extraction & utilisation (E-axis)	D) Socioeconomic parameters a) Prices for secondary products (recovered resources/land/new landfill space) b) Costs c) Avoided costs d) Indirect financial effects e) Non-monetary effects (environmental, social)	DCF* analysis & cut-off values for key parameters Net Present Values (NPV) ** a) NPV > 0: Resource b) NPV < 0: Resource or not? Social & environmental effects can or cannot be monetised
5. Classification	<b>Combination of all criteria &amp; classification under UNFC</b>		

\* DCF = Discounted Cash Flow Analysis, \*\* NPV = Net Present Value

and the embedding system (e.g. legislation).<sup>52</sup> Preconditions and site-specific parameters are decisive for project related choices. By nature, systemic factors have an impact on the preconditions, to a certain extent on the site and project specific parameters and most importantly on the socioeconomic parameters (“modifying factors”).<sup>44</sup>

## Case study: landfill site Bornem

The investigated landfill site is located in Bornem, a municipality in the Belgian province of Antwerp. The nearest residential area is the community of Temse with 30,000 inhabitants, which is located on the other side of the Schelde river. The adjoining areas are largely undeveloped and are primarily used as forest and meadow. The landfill received over 390,000 tonnes of mainly municipal solid waste (MSW) between 1947 and the late 1970s, when it was closed. The nearest groundwater well is located at a distance of approximately 400 m across the Schelde river. Thus, no influence on groundwater extraction is expected. The former operator was under contract with the municipalities Bornem and Puurs. Today the landfill site covers an area of 50,000 m<sup>2</sup>.<sup>60</sup>

For this landfill site test excavations, trial sortings and waste characterisations of a batch of 500 tonnes have been performed in order to generate knowledge on the landfill body's composition as well as on the best suited sorting option.<sup>61</sup> The share of metals is almost negligible and therefore not being recovered.<sup>61</sup> The landfill is expected to be excavated within one year. As OVAM takes the lead, the evaluation is performed from a public entity's macro perspective, considering direct financial effects (*i.e.* costs for excavating, transporting, processing materials and the disposal of residues, revenues for selling secondary products and avoided aftercare costs) as well as some selected non-monetary (avoided GHG emissions) or indirect financial effects (newly gained land tax). The fine fraction is sold as construction material after extraction, while plastics and wood fractions are entirely turned into Solid Recovered Fuel (SRF) and used in an off-site cement kiln in Antwerp. A certain amount of excavated materials has to be re-landfilled off-site. At the end of excavation activities the regained, cleaned-up land will be sold at a price of 150 €/m<sup>2</sup>. Potential greenhouse gas emission (GHG) savings of a landfill mining project compared to a “Do-Nothing” scenario are included *via* a hypothetical CO<sub>2</sub> tax. Additionally, the prevented pollution of soil, ground and surface water due to landfill mining is counted in by avoided aftercare costs for a period of 70 years. In addition, after selling the cleaned-up land, revenues from annual land tax are incorporated as indirect financial long-term effects for municipalities.<sup>52</sup>

As a result of the Material Flow Analysis, Table 2 shows the potentially recoverable and saleable quantities of secondary products as well as the amount of materials, which will have to be re-landfilled again at a fee of about 65 €/t.<sup>54</sup>

**Table 2:** Total potentially recoverable and usable quantities from the Bornem landfill (wet matter)<sup>54</sup>

	Unit	
<b>Regained saleable land (100% of total landfill area)</b>	[m <sup>2</sup> ]	50,000
<b>Solid Recovered Fuel (SRF)</b>		129,200
<b>Soil / construction material</b>	[t]	207,400
<b>Amount of materials to be re-landfilled off-site (sorting residues)</b>		34,600

With respect to the project's socioeconomic performance, the overall evaluation yields a negative NPV of in total -17 million €, which equals to -44 € per tonne of excavated waste. This implies that the project is currently not economically viable, and can therefore certainly not be classified as E1 ('reserve'). Total discounted cost amounts to -28 million € (-73 €/t) (cf. Table 3).

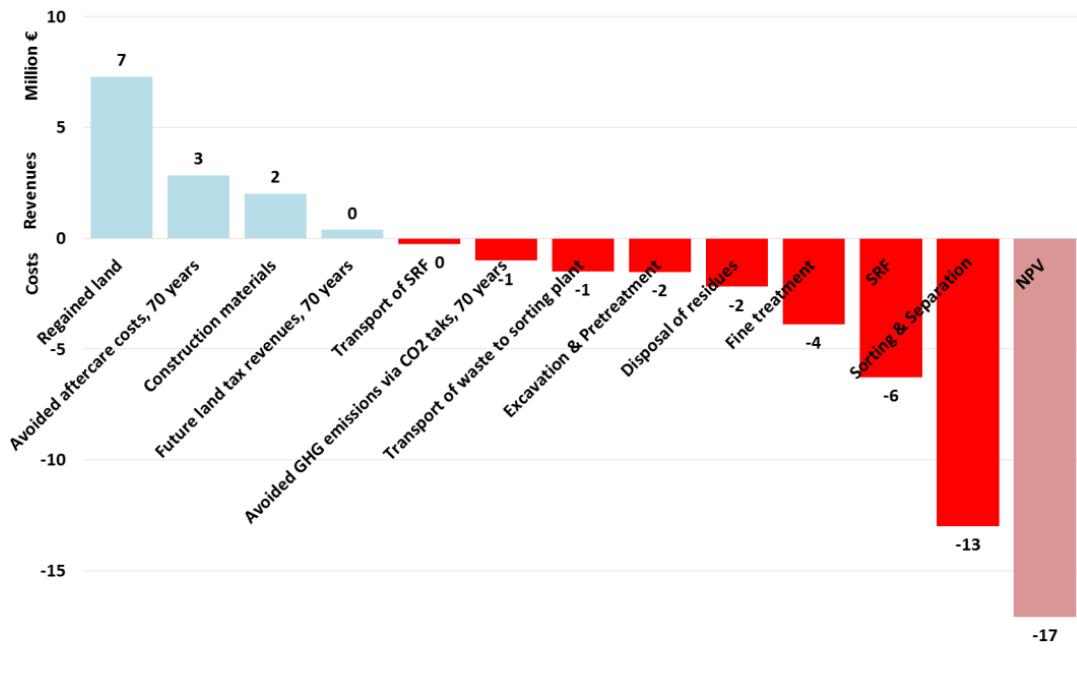
**Table 3:** Total discounted cost and NPV (total and per 1 tonne of excavated waste). Cash flows are discounted over 1 year (planned project period) with a discount rate of 3%.<sup>54</sup>

Costs and revenues	Million €	€/t excavated waste
<b>Total discounted costs*</b>	- 28	- 73
<b>Total discounted revenues</b>	11	29
<b>Total NPV</b>	- 17	- 44

\* Costs are indicated by negative values

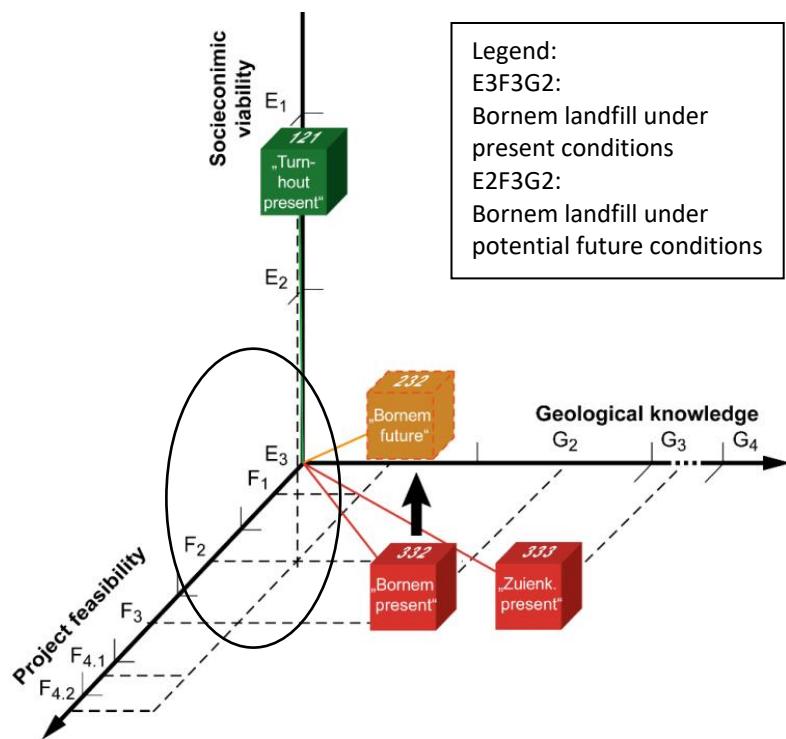
Figure 2 shows that the main drivers on the cost side are clearly the relatively high sorting costs, owing to the complex sorting procedure selected.<sup>61</sup> Gate fees for co-combustion in a cement kiln (50 €/t SRF) amount to 22%, representing the second biggest share of total costs. Compared to other landfill-mining projects, total revenues are lower, as the share of metals present in the landfill is relatively small and therefore not being recovered. Avoided aftercare costs for 70 years and selling regained land represent the biggest sources of revenues. In practice, the landfill is not managed, hence no aftercare measures are taken. However, in order to evaluate the avoided "environmental damage" caused by the landfill, a hypothetical aftercare period of 70 years is assumed. The land tax gained by the municipality for a period of 70 years plays a minor role (10%). The greenhouse gas emission saving potential,

compared to a “Do-Nothing” scenario, turned out to be negative (mainly due to the cement kiln co-combustion of SRF) and therefore appears on the cost side. More information on the Bornem landfill’s economic evaluation and the life cycle impact assessment can be found in Wintersteller & Wille.<sup>54</sup>



**Figure 2:** Total costs and revenues of the Bornem landfill-mining project, discounted over 1 year with a discount rate of 3%<sup>54</sup>

Based on required future changes in key modifying factors to make the project economically viable, it could be decided, whether the landfill can be labelled at least as E2 (“resource”) or not. A combination of increasing land prices up to 350 €/m<sup>2</sup> and parallel decreasing sorting costs to 15 €/t (from currently 35 €/t), can in the authors’ opinions realistically be reached. Consequently, the landfill has reasonable prospects for economic extraction in the near future and can be classified as “resource”, *i.e.* move from E3 under current conditions to E2 under potential future conditions. Figure 3 shows the classification of the Bornem landfill-mining project under UNFC.



**Figure 3:** Classification of the Bornem landfill-mining project under UNFC<sup>54</sup>

In terms of “knowledge on the landfill’s composition and its extractable and usable material content/share of recoverable land”, the Bornem landfill-mining project is graded with G2. The material quantities contained in the landfill can be estimated with a medium level of confidence based on data from the test excavations, trial sorting and waste characterisations and the landfill’s logbook data. The applied technologies’ recovery efficiencies can be estimated with sufficient detail for assessing the landfill’s extractable raw material potential. If it had been a pure land development project, G1 would have been justified. The land recovery potential is very well known due to the fact that residues are re-landfilled off-site and so the entire former landfill area can be reclaimed<sup>54</sup>.

For the F-Axis, displaying the project’s “field project status and technical feasibility”, the landfill-mining project is graded with F3. Even though only well-known technologies are applied and OVAM is taking the lead, there are no activities on-going other than test-excavations and trial sortings. The LFM project is still in the pre-feasibility stage with mainly planning activities and operations on a very small scale. The project duration in the economic evaluation was assumed to be one year, although it is not clear yet, whether there is enough capacity in nearby recycling facilities to sort and treat the entire amount of waste within one year. In addition, a legal framework for landfill mining has not been developed so far and, hence, various individual licenses are needed to advance the project. Therefore, the project obtains

F3, and is in total classified as E3F3G2 under present conditions, but as E2F3G2 under potential future conditions.<sup>52,54</sup>

## Conclusion

The purpose of modern primary resource classification systems is to help managing scarce commodities by categorising resource deposits and by making potential resource extraction projects comparable for involved stakeholders. While there are some first attempts to classify anthropogenic resource stocks under primary resource classification frameworks, most landfill mining projects so far have focused only on characterising a specific landfill's composition and on investigating its resource potential, with some studies including environmental and economic evaluations.

Similar to a conventional mine, where resources are depleted over time, each landfill mining project needs to be investigated and evaluated on a case-by-case basis<sup>54</sup> as a function of various possible project decisions, considering its local conditions and its systemic context. The most crucial point here is to make the classification of resource and/or land recovery as comparable and therefore as transparent as possible. The presented ECLAR methodology in line with UNFC helps to systematically decide, whether certain sites are to be mined or not and under which framework conditions, by considering each landfill's specific characteristics.<sup>54</sup> Displaying the technical feasibility of a potential landfill-mining project as well as the knowledge on composition and the recoverable share of materials/land helps to identify missing or uncertain data. Actual mining activities will only start once these information gaps are closed, which might take some time. Classifying the socioeconomic viability is of particular relevance for long-term resource planning purposes, as for certain historic landfills, mining is not (yet) economically viable under current conditions, but perhaps in the foreseeable future, with changing modifying factors. An iterative evaluation and classification process is therefore essential to keep data bases up to date. Integrating latest data and information allows for taking changing market/legal/technical situations into account, *e.g.* wait until commodity prices increase over time, technologies become mature or more cost-effective, or changes in legislation occur.<sup>54</sup> The presented methodology can help various stakeholders with communicating, decision making and prioritising potential landfill mining projects in a systematic and transparent way.

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# A ‘LOCALS’ PERSPECTIVE TOWARDS SOCIAL ACCEPTANCE OF THE CLOSING-THE-CIRCLE PROJECT IN HOUTHALEN-HELCHTEREN

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## Introduction: Why did citizens take the initiative to start up a 'Locals Working group'?

The *First Enhanced Landfill Mining (ELFM) Smposium* was held in Houthalen-Helchteren in Molenheide (Belgium) in 2010. This was the result of an initiative launched by a multi-actor research consortium and the company Group Machiels, which operates the Remo landfill, located in Houthalen-Helchteren (Province of Limburg, Region of Flanders). Group Machiels aims at the development of an ELFM project at the Remo site, termed “Closing The Circle (CtC) project”. Maurice Ballard initiated the idea to invite not only members of the scientific community but also representatives of the local people (“The Locals”) to jointly express the residents' concerns to the symposium attendees.

Following this conference, The Locals, a pure citizens' initiative, realised there was a need to continue with their 'working group'. “The Locals” is a working group made up of local people mainly from Houthalen-Helchteren and Heusden-Zolder, who have adopted the objectives of the not-for-profit association CleanTechPunt. Currently, the group consists of fourteen inquisitive and extremely watchful members who critically examine the plans for the ELFM project of Group Machiels. They scrutinise every detail and will continue to do so over a follow-up period.

It is evident that the approach taken by The Locals is a dialogue model. Although the follow-up of such a project over six to seven years occurs on a completely voluntary basis, every member of the group is fully committed.

## **Acquiring knowledge and building trust**

The Locals, as a group, have clearly chosen not to use a conflict model and instead engage at every level. This enables them to closely follow and influence the development of the Closing the Circle-project of Group Machiels. They trust the scientific and technological community but are aware that blind trust may be dangerous. The group is led by Mr. M. Ballard, chairman of CleanTechPunt, who has expertise in the principles of circular economy. Group meetings always include further training in related subjects. The Locals have established contacts with scientists, universities, business leaders, tech companies and public bodies. To date, more than 45 information gathering meetings and 25 internal working meetings have taken place. By acquiring knowledge from unbiased and trustworthy sources, the Locals consider themselves well placed to listen to concerns of other citizens, to understand their anxieties and fears, to analyse their concerns and establish the essence of their objections in order to jointly look for a solution.

## **A critical approach whilst being receptive to change**

With respect to the impact of the CtC-project, The Locals adopt a rather conservative, buffering and controlling role. The Locals' aim of this cautiously optimistic approach is to obtain as many safeguards as possible in this transition experiment to ensure it is executed in a reliable way and without causing nuisance or adverse effects in the short or long term. Transparency throughout the entire project will allow for the appropriate follow-up and perfect controllability.

ELFM offers an opportunity to write the final chapter in the long waste processing story in the municipality and to round it off. This project replaces waste disposal methods such as incineration and landfilling with waste processing technologies that enable the waste to become part of the circular economy. Of paramount importance here is the protection of the environment, as well as health and safety.

When engaging in the public debate, the Locals take a rather exploratory and stimulating approach. In addition to the identification of necessary safeguards for which the appropriate mechanisms and communication channels have to be put in place, there is further exploration of the potential for additional benefits and gains for the local people. Which concrete, positive outcomes could the CtC project deliver for the residents and the local community? Are positive effects only possible in the long term or also in the short term? Which elements could make the CtC project intrinsically attractive, and is this feasible, or can one only find drawbacks which may need to be compensated?

## **What is the driving force that has kept 'The Locals' going for more than seven years?**

Clearly, the project has great importance for society on environmental, economic and technological levels. And of course, after seven years one might wonder: when will this project be realised and what improvement in know-how is still needed? The preparation of the project is often a theoretical approach designed to provide sufficient detail to enable someone to have a good understanding of the activities and outcomes involved. Only after execution it's possible to measure in practice how closely those preliminary studies resemble reality. This is also one of the reasons why The Locals pose great significance to the environmental impact of test excavations, transport and storage of waste to be processed. Of equal importance is an understanding of residents' attitudes towards this form of waste processing, which is totally new to them, and also of the possible nuisance this may cause.

## **First 'The Locals' need to be informed, then they inform the local people**

The Locals' starting point was for all members of the group to be well informed. As mentioned previously, information gathering by The Locals is from unbiased and trustworthy sources, and obtained first hand. The focus was on fundamental questions such as: should there be a landfill clean-up, knowing that the oldest ones were constructed without a protective lining? And is it not our responsibility – here and now – to protect the environment for our children and future generations?"

Further questions were then asked such as: can local residents agree to such a project in their neighbourhood? And how would residents respond if they were also informed with first-hand information? This is an important and necessary step towards a shared project that is socially relevant in terms of both the restoration of nature and available open space, together with the recovery of raw materials and energy.

## **Jointly overcoming obstacles**

**'Participation without insight leads to an utterance without perspective.'**

To get either a well-founded agreement or no agreement, both require that everyone has a clear understanding of the project. Coming from a critical stance, we know that authorities and businesses want to convince society to go ahead with this project. The principles of The Locals' approach are as follows:

- Knowledge about the project does not mean that one can immediately agree with the implementation of it.
- If the agreement of local residents is sought, then the first step is that we understand what will happen here and how, including the use of new technologies and processes.
- In case we do understand but do not agree we are able to clearly justify our decision.
- The foundation for dialogue is laid by the acquisition of appropriate knowledge and insights, which then enable well founded objections to be described precisely.
- Higher education institutions, scientists and business leaders are all more likely to listen to such clearly formulated objections.
- Also politicians will show an interest.
- This method of jointly sharing information and knowledge, and a willingness to listen to each other's arguments are essential steps in the development of a community supported project.

The Locals consider it to be a very important task to work together with the scientific community to “translate” complex information regarding “modern and innovative landfill mining” to make it understandable for the general public. When conveying this information, they take into account the current social issues and the reasons for resistance.

## **Knowledge overcomes fear**

When attempting to address resistance thresholds for this project, repeating the economical, technological and environmental benefits again and again is unlikely to form a successful strategy. On the other hand, filling in any gaps in people's knowledge with objective and impartial information is helpful. It is important to deliver a clear and focussed communication at a suitable pace in order to eliminate assumptions and uncertainties. It is not The Locals' aim to win over the general public for this project since Locals are not missionaries. The intention is to offer the public sufficient objective scientific knowledge so that they are empowered to make fully informed decisions.

In contrast, equally motivated people who lack factual information and rely on false assumptions in order to develop objections or concerns, often become frustrated as their opinions are rejected as unfounded. Such objections cannot be relied upon to make adjustments to the project or to stop it altogether. Worse is that the current resistance continues to persist, public support further erodes, and whilst these objectors are genuinely concerned, it creates the impression of “not being heard”.

However, people have the right to be concerned. A history of dust and odour nuisance and heavy traffic on local roads, have made the inhabitants around the Remo landfill site very suspicious. Ten years ago, those pollution problems had stopped; would this now start all over again? Worried about a radiation related risk? What is the impact of dust emitted during excavation of this landfill site? Will we have to live with foul air again? How will it affect our health? These are all very justified questions and every questioner has the right to a clear and honest answer. This is exactly the reason why The Locals wanted to continue with their task after the first ELFM Symposium in Houthalen-Helchteren in 2010.

