Landfill Mining: An empirical review on past and state-of-the-art applications

Zoi Gaitanarou[1,2], Georgios Tentes[1], and Yannis Katselis[1]

[1] ENVECO S.A., 1, Perikleous str., Marousi, 15122, Greece, www.enveco.gr

[2] Corresponding author. Contact e-mail addresses: zgaitanarou@enveco.gr; life@reclaim.gr

Abstract: Landfill Mining (LFM) is a solid waste management method which combines landfill engineering and mining techniques and can be generally described as "a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground". LFM was first used in 1953 in Israel to produce soil for agricultural use and it has become more popular since the late 1980's, when newer landfill regulations were applied. In the present research we utilised literature resources, interviews with experts on the field and site visits to LFM sites. We examined different models of LFM applications which have been applied in various EU countries, and analysed them according to their specific objectives: LFM as a tool of environmental policy, LFM as waste valorization opportunity (including the concept of 'temporary storage') and LFM as a future possibility. An assessment of the current state-of play in Europe showed that there is a lot of applied research needed in order to produce alternative technological and financial models that could potentially support large-scale LFM. To this end, the Life+ reclaim project wishes to actively contribute.

Key words: landfill mining, recycle, waste valorization, metals, waste-to-materials; waste-to-energy

Introduction

Organised and controlled solid waste management is important for modern communities. The Waste Directive was firstly introduced by Council of the European Communities in 1975 and has been amended by two later Directives, one decision and one regulation (1991 and 2003) and all corrections and amendments have been re-codified and included in the Directive of 2006, on Waste. Finally, the Waste Directive was reviewed, revised and re-released in 2008, as the Waste Framework Directive (WFD) 2008/98/EC. The main declaration of EC through this latest Directive is the following:

> *"The first objective of any waste policy should be to minimise the negative effects of the generation and management of waste on human health and the environment. Waste policy should also aim at reducing the use of resources, and favour the practical application of the waste hierarchy."*

The recent WFD 2008/98/EC established the waste hierarchy, as illustrated in Figure 1. Disposal (i.e. landfilling and incineration) of waste is at the bottom of the hierarchy pyramid and should be used as the very last option. However, even though following the WFD is probably the best environmental option, the Member States are free to decide on their individual waste management strategies as *"in some cases refining decisions within the hierarchy or departing from it can lead to better environmental outcomes"* (EC & JRC, 2013).

INSERT FIGURE 1 HERE

Landfills represent the oldest and most common form of waste disposal, especially for MSW (Ghosh & Hasan, 2010). Currently, it is estimated that the total number of landfills and old dumps in Europe (operational and closed) is around 150.000-500.000 (Hogland *et al.* 2010). Many of them are considered to be hazardous for the environment and many member states have special public services dedicated to organise and supervise the remediation actions needed. The Council Directive 99/31/EC is focusing on the landfilling (LF) of waste. The main aim of this Directive is the minimisation of the environmental impacts on surface water, groundwater, soil, air, climate and human health caused by LF (EC, 2011), and especially the negative effects on the environment from the uncontrolled or arbitrary disposal of waste in uncontrolled landfills (ULF or dump-sites). The Directive also gives specific guidelines and technical requirements for waste and LF, combined with the Decision 2003/33/EC on the acceptance of waste in landfills.

Landfill reclamation or Landfill Mining (LFM) is a less known solid waste management method. As its name suggests, LFM can be defined as "*the excavation and treatment of waste from an active or inactive landfill for one or more of the following purposes: conservation of landfill space, reduction in landfill area, elimination of a potential contamination source, mitigation of an existing contamination source,*

energy recovery from excavated waste, reuse of recovered materials, reduction in waste management system costs and site re-development" (Cossu et al., 1996). More recent researchers define it as "a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground" (Krook et al. 2012). Even though it is less-known than other solid waste management methods, LFM was firstly used in the 50's in Israel (Savage *et al.*, 1993; Vander Zee et al. 2004). It appears again in the mid-1980's, mainly in the US, where many pilot studies as well as full-scale LFM projects took place such as the Edinburg and Hague landfills projects in New York, US (Spencer, 1990; Spencer, 1991; Nelson, 1994; Nelson, 1995; US EPA, 1997; Kurianet al., 2004). In view of the popularity that the method gained, the US EPA (1997) even published a presentation and guidelines on "*Landfill Reclamation*" to promote the method to interested contractors. The present paper follows a series of recent papers that aim to explore the potential of LFM in Europe, under the light of the European legislation.

