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Review

Enhanced Landfill Mining in view of multiple resource recovery: a critical review

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ABSTRACT

In a circular economy material loops are closed by recycling of pre-consumer manufacturing scrap/residues, urban mining of End-of-Life products and landfill mining of historic (and future) urban waste streams. However, in the past landfill mining was not performed with a focus on resource recovery. This paper addresses this gap by introducing the concept of Enhanced Landfill Mining, defined as the safe conditioning, excavation and integrated valorization of landfilled waste streams as both materials and energy, using innovative transformation technologies and respecting the most stringent social and ecological criteria. The feasibility of ELFM is studied by synthesizing the research on the Closing the Circle project, the first ELFM project targeting the 18 million metric ton landfill in Houthalen-Helchteren in the East of Belgium. It is argued that Environmental Impact Assessments of ELFM projects should be wide in scope and time. Embedded in a broad resource management perspective, the worldwide potential of ELFM is highlighted, in terms of climate gains, materials and energy utilization, job creation and land reclamation. The potential is quantified for the EU-27 with its 150,000–500,000 landfills. However, for ELFM to reach its full potential, strategic policy decisions and tailored support systems, including combined incentives for material recycling, energy utilization and nature restoration, are required.

1. Introduction

As the world is facing unprecedented environmental challenges (Rockström et al., 2009) and resource shortages (European Commission, 2010), the transition towards resource efficient, low-carbon circular economies is a necessity. In its *Roadmap for a Resource Efficient Europe* the European Commission (2011) envisions that by 2020 waste is managed as a resource, recycling and re-use of waste have become economically attractive options, energy recovery is limited to non recyclable materials and landfilling – as we know it – is eliminated. As described by Jones et al. (2011), in a circular economy material loops need to be closed by direct recycling of pre-consumer manufacturing scrap/residues (e.g. steel slags), urban mining of post-consumer End-of-Life products (e.g. recovery rare earth metals from electronic waste), and landfill mining of historic (and future) urban waste streams (Fig. 1). In all three cases the need for energy and carbon intensive mining of primary materials can be reduced (Ayres, 1997).

The third approach transforms landfills from a major cost to society (contribution to global warming (Sormunen et al., 2008), groundwater pollution (Flyhammar, 1997), occupation of valuable land) into a resource recovery opportunity. Estimates indicate that throughout the EU there are between 150,000 and 500,000 historic and still active landfills (i.e. Hogland et al., 2011; Vossen, 2005), which can deliver a significant stream of secondary materials and energy. Nevertheless, integrated resource recovery from landfills is a topic which has received surprisingly little attention in the literature (Krook et al., 2012). This study therefore focuses on a landfill-for-resources strategy. After providing an overview of different landfill mining strategies this paper defines the *Enhanced* Landfill Mining (ELFM) approach. Subsequently, a synthesis is provided on

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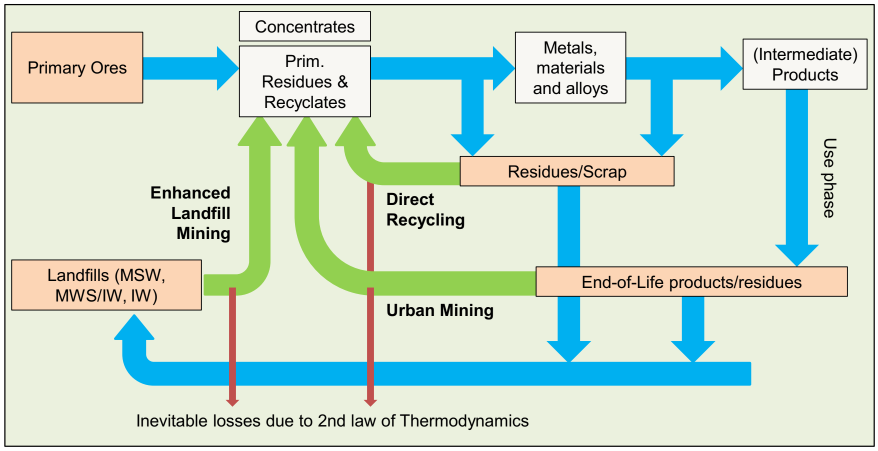

Fig. 1. Different ways to close materials loops in a circular economy: (1) direct recycling of preconsumer scrap and residues (e.g. slags), (2) urban mining of End-of-Life consumer goods and other products, (3) landfill mining of historically landfilled pre-consumer and post-consumer waste streams. Reproduced from Jones et al. (2011).