## To inform without causing polarisation

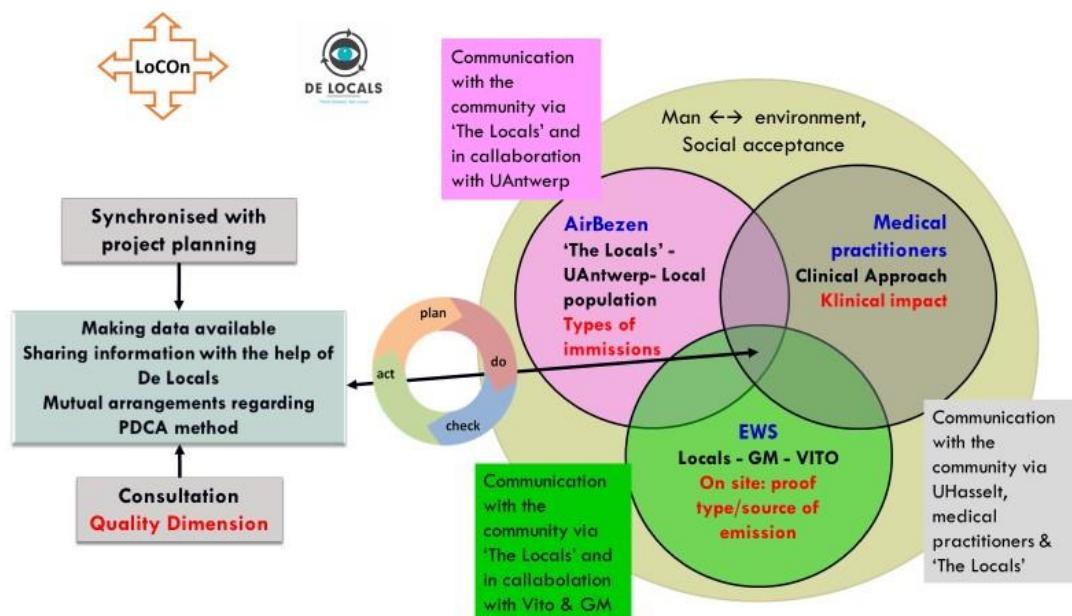
An important question is: how can we inform local people when polarisation of views already started a long time ago? Polarisation is, in principle, not necessarily an issue if it helps focusing on the problems and/or the lack of clarity. This changes however, when “not informing” and “taking things out of context” become a clear strategy to continue to say what one wants to hear or believe.

The Locals thoroughly assess and consider each argument, they weigh up all the pros and cons of the CtC project. This stands in stark contrast to those opposed to the project who selectively deliberate certain issues and often present themselves as experts. Arguments based on popular wisdom are often incorrect and unsubstantiated. Also the media for whom newsworthiness takes precedence over accuracy may be a source of inaccurate information. This increases the likelihood of the demise of the CtC project even before it has started. It is therefore important to provide the local community with a sustained and easily accessible stream of reliable, well-founded information in order to reduce the risk of any form of polarisation.

A survey of local residents undertaken by The Locals in early 2016 entitled “*What do local people know about the plans for the Remo landfill site?*” revealed a need for understandable, non-biased, independent and accurate information regarding the CtC project. The Locals were perceived as a reliable source. This is consistent with The Locals' philosophy as illustrated by the open character of the organisation: everyone is welcome to take part in the group. Another important observation was the lack of interest of the general public to information sessions which were organised jointly by the company Group Machiels and the municipality of Houthalen-Helchteren. This was the main reason why The Locals wanted to start a communication project with direct involvement of the local community by responding to their principal concerns, namely the consequences for their health and the environment.

The following example clarifies this: the Locals plan a specific measuring project, using the “Citizen Science” approach. Local people will be involved in a measuring campaign with plants, from which the leaves will, after several weeks, be examined and assessed by scientists. The resulting data will then be compared with measurements obtained by the project operator. Once unbiased conclusions have been drawn, they will be intelligibly conveyed by The Locals to the local community. By communicating openly and transparently with local people, we are convinced we are able to arouse their interest so that they can share their concerns, which facilitates a more focussed search for an appropriate solution.

## The Locals' communication & research project



**Figure 1:** The Locon project creates added value due to the interaction between several research projects which makes it possible to link cause and effect. Communication of the results generates public acceptance.

## An issue without closure stays with you all your life

It would be too simple an explanation to cite the NIMBY (not in my backyard) syndrome as an argument to downplay the anxieties of local people and to stigmatise them. A fundamental requirement is the buildup of mutual trust: the company has to use everything in its power to detect a nuisance at an early stage and to act effectively before any nuisance is noticed by the neighbours; and local people with concerns and issues must be able to communicate directly and effectively with the company *via* an open dialogue so that both parties benefit from the exchange of information. Surely, people have the right to be genuinely concerned about their quality of life and their

health. However, in the past, a breakdown in the necessary two-way communication left these issues unresolved.

We are convinced that those who were not listened to in the past and may still feel resentful, must be given the chance to speak. Give them the right to a broad forum, otherwise lasting frustration will prevent them from being open to new ideas. When they feel heard and understood, they will be able to join a renewed and open dialogue. Maybe they do not yet realise how effective new technologies have become. Would it not make sense to recover raw materials and energy from waste? To persuade them is a first step towards persuading the world of tomorrow's circular story.



# FLOODING RISKS AT OLD LANDFILL SITES: LINEAR ECONOMY MEETS CLIMATE CHANGE

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## Introduction

On the 4<sup>th</sup> of September 2017, CNN<sup>1</sup> spread the following news: “Toxic waste sites flooded: at least 13 toxic waste sites in Texas were flooded or damaged by Hurricane Harvey, according to the Environmental Protection Agency.” This was possibly the first announcement of extreme weather conditions causing large environmental damage at landfill sites, mostly denominated as final waste disposal facilities”. Suddenly, due to this climatological impact, eternity seems to last only several decades. These eternal storage sites of waste were commonly regarded as sources of methane, which, as such, cause greenhouse gas emissions and, hence, contribute to climate change. This paper gives an overview on the general aspects of flooding of landfills, the risks and the potential contribution of the ELF-M-concept as a solution. The development of the specific approach by the governmental agency in Flanders will be shown.

## Landfills and flooding risks

Since the 1950s Europe has been disposing vast levels of waste in landfills. Estimates have revealed 350,000 to 500,000 landfills in the EU.<sup>2</sup> The majority of these landfills is no longer operational and/or monitored. According to estimations based on limited mapping results, tens of thousands of historic landfills are situated in coastal and alluvial areas. The content of these historic landfills could pose a significant environmental threat if they are flooded and erode.

Already in 2009, Laner *et al.*<sup>3</sup> investigated the risk of flooding of MSW landfills in Austria. Out of 1,064 landfills, 312 sites or about 30% are located in or next to areas flooded on average once in 200 years. Around 5% of these landfills are equipped with flood protection facilities. Material inventories of 147 landfill sites endangered by flooding are established, and potential emissions during a flood event are estimated by assuming the worst case of complete landfill leaching and erosion.

More recently, Brand<sup>4</sup> performed research on the UK’s 21,027 historic landfills and assessed their individual vulnerability to flooding and coastal erosion. Nearly 3,000 of them are located in flood plains and a further 1,264 in low-lying coastal areas, often

in the vicinity of the sea. Hence, many waste sites risk being flooded from heavy rain, storm surges and coastal erosion.

The Alaska Department of Environmental Conservation conducted a four-year \$1.4 million project to inventory and rank vulnerable sites, and generate detailed action plans for the sites of highest concern. Its Final Report<sup>5</sup> in May 2015 includes the preliminary reports for each community visited, which provides a brief narrative of the community's sites and photos of each site. It also contains the detailed action plans for the 20 sites of highest concern, *i.e.* those that are prone to flooding within the next 50 years.

In order to reduce damage caused by flooding, siting of hazardous facilities is an important element in the decision-making process. According to Sara,<sup>6</sup> the 100-year floodplain is normally an exclusion zone for the disposal of solid waste. As a part of the National Flood Insurance Program, Flood Hazard Boundary Maps (FHBM) have been prepared for virtually all communities that have been identified as "flood prone". The regulations of Harris County<sup>7</sup> (*cf. supra* CNN) stipulate that construction of critical facilities (*e.g.* waste disposal/storage) shall be, to the extent possible, located outside the limits of the 0.2% floodplain or 500-year floodplain (Shaded Zone X) and any "A" Zone. Despite these restrictions, 13 waste facilities were damaged and flooded during the Harvey hurricane (US EPA<sup>8</sup>).

At the EU-level, the Directive 2007/60/EC<sup>9</sup> on the assessment and management of flood risks entered into force on 26 November 2007. This Directive requires Member States to assess if all water courses and coast lines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk. Member States should carry out a preliminary assessment by 2011 to identify the river basins and associated coastal areas at risk of flooding. For such zones they would then need to draw up flood risk maps by 2013 and establish flood risk management plans focused on prevention, protection and preparedness by 2015.

Regarding landfills, flood risk maps shall show the potential adverse consequences associated with installations as referred to in Annex I to Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control which might cause accidental pollution in case of flooding and potentially affected protected areas. Best management practices on this specific issue are lacking to date.

## Climate change and landfills

Landfills produce landfill gases (methane) and contribute as such to the greenhouse effect and climate change. This concept is not at stake but recent landfilling practices reveal a minor impact due to the fact that organic waste is no longer allowed to be landfilled. This implies a lower impact of landfills on climate change. Moreover, specific initiatives on greening landfills and installing solar energy panels on top, result in a positive effect in view of climate change.

On the other hand, the impact of climate change on landfills is barely investigated. As mentioned above, the main risks come from higher rainfall intensity in short intervals causing erosion and flooding. Especially landfills in lower areas are vulnerable to these changes. The environmental consequences due to higher flooding patterns were seldomly taken into account in the commonly used risk models.

The external impact on landfills might be of larger importance than the internal adverse effects of the landfilled waste. The traditional management concepts aim at a continuation of the static feature, although the boundary conditions of the complex system are substantially changing. If flooding becomes an increasingly important factor, the stand-still principle is far more a *contradictio in terminis* than a sustainable solution.

## Situation in Flanders (Belgium)

Since the end of the 18<sup>th</sup> century general regulations on waste management came into force. The decree of 16-24 August 1790<sup>10</sup> emphasised the rapid evacuation of waste out of the (medieval) city centre. Those cities were often situated along rivers and waste was initially transported to the adjacent lowlands. It can be regarded as a kind of land reclamation. Later on, shipment to larger landfills close to the water network became a common practice. Based on the OVAM inventory of landfills, VITO detected 965 landfill sites vulnerable to flooding on a total of 1,735 sites, *i.e.* 55% (Table 1).

**Table 1:** Landfills and flooding risks in Flanders

Province	flooding risk		no flooding risk	
	number	ha	number	ha
Antwerp	260	1898.7	283	1368.8
Limburg	124	278.5	145	917.1
Eastern Flanders	132	930.7	75	930.7
Flemish Brabant	193	690.5	81	195.8
Western Flanders	256	1020.3	186	560.1
Total	965	4818.7	770	3972.4

The vast majority of the landfill facilities were closed before 1984 and currently only 28 landfills are operational. Only 7 landfill zones have public access and since the last decade less than 2% of the Municipal Solid Waste is landfilled. Landfill bans on both unsorted waste and on separately collected waste materials since 1998, and a landfill ban on combustible residual wastes since 2000, resulted in a decreasing content of biodegradable waste. The recovery rate of landfill gas is diminishing over the last decade: 13 installations produced 865 TJ in 2004 and 12 installations recovered 415 TJ (VITO<sup>11</sup>). A similar decreasing tendency was pointed out in the Environmental Status Report MIRA-T.<sup>12</sup>

**Table 2:** Methane emissions in Flanders

Emission methane (kton CO2-eq)					
1990	1995	2000	2005	2006	2007
1 641	1 519	1 193	632	544	479

This positive effect of lower methane production is jeopardised by the increasing risk of flooding. Beside the erosion of waste, intrusion of water in old landfills can initiate renewed biogas production. Recently, OVAM discussed the issue with the responsible agencies on Flooding risk control (Sigma plan<sup>13</sup>). The presence of landfills is now integrated in the planning process in order to avoid supplementary risks.

The possibility of eliminating/mining landfills in alluvial areas is tested in 2 pilots. By introducing the concept of ELFM, the reduction of the landfilled material offers more options to create a safer environment to flooding. The reuse of the recycled material in new infrastructure is considered and was already proven in an earlier project at Zaventem. The surface occupied by the old landfill was reduced to less than 50% and the reclaimed space was reshaped as a buffer basin. The construction and demolition material was processed and partly reused on site. This action resulted in a remediated landfill site and better flood control; no dwellings were flooded since its installation in 1996. Landfills are no longer a threat but can also present an opportunity regarding climate change. Besides the recycling of materials, landfills may contribute to a multi-layer flooding safety management and be part of measures on climate adaptation.<sup>14</sup>

## Conclusion

The waste management policies of the EU resulted in a significant decrease of landfilled waste and its biodegradable content. These actions imply an on-going reduction of methane production and the release of this greenhouse gas is also limited due to its energetic valorisation. This positive tendency is under pressure because of increasing flooding risks. A vulnerability index for historic landfill sites is needed to determine where resources and attention might best be focused. The

concept of Enhanced Landfill mining could become an appropriate option if (partial) relocation of landfills is required.

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# **ENHANCED LANDFILL MINING AT THE REMO SITE: ASSESSING STAKEHOLDERS' PERSPECTIVES FOR IMPLEMENTATION**

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## **Introduction**

The resource potential as well as environmental and societal risks and impacts of landfills and Landfill Mining (LFM) have been discussed in literature.<sup>1-3</sup> Different objectives can drive LFM projects and can range from sanitation purposes, conservation of landfill space or reclamation of land to resource recovery and energy generation.<sup>4,5</sup> For taking economic pressure from sanitation projects or even developing business models, the concept of LFM further developed into Enhanced Landfill Mining (ELFM). ELFM aims to valorise urban waste streams as materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE) using innovative technology in an integrated, environmentally and socially sound way.<sup>2</sup> Along with this development, the concept of landfills, as some kind of eternal disposal site, also shifted towards the idea of temporary storage.<sup>6-8</sup> Hence, environmental risks and impacts of landfills as well as ELFM activities have received growing interest in the past years<sup>9-11</sup> along with economic and societal evaluations of ELFM projects.<sup>7,12-14</sup> While the benefits in these studies usually focus on the mitigation of risks or the reclamation of land, it remains unclear how different stakeholders approach ELFM and on which risks and benefits they focus. The importance of economic and societal drivers and barriers to stakeholders has to be assessed. This will help to mitigate risks and develop effective communication strategies and policy guidelines. Moreover, it should be identified which key stakeholders should be involved in an ELFM project. Krook, Svensson & Eklund conclude in a review paper that further investigations on stakeholder perceptions with societal actors are “essential for understanding the capacity of technology and conditions for realisation” of ELFM projects. This will help, for example, to identify the recyclable share of resources deposited in landfills or the effects of current policies on ELFM.<sup>1</sup>

## **Method**

To investigate how different stakeholders perceive ELF M activities, semi-structured interviews were conducted. The interviews were recorded and consequently transcribed. From an initial review of the relevant literature, five major themes were identified. These included (i) ‘perspectives on landfills and their management’, (ii) ‘economic drivers and barriers of ELF M’, (iii) ‘environmental benefits and risks of ELF M’, (iv) ‘societal challenges for the implementation of ELF M projects’ and (v) ‘the role and responsibilities of institutions and other stakeholders involved in the realisation of ELF M activities’. While the first theme (i) was chosen to identify the general approach of participants to landfills, the second, third and fourth theme (ii-iv) aim at determining the perceived sustainability of ELF M. The last theme (v) was chosen to describe how different stakeholders are involved in ELF M projects and where they are able to influence processes along the way of realisation. Furthermore, four major stakeholder groups have been identified by applying the logic of the quadruple helix, being (i) local community members, (ii) institutional actors, in this case governmental bodies, (iii) scientists and (iv) business actors. During the analysis, the software NVivo was used and statements of the interviewees were assigned to the themes to carve out differences in perspectives according to the different stakeholder groups involved. In a first step, interviewees were assigned to one of the four stakeholder groups. To interpret responses, a structure of topics and subtopics was derived, based on the interview guide and a first screening of the interviews. Consequently, statements of participants were categorised according to themes by assigning them to the structured topics and subtopics as well as stakeholder groups. This made it possible to identify relations as well as emerging patterns and ideas. If a statement was relevant for multiple topics or subtopics, it was possible to assign the response multiple times.

## **Case-study and sampling**

To get relevant results from the interviews, an active engagement of the interviewees in an ELF M project was considered important.<sup>15-17</sup> A case was needed where operations had either already started or were planned to start within a considerable timeframe. Authorities and the local community also needed to be involved. The REMO landfill, located in the Flemish region of Belgium, provided such a stakeholder environment and was additionally subject to prior scientific investigations.<sup>5,12,18</sup> Interviews were taken with individual participants and interviewees included (i) two members of the residential area around the landfill organised in a group called ‘De Locals’. This group seeks to gather information about the planned ELF M activities at REMO and inform residents. Also included were three members from (ii) relevant authorities as OVAM, the Flemish waste, material and soil agency and the European Commission as well as one (iii) scientist and (iv) two managers from the operating

company of the landfill site, Group Machiels. To select interviewees the quadruple helix framework was further subcategorised and subcategories were prioritised according to their relevance to the REMO case. For example, business actors were split into operators, technology providers, purchasers and financiers or institutional actors into governmental and non-governmental bodies to identify potential participants. The main criteria for the selection of interviewees were (i) their affiliation to a prioritised subcategory of the quadruple helix, (ii) their level of involvement in the REMO case or research, and (iii) an approximate evenly distributed share of participants over the quadruple helix framework. In total eight interviews were conducted and analysed.

It has to be mentioned that some participants were biased towards the REMO project. Operators, of course, have already committed to the projects by making investments and want the realisation to move forward. The local community members interviewed were part of a specific group concerned with the development of the REMO landfill. They have been working closely with the operators and are represented within EURELCO, the European Enhanced Landfill Mining Consortium, an organisation with a positive attitude towards ELFM. Community members who publically oppose the REMO project were not interviewed.

## Results

The results show differences and similarities of various stakeholder groups. The individual themes will be presented hereafter.

### Approach to landfills

There are differences and similarities in how each stakeholder group approaches landfills in general. Topics like “Safety of a landfill” or “Disadvantages of a landfill” are understood differently between stakeholder groups. Associations with the REMO site are mostly positive and most critique came from the operating company itself.

All stakeholder groups primarily perceive the function of a landfill as temporary storage of waste and resources. Landfilling is considered the least favourable waste treatment option but was also identified as being necessary by all interviewees. The operating company emphasises the offered service of waste disposal for its customers, whereas the scientific side also mentioned landfills as a source of pollution and land occupation. Furthermore, institutional participants make an explicit distinction between “dump sites” that pre-date the European Landfill Directive from 1999 and “(sanitary) landfills” that comply with the EU Landfill Directive. While “dump sites” were less regulated regarding materials to be landfilled and were more considered to serve as an eternal storage of waste, “landfills” under

the EU Landfill Directive take environmental aspects into consideration and implement a clear hierarchy to the waste being disposed. This could partly explain a change in the institutional perception of landfills from a final storage towards a resource reservoir. Moreover, one participant from the institutional side made it clear that extractive waste from traditional mining processes does not fall under the *EU Landfill Directive* but, instead, under the *Extractive Waste Directive* and is, therefore, not part of landfills in their understanding.

An overarching agreement on the safety of landfills can be found considering modern landfills. Overall, all stakeholder groups consider those rather safe. Nevertheless, differences in perceptions are situated in the details: all groups accentuated that a properly operated landfill under current legislation can be considered safe, but older landfills are often perceived as less safe, posing potential risks. The landfill operators also made a distinction to “very old landfills” justified by changes in waste streams to be landfilled: “...when you go back in the past there are not that many risky waste streams...” This is coherent with the experiences of institutional participants stating that most landfills are in a better condition than estimated and the expected toxic “time-bombs seem not to be reality after all”, when talking about municipal solid waste (MSW). Additionally, the institutional side stressed that changing circumstances can affect the safety of a landfill, for example through higher flood risks due to changes in climatic conditions. Flooding a landfill could potentially expose groundwater reservoirs to a higher content of toxics than common precipitation and, as such, floods endanger the stability of landfills through soil movements.

Perceived advantages of landfills are the potential for resource recovery and the removal of waste from the local communities. While the landfill operators focused more on the resource potential, participants from institutions and the local community also emphasised waste removal. The institutional side also stated an advantage in being able to control the process of waste disposal. Perceived disadvantages, on the other hand, were approached differently. While all stakeholder groups mentioned a suboptimal use of land and environmental risks like ground water contamination through leachate, operators also mentioned the installation of additional security measures against wildlife as well as risks coming directly from on-going operations as a disadvantage. The local community further perceived a risk for human health coming from toxic materials in landfills, *e.g.* mercury or asbestos, whereas a researcher stated a disadvantage of industrial landfills often containing toxic material in combination with a lack of control mechanisms.

Concerning the REMO site, all stakeholder groups had positive associations, although opposing groups to the project from local communities and politics were also mentioned. The operators were described as “thinking in a modern way” or

“courageous” for taking new risks and trying to implement new technology. Most critique about the REMO site came from the operators themselves, where the need for optimisation of processes and technology was expressed. Negative associations from local community members and the institutional side were mainly towards landfills in general and coming from experiences pre-dating the EU Landfill Directive.

### **Concept and attitude towards ELFM**

The concept of ELFM and distinctions to traditional LFM were perceived quite differently between stakeholder groups. At the same time, all stakeholder groups stated a mostly positive attitude towards ELFM. For the operators, the primary objective of ELFM lies in the recuperation of land, energy and resources and should be carried out as a private business activity. The main difference to traditional LFM was presented by involving stakeholders in the process to produce higher-added values. The local community members and institutional participants put a focus on material recovery using high-level recycling and sorting technology, whereas the institutional side even expanded the concept of ELFM to *Enhanced Landfill Management and Mining* (ELFM<sup>2</sup>) including management of landfill sites and their interim-use until mining activities would start. Both institutions and operators shared the view that most landfills will be mined in the future, while it remains unclear when exactly this will happen. The scientific side emphasised the importance of ELFM having almost no discharge flow and described it as an (economically) “risky recycling activity”.