Materials and methods:

An extensive research was conducted to gain a deep understanding all the aspects of the LFM method and define the methodology that should be used for the LIFE+ reclaim project. The work had been organised in detail during the proposal stage and was carried out by employing communicational and research tools. These can be divided into two major categories: literature review and expert interviews. The literature review is a strong tool which was used during the vast research on the LFM method. It was an essential part of the process at it provided the project with all the necessary information which was used to define LFM and create its profile: The history of LFM since its birth, its main positive and negative aspects, the technology used and how this has changed through the years. Other subjects explored during this stage included the materials present in the landfill and the potential end-products, the hazards that might arise, the financial issues faced by the contractor, the environmental and the social issues that could be created.

Used literature sources included peer reviewed papers published in waste management magazines such as *BioCycle* and *Waste Management*, proceedings from conferences such as the *Global Landfill Mining Conference and Exhibition* and *International Academic Symposium on Enhanced Landfill Mining* and *International Waste Management and Landfill Symposium*, as well as various other reports and studies, PhD and MSc theses. Most recent publications also include reports from private organizations which explore the potential of landfill mining in various areas of the world, e.g. India (Kurian et al. 2003), Scotland (Ford et al. 2013) in parallel, many publications are related to general scoping of LFM, like the recent Key Issue Paper of Fisher (2013).

Regarding expert interviews, the research team followed a selective approach, aiming at applying this data collection method to gather a wealth of information from specialised scientists involved in the relevant industry (Dorussen et al. 2005). Firstly, a group of European territories were selected, i.e. Belgium and the Netherlands, owing to their relevance to the avant-garde of LFM, as well as UK and Spain, owing to the limited, if any, real applications of the LFM concept. Secondly, a targeted mailing campaign was held to identify willingness-to-participate of representatives of various public and private bodies. Among those who answered positively, the most likely to have a global overview of the state-of-play were selected. Thirdly, personal and group interviews were conducted. Although a structured questionnaire was available to the interviewers, it was used only to guide the conversations and not to restrict them to specific issues. All interviews were conducted in each representative's headquarters and detailed minutes of the interview have been kept. The material was replenished with other documents, including presentations, statistics, figures and images.

In order to assess the state-of-play of LFM in the EU, a codification approach was adopted. The codification provides the advantage that it is an analytical way of describing practices and concepts, useful to the assessment, enabling a final synthetic approach. The necessary methodological steps included:

i. General description of concepts applied throughout the EU, based on published research and policy papers

ii. Specific descriptions of the assumptions that underlay each of the concepts;

iii. Assessment of the advantages and disadvantages of each concept;

iv. Overview of the current status in relation to applications and success stories in the literature.

Finally, the collected material guided the assessment and, combined with the literature review, lead to the deduction of the following results.

Results and discussion

Landfills and landfill mining

In Europe, LFM was introduced much later than in the USA and, therefore, it is less widespread. Many pilot applications have been reported in the literature, but as the environmental legislation tends to be stricter, full scale projects are fewer, located mainly in Germany (Hogland 2002), the Netherlands (Van der Zee et al. 2004), Finland (Kaartinen et al. 2013). In addition, projects reported in the United Kingdom (Hayward-Higham 2008) did not prosper and, although designed, were finally abandoned. Currently, the LFM has regained popularity in Flanders, Belgium, where research and pilot studies have led to a series of publications (Van Passel et al. 2010; Van Vossen & Prent 2011; Wille et al. 2013), and an initiative named the EURELCO consortium has been built around these concepts to include companies, agencies, organisations and academics interested in LFM. Similarly, several studies and LFM projects have carried out in the rest of the world, mainly in Asia. Most of them are located in India (Kurian et al. 2003; Hogland et al. 2005) and China (Zhao et al. 2007; Lou et al. 2009), as their vast population has created issues related to landfilling.

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Primary typology of landfill mining

The first category includes LFM applications that are been used as complementary tools for environmental policy. The approach is related to the concept of Sustainable Materials Management and represents a broader shift to a circular economy. From this viewpoint, landfills are considered as a part of the materials cycle, and not as a final destination for waste. Therefore, the valorisation of the disposed waste constitutes a major aspect in the environmental impact assessment of landfills. It is based on the three-step approach of Mapping-Surveying-Mining (Wille et al. 2013). The main characteristic of this approach is that it is never applied alone but as a secondary activity in a broader rehabilitation – restoration plan for brownfields and depleted areas or redevelopment schemes, and this peculiarity differentiates this category from the other two. Thus, LFM is used as a means of obtaining economic benefits from actions that involve costs but pose positive social externalities. The basic assumptions involved are:

i. Existence of brownfields or ULFs which have secured funds for rehabilitation (through public spending or environmental liability obligations);
ii. Efficient technologies for separating and manipulating the extracted materials (usually, partly MSW and partly industrial waste;
iii. Social pressure for rehabilitation (especially in urban areas) and social acceptance of the work that needs to be done;