ELFM research that has been performed in 2009–2012 with respect to the Closing the Circle (CtC) project in Houthalen-Helchteren, being the first concrete ELFM study. Next, the non-technical barriers are described. Finally, a first estimate of the societal, environmental and economic impact of the full implementation of ELFM is provided, based on EU-27 data.

2. Overview of landfill mining concepts

Landfill mining was defined by Krook et al. (2012) 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*". Although the first project already occurred in 1953 (Savage et al., 1993), real interest only surfaced in the 1990s (Krook et al., 2012; Hogland et al., 2011; Jones, 2008). However, past landfill mining activities were in most cases limited to extraction of methane, partial recovery of valuable metals and/or land reclamation (Prechthai et al., 2008; Van der Zee et al., 2004), as corroborated by Krook et al. (2012): "*so far, landfill mining has primarily been seen as a way to solve traditional management issues related to landfills such as lack of landfill space and local pollution concerns. Although most initiatives have involved some recovery of deposited resources, mainly cover soil and in some cases waste fuel, recycling efforts have often been largely secondary. Typically, simple soil excavation and screening equipment have therefore been applied, often demonstrating moderate performance in obtaining marketable recyclables.*"

2.1. *In situ and ex situ landfill mining approaches*

Nevertheless, landfill mining strategies are being further developed. Broadly speaking these can be subdivided in two main categories. Firstly, *in situ* landfill mining refers to resource recovery activities (e.g. methane extraction and elimination of contaminants from soil and water), which occur on the landfill site without excavating the stored waste streams. Secondly, *ex situ* landfill mining involves resource recovery by partially or fully excavating the waste materials for further treatment. Currently, the present authors distinguish five different landfill mining/management concepts, which are described in Table 1: Enhanced Landfill Mining, enhanced biodegradation, sustainable landfill, natural cap/catch, temporary storage. The relevance of the different concepts depends on intrinsic parameters, like the size, location, age, type, composition and available documentation level of the targeted landfill, and extrinsic parameters such as availability of suitable technologies and societal and economic boundary conditions. For instance, landfills containing large fractions of industrial waste (including metals, slags etc.) tend to be more interesting for an *ex situ* approach while MSW landfills are better suited for the bioreactor concept. Mixed landfills can be simultaneously addressed by *in situ* and *ex situ* landfill mining. Other possibilities are that for a certain landfill part an *in situ* phase precedes an *ex situ* approach. Fig. 2 shows the various resource recovery options, with respect to secondary raw materials, energy, land, soil and water.

2.2. *Landfill mining flow sheet integrating ex situ and in situ mining*

In Fig. 3 the various steps in the landfill mining operation are depicted. Essential for business planning is detailed knowledge of the content. New and well-managed disposal sites have a log book containing the quantity and type of waste that is landfilled per cell. However, most landfills lack detailed registration. Hence, exploration of the content is required to identify the available resources and their suitability for recovery (Paap et al., 2011). Prior to resource recovery from landfills, conditioning of the material is necessary in order to enable cost-efficient mining and reduce risks related to landfill re-use. Conditioning encompasses both pretreatment for immediate mining, such as measures preventing dust and odour problems, and *in situ* transformation to a temporary storage, which includes innovative recovery, for instance by enhanced leaching of valuable materials and energy production as well as remediation in order to prevent future environmental threats. In most landfills, not only a number of critical compounds are present, but also specific situations (mechanical instability, high leachate level, areas with reduced permeability or too low moisture content etc.) have to be addressed (Ritzkowski et al., 2006). Though *in situ* treatment the landfill is effectively transformed into a temporary storage place (double arrow in Fig. 3). This concept needs to be developed in such a way that these resource sites are environmentally and structurally safe, already permitting present *in situ* recovery of energy, soil, groundwater, land and nature, and allowing future *ex situ* resource recovery.

If the landfill, or part of it, can be *ex situ* mined, then the next step is to develop tailored separation techniques for the excavated materials. Innovative separation flow sheets are required which will deliver (1) materials directly recoverable as new resources for the technosphere, and (2) materials to be further valorized after transformational technologies. The latter include the development of recipes to transform landfill residues (e.g. slags) into high added-value products (e.g. construction materials) and transformational