Operators stated they are for actively engaging in ELFM for the value of land, energy and materials as well as environmental reasons, given a “clear, positive, net balance”. However, the institutions, science and local community members were mainly motivated doing so for environmental reasons and the necessity of ELFM to avoid future risks mentioned before. Nevertheless, ELFM should be able “to be economically independent” from an institutional point of view. Yet, operators and institutions both stressed that not every landfill is suitable for ELFM.

### **Economic challenges, drivers and barriers of/for ELFM**

All stakeholder groups consider similar economic drivers and barriers for ELFM. Yet, the economic dimension has a different significance for different stakeholder groups within the sustainability framework. While participants from the scientific world and local communities emphasised the importance of environmental aspects of ELFM, Institutions and operators focused on economic factors with environmental and social “spill overs”.

Operators and institutions both mentioned land-recuperation as the clear primary economic driver of ELFM. Operators also stressed the integration of stakeholders

through platforms like EURELCO and the necessity for “doing activities” in the form of large-scale pilot projects, helping the development of ELFM towards an industrial activity. One participant stated that, “when we start mining the REMO site, from this one activity many spin-offs will develop”. With technological development, not only costs could be reduced, but also new opportunities for processing unusable waste fractions could open up. In agreement with the scientific participant, operators are also favouring the idea of combining public and private money for investment support to build up a new industrial sector. This could take the form of private-public partnerships (PPP) or public insurances. The reasoning for this belief lies in the societal and environmental benefits ELFM generates, and would be at least needed in the beginning. No participant mentioned the internalisation of environmental and societal costs in monetary terms. Rising market prices for primary and secondary raw materials would strengthen the economic viability of ELFM. The institutions also mentioned an economic driver in the avoidance of long-term monitoring costs as well as cost reductions through interim use of landfill sites, for example by generating electricity through solar panels. Additionally, a long-term industrial activity would stimulate the regional economy. Local communities, on the other hand, identified the generation of employment, especially of low-skilled labour, as well as energy generation and material recovery as main drivers for ELFM.

While the operators mentioned technological development as a driver for ELFM, it could also work as a barrier for investments, if new technology emerges before the planned return on investments. Local community members and the scientific participant share this view with the operators. More importantly, institutions and operators described finding investors in general as one of the most difficult challenges for ELFM. This is explained partly by a lack of awareness about ELFM in the relevant sectors and partly by known risks in the development of market prices, new technology and social acceptance: “You get investment support a bit there, a bit there. So, you have to combine all these bits and pieces of support for your large investment and this is, of course, time-consuming.” A lack of public money for large-scale pilot projects including technology providers was also mentioned. Operators emphasised that high monitoring and sampling activities would drive up costs and could hinder ELFM projects from being implemented. Institutions and local community members mentioned that large and time-consuming projects tend to be very costly, yet permitting processes and changes in regulations need this time. Currently, low market prices for primary and secondary raw materials seem to hinder ELFM activities, although, as mentioned before, change is expected by three of four stakeholder groups. As stated by institutional and scientific participants, for individual projects the location of the landfill and waste composition could also be a relevant barrier or driver for implementing an ELFM project.

## **Environmental benefits and risks of ELFM**

Environmental benefits are generally perceived as coming from the reduction of risks through waste removal and the mitigation of primary resource use. Such benefits included the mitigation of ground water contamination, the elimination of potential pollutants to the soil or the mitigation of traditional mining activities. Although an overall agreement on the risks coming from ELFM activities could be discerned, they are still perceived with different importance to each stakeholder group. Thus, differences are mainly perceived with respect to the distinct focus on those risks.

In general, risks were described as being similar to those coming from having and operating landfills at current times. This included odour, noise and risks for human health coming from dust or ground water contamination, since the landfill would have to be re-opened. Institutional and the local community members also expressed their concerns about auto combustion of gases coming from the change of anaerobic to aerobic conditions in the landfill. The operators also mentioned that the energy consumption of ELFM activities today is mainly fossil fuel based and, as scientific and institutional participants also point out, were aware that not all waste could be processed. This again implies that waste streams from ELFM activities would partly be re-landfilled, which again implies the same risks as traditional landfilling for an uncertain timeframe. Local community members were also concerned that toxic materials could be brought back into the material circle and the scientific participant brought up the point that poor execution could lead to bigger environmental problems than before: "These are huge risks, also on the environmental level the risk of creating a bigger environmental problem than before is still there."

## **Societal challenges, drivers and barriers of ELFM**

All stakeholders perceived the biggest societal challenge in involving the public in ELFM projects. Operators, for example, fear public opposition by non-involvement but also consider a need for more awareness of ELFM in general to make financing and permitting processes easier. The time-consuming permitting process played an important role for most interviewees. An institutional participant also included public authorities in this challenge, stating "[The] most important thing from my point of view is the transitioning of the mind-sets, that's a policy aspect."

The inclusion of stakeholders was also recognised as the main possible societal driver for the implementation of ELFM projects. By raising awareness about ELFM and anticipating opposing views a project would benefit. To maximise gains from stakeholder integration, it was considered important to include all relevant actors from an early stage on.

Local community members also expressed the wish for more information about processes, risks and benefits of ELFM activities and a broad distribution of this information: "I think it's very important that people should be more informed..." Furthermore, they urged, on a par with the institutional side, that politicians should also be included in this process and criticised the conflict of interest between short-term politics and long-term development. Other drivers mentioned were the reclamation of land for recreational purposes and the mitigation of risks through waste removal.

All stakeholder groups identified a lack of social acceptance as a project's biggest societal barrier at this time: "That's the barrier number one." Operators, institutions and local community members explained this partly by knowledge and awareness gaps between the different parties involved, like local residents and politicians. Other reasons mentioned were the increase in traffic and the fear of smell and dust reoccurring with new ELFM activities. Local community members and operators also perceived a barrier in small groups being able to hinder a project through legal procedures overpowering a "silent", but supportive, majority. A situation where "a small group talks for a large community that doesn't talk."

### **Key actors of ELFM and the role of institutions**

All stakeholder groups – apart from the operators themselves, who perceived investors as highly important – named the operating company as the most important actor involved in ELFM activities. Besides, regulatory bodies should play a crucial role according to all stakeholder groups. The institutional and the scientific side also stressed that the involvement of local communities is important, yet difficult, because of a lack of knowledge and experience. For the institutional side the general public is perceived as even more important than local residents. Scientific bodies are mostly perceived as platforms for knowledge transfer between the involved parties, but would play a secondary role in the realisation of ELFM projects.

All stakeholder groups perceived the role of institutions, *i.e.* governmental bodies, as overall positive. Most participants named OVAM as one of the key actors involved and were overall satisfied with their role. The subsidiarity principle of the EU was positively acknowledged by institutional participants, who also perceived OVAM as a platform for experimentation and trials. It was criticised by a local community member as well as by scientific and institutional participants that advice from regulatory bodies is often not followed on a political level. Although no participants identified regulations "hampering" ELFM projects, institutional participants and operators would appreciate regulations that "help and stimulate landfill mining activities" and make them easier to monitor.

Operators and local community members described permitting procedures as too time-consuming, due to being in an early phase of a learning process coming with new industrial activities, also affecting authorities and regulatory bodies. The institutional side also emphasised the need for regulations concerning the interim use of landfills to be mined and expressed the wish for amendments on ELF M implemented at a European level. Finally, local community members and operators recognised a need for regulations also in production processes of non-ELF M products, for example a quota for recycled content in certain products. This would stimulate markets for secondary materials and drive ELF M projects.

## Discussion and conclusion

Interestingly, landfills are in general perceived as temporary storage facilities by all stakeholder groups, which most probably contradicts the view of the general public. This might be explained through the involvement of all participants in a specific ELF M project and a higher awareness for other perspectives through this involvement.

Overall, participants had a mostly positive attitude towards ELF M, although focusing on different aspects. Moreover, some drivers of ELF M projects could also work as barriers, depending on the context. While technological development would push ELF M through the ability to process unusable waste streams, it could also hinder investments by raising uncertainty and, hence, the risk for lower returns if technological development is faster than the payback period, for example. Similarly, the integration of stakeholders raises the awareness of ELF M and, therefore, serves as a driver. On the other hand, it could also attract opponents to such projects and therefore cause delay or even cancellation. Local community members and scientific participants put a focus on the mitigation of environmental risks, while institutions and operators also emphasised the need for an economic sound model for ELF M. This is reasonable since local residents are primarily concerned for the environment they live in, whereas the institutional side has to keep in mind the larger picture to ensure all parties involved are considered. Furthermore, the number of participants to this study, with eight interviewees, can be considered rather small and other points of views on ELF M remain unclear.

The results of this study show perceptions of different stakeholder groups. To determine if those perceptions can be generalised and transmitted to other cases of ELF M projects, more research is needed. To do so, it is not only important to raise the number of interviewees, but also to put the perceptions into context with semi-quantitative results from questionnaires and contrast them against state-of-the-art knowledge on environmental benefits and risks, economic drivers and barriers as well as societal challenges identified by other case-studies. Moreover, stakeholders along

the value chain of ELFM, as technology providers, investors and purchasers, should be included in future studies. From this and future research, knowledge gaps can be identified and help develop communication strategies for an enhanced stakeholder integration. The findings could also help defining policy guidelines for ELFM and mitigate societal risks.

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# **TO MINE OR NOT TO MINE: A REVIEW OF THE EFFECTS OF WASTE COMPOSITION, TIME AND LONG-TERM IMPACTS OF LANDFILLS IN THE DECISION MAKING FOR ELFM**

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## **Introduction**

The environmental impacts of municipal solid waste (MSW) landfills have been addressed in comparison with other waste management strategies, in relation to the variation of site-specific and time-dependent parameters, and in the framework of landfill mining.<sup>1–13</sup> Environmental and economic assessments have been performed to determine the profitability of Landfill Mining (LFM) and, more recently, on Enhanced Landfill Mining (ELFM).<sup>13–20</sup> The environmental assessment of landfill mining and the benefits of resource recovery compared to remediation are an important incentive for policy implementation in the different countries.<sup>21</sup> Therefore, it is of great importance to develop a methodology for the environmental impact assessment which takes into account all site-specific and time-dependent parameters that affect the environmental performance of landfills. The more comprehensive methodology could allow to better assess the impacts of landfills as final disposal solutions and their environmental potential for Enhanced Landfill Mining.

As landfills represent complex and highly heterogeneous systems, the analysis of their impacts cannot be carried out as for other waste management solutions. In fact, landfill impacts occur over a much more extended period, thousands of years, and at different rates.<sup>22,23</sup> The emission potential of landfills depends on the degradation of waste and on the chemical, biological and physical processes that occur in the landfill.<sup>3,9,10,24,25</sup> These processes depend on time-related variations in the landfill and in the environment, and on site-specific characteristics. Soil conditions, hydrological, geological, climatic conditions, landfill management strategies, landfill design, waste composition and age of the waste: they all affect the short- and long-term emission potential and the actual release of contaminants.<sup>9,12,22,25–28</sup> Therefore, the reliability of the results significantly depends on the system boundaries, time frame and data quality and availability.<sup>22</sup> When assessing the environmental impacts of different landfills it is therefore important to consider aspects such as time-dependency, site related parameters and multi-input processes. Landfill sites cannot be considered as

black boxes. The mechanisms underlying the emission potential need to be addressed to estimate the impact of landfills on a longer time horizon. Time-related emission profiles from landfills could lead to more accurate and consistent estimations of the long-term impacts of disposal sites. In this framework, this paper will address the evaluation of long-term emissions of closed landfills by analysing the literature related to landfill gas (LFG) and landfill leachate emissions. In particular, the paper will address the remaining available content of substances within the landfill body and the mobilising substance potential linked to leachate generation.

## **Waste composition and time-dependency in the environmental impact assessment of landfills**

### **Waste composition**

Waste composition is an important factor influencing the rate of generation of leachate and landfill gas, but also the valorisation potential for materials and energy in the framework of Enhanced Landfill Mining (ELFM).<sup>26</sup> The different waste compositions depend on the landfill location, due to local regulations on waste management, but also on the time period when the waste was landfilled, and on the type of waste landfilled in the site.<sup>26</sup> The importance of a qualitative and quantitative evaluation of the landfilled waste in terms of composition and properties has been highlighted in several studies.<sup>29–33</sup>

An important factor to consider when defining the waste composition in landfills is the degradation rate of waste over time. For waste fractions such as metals, plastics, glass, ceramics, textiles, inert fractions, etc., which are less-easily degradable and undergo slower changes over time, the amounts in the excavated waste are usually comparable with the amounts originally landfilled.<sup>26</sup> On the other hand, organic fractions degrade more easily into a soil-like material.<sup>26</sup> Indeed, landfilled waste undergoes different biological, chemical and physical transformation processes over time that result in different impacts and conditions, even within a landfill, depending on the location and waste characteristics. Waste age and composition, together with weather conditions and landfill design and management, affect the outcome of waste recovery strategies.<sup>34</sup>

Additionally, both waste composition and the related biodegradation potential have a significant influence on the environmental impacts of landfills and on the estimation of the ELFM potential from an environmental perspective. Different fractions determine different impacts to either water, air or soil.<sup>22</sup> Several studies have reported how the organic content highly affects the final results,<sup>4,35</sup> as waste with lower organic content can lead to lower environmental impacts.<sup>4</sup> Previous literature

has highlighted that large amounts of pollutants, as heavy metals, ammonium, chemical oxygen demand (COD), are still available in closed landfills and can pose a threat to human health and the environment if released. The availability of these substances depends on the waste type and age. It has been shown that the concentrations of elements such as As, Cd, Cr, Cu, Ni, Zn, Pb, Hg increase with increasing storage time due to the different composition of landfilled MSW over the years.<sup>26</sup> Indeed, the presence of these elements in landfill bodies could be responsible, in the future, for significant emission potentials. In this context good data quality is important in order not to neglect impacts in different impact categories. Consistent methodological choices should then be made not to underestimate future emission potentials.

### **Time dependency**

As mentioned, degradation of waste, landfill waste characteristics and long-term emission potentials of available substances are affected by time. On the other hand, time is also a challenging parameter in the environmental impact assessment of landfills. In fact, landfill gas and leachate production varies in time, the technologies used in the landfill have a limited lifespan and/or can deteriorate. However, in life cycle assessment (LCA), impacts are aggregated over time. Therefore, the effect of emissions on the environment, soil, air and water, are considered to be identical, regardless of whether emitted in one second or over a century.<sup>36</sup> This lack of site- and time-dependent information in the life cycle assessment (LCA) of landfill sites is a significant source of uncertainties and could lead to misinterpretation, underestimation or overestimation of the impacts.<sup>11,24,37–41</sup> Moreover, not every landfill-related impact or process can be foreseen if the long term horizon is taken into account ( $10^4$ - $10^5$  years).<sup>39</sup> These considerations lead to the necessity of interpreting the results as a function of time<sup>39</sup> and to identify the most adequate time period to comprehensively assess the environmental impacts of landfills. This issue has been addressed in many studies where temporal emission profiles have been included in the life cycle inventory (LCI) stage of the LCA.<sup>42–45</sup> Moreover, there is ongoing research to try to include time- and site-dependent variations in the definition of characterisation factors also for the toxicological categories.<sup>45–50</sup> As a first step, the importance of time-related emission profiles from landfills could lead to more accurate and consistent results. In this framework, this paper will address the evaluation of long-term emissions of closed landfills by analysing the literature related to landfill gas (LFG) and landfill leachate emissions.

## Long-term emissions from landfills

### Landfill gas generation potential

Most studies aiming to assess the potential of ELF compared to the reference landfill scenario take into account the waste composition and in particular the landfill gas potential to define the environmental impacts of the reference scenario.<sup>12</sup> However, LFG emission profiles decrease substantially after the methanogenic phase, the fourth identified stage of the LFG generation curve, reaching negligible values in a few decades.<sup>11</sup> When considering long-term impact, LFG does not represent the major concern for landfills. Therefore, considering landfill impacts as only dependent on LFG and on the amount of organic carbon would tend to underestimate the impacts of landfills. Nevertheless, in light of the need to define time-dependent emission profiles for more consistent impact assessments, different models can be adopted for the estimation of landfill gas (LFG) generation. The assessment of landfill gas production is usually carried out by adopting the first order decay model (FOD).<sup>35,51,52</sup> The FOD model relies on the amount of biodegradable organic content in the waste, as this is the main factor affecting the LFG generation potential.<sup>52</sup> One of the inputs to the model is the methane generation potential,  $L_0$ [m<sup>3</sup> CH<sub>4</sub>/tonne waste], which is usually calculated based on the DOC present in the waste.<sup>52</sup> This highlights the dependency of LFG generation on the amount of degradable organic fraction and thus the dependency of landfill impacts on the waste composition.<sup>4,35</sup>

### Landfill leachate

On the other hand, leachate generation and composition is a long-term and more concerning issue. The quantity of leachate production within a landfill depends on the water balances at the site, the moisture content of waste and the water flow within the landfill body.<sup>11,25</sup> Consequently, the amount of leachate produced is also dependent on the efficiency and the type of the top cover and on the climatic conditions of the location.<sup>11</sup> The quality of the leachate is then highly dependent on site-specific factors such as waste composition, chemical, physical and biological processes that occur within the landfill body, the water flow distribution, or different landfill design and management systems.<sup>11,24,28,47,53-56</sup> As a general trend, decreased concentrations of leachate constituents can be observed with landfill age<sup>11</sup>. According to Laner,<sup>11</sup> organic leachate pollutants usually decrease around an order of magnitude in 20 years after closure. Similar trends can be observed for other pollutants such as iron, chloride and ammonium. On the other hand, xenobiotic organic compounds may persist for longer time frames. MSW is also characterised by amounts of heavy metals, which are usually found in low concentrations in leachate due to their low solubility. However, metal solubility and thus bioavailability in leachate, is influenced by site-specific conditions such as pH, redox potential, L/S ratio, heterogeneous water flow, etc.<sup>11,24,25,27,54,57</sup> Therefore, the concentrations of

heavy metals in leachate could vary between landfills or according to the landfill phase, or depending on the occurrence of events that could lead to the alteration of these mentioned parameters. An example could be the failure or gradual deterioration of the containment system. In fact, together with the *pH* and the amount of oxygen present, the liquid to solid ratio (*L/S*) within the landfill body highly affects the mobilisation of substances. The failure of the top cover, for example, could result in an increase of the *L/S* ratio, the infiltration of oxygen, and a variation of the *pH* within the landfill. Such an event could lead to the flushing of substances to the environment. Generally, the quantity of leachate is meant to decrease with the installation of top covers, with a consequent reduction in the total substance loads, meaning the amount of substance contained in the leachate over the year.<sup>11</sup> However, that does not mean that the available amount of substance remaining in the landfill decreases too. On the contrary, the installation of the top cover with a decrease in leachate generation could lead to substantial substance potential remaining in the landfill body. Therefore, the important aspect for the estimation of future emission potential is the understanding of the actual fractions that can be mobilised of the total amount of substances present. These and the related long-term emission potential of landfills can be estimated with different models. Geochemical modelling is gaining relevance for the modelling of long-term emissions due to the possibility of including different parameters in the scenario analysis.<sup>25,57</sup> Another model was developed by Belevi and Baccini in 1989 and reported by Laner.<sup>11</sup> The model follows first order kinetics and is based on the assumptions of a constant release mechanisms, homogeneous water flow, and a negligible biodegradation process after the reactor phase. Of course, these assumptions lead to increased uncertainties on the actual behaviour of leachate and its pollutants. Nevertheless, the model gives an estimate of the emission potential for certain substances that could remain in the landfill body in significant quantities for a long term.

## Discussion and conclusions

The review was carried out to stress the importance of considering long term emissions of landfills and the necessity of understanding the mechanisms underlying them. A deeper analysis is crucial for the environmental impact assessment of landfills as final disposal sites and as reference scenario for the comparison with ELFM. In fact, based on the above considerations, the assessment of landfill impacts on a long time frame could lead to building a more consistent reference scenario for the evaluation of the environmental profitability of ELFM. The consideration of site- and time-dependent parameters is then important for both the resource recovery potential and for the environmental impacts of the landfill site. It is therefore crucial to validate all models with site-specific data, as site-specific conditions could significantly alter the results and lead to different conclusions.

The models mentioned for the estimation of long-term emission potentials have limitations due to the assumptions made and can lead to the overestimation of the generation trends of, for example, LFG.<sup>11,58</sup> However, based on the review and on the results of other studies reported by Laner,<sup>11</sup> the analysis of the stored available substances would lead to a better estimation of the long term emission potential of landfills. Different scenarios could then be built to account for the variation in environmental conditions in the long time frame. The *L/S* ratio would be the major parameter to consider, as unforeseen events could lead to the variation of this parameter. Different models can then be adopted, with the inclusion of more parameters for a more realistic inventory. The obtained time-dependent emission profiles could then be integrated in LCA to model the impacts of landfills on a long term perspective and as a function of time.