In rehabilitation projects, costs are usually related (or reduced) to per unit volume cost. If rehabilitation is combined with an LFM application, benefits from LFM are seeing as negative costs. This model requires

that only profitable materials will be exploited, to avoid expensive solutions. Focusing on the advantages and disadvantages of the approach, the attractive aspects are the following:

i. Potential for recovery of energy (waste to energy concept - WtE) and materials; (waste to energy concept - WtE)
ii. Efficient land reclamation;
iii. Soil decontamination and proper removal of extraction waste;
iv. Parallel benefits related to rehabilitation (e.g. nuisance combating through efficient rehabilitation)

On the other hand, the disadvantageous aspects are:

i. There is no business model therefore there is no incentive for adopting LFM, apart from a marginal financial benefit from the commercial value of the extracted waste (Geysen 2013). If quantities are not large enough, exploitation of waste may prove costly instead of beneficial and incur indirect or hidden costs (e.g. high machinery rents).
ii. The results are still premature, therefore practicality of approach is not sufficiently proven
iii. Application requires a priori investigation, usually through geophysical methodologies. These methodologies supposedly reduce surveying costs, but no margins have been established yet for the cost-efficient application. (Van Dyck & Wille 1998).
iv. More suitable for the public sector than for the private sector, owing to the pre-mentioned economic approach.

Currently the view of LFM projects as tools for environmental policy is practiced only by public waste management authorities in Belgium (mainly Flanders), while other projects are being sought for in Sweden and Denmark.

The second category is generally known as the mined waste valorization model, which supports the concept of ‘temporary storage’, which has been recently defined as “environmentally and structurally safe storage places that already permit present in-situ recovery of materials and energy from waste streams and allow easy future access to resources whenever needed” (Hoekstra and Groot 2013). In temporary storage, delivery and excavation in bulk is the easiest and cheapest method. Storage can be performed relatively dry, so there is no need for storage in bales. In landfill operations, compactors are used. In general, the waste valorization model requires the existence of old (20 years at least) to very old (older 20 years at least) landfills with mixed municipal waste. Benchmark age depends on each country’s milestones in EU directives application. Another requirement is the existence of large operative landfills that can provide materials for a time long enough to outweigh the initial preparation stage. An important prerequisite is the existence of suitable and sufficient markets for the produced materials. Alternatively, strict landfill policies (e.g. in the form of landfill moratoriums, as in the case of Catalonia) may provide sufficient incentive for LFM applications to be used for increasing the available space in existing landfills.

On the one hand, among the main advantages of this approach are:

i. Direct land reclamation and development opportunities on the new land;

ii. Sustainable landfilling into the temporary storage facilities;

iii. In situ and ex situ mining potential (Spooren et al. 2013);

iv. Sufficient resources for cover material (wherever needed);

v. Biogas enhancement and production

On the other hand, the disadvantages usually are:

i. Expensive set-up and operation;

ii. Need for large and old landfills which are usually situated next to large cities;

iii. Innovative technologies are usually experimental, so they entail a business risk for full scale applications;

iv. Hidden opportunity costs in developing new markets and new technologies. ;

v. Difficult to manage by the public sector, owing to many factors related to the complexity of the approach.

Currently, there are two main applications under consideration within the EU:

i. Remo landfill in Flanders, Belgium, ran by a private company;

ii. A sustainable landfill application in the Netherlands, under negotiation for adoption by the government

The current experiments pinpoint that the model is sub-optimal in EU, although it is better developed in the USA.

The third category, under the generic title: 'LFM as a future opportunity' is common among the researchers that are skeptical on LFM (Ford et al. 2013). Although it does not exclude mined waste from the waste management process, nevertheless, many researchers hold that the market (technology for valorization and sales market) is not ripe for such an approach, simply because.

i. there is no demand for recycled materials that can seriously support long-term LFM

ii. there is luck of technical advancements for full exploitation which makes the attempt futile

iii. there is evidence that storing waste may contribute to CO_2 sequestration.

Economics of landfill mining

The CAPEX and OPEX of landfill mining projects vary significantly from case to case (Ford et al. 2013) and depend heavily on:

i. Landfill size

ii. Waste composition

iii. Hazardous waste content

iv. Operational model (investment on installations or use of contractors)

v. Degree of waste treatment and valorization

According to various researchers, the work of which has been recently summarised by Ford et al (2013), The CAPEX, stemming mainly from LFM projects in the USA lays between 8 €/t and 25 €/, while the OPEX of each stage of waste separation (from excavation to magnet and drum separators) lays between 1.00 €/t and 14.00 €/t. Handpicking is the cheapest stage and air-knife separator for light materials (paper, wood) is the most expensive stage. Depending on the degree of separation, it is expected that the total cost cannot effectively be less than 35 €/t. In an older publication, Fisher & Findlay (1995) argue that although LFM might be a preferrable option when re-siting a landfill, the cost-effectiveness result may heavily depend on indirect factors, e.g. soil material quality and legislative requirements on quality control, which can significantly increase opex.