## Acknowledgement



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# THE ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF A LANDFILL MINING PROJECT FROM THE VIEWPOINT OF AN INDUSTRIAL LANDFILL OWNER

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## Introduction

The EU Commission's circular economy strategy pushes for a higher recycling rate and a more long-term waste management practice.<sup>1</sup> Enhanced Landfill Mining (ELFM) can contribute to this agenda as a better landfill management option, by shifting the landfill paradigm from dumping or as end-storage of waste to resource recovery or as temporary storage of resources.<sup>2-4</sup> Through ELFM, landfills becomes a secondary source of both material (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE) with the use of innovative technologies.<sup>3,4</sup>

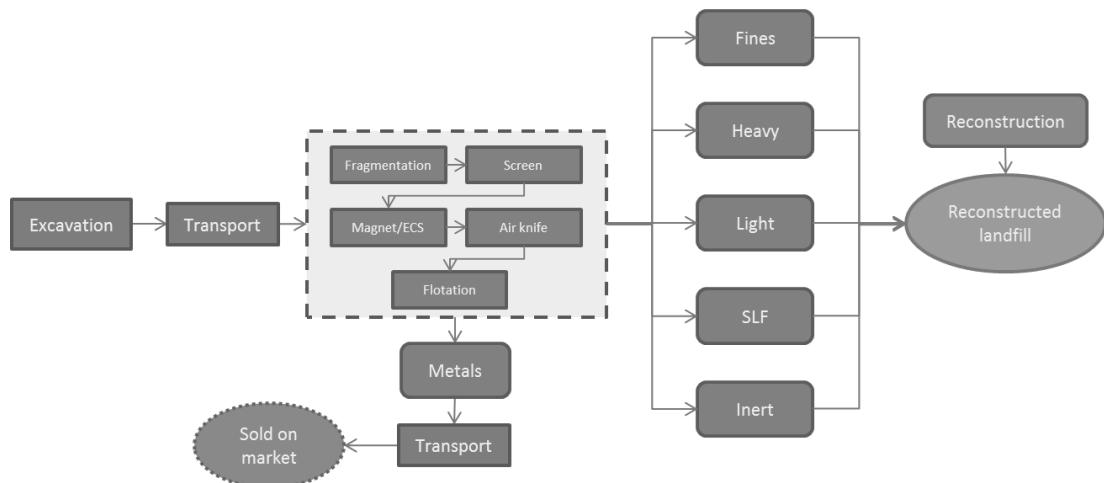
Several studies explored the environmental and/or economic aspects of ELFM having different scopes and objectives. Some cover the entire process value chain while others additionally focused on comparing technological choices for WtE,<sup>5-7</sup> WtM,<sup>8,9</sup> and even ELFM waste valorisation.<sup>10</sup> Furthermore, for the economic assessment, regulation-related costs and benefits as landfill taxes, gate fees and green certificates<sup>5,11,12</sup> are also accounted for. Regarding the identification of economic hotspots, many of these studies concluded similar processes to be important. However, most of these studies were based on either hypothetical cases, or real cases but with small-scale excavation and separation using non-sophisticated set-ups, which are not likely to be used for large-scale processing. Hence, more uncertainty is expected from the lack of actual ELFM demonstration projects.

The aim of this study is to analyse the main contributing factors that influence environmental and economic performance of ELFM, considering the landfill owner's

viewpoint. The study is based on a real case of excavation and subsequent separation in an existing stationary facility. Specifically, the influence of the prevailing system conditions is investigated as defined by the current legislation and the market situation.

## Method

This study analyses a landfill owned by a large Swedish recycling company, Stena Recycling AB (Stena). The landfill contains about 650,000 tonnes of shredder-waste, mainly from old cars. The main driver for Stena to do landfill mining is to regain landfill space considering that it has only 10-year capacity remaining. Moreover, with restrictions of constructing new landfill sites, the demand for landfill space is expected to be higher and so is its market value. In addition, another motivation is metal recovery, which is Stena's long-standing core business. As a step for landfill mining realisation, a feasibility study was performed involving 260 tonnes of landfill waste. This case is interesting compared to most of the previous studies as it includes actual feeding of excavated waste in an existing stationary plant with a relatively sophisticated separation scheme (Figure 1). The sub-unit processes boxed with broken lines are performed more than once.



**Figure 1:** Process flowchart of Stena's landfill mining case as defined by the prevailing system condition wherein all fractions, except for metals, are bound for re-landfilling.

Several fractions were generated from the defined separation technology set-up. Fines (material < 20 mm) are separated by a screener. Metals (ferrous and non-ferrous) are sorted using magnets, eddy current separators (ECS), and flotation processes. Both fines and metals are separated in several points in the process. Shredder light fraction (SLF) contains lightweight materials separated by suction of the air classifier. Heavy and light fractions consist a mix of residual materials separated by flotation, mostly containing rubber and plastic. Finally, inert materials

consist mainly of stones and glass. With the prevailing system condition, all fractions, except for metals, go to re-landfilling on the same site for this feasibility study. SLF, heavy, and light fractions have a high calorific value, which is an advantage for incineration. However, they also contain chlorine and heavy metals that exceed the regulatory limits, resulting in these fractions being re-landfilled.

For a full-scale landfill mining project, scenarios were developed by changing the prevailing system conditions to determine opportunities for outlet of these fractions while considering the environmental and economic performance (Table 1). Reference scenarios include “Do Nothing” (no processes) and “remediation” (relocation to another landfill). Landfill tax refers to the regulation-based payment required for re-landfilling of waste. Classification of landfill mining as a remediation process (lifting of re-landfilling tax), is currently under review in Sweden.<sup>13</sup> Lastly, secondary waste management refers to redirection of SLF, heavy, and light fractions to incineration through mixing with other combustibles instead of re-landfilling. In all scenarios, fines and inert fractions are re-landfilled. With the aim of maximising the landfill space to be regained, an external landfill site is considered for re-landfilling.

**Table 1:** Exploratory scenarios generated by varying the system conditions.

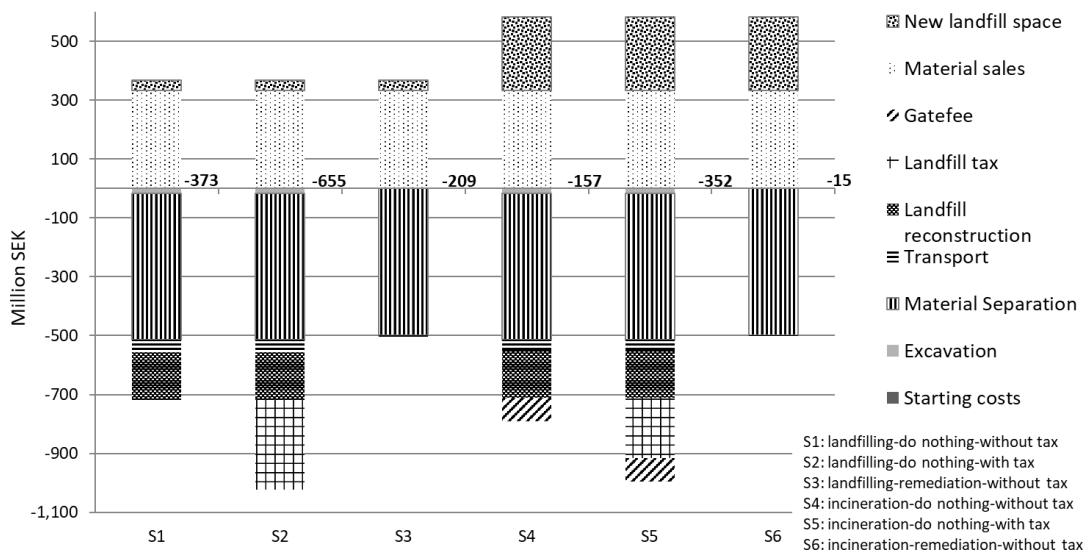
Scenario	Secondary Waste Management of SLF, heavy and light fractions		Reference Scenario		Re-landfill Tax	
	Re-landfilling	Incineration	Do Nothing	Remediation	With	Without
1	✓	-	✓	-	-	✓
2	✓	-	✓	-	✓	-
3	✓	-	-	✓	-	✓
4	-	✓	✓	-	-	✓
5	-	✓	✓	-	✓	-
6	-	✓	-	✓	-	✓

Both the environmental and economic assessments were based on a life cycle perspective. Stena provided the data on material flows and the corresponding economic details. The environmental inventory and subsequent impact assessment was done using Ecoinvent 3.0 and ReCiPe 2016, respectively. Parametric uncertainty analysis was also performed through Monte Carlo simulation with 30,000 runs. This is important to account for the uncertainties when extrapolation is performed from the small-scale feasibility project to the actual full-scale processing.

## Results and Discussion

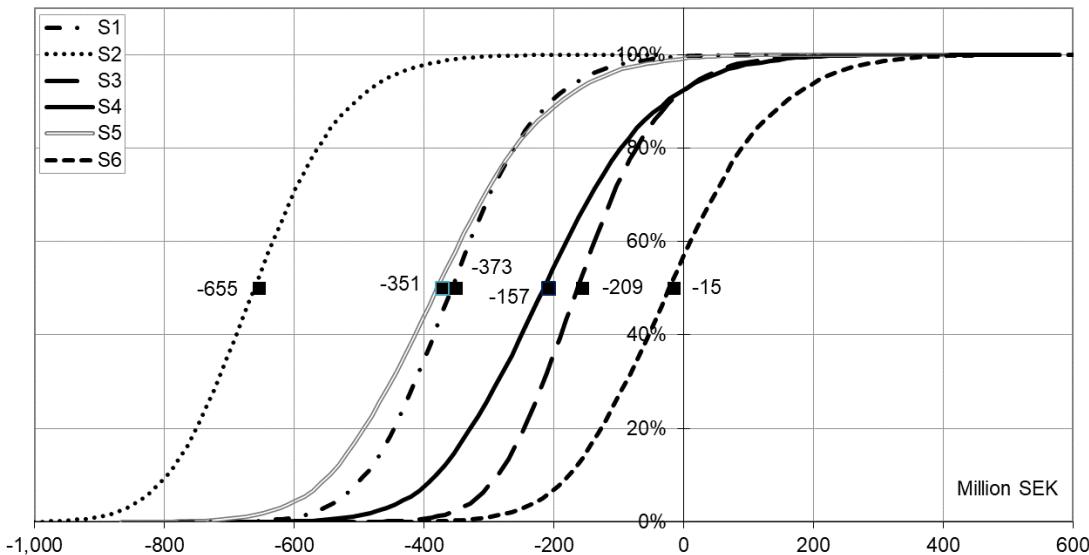
### Economic Assessment

In Figure 2, the costs and revenues of all scenarios (S1-S6) are shown detailing process-specific contributions. Generally, the major revenue comes from material sales ranging from 57 to 91% of the total revenues, while the major cost comes from material separation ranging from 49 to 94% of the total costs. Specifically, material sales refer to metal sales such as iron, copper, aluminium, and stainless steel. Metals are the highest value material recovered. As expected in this study, significantly higher metal contents were recovered when comparing to performing ELFM to a municipal solid waste (MSW) landfill, which agrees with other studies on metal-rich industrial landfills.<sup>14,15</sup> On the other hand, several studies noted WtE as typical main costs contributor while WtM is second.<sup>5,7–9,12</sup>



**Figure 2:** Process-specific costs and revenues (million SEK) for all scenarios (S1-S6), given as positive and negative values, respectively. The net results are presented in bold.

In Figure 3, the net economic results for S1-S6 are shown as cumulative probability distribution through Monte Carlo simulation. All scenarios are net negative with mean values ranging from -655 to -15 MSEK with only 0 to 10% of probability distribution values as net positive. S6 is approaching net profitability with about 50% of its probability distribution values as net positive.

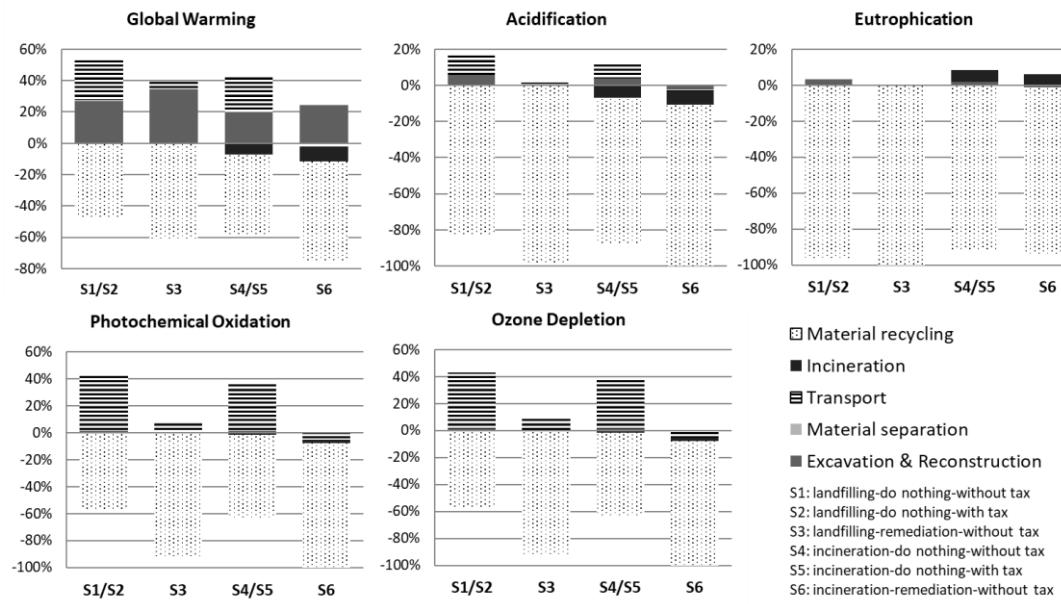


**Figure 3:** Cumulative probability distribution plot of the net economic results (million SEK) for all scenarios (S1-S6), generated through Monte Carlo simulation with 30,000 runs

Using S1 as reference, the effect of the system conditions to the net result were derived; decrease by 70% with landfill tax (S2), increase by 54% with remediation (S3), increase by 12% with incineration (S4), decrease by 26% with both landfill tax and incineration (S5), and increase by 66% with both remediation and incineration (S6). Remediation accounts for higher cost than Do Nothing as an alternative to landfill mining, while incineration accounts for lower cost (gate fee 400 SEK/tonne) than re-landfilling (landfill tax 500 SEK/tonne plus handling cost 300 SEK/ton) as secondary waste handling option. Additionally, landfill tax is lifted for remediation while more landfill space is recovered with incineration, which reduces the costs and increases the revenues, respectively.

### Environmental Assessment

In Figure 4, results are shown for all scenarios, detailing the contribution of processes for the five impact categories such as global warming ( $\text{CO}_2$  eq.), acidification ( $\text{SO}_2$  eq.), eutrophication (P eq.), ozone formation ( $\text{NO}_x$  eq.), and ozone depletion (CFC-11 eq.). As expected, several scenarios gave the same results (S1-S2 and S4-S5) due to having only economic differences (with or without landfill tax). All scenarios resulted in net avoided emissions across all the impact categories. This is mainly accounted to the high amount of recovered metals, wherein avoided emission from primary resource substitution is considered. Previous studies have not demonstrated the same result dealing with landfill site for municipal solid waste and/or mixed waste with expected lower metal resource.<sup>8,12</sup> On the other hand, the main added emissions are accounted to transport to external re-landfilling (up to 100 km) and incineration.



**Figure 4:** Process contributions (%) in five environmental impact categories for all scenarios (S1-S6). Avoided and added emissions are shown as negative and positive values, respectively.

Using S1/S2 as reference, the effect of the system conditions to the net global warming impact, for exemplification, were derived; decrease by 197% with remediation (S3), increase by 420% with incineration (S4 and S5), and increase by 223% with both remediation and incineration (S6). Despite the avoided emissions accounted to heat and electricity recovery, incineration worsens the net environmental results. The Swedish energy system has a better environmental performance than the substituted waste incineration in this case study.

## Conclusion

This study highlighted the significance of system conditions on the profitability of ELFM. Defined by current legislation and the resulting market situation (landfill tax, default reference scenario, and waste quality limit), this study recognises and supports the necessary policy-making decisions. For further research, an integrated approach can be developed to weigh the economic benefit and environmental burden of incineration. In addition, it is interesting to perform a multi-factor sensitivity analysis acknowledging that in reality, adjustments of multiple parameters can contribute to a better understanding and further realisation of ELFM.

## Acknowledgement



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# **APPROACHING ZERO-WASTE METALLURGY THROUGH PLASMA FUMING AND INORGANIC POLYMERISATION OF RESIDUES FROM ZINC PRODUCTION: ENVIRONMENTAL EVALUATION BASED ON LIFE CYCLE ASSESSMENT**

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## **Introduction**

Today, over  $13 \times 10^6$  million tonnes of refined zinc are annually produced at a global level from ores, concentrates, and recycled materials.<sup>1</sup> Due to this vast production, demands for information concerning the environmental footprint of the zinc production processes have emerged from regulators, engineers and final zinc users. Industrial goethite, in particular, is a waste deriving from the zinc production process. While goethite still contains an appreciable amount of valuable metals, it also creates environmental threats due to the presence of heavy metals. The feasibility of metal recovery from goethite is demonstrated, but not viable on an industrial scale with the available technologies. Therefore, goethite is currently mostly landfilled in tailing ponds with considerable economic costs and significant environmental risks.

Some processes have therefore been investigated in the past, to make the management of goethite economically profitable and environmentally sustainable.<sup>2</sup>

<sup>3</sup> In this paper a new strategy for goethite management is presented, with the aim of recovering valuable metals from goethite and subsequently valorise the fumed goethite to make new products. This near-zero-waste strategy is based on the combination of two existing processes, (i) plasma fuming and (ii) inorganic polymerisation.

In the conventional plasma fuming for Zn-containing residues, the slag is heated up by electric plasma torches, which supply both heat and mixing to the slag bath. The metals contained in the slag are vapourised and leave the system through the fumes. The vapourised metals are subsequently precipitated in the form of metal oxide powder. This powder can be then recycled in metals smelters, substituting metal concentrates coming from natural zinc/lead ore mining. The leftover of the fuming

process is a nearly metal-free fumed slag that can be valorised, e.g. as in inorganic polymer based products.<sup>4-6</sup> Inorganic polymerisation of industrial residues consists of mixing the residue with alkaline activators to produce a high strength binder. This binder has great potential as an environmentally-favourable alternative to Portland cement.<sup>7-10</sup>

The application of plasma fuming and inorganic polymerisation for goethite involves several technical and environmental issues. This paper is specifically focused on the final environmental balance of the whole goethite valorisation strategy. Life cycle assessment (LCA) is used as the environmental impacts evaluation methodology. LCA is a framework for estimating the environmental impacts attributable to the life cycle of a product, and is widely used today to evaluate alternative products coming from waste recycling.<sup>11-12</sup>

The goal of the present study is to use LCA to evaluate the environmental performance of the near-zero-waste strategy for goethite, consisting of zinc recovery from goethite and the production of an inorganic polymer, with the aim of highlighting the environmental hotspots of the whole process. The LCA results will help to understand the trade-off between the environmental costs of the fuming process and the subsequent slag valorisation versus the environmental benefits of avoided landfilling and metal recovery.

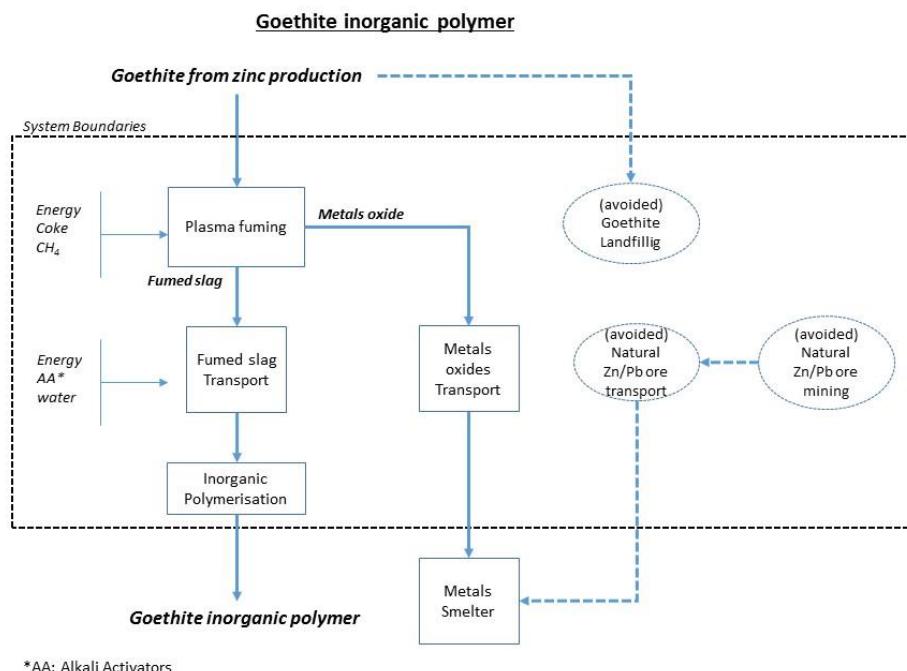
## Methodology

LCA is a methodology used to evaluate the environmental impacts and benefits of a product, process or system, by considering the whole lifecycle. As described in ISO 14040,<sup>13</sup> LCA consists of four main steps: (1) defining goal and scope; (2) creating life cycle inventory; (3) assessing the impacts, and (4) interpreting and analysing the results.

### Goal and scope, functional unit and system boundaries

The goal of the LCA study is to analyse the environmental impacts and benefits of the presented near-zero-waste strategy for goethite, consisting of the recovery of Zn through plasma fuming of goethite and the production of a newly developed inorganic polymer made from the slag resulting from the plasma fuming. The functional unit (FU) provides a reference to which all the inputs and outputs must be referred. For this study, the FU is defined as the treatment and valorisation of one tonne of goethite. The system boundaries define the processes to be included in the analysis. Figure 1 shows the considered system boundaries. Considering that the goethite landfilling and the natural Zn/Pb ore mining and transport are considered as avoided impacts, they are accounted as a credit (negative value) to the recycling

process. The approach used in this study is a cradle-to-gate analysis, meaning that only the production phase is considered.



**Figure 1:** System boundaries for goethite inorganic polymer production

## Life cycle inventory

The life cycle inventory (LCI) phase estimates the consumption of resources and the quantities of waste flows and emissions caused by or attributable to a product's life cycle.<sup>12</sup> Therefore, the LCI phase creates a list of inputs and outputs related to the functional unit chosen and it represents the basis for the calculation of the environmental impacts. The process-input table has been built using data collected from real industrial applications and laboratory works, integrated with data from literature. The following (hypothetical) scenario is studied: first, a plasma fuming plant fumes goethite in Norway; after this, the fumed slag and the recovered metal oxides are shipped to Belgium (1,500 km), where the fumed slag is activated to form inorganic polymers, and the metal oxides are recovered in a metal smelter.

The production treatment of goethite through this process avoids the landfilling of the goethite in tailing ponds. The avoided goethite landfilling, hence, can be given as a credit to the process is accounted as a negative value in the impact calculation (positive impact). The inventory for the goethite landfilling refers to the Ecoinvent module described in Doka.<sup>14</sup>

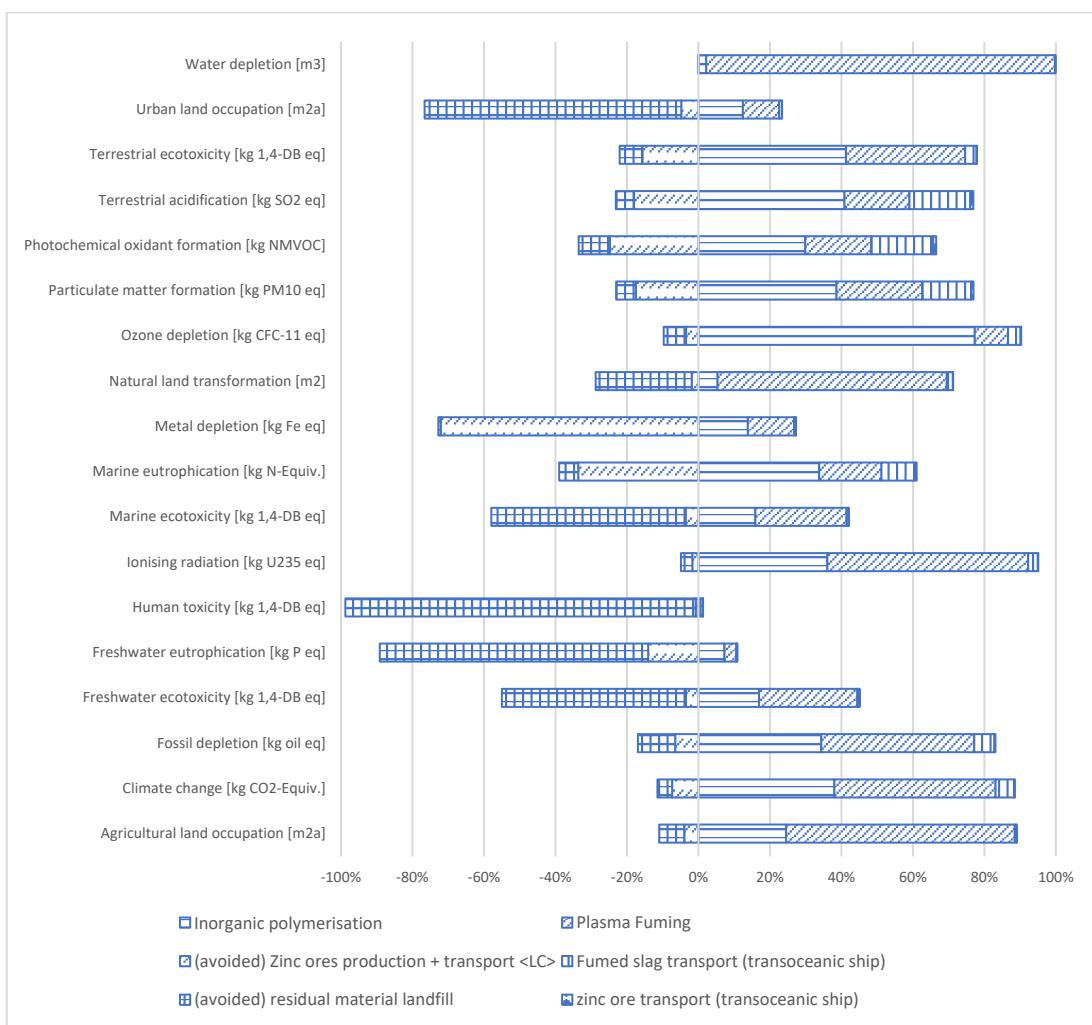
The pilot plasma fuming process in Norway is equipped with two electric plasma torches, able to fume up to 2,000 kg of slag, as it is described in ISO 14040.<sup>5</sup> Per tonne of goethite fumed, the fuming plant consumes 1.2 MWh electricity, 40 kg of coke and 7.8 m<sup>3</sup> of methane, and it produces 600 kg of fumed slag, 16.3 kg of CO<sub>2</sub> and 30 kg of ZnO powder.<sup>5-6</sup> The fumed slag is used for the inorganic polymerisation process, where it is mixed with an activating solution at a ratio of 3.04 (slag to activating solution). The activating solution is a mixture of two commonly used alkaline activators, sodium silicate and sodium hydroxide, with a composition in wt% of Na<sub>2</sub>O: 14.11; SiO<sub>2</sub>: 22.49; H<sub>2</sub>O: 63.4. From the inorganic polymer, a porous block is produced through the addition of 0.05 wt% Al powder to the mix as foaming agent. As plasma fuming theoretically removes a large quantity of metals from the fumed slag, for the present study it is assumed that no significant heavy metal leaching occurs from the inorganic polymer end-product.

### **Life cycle impact assessment**

The life cycle impact assessment (LCIA) phase translates LCI data into the corresponding environmental impacts. For the current study, the LCA model is implemented in the software Gabi. For the LCIA phase, the midpoint-Recipe 1.08 calculation methodology is used, which shows how each individual process contributes to different environmental impact categories, translating physical flows into environmental impacts.

## **Results**

The results of the LCA analysis are reported graphically in Figure 2. As the environmental impact categories are measured with different units, their results cannot be directly compared. Therefore, all impacts are rescaled to 100%. The positive contribution on the right side represents the impact caused, while a negative contribution on the left side represents an avoided impact. Looking at the impacts caused on the right side of Figure 2, it is possible to note that plasma fuming and inorganic polymerisation are the processes with the highest contribution in almost all categories. The shipping of the fumed slag from Norway to Belgium has an environmentally significant contribution only in the categories terrestrial acidification, photochemical oxidant formation and particular matter formation. Looking at the avoided impact, the avoided landfill of goethite has an important effect on the categories urban land occupation, human toxicity, freshwater eutrophication and freshwater ecotoxicity, while the avoided zinc ore mining is significant in the categories metal depletion and marine eutrophication.



**Figure 2: LCA results**

## Conclusions

Industrial goethite, a residue formed in the roasting-leaching-electrowinning process production process of zinc, is today mostly landfilled. However, goethite landfilling poses several economic and environmental disadvantages, due to the high cost it impounds and to the risk of heavy metals leaching. Although goethite contains a substantial amount of valuable metals, the current available technology does not permit an economically convenient extraction of these metals. Therefore, industries are currently looking for new technologies for goethite recycling and metal recovery. The present study analyses the environmental performances of a newly developed strategy for sustainable industrial goethite management, aiming at the production of goethite-based inorganic polymer that can be used in construction applications. Life cycle assessment methodology is used to evaluate the environmental performances, using Recipe midpoint as the impact calculation method. Life cycle assessment is useful to identify the environmental hotspots in the analysed production system. The

analysis of the LCA results shows that the fuming and the inorganic polymerisation represent the main environmental hotspots of the study, providing the main contribution in all considered environmental categories. Considering that the electric mix used for the plasma fuming is based for 96.8% on hydro power, the electric consumption in plasma fuming resulted to be the most significant environmental hotspot of the whole process. At the same time, goethite recycling presents important positive impacts in many impact categories, for the avoided processes of goethite landfilling and natural zinc ore mining.

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# **LEGAL BASIS FOR AN ENHANCED LANDFILL MINING FRAMEWORK IN THE EU CIRCULAR ECONOMY LEGISLATION**

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## **Abstract**

Enhanced Landfill Mining (ELFM) and circular economy are strongly interlinked concepts. ELFM is associated to circular economy because it returns landfilled materials back into the economy as secondary raw materials (SRM). The use of SRMs instead of virgin materials, will result, for example in decreased need of mining of primary ores and an increase in supply security.<sup>1</sup> ELFM also exploits the energy potential of landfilled waste through waste-to-energy (WtE) technology. But unlike SRM, the role of WtE is not emphasised in circular economy.<sup>2</sup> Since ELFM includes both SRM and WtE aspects it is important to study the interlinkage of ELFM and circular economy thoroughly. The focus of this study is on the legal uncertainties in the context of ELFM and the European circular economy. This study examines the legislative basis for an ELFM framework in EU's circular economy legislation by comparing circular economy goals to ELFM.

## **Introduction**

To date, Enhanced Landfill Mining (ELFM) projects in the EU have been mostly experimental. Previous studies on ELFM show promising results, but commercial projects are yet to surface. According to earlier research; financial uncertainties, technological challenges and the absence of supportive policies and legislation are the main reasons delaying the development of ELFM projects.<sup>3</sup> Most of the earlier research has been about technological aspects and analysis of excavated waste. Published research focusing solely on regulation consists only of two studies by Römpph<sup>4,5</sup> and conference papers by Hogland<sup>6</sup> and Wante.<sup>7</sup> Based on the literature review for this study, an observation was made: while ELFM and circular economy are strongly interlinked, the linkage is often not clearly explained. Analysing this linkage is important. Assuming that ELFM fits into circular economy can result in disregarding possible difficulties when pairing the two concepts.

One of the ways to study this interlinkage is to research, from a legal perspective, how ELFM fits into the circular economy context. Studying the issue from a legal

perspective is valuable, because there are attempts to implement ELFM into EU legislation, *cf.* the European Parliament's "Waste Package",<sup>8</sup> voted on March 14, 2017, with respect to the revision of the EU's Waste Policy. The agreed "Waste Package" concerns the adaptation of four EU Directives, including the Landfill Directive (*i.e.* Directive 1999/31/EC). Differences between EU's circular economy goals and ELFM can cause uncertainties in establishing a legal framework for ELFM within the circular economy. Therefore, assessing the similarities and differences within the concepts is important to predict possible problems in legal implementation.

## Research questions and scope

### Research questions

The European Parliament's "Waste Package" includes a new paragraph, proposing the commission to "*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*".<sup>8</sup> As ELFM is being implemented into circular economy law, it is important to examine the legal basis for ELFM in a circular economy. A legal basis makes it feasible to establish regulatory framework. In this paper, the legal basis is studied by examining circular economy objectives and ELFM, and analysing how they pair-up. This paper will examine the interlinkage between ELFM and circular economy goals and highlight the possible differences. After identifying possible differences, this paper highlights the problems that differences might bring forward when establishing a legal framework. The study focuses on finding answers to the following research questions:

1. What are the differences and similarities between circular economy and ELFM targets?
2. If differences are found, what kind of problems do they present for implementing ELFM into circular economy legislation?

### Relevant legislation

The legal acts that are analysed in this study are chosen based on previous studies in which legislation has been researched, either as a subject or a side note. Relevant legislation was chosen to provide a thorough outlook on the objectives of EU circular economy on different levels of EU law. In addition, this study examines the few legal studies about ELFM that have been published. The relevant legislation analysed in this study in order from higher to lower law are: The Treaty on the functioning of the European Union<sup>9</sup> (TFEU), Waste Framework Directive<sup>10</sup>, Landfill Directive<sup>11</sup>, The Circular Economy Action Plan (CEAP)<sup>1</sup>, The Role of Waste-To-Energy in The Circular Economy<sup>2</sup>, and the renewed Landfill Directive<sup>8</sup> from the Circular Economy Package

yet to come into force. Regulations considering traditional mining are left out because previous research has shown that it is not applicable to ELF M. Mining is the extraction of minerals, that are defined in the Mining Waste Directive as naturally occurring deposits in the earth's crust. Waste does not fit in these criteria.<sup>4</sup>

## Analysis

### Objectives of primary law

Primary EU law is the highest of EU law and therefore all following EU legislation has to reflect primary law objectives. The legal basis for EU environmental legislation, including waste management legislation, comes from primary law's the Treaty on the Functioning of the European Union (TFEU).<sup>9</sup> The environmental objectives laid down in article 191 of the TFEU, are to be emphasised in the interpretation of the Waste Framework Directive and other legislation associated to circular economy. The environmental objectives are:

- “—preserving, protecting and improving the quality of the environment,*
- protecting human health,*
- prudent and rational utilisation of natural resources,*
- promoting measures at international level to deal with regional or worldwide environmental problems, and in particular combating climate change.”*

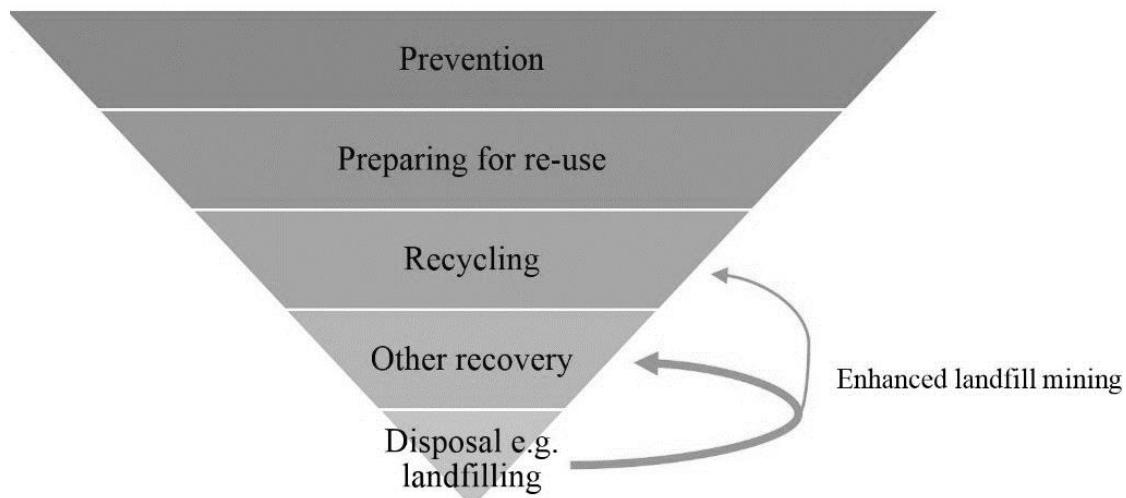
Another target of the TFEU is to help the EU turn to a recycling society, which is explained as a society that avoids waste generation and uses waste a resource, such as in a circular economy. These objectives are to be interpreted to minimise the environmental impacts of waste and waste management. In particular, the “*prudent and rational utilisation of natural resources*”, speaks for circular economy, as well as ELF M through secondary raw material extraction. The objectives of preserving and protecting the environment and human health from waste related environmental problems could be applied to ELF M in cases where an old landfill is polluting the surrounding environment. ELF M could in some cases even be applied to the objective of combating climate change by replacing fossil fuels with waste fuel. It does depend, however, on the specific landfill case and implemented technology whether or not ELF M has a negative or a positive effect on the climate, and there is still some controversy around the subject in academia.<sup>12</sup>

### Objectives of waste management laws

The Waste Framework Directive<sup>10</sup> introduces a waste hierarchy for the EU. The waste hierarchy is designed to guide waste prevention and management throughout EU policies and legislation. The waste hierarchy helps to implement circular economy, to reduce the consumption of resources by prevention of waste and to ensure that

resources are rather re-used and recycled than disposed of.<sup>13</sup> The priority order of waste prevention and management starts with prevention being most favourable followed by preparing for re-use, recycling and other recovery (including energy recovery). The least favourable option is disposal (art. 4, par. 1). Enhanced Landfill Mining fits in the waste hierarchy because it removes waste from the disposal category and relocates waste into the categories of recycling and “other recovery” (Figure 1). Since the waste hierarchy is a significant part of circular economy, it can be reasoned that ELFM fits into circular economy with respect to this point.

Waste hierarchy and circular economy target a reduction of incineration and an increase in recycling. WtE has an important role in some countries, in particular the Nordic countries, and there is controversy between circular economy targets and existing WtE operations.<sup>2</sup> The controversy is that according to the idea of circular economy waste should be injected in production again as secondary resources rather than using it for WtE. ELFM could provide a solution for the problem as maximal recovery as material is aimed for in ELFM; only non-recyclable fractions are fed to WtE. ELFM does not move waste to the category of prevention even in the case of plasma technology, where waste is turned into syngas and plasmastone, a cement substitute material.<sup>14</sup> The definition of prevention is explained in Article 3 paragraph 12: “*‘prevention’ means measures taken before a substance, material or product has become waste*”. As landfilled material is categorised as waste in the Landfill Directive, prevention cannot be paired with Enhanced Landfill Mining.<sup>1</sup>



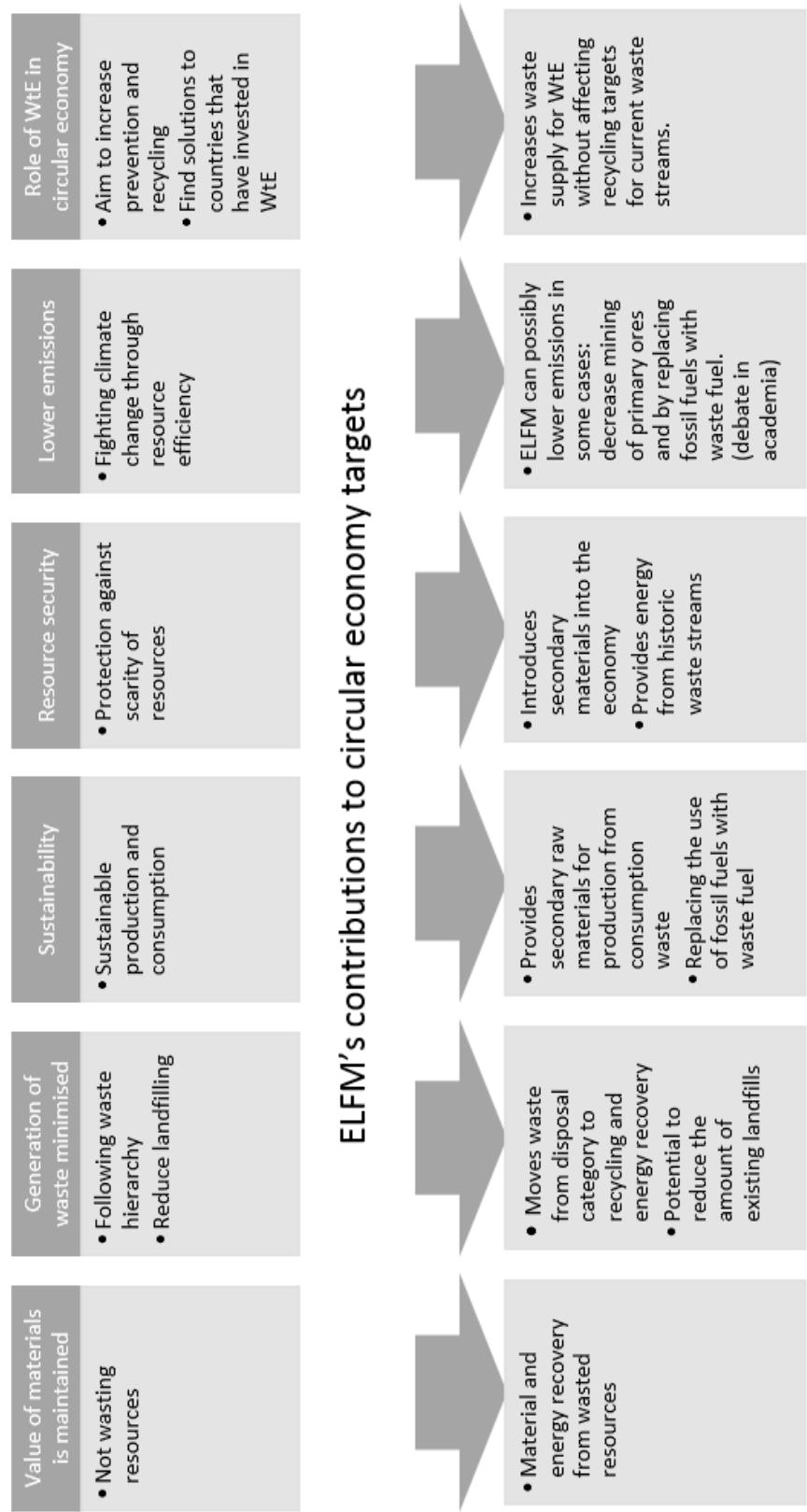
**Figure 1:** Waste hierarchy, according to Article 4 of the Waste Directive (2008/98/EC), where prevention is most favourable and disposal is the last option for waste management. ELFM moves waste up in the waste hierarchy, from the least favourable category disposal to categories of other recovery (e.g. energy recovery) and recycling.