Furthermore, the development of technologies for recycling waste is an expensive goal, especially when referring to disposed waste. The recycled products markets are highly demanding, and potential investors are more interested in improving markets and then base their business model development on a mature market. The scale of operation (i.e. the size of the LF and the type of materials), researchers claim that will affect the business plan of a waste to resource transformation. Temporary Storage can help in providing the appropriate amounts coming from one or more producers. Certain best practices, such as baling may add significantly (e.g. 5€/t to 30€/t) to the total mining cost, making it less attractive for separating material streams, or setting it off the market. To conclude, the business model for this kind of an approach is heavily dependent on the market for recyclable materials and on the available valorization techniques, that will leave as little residues at possible (e.g. plasma gasification, glassification of assess and residues).

Conclusions

LFM applications are only indirectly related to the legal framework within the European acquis, and their dual nature (partly waste management, partly raw materials industry) connects them to the waste framework directive and the raw materials strategy of the EU. On the one hand, according to waste directive and hierarchy, landfilling should be restricted in the long-run; therefore, member-states should prioritise on waste prevention. On the other hand, raw materials strategy calls for resource efficiency and recycling; therefore available resources should be valorized and new advances should be made in terms of mechanical separation, organics neutralization or gasification and energy recovery. The common practice of landfilling, either of mixed or of pre-separated waste, which is still active in many countries like Spain, Greece, Cyprus and countries in accession, is far from being optimal under any of the pre-mentioned policies. In addition, existing legal framework seems to ignore already landfilled materials, therefore, throughout Europe, the avant-garde of landfill mining seeks ways of introducing old waste valorization into new waste management practices, within the existing framework or through extensions of the existing framework. This is particularly the case in the Netherlands and Belgium, where temporary storage has been proposed to enter the waste hierarchy scheme of Fig.1.

To conclude, LFM is still evolving, as technologies and processes are advancing, but lack of standardization has only led to case by case applications. Therefore, there is great need for organisation and preparation of action plans to solidify its technical and legal framework. This could positively affect solid waste management practices on national and EU-wide level and can be achieved more efficiently if the public sector embraces the concept, in close cooperation with EU-wide consortia like the EURELCO, within the EU legal umbrella.

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Fig. 1 The waste hierarchy according to the WFD 2008/98/EC [source: http://ec.europa.eu/environment/waste]

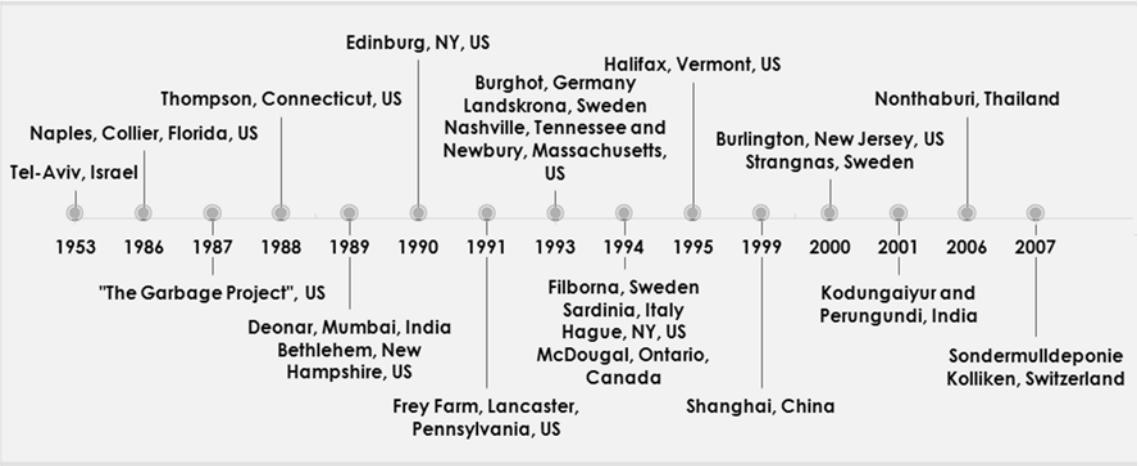

Fig. 2 The timeline of Landfill Mining: the evolution of the method through documented applications [Source: Life+ reclaim Project]

Fig. 3. World atlas of landfill mining projects [Source: Life+ reclaim Project]