## **Specific law with respect to landfills: the landfill directive**

The available legal studies about ELF M have used a literal interpretation method, which has resulted in findings that propose terminological challenges for the implementation of ELF M into European environmental law.<sup>4</sup> The term landfill is considered problematic because it is defined as a permanent storage of waste, whereas ELF M's purpose is to extract waste materials away from this permanent storage. Thus, the goals of landfills and ELF M are in a conflict.<sup>5</sup>

Römpf mentions in his article<sup>5</sup> the "*intent of the legislator*" when explaining the purpose of a landfill. Römpf argues that the landfill is intended by the legislator to serve a purpose of final storage and therefore it would be contradicting to perform actions where waste is excavated. The legislative intent is to keep the waste in the landfill, but most importantly in a way that the environment is protected. Environmental protection is the objective of the Landfill Directive (art. 1, par. 1), i.e. to shield the surrounding environment and human health from waste related environmental problems. The basis for this is found in the Waste Framework Directive, which in turn has its legal basis in the TFEU environmental objectives. If the environmental safety conditions of a landfill are met, then the intent of the legislator is completed and there is not a good justification to open the landfill based on current legislation. However, if the landfill is considered unsanitary and it does not comply with the Landfill Directive, then actions need to be taken to assure that environmental damage is prevented. This can be achieved by landfilling the waste again correctly or by another solution, such as ELF M combined with renovation of the emptied landfill.

## Circular economy targets according to the EU action plan



**Figure 2:** How ELFMs fits into the circular economy action plan1 targets

## Conclusions

Working towards a circular economy is one of the EU's main goals at the moment. Therefore, researching the legal implementation of technologies, such as ELFm, which might help to reach circular economy targets, is topical and societally important. This paper introduces the interlinkage of ELFm and circular economy concepts from a legal perspective. The linkage has not often been clearly explained in previous research. This study shows that ELFm mostly aligns with circular economy goals that are presented in different levels of EU legislation (Figure 2). The shared objectives of circular economy and ELFm introduce a legal basis for a regulatory framework of ELFm within the circular economy. Terminological challenges provide uncertainties in legislation, but the general objectives of circular economy and ELFm mostly interlink. Although there is existing legislation that is applicable to ELFm, specific legislation is needed. That is to provide a functioning regulative framework with working terminology and unified criteria for all future European ELFm projects. This will help, for example, ensuring that a high level of environmental protection is achieved within all ELFm projects.

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# **PRINCIPLES OF ELFM INTRODUCED IN THE FLEMISH MULTI-CRITERIA ANALYSIS (MCA) FOR SOIL REMEDIATION PROJECTS OF LANDFILLS**

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## **Introduction**

Over the last four years, OVAM has, by means of different framework contracts, performed enumerate actions to further complete the inventory of the landfills present in Flanders. For every landfill investigated up till now, a verdict has been given about the need for a soil remediation, based on the results of a descriptive soil survey. A classical soil remediation project results in a balanced judgement based on the factors such as the attainment of the objectives of the soil decree, pollutant removal, nuisance for the environment and total remediation cost price as described and recorded in a multi-criteria analysis (MCA). However, when a soil remediation project concerns a landfill site, some adjustments to the criteria are proposed, compared to the classical MCA for remediation projects. In case of landfills, the MCA is extended with an additional criterion, namely “the production of raw materials”, which is further subdivided in four sub-criteria, namely “Waste-to-Energy” (WtE), “Waste-to-Material” (WtM), “Waste-to-Land” (WtL) and “Resource Management/ interim use” (RM). The four sub-criteria presented below are only applied in case of a landfill remediation project and, by way of testing, implemented on an existing landfill. The application of the new MCA is now being tested in an *ex officio* remediation project by OVAM in order to fine-tune the new methodology.

## **Description of the sub-criteria**

In order to obtain an objective assessment, three of the four sub-criteria: Waste-to-Energy (WtE), Waste-to-Material (WtM) and Waste-to-Land (WtL) are quantified, while the criterion Resource Management will be evaluated on a qualitative basis.

## **Waste-to-Energy**

A way to quantify the criterion WtE is to examine the caloric value of the recovered waste material. This is only valid when combustible wastes are involved (municipal waste, pure product *etc.*). This caloric value can, on the one hand, be determined by testing the caloric value in the lab on samples taken from the waste material or, on the other hand, be estimated based on theoretical data of the caloric value of different materials. Whether determined under lab conditions, or estimated on the basis of literature, the moisture content, the purity of the waste material (percentage of undesired fractions like sand) always has to be taken into consideration before predicting a realistic caloric value. The next step is to determine the total amount of energy that can be extracted from the waste material per considered remediation variant followed by a calculation to assign scores to each remediation variant as a function of recovered energy. The formula to assign these scores is explained in the test case (see further).

## **Waste-to-Material**

To quantify the criterion WtM in a correct way, the waste material should first be carefully characterised in the course of a preliminary investigation prior to the soil remediation project (*e.g.* the descriptive soil survey), followed by subdividing the waste material in the different volume fractions of *e.g.* construction debris, organic waste, soil, slags *etc.* Subsequently, the sub-criterion WtM will receive a score for each remediation variant, in which a variant aiming on a higher percentage of re-use of wastes, will receive a higher score in the MCA.

## **Waste-to-Land**

The feature on which the subcriterion WtL can be quantified is based on the land surface that can be recovered once the landfill is remediated. Taking the future destination of the regained land into account (industrial zone, residential area, nature reserve) the potential land value can be calculated and quantified in a score.

## **Resource management/interim use**

A landfill can be considered as (possible) source for raw materials (resources), or be given certain functions for interim use, awaiting the remediation (cultivation of energy crops, temporally use to harbour a solar panel or windmill park, use as golf course *etc.*). These features, bundled in the sub-criterion RM, cannot be quantified but will be evaluated qualitatively.

To illustrate the final weighing factors when the ELFM-criteria are taken into account, two tables are added to clarify the MCA working principle in case of a classical soil remediation project (Table 1) and in case of the remediation of a landfill (Table 2).

**Table 1:** MCA for 3 remediation variants, in case of classic soil remediation project

<b>MCA standard soil remediation project</b>		<b>Weight</b>	<b>Variant 1</b>	<b>Variant 2</b>	<b>Variant 3</b>
highly positive = 14, highly negative = 1					
Total sum must equal 15					
	<b>Criterion</b>				
<b>Environmental</b>					
<b>Local</b>					
1	Level achieving requirements soil decree for soil	6,6			
2	Level achieving requirements soil decree for groundwater	6,6			
3	Total reduction pollutant load	6,6			
4	Direct emission to other environmental compartments	6,6			
5	Duration remediation and accordance with policy objectives	6,6			
	<i>Total weight of the criteria "Environmental"</i>	33			
<b>Regional/global</b>					
6	Use of secondary raw materials	8,0			
7	Production of waste (non recyclable)	4,0			
	<i>Total weight of the criteria "Regional/global"</i>	12			
<b>Technical and public/social</b>					
8	Hinder and public nuisance	5,5			
9	Future land use restrictions	5,5			
10	Damage caused by remediation	5,5			
11	Safety measures during remediation	5,5			
	<i>Weight criteria technical and public/social</i>	22			
<b>Financial</b>					
12	Remediation cost	22,0			
13	Value of remaining pollutants	11,0			
	<i>Weight criteria financial</i>	33			
	<b>Totaal</b>	<b>100</b>			

**Table 2:** MCA for 3 remediation variants, in case of ELF M

MCA in case of soil remediation project with principles ELF M incorporated					
	Criterion	Weight	Variant 1	Variant 2	Variant 3
<b>Environmental</b>					
<i>Local</i>					
Level achieving requirements soil decree for soil	6,6				
Level achieving requirements soil decree for groundwater	6,6				
Total reduction pollutant load	6,6				
Direct emission to other environmental compartments	6,6				
Duration remediation and accordance with policy objectives	6,6				
<i>Total weight of the criteria "Environmental"</i>	33				
<i>Regional/global</i>					
Use of secondary raw materials	4,0				
Production of waste (non recyclable)	4,0				
Production of raw materials	4,0	Average of the scores for Wte, WtM, WtL en RM	Average of the scores for Wte, WtM, WtL en RM	Average of the scores for Wte, WtM, WtL en RM	
<i>Waste for energy</i>					
<i>Waste for material</i>					
<i>Waste for land</i>					
<i>Resource management</i>					
<i>Total weight of the criteria "Regional/global"</i>	12				
<b>Technical and public/social</b>					
Hinder and public nuisance	5,5				
Future land use restrictions	5,5				
Damage caused by remediation	5,5				
Safety measures during remediation	5,5				
<i>Weight criteria technical and public/social</i>	22				
<b>Financial</b>					
Remediation cost	22,0				
Value of remaining pollutants	11,0				
<i>Weight criteria financial</i>	33				
<b>Totaal</b>	100				

## The test case: Acid tar dumpsite

In the following paragraphs the working principle of the MCA for landfills is illustrated by means of a test case. The case study indicates how the different sub-criteria can be quantified, based on a probable characterisation of the waste material. Since no remediation project has been reported yet, a detailed identification/characterisation of the waste material (by means of an intensive sampling to evaluate and to characterise the waste material) is still required as part of the remediation project.

### The dumpsite

On an acid tar dumpsite approximately 12,000 cubic meters of soil and groundwater are contaminated to a depth of 3 m-bgl with heavy metals, TPH, sulphate, low pH, as well as pure product of acid tar. The dumpsite is situated in an urban natural reserve and will, according to the municipal services for spatial planning, be transformed to a recreational area. The volume fractions of the different waste streams (pure acid tar, construction debris, organic waste, contaminated soil) were assessed, based on

the summary information of the preliminary investigation. Additionally, the estimated caloric values of the pure product and the organic waste were based on a literature review. The unit cost per square metre of the regained land surface is based on the possible future land use scenarios. With regard to the valorisation of the waste material, this example assumes that excavated construction debris can be recycled and re-used as foundation material in road construction works. An overview of the different input data is given below.

**Table 3:** Overview of the results of the characterisation

Surface to remediate	4,000 m <sup>2</sup>
Depth of excavation	3.0 m-bgl
Density organic waste	1.3 tonne/m <sup>3</sup>
Density concrete debris	2.2 tonne/m <sup>3</sup>
Density acid tar	0.95 tonne/m <sup>3</sup>
Density polluted soil	1.75 tonne/m <sup>3</sup>
Acid tar (volume percentage)	5%
Organic waste (volume percentage)	30%
Concrete debris (volume percentage)	15%
Organic waste (volume percentage)	30%
Polluted soil (volume percentage)	50%
Caloric value (acid tar)	20.934 MJ/kg
Caloric value (municipal waste)	11.12 MJ/kg
Weighing factor with regard to value of the regained land	
Reallocation as industrial zone	110 Euro/m <sup>2</sup>
Reallocation as residential area	300 Euro/m <sup>2</sup>
Reallocation as farmland	2.5 Euro/m <sup>2</sup>
Reallocation as recreation area	2.5 Euro/m <sup>2</sup>
Reallocation as nature reserve	2.5 Euro/m <sup>2</sup>

For each considered variant, the recovered energy, the amount of concrete debris to be re-used and the value of the regained land are calculated. An example of such a calculation is given in Table 4, in which the following remediation variants were compared:

- Variant 1: Total excavation and treatment of the excavated material (soil, waste, pure product, ...) *ex situ*;
- Variant 2: Total excavation and treatment of the excavated material (soil, waste, pure product, ...) on site (immobilisation);
- Variant 3: Capping the dumpsite with a clean top layer.

**Table 4:** Weighing remediation variants

	<b>Variant 1 (V1)</b>	<b>Variant 2 (V2)</b>	<b>Variant 3 (V3)</b>
Treated surface (m <sup>2</sup> )	4,000	4,000	4,000
Excavation depth (m)	3	3	0.3
Excavated and disposed volume (m <sup>3</sup> )	12,000	0	1,200
Use primary raw materials (m <sup>3</sup> )	12,000	0	1,200
Use of aggregates/auxiliary materials (m <sup>3</sup> )	0	1,200	0
Variant-specific output			
Recuperated combustion heat of pure product (MJ)	119E+09	0.00E+00	1.19E+08
Recuperated combustion heat of organic waste (MJ)	5.20E+09	0.00E+00	5.20E+08
Re-use concrete debris as foundation material (m <sup>3</sup> )	1,800	0	180
Re-use cleaned soil (m <sup>3</sup> )	6,000	0	600
Maximal value of regained land (Euro)	1,200,000	10,000	10,000

Subsequently, the MCA-score of each sub-criterion is calculated on a total of 15 points, to be divided between the three variants and based on the quantification of the three sub criteria WtL, WtM and WtE, using the following formulas:

- Sub-criterion Waste-to-Energy WtE:  $M_{1.1} = 15 \times E_1/E_t$ 
  - M1.1: score for environmental hygienic aspect (M) variant 1, sub-criterion 1;
  - $E_1$  = profit in energy, expressed in Joule for variant 1;
  - $E_t$  = total energy profit as the sum of the three variants:  $E_t = E_1 + E_2 + E_3$
- Sub-criterion Waste-to-Material:  $M_{1.2} = 15 \times Ma_1/Ma_t$ 
  - M1.2: score for environmental hygienic aspect (M) variant 1, sub-criterion 2;
  - $Ma_1$  = profit in materials, expressed in m<sup>3</sup> for variant 1;
  - $Ma_t$  = Total profit in materials as the sum of the three variants:  $Ma_t = Ma_1 + Ma_2 + Ma_3$
- Sub-criterion Waste-to-Land:  $M_{1.3} = 15 \times La_1/La_t$ 
  - M1.3: score for environmental hygienic aspect (M) variant 1, sub-criterion 3;
  - $La_1$  = Regained land expressed in m<sup>2</sup> for variant 1;
  - $La_t$  = Total surface of regained land as the sum of the three variants:  $La_t = La_1 + La_2 + La_3$ .

For the sub-criterion “Resource management”, the scores are attributed qualitatively. Variant 1 gains the highest score: the resources are made available for optimal use immediately after excavation and separation, whilst in case of variant 2 the excavated material is not available for future use, due to the immobilisation.

Variant 3 comes down to an isolation of the waste material and this also implies no possibilities on future re-use of materials. Finally, the average score of the different sub-criteria is imported to the adapted MCA for landfills, in the additional criterion “production of raw materials”, with a weight of 4% in the global MCA for landfills. Eventually the extended MCA did, for this case, not result in a new preferred variant, but only led to a switch in ranking for the variants 2 and 3 in comparison with the present MCA.

**Table 5:** Overview of the calculations of the different scores

	Variant 1	Variant 2	Variant 3	Sum of the scores
<b>MCA Scores</b>				
Quantification Waste-to-Energy	6.40E+09	0.00E+00	6.40E+08	7.035E+09
<i>Score in the MCA (WtE), M<sub>1.1</sub> until M<sub>3.1</sub></i>	13.64	0	1.36	15
Quantification Waste-to-Material	7,800	0	780	8,580
<i>Score in MCA (WtM), M<sub>1.2</sub> until M<sub>3.2</sub></i>	13.64	0	1.36	15
Quantification Waste-to-Land	1,200,000	10,000	10,000	1,220,000
<i>Score in MCA (WtL), M<sub>1.3</sub> until M<sub>3.3</sub></i>	14.75	0.12	0.12	15
<i>Scores resource management M<sub>1.4</sub> until M<sub>3.4</sub></i>	13	1	1	15
<b>Summary limited MCA</b>				
<i>Scores Waste-to-Energy</i>	13.64	0.00	1.36	
<i>Scores Waste-to-Material</i>	13.64	0.00	1.36	
<i>Scores Waste-to-Land</i>	14.75	0.12	0.12	
<i>Score Resource Management</i>	13	1	1	
<i>Total</i>	55.03	1.12	3.85	60.00
<i>Average score of the 4 sub-criteria</i>	13.76	0.28	0.96	15.00

## Conclusions

Based upon this one case and only taking the ELFm-principles WtL, WtM, WtE and RM into account, the complete excavation of the landfill and valorisation of the waste materials seems to be the most favourable way to remediate the landfill. However, at this moment it cannot yet be stated that the best way to remediate landfills is a complete excavation: more practical cases need to be elaborated before a well-founded conclusion can be drawn whether the MCA+ brings an substantial added value in evaluating the remediation of dumpsites and increases the sustainability of

dump site remediation. It is clear that further investigation and fine-tuning is required. OVAM is testing the new procedure parallel to the existing MCA in order to obtain more information on possible differences and on where adjustments are necessary. Final results are not yet available, since the testing phase is still on-going.

# **THE RAWFILL CONCEPT: AN INTEGRATED METHODOLOGY AND TOOLBOX FOR SELECTING AND LAUNCHING ENHANCED LANDFILL MINING (ELFM) PROJECTS**

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## **Introduction**

RAWFILL (“Supporting a new circular economy for RAW materials recovered from landFILLS”) is an INTERREG EU-funded landfill mining project, gathering partners and associated partners of North-West European regions and supported by EURELCO. RAWFILL was launched in March 2017 and will end in March 2020. The ultimate goal of RAWFILL is to allow North-Western European public/private landfills owners and managers to implement profitable resource-recovery driven landfill mining and enhanced landfill mining projects, hereunder named ELFM.<sup>1</sup> RAWFILL develops a cost-effective standard framework for creating landfill inventories (ELIF) based on existing experiences; an innovative landfill characterisation methodology by geophysical imaging and guided sampling; and an associated Decision Support Tool (DST) to allow smart ELFM project prioritisation. The whole concept will be demonstrated in 2 pilot sites in Flanders (Meerhout) and France (Les Champs Jouault). Additional geophysical calibration operations will take place at a few other landfills where specific information is available. More information about RAWFILL and its progress reports can be found at the project website: [www.nweurope.eu/rawfill](http://www.nweurope.eu/rawfill).

The ELIF will be used to describe landfills not only in terms of environmental and risk issues, but will focus on the quality and the quantity of dormant materials present in the landfills, in order to supply relevant data for stakeholders involved in ELFM projects.<sup>2</sup> The ELIF is the basis for the DST ranking tool and a prerequisite to assess feasibility, business plan and business cases for launching profitable projects. The DST is a ranking tool that will allow ELFM projects prioritisation based on a set of suitable physical, chemical, environmental, technical and social information. It will integrate the multiple aspects involved in ELFM projects, *i.e.* economical, technical, environmental and social factors in order to compare and classify landfills regarding their ELFM interest.

## **ELIF – Enhanced Landfills Inventory Framework**

One main challenge for stakeholders involved in ELF M operations is to evaluate the project profitability risk based on quantity and quality of dormant resources that can be excavated and recovered from a particular landfill site. Related reliable decision elements are missing in most of the landfill inventories we have reviewed, covering the NWE region.<sup>3</sup> The most advanced inventories describe landfills in terms of environmental and risk issues, but give no way to evaluate, even roughly, their dormant resources potential. In most cases, even the volume of waste remains unknown and only very general information is given about the waste types present (which is very often a mixture of domestic, industrial and construction wastes).

### **Existing inventories, landfill mining experiences and accuracy of information**

A review of inventories existing North-Western Europe is currently being written and shows that most of the inventories describe only generic information on the landfills included (name, location, ownership, sometimes periods of landfilling, sometimes waste volume estimation, etc.). In the most advanced inventories, environmental and risk issues are described<sup>4</sup> (type of wastes, physical state, presence of leachates and biogas, geology, hydrogeology and hydrology, environmental impacts surrounding population, etc.). Detailed information about the quantity, distribution of materials within the landfill volume and composition of buried wastes is missing.

A short review of landfill mining experiences,<sup>5</sup> also currently being written, focuses on the methodology used to evaluate the landfill resources potential. The study shows that in the studied cases no specific particular attention was given to the precise evaluation of resources. Other important factors lead to the decision of mining the landfill, as solving an environmental issue, recovering valuable land or performing feasibility tests. This situation is expected to change once the ELF M market will grow and, within North-Western Europe, because some mineral resources will request more attention. For sure, in a highly populated area, the economic value of land that can be reclaimed through an ELF M project will remain a key decision factor.

Within existing information, it is difficult to estimate the level of accuracy, for example the extension of a landfill within the total area of the site, the mode of how the volume of waste was calculated (sometimes an estimation can be based on a mean height), etc. As this required level of accuracy is very important for launching an ELF M feasibility study, the ELIF should specify an accuracy estimation for each DST-relevant field which will be taken into account for the ranking. The least complex classification is one based on “poor/average/good/unknown” accuracy of information.

## **The ELIF challenge**

The ELIF ambition is to supply stakeholders with an inventory framework that can be filled with suitable data, in order to evaluate the ELF potential of the site. We are aware that it will demand lots of efforts to find, validate and encode information based on general documentary studies performed by on-site geophysical investigation. We also know that this information will remain on general level and that it will not be sufficient to design a detailed and precise business case model. But ELIF is expected to be useful to (1) demonstrate to stakeholders the interest of reliable, enhanced inventories seen from a perspective of material and energy recovery, which is a quite recent approach; (2) eliminate sites with obviously limited ELF potential and (3) select the most promising sites where further investigations can be concentrated.

It has to be noted that RAWFILL ELIF is not a database in itself, but a database structure that will not contain information about any particular site. It will be presented as a spreadsheet and proposed to stakeholders in order to be integrated in their database structure and filled with information. Information will come first by exporting or transposing existing data and then by completing as much missing information as possible, using RAWFILL historical surveys and a geophysics imaging methodology. The challenge is to present a useful, easy-to-use, cost-effective and reliable structure that can be adopted in every NWE region or elsewhere, to build a new generation of landfill inventories focused on the principles of circular economy, sustainable development and ELF perspectives.

## **Geophysical imaging**

Within RAWFILL, information extracted from the landfill geophysics methodology will be described as a 3D RDM “Resources Distribution Model”, mainly based on historical documentary works and geophysics investigations on site. This study of historical documentation and geophysical imaging is set up to study the distribution of homogenous zones inside a landfill, and to link the identified zones with information about the average waste composition and physical conditions (metals, organic materials, water content, etc.). The RDM of a landfill, when established, will feed the ELIF fields related to “geometry” and “waste composition” sections described hereunder.

Geophysical imaging will result in a flexible combination of most modern geophysics methods, designed to precise many parameters related to the geometry of the landfill (surface, waste volume, depths), waste conditions (groundwater, biological activity, etc.) and waste composition (density, metal content, organic content, etc.). Imaging will be used to identify homogeneous zones within the landfill with some

relevant contrasts and will be validated by guided sampling and analysis. Prior to geophysics operations on site, documentary works will be performed. These works can be based on a specific historical investigation methodology such as the one developed and applied by SPAQuE for Wallonian landfills and industrial sites.<sup>6</sup> The purpose is to obtain as much information as reasonably possible from various sources as written documents (permits and authorisations, reports, contracts, site pictures, etc.), testimonies of workers and neighbours, maps and aerial pictures. Historical results are related to wastes volume, wastes types, age and origin and when possible the distribution of waste types within the landfill. Historical investigations will allow to precise certain fields of the ELIF structure, and supply a guideline for more effective site investigations. However, geophysicists have to take into account that, in many cases, no historical information will be obtained at all, or some specific hazardous wastes may have been landfilled illegally and will not appear in any document.

## **ELIF structure**

The first version of ELIF structure is currently mostly completed. It will be tested on some representative landfills, especially the ones selected within the RAWFILL project as demonstration sites. The individual landfill data sheets will also be used to develop and test the DST ranking tool. ELIF will be divided into 4 large sections: Landfill ID card, landfill surroundings, landfill geometry and specific waste information, this last section mostly based on geophysics operations. Some fields will be used by the future RAWFILL's DST in order to rank ELF projects, while others will gather suitable information for stakeholders.

**Table 1:** ELIF divisions and most representative fields

Section	Definition	Fields examples
1. Landfill ID Card	All administrative information about a given landfill	Name, location, owner, operator, monitoring, aftercare, legal status, permits
2. Surroundings	All relevant data about the landfill's surroundings	Land planning, territorial strategy, current use, specific risks, geology, groundwater, access
3. Geometry	Landfill geometry, without waste information	Surface, volume, depths, stability, bottom, capping, biogas network
4. Wastes	Specific information about the landfill's waste streams	Types, density, water and gas content, temperature, estimated composition from RDM

Landfill ID card will be the easiest part to fill, even if some searches can be necessary to precise some fields. Landfill surroundings will require some completion in order to

precise specific environmental and social site-related questions. As land reclamation is an important aspect for the economic feasibility of projects, specific attention will be given to the expected future of the area surrounding the landfill through several fields coming from national/regional/local policies, as strategic territorial intelligence, land planning and existence of territorial tools to modify land use and local land pressure. Geometry will obviously cover all information related to the physical shape of the waste mass, but also information available on the bottom and capping layers and an appreciation of stability issues that can be encountered during a partial or total excavation phase. Wastes is the most complex and most important section regarding ELF M opportunities. The landfill is intended to be divided into 4 or 5 homogenous and contrasted parts that will be deducted from the RDM, in most cases it should be bottom layer (the oldest part of the landfill), top layer (most recent – and probably most documented – part) and 2 or 3 other volumes in between. Ideally, for each part precise data about surface, volume, *in situ* density, tonnes buried, water content and temperature should be measured and calculated and an indication about the waste composition should be formed, including the percentage of fine materials, which currently have limited valorisation possibilities.

## **RAWFILL's DST – Decision Support Tool**

Estimations pointed out that there is a huge number of landfills in the EU (350,000 to 500,000).<sup>7</sup> Most of these landfills are no longer operational and descriptions of the content and environmental risks are not always available. In order to deal with such a large number of landfills and their uncertainties, a phased approach is required and *ad hoc* choices cannot be part of a long term sustainable management. Therefore, RAWFILL will introduce a 2-level Decision Support Tool.

The RAWFILL DST is a ranking tool that will allow ELF M project prioritisation based on a set of suitable physical, chemical, environmental, technical and social information. It will integrate the multiple aspects involved in ELF M projects, *i.e.* economical, technical, environmental and social factors. The DST will help stakeholders to take suitable decisions. A generic structure of relevant information to handle is presented hereunder, mostly under “risks”, “drivers” and project “scales” (we see that ELIF information is treated as “actions” as well as the geophysical imaging).

RAWFILL's DST will operate at 2 levels:

- “Selection”: a first level of quick screening to identify landfills with *a priori* interesting potential but which need further historical investigations and geophysical survey.

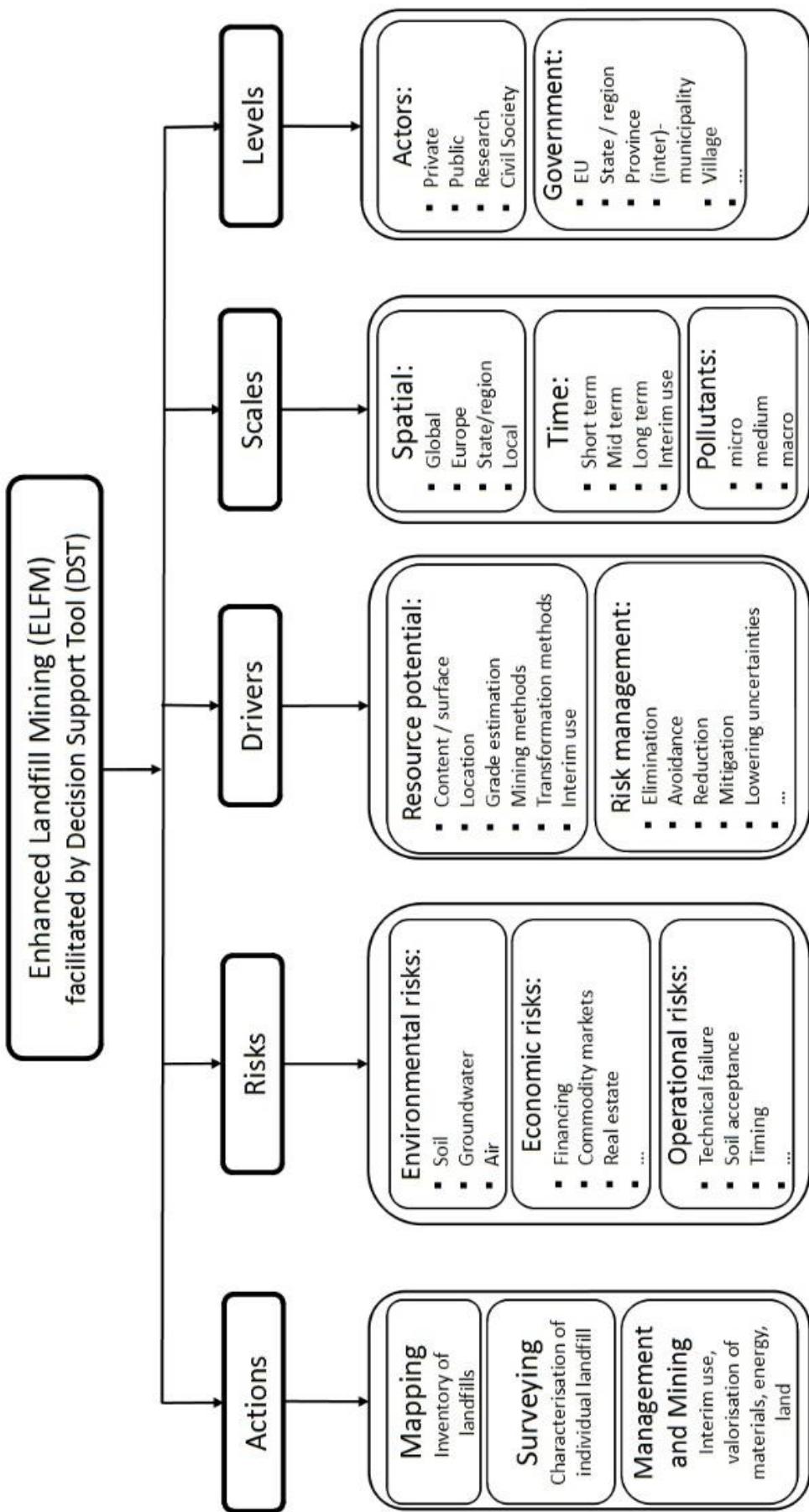
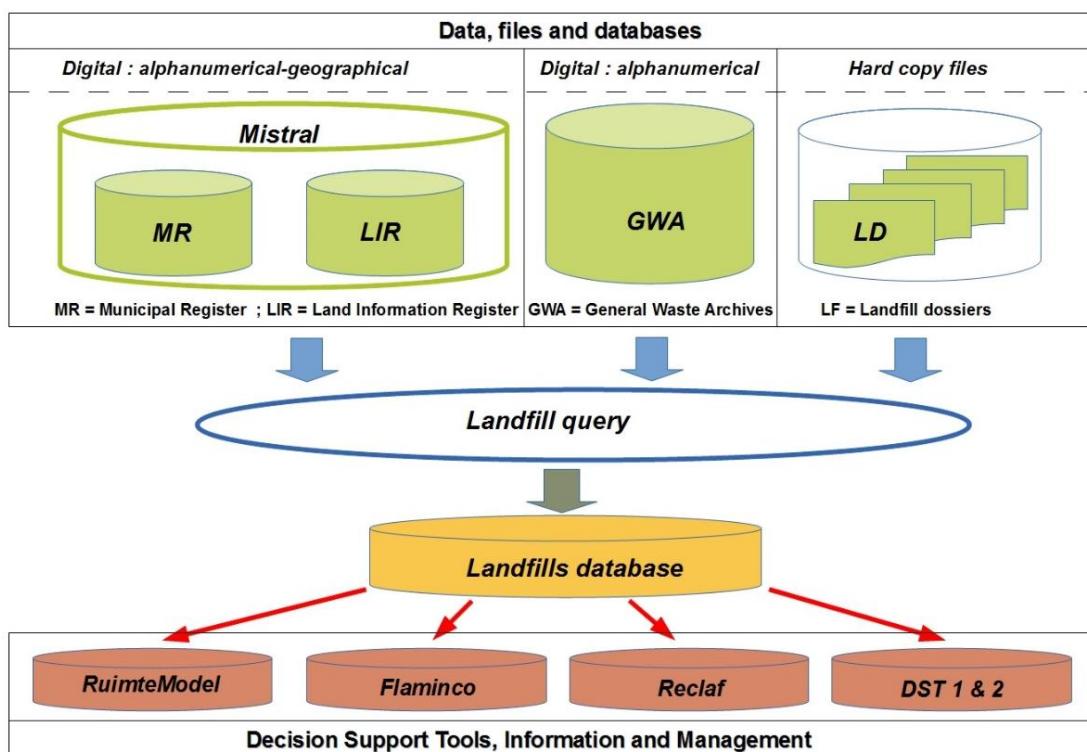


Figure 1: Overview of relevant aspects for an ELM DST

- “Ranking”: a prioritisation tool to rank pre-selected and fully investigated landfills of economic interest for raw material recovery purposes. This second level of the DST is a more dynamic model integrating the landfill in its physical, economic and social environment, including safety aspects of the operations.

The DST will be built based on a table of suitable ELFM indicators extracted from the most relevant ELIF fields, for which a specific weight will be given. Not all fields will be relevant for DST; only those necessary to rank landfills on an ELFM point of view will be considered. The link between data collection, data storage and DSTs is presented hereunder<sup>8</sup> when several databases are used to manage landfill information, which is the case of OVAM. RAWFILL ELIF can be positioned at the level of “landfills database” and can be fed by several datasets, including the ones from geophysical imaging that have to be added on digital form. RAWFILL DST can be added as an additional tool that will treat suitable data extracted from ELIF datasheets.



**Figure 2:** Link between data collection, data storage and DSTs within OVAMs structure

Main future users of the DST will be landfill owners, developers and investors in charge of landfill mining projects. But also public bodies could use these DSTs as part of their tasks in the field of policy making and data management of landfills. OVAM developed the FLAMINCO-DST<sup>9</sup> where a set of non-financial parameters are used to undertake a multi-criteria analysis in order to prioritise landfills for ELFM.

The RAWFILL DST will deliver reliable information about the feasibility and the costs and benefits of a planned landfill mining project. The reports will provide information on the degree of uncertainty of the knowledge on the landfill composition, the potential recovery of resources/land and the necessity of remediation actions. In the new approach, ELFMs-projects are seen as business cases, where the decision to undertake a landfill mining project is considered as an investment decision making process. A. Winterstetter<sup>10</sup> proposed a coherent concept in which different technical, environmental and socio-economical parameters are integrated to determine the mining-potential of a specific landfill. The method is in line with the United Nations Framework Classification for Resources (UNFC<sup>11</sup>) which is applicable on geogenic resources. In a cooperative project (RECLAF<sup>12</sup>) between the TU Wien and OVAM this method was tested with success on specific Flemish landfills. The RAWFILL partners will develop an integrated method on mapping and surveying, which will feed the DSTs and deliver information to guide the future actions on landfills.

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# INTEGRATED ECONOMIC AND ENVIRONMENTAL ASSESSMENT AS DRIVER FOR INNOVATION OF METALLURGICAL SYSTEMS FOR THE VALORISATION OF LOW-GRADE INPUT MATERIALS

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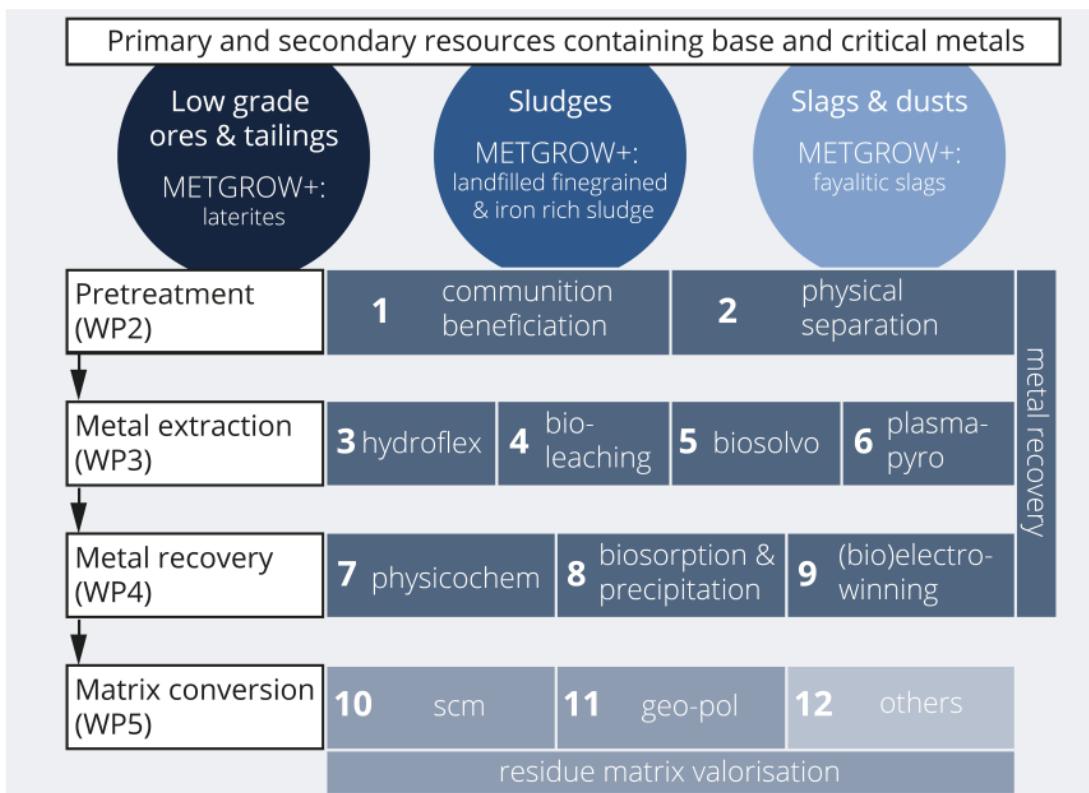
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## Introduction

Low-grade primary ores and secondary industrial residues often yield significant amounts of (critical) metals. As Europe doesn't possess easily accessible deposits of raw materials, these low-grade resources (some of which can be found in landfills) could serve as a reliable source of metals. Traditional pyro- and hydrometallurgical methods don't suffice to exploit metals from these resources.<sup>1</sup> Within the METRGROW+ project the aim is to valorise the low-grade resources by implementing novel methodologies in a metallurgical system. As target raw materials four, in Europe widely available and complementary low-grade resource families were selected: (1) primary laterite deposits, (2) fayalitic slags, (3) iron-rich sludges and (3) fine-grained poly-metallic sludges. The zero-waste approach is a crucial factor for the successful valorisation of these four materials, which captures not only the contained metals but also valorises the residual matrix (often > 95 wt% of the bulk material).

The focus of the METGROW+ technology developers is the development of novel unit operations (WP2-5, Figure 1) that in a later stage of the project will be combined to actual metallurgical flow sheets. To achieve valorisation of all outputs (e.g. metals and matrix material) of the new metallurgical flow sheets, an integrated Life Cycle<sup>2,3</sup>, Risk<sup>4,5</sup> and Techno-Economic<sup>6</sup> Assessment (LCA-RA-TEA) will be performed. The goal of the integrated LCA-RA-TEA is to quantify environmental impacts, environmental risks and economic impacts of the metallurgical systems for the four material streams. This to support and steer the further development of the technologies.



**Figure 1:** Project structure and different metallurgical unit operations under development in the METGROW+ project

## Approach and Methodology

### Goal and Scope

Within the METGROW+ project the integrated LCA-RA-TEA methodology aims to quantify the environmental impacts, risks and economic impacts of the metallurgical systems that are developed during the project and applied to the material streams under research. One of the aims of developing these metallurgical systems is to realise the zero-waste concept where valuable metals are extracted and the matrix material is valorised. As the different mineral processing and metallurgical unit operations are in different stages of development and are developed separately in the initial stage of the project, impacts assessments will be performed in a phased approach. The first impact assessments will be performed on the individual unit operations and overall metallurgical flowsheets will be evaluated by combining the data of different unit operations. To make meaningful assessments, the different unit operations will be modelled at an industrial scale with a default setting of 200,000 tonne incoming raw material per year. In the later stages of the project assessment will be based on data of the complete metallurgical system in place (pilot scale)

The goals for the LCA-RA-TEA studies in METGROW+ are:

1. Support the development of the METGROW+ metallurgical unit operations, by considering intermediate results from the first two iterations of the economic and environmental assessment.
2. The project results of the LCA-RA-TEA assessment will provide an overview of the viability of several metallurgical systems based on economic and environmental impacts which are key parameters for the future exploitation.
3. Development of a methodology that facilitates the evaluation and implementation of novel technologies.

### **System boundaries**

For the LCA-RA-TAE study a gate-to-gate approach will be used. The system boundaries of the metallurgical systems studied comprise the pre-treatment and the smelting-refining steps of the raw materials to the production of refined metals and matrix products (Figure 2). Because the refined metals will be sold on international markets, no distinction can be made with metals produced by the conventional systems and the corresponding downstream activities are excluded from the system boundaries. Downstream activities of the matrix products will be included in the system boundaries in case these will comprise novel products and uses. The matrix valorisation will depend on the market demand, the market value and the market access, which will be influenced by human health and environmental safety aspects.

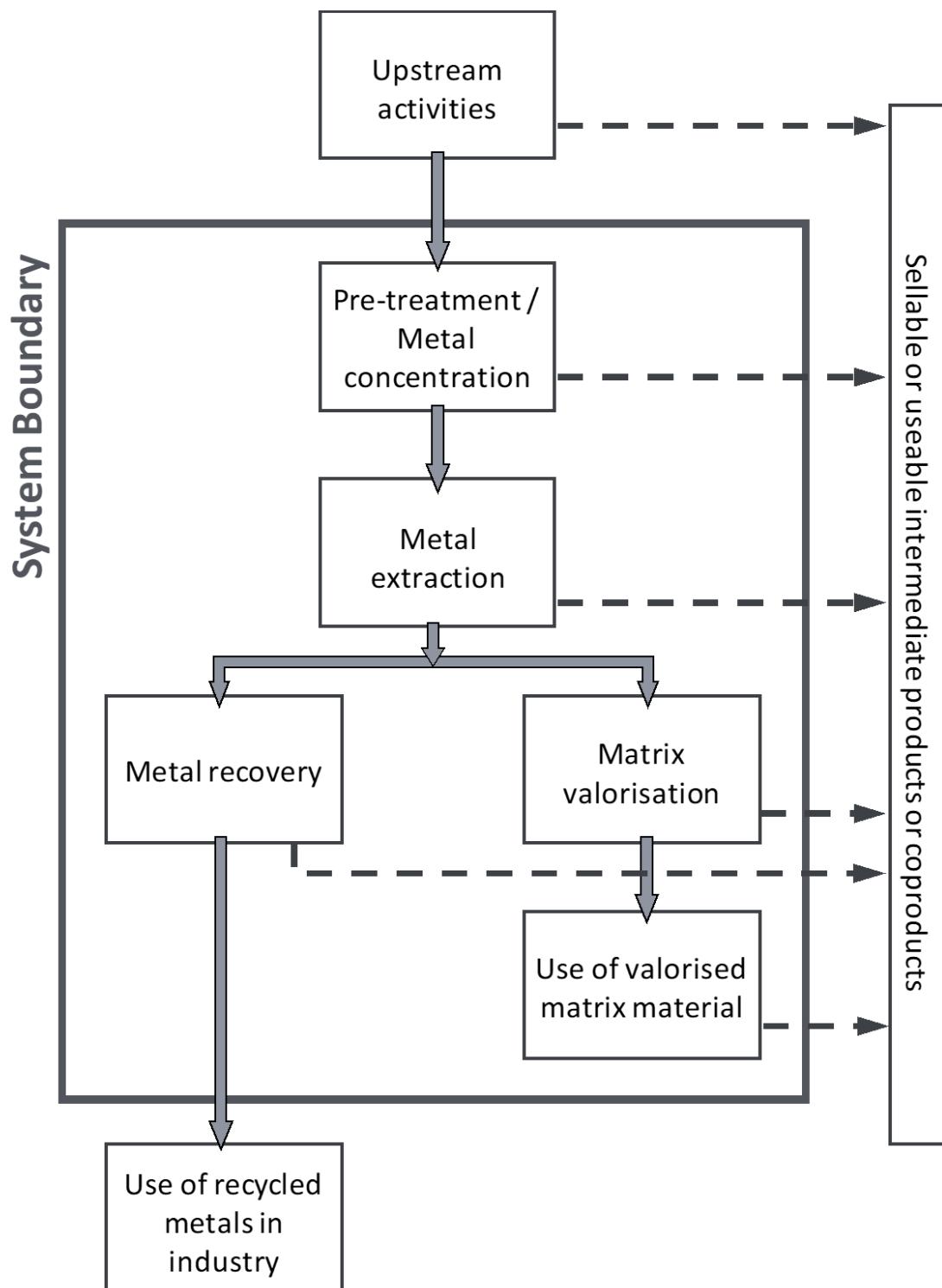
### **Function, functional unit and reference flow(s)**

The function of the product system is defined by the service provided by the system, in this case the recovery of valuable metals and the valorisation of the matrix material of low grade secondary or primary input materials. The functional unit can be described as follows: *"the treatment of 1 tonne raw input material for the recovery of valuable metals (e.g. Cr, Ni, Zn & Co) and matrix products at a scale of 200,000 tonne raw material per year"*. As reference scenarios, a Do Nothing scenario (no mining) and landfilling will be used for, respectively, the primary laterite deposits, and, the fayalitic slags, iron-rich sludges and fine-grained polymetallic sludges.

### **Life cycle inventory**

Process data of the individual unit operations were collected from the technology developers. As the technologies are not yet mature, only limited lab-scale data are available for the first iterations of the LCA-RA-TEA study. Therefore, it is chosen to model these unit operations to an industrial scale for the treatment of 200,000 tonne incoming raw material per year using the HSC Chemistry software.<sup>7</sup> For background processes, data are used that are applicable to the EU-28 and as primary database the ELCD (European Life Cycle Database) dataset is used. To tackle more specific

background processes the commercial Ecoinvent database v3.3 is used or relevant literature is consulted.



**Figure 2:** The system boundaries of LCA-RA-LCC for the different metallurgical systems

## **Impact assessment**

**Life Cycle Impact Assessment.** The ILCD2011 (International Reference Life Cycle Data System)<sup>8</sup> methodology, as recommended by the European Commission is used to perform the life cycle impact assessment. This is also in accordance with the recent EU Product Environmental Footprint (PEF) Guidelines.<sup>9</sup> In the first iterations, the 15 impact categories, as described in the ILCD methodology, are taking into consideration. Afterwards, more focus is given to those impact categories that are most relevant for the unit operations and for the overall metallurgical flow sheets.

**Risk Assessment.** Within the framework of METGROW+, the risk assessment is mainly focused on the potential risks for workers and the environment due to emissions during newly developed technologies or due to exposure during use of new products derived from valorisation of the residues. Hazard threshold concentrations for human health (Derived No Effect Levels, DNEL or Derived Minimal Effect Levels, DMEL) or the environment (Predicted No Effect Concentration, PNEC) are based on an integration of all available and relevant hazard data for a substance and derived following the ECHA Guidance documents.<sup>4,5</sup> Comparison of the predicted exposure concentrations, using MEASE and spERCs, with the hazard threshold concentrations for human health and the environment will indicate the potential need for additional risk management measures to prevent or decrease emissions and exposure.

**Techno-Economic Impact Assessment.** For each of the unit operations a techno-economic model is constructed in Excel where the economic outcomes (CAPEX and OPEX) for each year are related to the process and flowsheet model of each unit operation. Based on this, the projected cash flows for the evaluation period (typically 20 years) can be calculated.

**Multi-criteria analysis.** For the LCA-RA-TEA to support the decision making, integration off all relevant decision aspects is needed. Therefore, a multi-criteria analysis (MCA) is performed on the different assessment results to select the best metallurgical system for a specific raw material stream. Different stakeholders will be consulted to align with their needs and with local conditions.

## **Outlook**

Analysis of the results from the first iteration are on-going. Due to the very early stage of the technology development, only very limited data is at hand. In contrast, the data demand for the modelling is rather intense as data on technical and chemical aspects of the technologies are required. Therefore, at this stage no complete assessment for all the individual unit operations can be performed. Nevertheless, during preliminary screening of some unit operations, main drivers for both economic

and environmental parameters could be identified. Further fine-tuning with the technology developers will be needed to model realistic industrial scale unit operations. Therefore, only in a later stage of the project, assessments will be performed on complete material flow systems, which can be compared to the reference flows.

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# **TECHNICAL AND ECONOMIC FACTORS AFFECTING ELFM IN FINLAND**

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## **Abstract**

The current paper presents the result of a master thesis performed in the framework of cooperation between Aalto University and a Finnish energy company. The aim of the study was to provide general information on ELFM, to study the factors affecting ELFM and to investigate its economic potential. Different categories of ELFM projects were studied as well as example cases. The results of this work can provide companies guidelines with respect to potential ELFM projects and their cost estimation.

## **Introduction**

In Finland, the different factors determining the possibility of performing ELFM have not been researched in detail. Research has focused on sampling and characterisation of products of mechanical separation.<sup>1,2,3</sup> Large-scale ELFM projects are still rare in the world, and their potential should be investigated further. Since 2008, Waste-to-Energy (WtE) is being used more commonly to treat municipal solid waste (MSW) in Finland.<sup>4</sup> The trend of declining rates of MSW production have been recognised<sup>5</sup> and there have been different plans for preparing for this decline. Uusimaa region in the southern part of Finland is the most densely populated region of the country and has the largest WtE capacity. In Uusimaa, there are 160 landfills altogether (excluding Helsinki).<sup>6</sup> In 1997, the Finnish Council of State acquired better post-closure information on landfills to reduce impacts on environment and health. Landfills that have been closed since are compelled to take charge of the necessary aftercare.<sup>7</sup> Older landfills, that were open when older legislation was in effect, are typically covered with a thin layer of soil; their closing was not done adequately with respect to the present requirements.<sup>1</sup> Many of the landfills in Uusimaa have not been closed according to current legislation because they were closed before 1997. There is probably a need for treating these landfills in the future and ELFM could be performed simultaneously to this process. In addition to valorisation of material streams from ELFM, for example, the effects of landfills to surface and ground waters could be diminished.<sup>7</sup> Few case studies in Finland indicate good fuel potential in the landfills, as long as the efficiency of the technology is adequate.<sup>2</sup> However, the economic potential has not been studied.

## **Research questions**

The aim of the current study is to summarise technical and economic factors of ELFM for a Finnish urban energy company, and also to provide technical solutions and cost estimations. The Master's thesis on which this paper is based, determines the factors affecting ELFM and its cost-effectiveness. It is important to understand which factors have an impact and how they are determined or calculated. All the phases from determining the composition of the landfill, ranging from sampling, to excavation, separation, transportation and disposal, need to be covered. Together these phases could help forming an overall picture of ELFM, which in turn could improve the determination of the economic potential. Once the different parameters are established, they can be applied to analyse the situation of the chosen landfill. The last phase is to estimate the costs for acquiring material streams from the landfill. The idea of the thesis is to create a general pathway, which could be used in planning future ELFM projects.

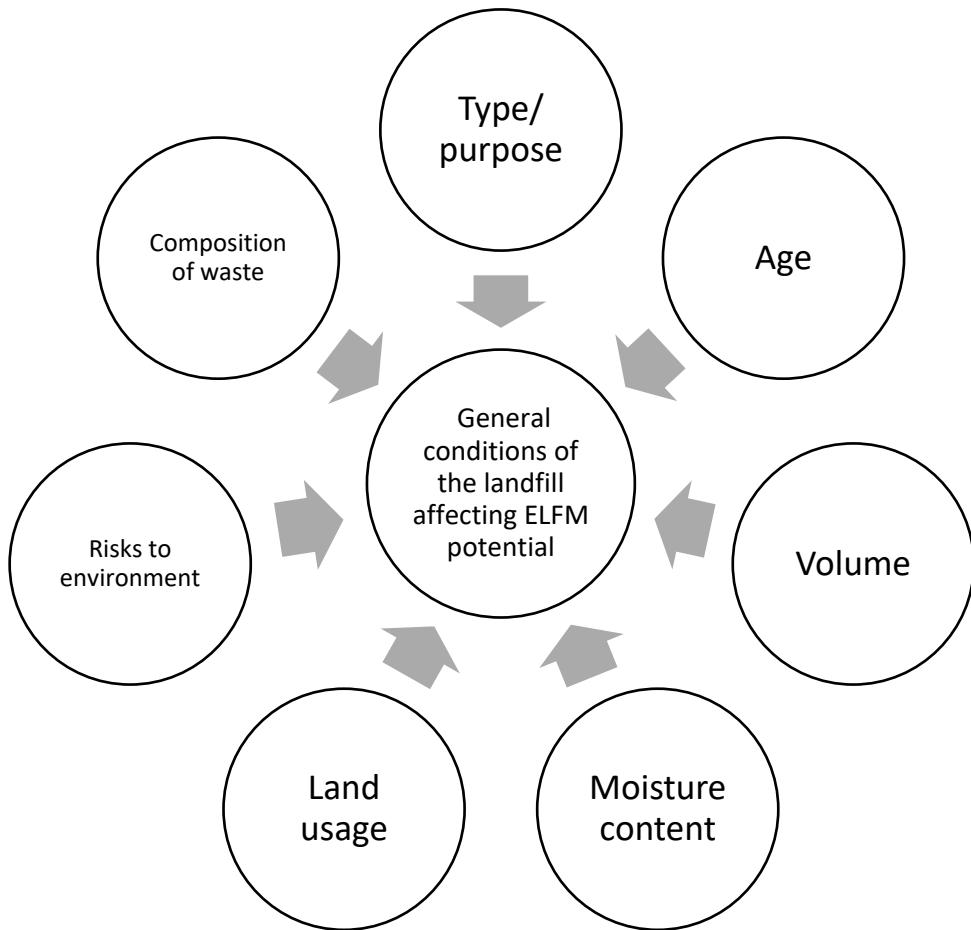
## **Factors affecting the possibility of performing ELFM and the economic potential of ELFM**

It is useful to define the different factors affecting the possibility of performing ELFM as well as the economic potential of ELFM, since the amount of ELFM projects studied and executed globally is still low and more information is needed.<sup>8</sup> Most of the articles written on ELFM concentrate on conceptual discussions on landfill mining and on pilot-scale studies. On the contrary, larger case studies are quite rare. The attention of the researchers has been on local risks related to the excavation of landfills, and also on technology for excavation, processing and upcycling of materials.<sup>8</sup> Resource recovery is still not the focus of research.<sup>9</sup> The beneficial aspect of ELFM relies on the assumption that a significant share of the excavated waste can be separated and recovered. However, the economics of ELFM have received relatively little attention.<sup>8,10</sup> Therefore, the thesis tries to explain how the costs in ELFM are structured and on which factors they depend.

From these factors, their uncertainties, and their combined profitability, it is possible to begin evaluating landfill mining. In this study ELFM is divided into different phases: determination of the composition of the landfill, determining the economic potential and active implementation of ELFM. Predicting e.g. prices of electricity, land prices and greenhouse gas emission reductions are beyond the scope this study.

Compositional determination of landfills is divided into sampling procedures and estimating the benefits of performing a pilot study. The active ELFM process itself has several sub-processes: excavation, separation, transportation, storing and disposal. The different aspects determined from these processes can then be used to define

capital and operational costs of ELFM. The composition of the landfill, for example, depends on the characteristics of the different fractions, *e.g.* combustibles, fine fraction (FF), metals, *etc.*<sup>11</sup> Figure 1 illustrates the general aspects of landfills that have an impact on their ELFM potential.



**Figure 1:** General conditions of a landfill affecting ELFM potential

## ELFM scenario based on data from a case-study

This study is done based on the requirements of urban energy companies in Finland that have WtE capacity. The scenario focuses on an active ELFM process and its economic potential. The thesis tries to illustrate the phases of planning of the project's costs through estimations based on exemplary sampling data. Therefore, if a company would start sampling in a potential landfill in the future, it would be possible to follow the study to determine an approximate cost structure.

### Fuel competence

Much research concerning ELFM has emphasised the importance of proper analysis of the landfill composition. Especially for older landfills, the documentation of the

landfill composition and the waste location is not sufficient.<sup>11</sup> In addition to proper analysis of the landfill composition, the treatability of waste fractions must be studied.<sup>2</sup> Sampling was performed in four different landfills in Finland.<sup>1,2</sup>

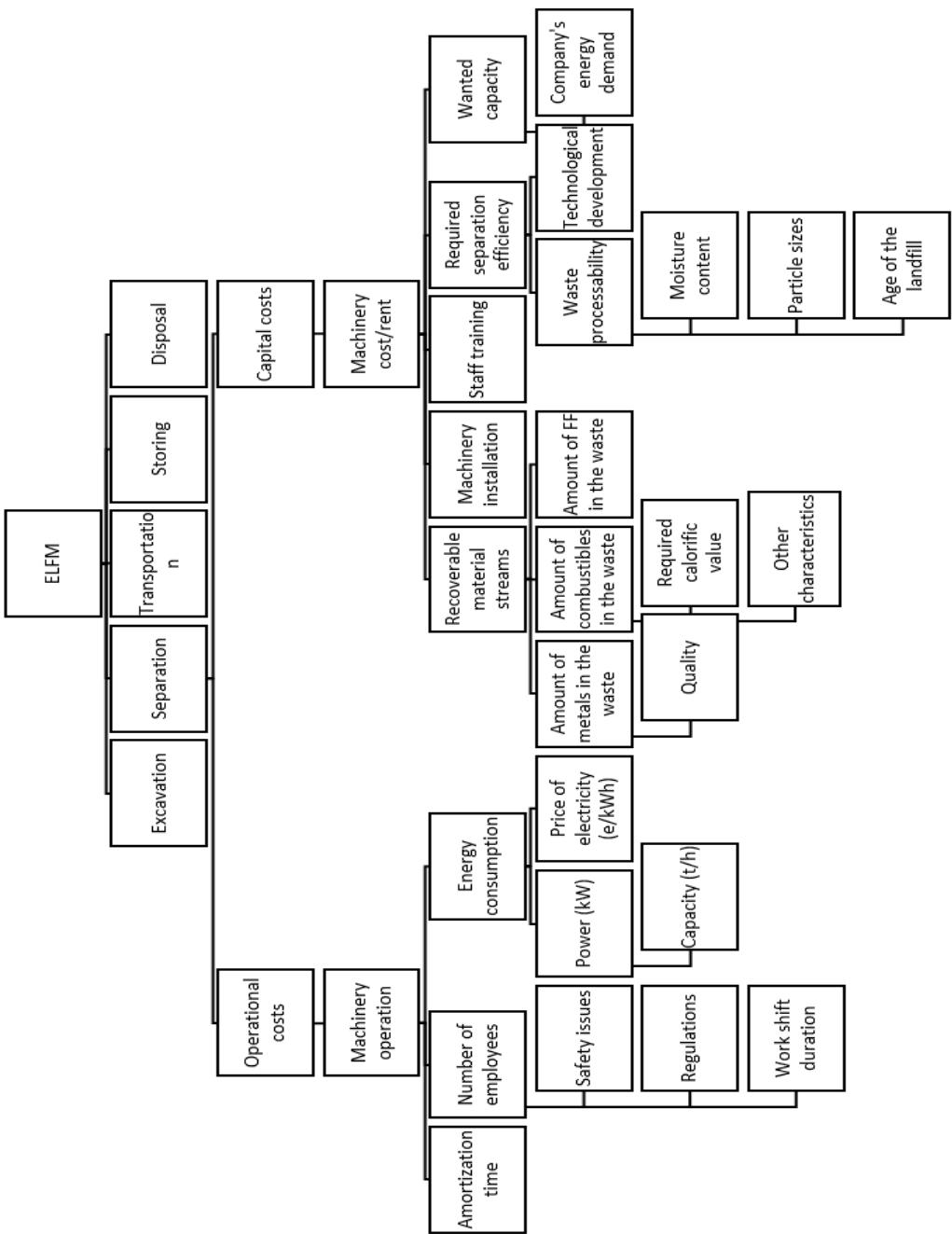
In order to evaluate the economic potential of ELFM, some estimations and scenarios are created for this thesis. The characteristics of the combustible fraction are important from the point of view of an energy company. The best-case scenario defined is a calorific value of the combustible fraction equivalent to 20 MJ/kg, as achieved through mechanical separation in a study in Finland.<sup>2</sup> The worst-case scenario is based on the assumption that mechanical separation is performed less efficiently or the quality of combustibles is lower. In this case the minimum calorific value would be 10 MJ/kg. With the efficiency of the WtE plant taken into consideration, the corresponding fuel amounts can be determined for the desired energy production level. Hence, the technical separation solutions can be designed based on the waste composition. Economic potential can then be evaluated for the best and worst case scenarios.

## Economic potential

Economic potential is based on the different aspects of each phase of ELFM. It does not take the benefits, such as the price of produced energy, reuse of metals, or greenhouse gas effects into consideration. In this study, economic potential is derived for acquiring the fuel, *i.e.* for the active ELFM performed by an energy company and the related costs of it, *e.g.* disposal of the fine fraction.

In the study, the active ELFM process has been divided into five different categories: excavation, separation, transportation, storing and disposal. The categories then divide into capital and operational costs.<sup>10</sup> Figure 2 shows an example of the different costs related to separation and which factors have an effect on them. Similar models can be created for each of the categories and costs can be determined by altering the factors and characteristics. Based on similar cost structure chains, it is possible to determine an approximation of total costs of ELFM. Subsequently, estimations of economic potential for active ELFM could be suggested.

The future of ELFM and many of its aspects are still unclear. Legislation is only now starting to acknowledge ELFM and there is a lot of discussion *e.g.* about disposal of the fine fraction, *i.e.* how it is classified, will there be a new disposal tax, could there be more valorisation potential for it? In the future, there might even be subsidy programmes, based on the societal benefits that ELFM have to offer.<sup>12</sup>



**Figure 2:** ELFM cost structure, separation efficiency as an example

## Conclusions

Enhanced landfill mining projects are rare in the world. Simultaneously, there are many landfills in Finland that require renewing and MSW production is decreasing, which affects the existing WtE-capacity. If an ELF M process can be evaluated and its subprojects can be recognised, the different factors determining the feasibility of ELF M can be derived. ELF M's economic potential can be derived theoretically through application of different scenarios, e.g. based on worst-case and best-case scenarios. The possible use of ELF M derived materials for WtE can be evaluated and the economic potential examined, as in this paper, where the benefits for energy companies using WtE are considered. Many aspects remain unclear, however. The study of an operational ELF M process could help in assessing its economic potential. In the future, the results could be used as a guideline to follow in potential ELF M projects.

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