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Valorization of thermal treatment residues in Enhanced Landfill Mining: environmental and economic evaluation

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ABSTRACT

Enhanced Landfill Mining is an innovative concept which allows the recovery of land, re-introduction of materials to the material cycles and recovery of energy from a considerably large stock of resources held in landfills. Plasma gasification is a viable candidate for combined energy and material valorization in the framework of Enhanced landfill Mining. Besides energy production, plasma gasification also delivers an environmentally stable vitrified residue called plasmastone, which can be converted into building materials. This paper presents an environmental and economic evaluation of the valorization of thermal treatment residues (plasmastone) in the context of Enhanced Landfill Mining. The most common valorization route, that is, the treatment of plasmastone via production of aggregates, is compared with two other possible, higher added value applications, which are inorganic polymer production and blended cement production. The evaluation is based on life cycle assessment and life cycle costing. The study suggests that the environmental and economic performances of the valorization routes depend mainly on the quality and quantity of the final products produced from a certain amount of plasmastone. The materials with the greatest contribution to potential global warming and to the net present value of the valorization scenarios are the process input materials of sodium silicate, sodium hydroxide and cement. The study concludes that the plasmastone valorization via inorganic polymer production yields higher environmental benefits, while the blended cement production provides higher economic profits. Plasmastone valorization via aggregates production does not yield economic or environmental benefits. Given the trade-off between environmental and economic performances, we conclude that the decisions regarding the selection of appropriate valorization routes should be made cautiously to obtain optimal environmental benefits and economic profits.

1. Introduction

The concept of landfill mining has been practiced around the world for more than 50 years as a way to reintroduce buried resources into the material cycle and minimize the environmental burden of landfill emissions (Hogland, 2002). However, most landfill mining studies have focused on conservation of landfill space and remediation, since getting permission to develop new landfills is increasingly difficult (van der Zee et al., 2004; Krook et al., 2012; Frändegård et al., 2013). Moreover, traditional landfill mining is often limited to reclamation of land, methane and a limited number of metals such as copper or aluminum (van der Zee et al., 2004; Jones, 2008). In the context of rapidly growing competition for resources, increasing raw material prices and declining availability of natural resources, Enhanced Landfill Mining (ELFM) has emerged. Related to the new perspective of extracting valuable material and energy resources from landfills, ELFM emphasizes intentional storage of currently non-recyclable materials and energy resources that can be valorized in the future (Hogland et al., 2010; Jones et al., 2013). As Jones et al. (2013) explained, ELFM is defined as “the safe conditioning, excavation

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List of acronyms: ELFM, Enhanced Landfill Mining; GWP, Global warming potential; IRR, Internal rate of return; LCA, Life cycle assessment; LCC, Life cycle costing; NPV, Net present value; OPC, Ordinary Portland cement; RDF, Refuse derived fuel.

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and integrated valorization of (historic and/or future) landfilled waste streams as both materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE), using innovative transformation technologies and respecting the most stringent social and ecological criteria".

Jones et al. (2013) and Danthurebandara et al. (2015) described the major process steps of ELFM, including vegetation and topsoil removal, conditioning, excavation, separation, transformation of intermediate products, and land reclamation. As these authors explained, the separation process results in many waste fractions that can be sold directly. In addition, intermediate products (fractions that need further treatment in order to obtain higher market prices) also are sorted out in the separation process. Refuse derived fuel (RDF) is an important intermediate product that can be valorized in a thermal treatment with energy recovery (Quaghebeur et al., 2013). Although many existing thermal treatment technologies can be used in processing RDF, an objective of the novel ELFM concept is to find integrated technologies that aim for "zero waste" processes, incorporating recycling, recovery, and upgrade of (residue) materials, in addition to energy production (Spooren et al., 2013). Bosmans et al. (2013) recently analyzed and compared several thermal treatment technologies, including incineration, gasification, pyrolysis, plasma technologies, and their combinations, for their suitability in ELFM. They concluded that plasma gasification/vitrification is a viable candidate for combined energy and material valorization in the framework of ELFM.

Plasma gasification offers a number of advantages, such as high heat and reactant transfer rates, formation of cleaner and high energy synthesis gas containing mainly hydrogen and carbon monoxide, and the use of low-energy fuels such as household and industrial waste (Chapman et al., 2010; Ray et al., 2012; Bosmans et al., 2013). Taylor et al. (2013a, b) highlighted that the plasma gasification technology is able to efficiently produce a clean synthesis gas and an environmentally stable vitrified product (plasmastone) from historically landfilled materials. The synthesis gas can be used for production of electrical energy and/or heat or as second-generation liquid fuels. In addition, several valorization possibilities have been proposed for plasmastone (Iacobescu et al., 2013; Pontikes et al., 2013; Machiels et al., 2014).

The residues (bottom ash) produced in traditional thermal treatment processes like incineration are disposed of directly to landfills in many cases. This material needs to be pretreated if it is to be utilized as a secondary aggregate. In contrast, plasmastone has a great potential and can be designed for use in rather diverse applications, mainly in the construction materials industry (Jones et al., 2013; Spooren et al., 2013). Leaching tests have indicated that plasmastone may be safely used as an aggregate/gravel replacement (Chapman et al., 2011). Hence, the most evident valorization route is the use of plasmastone as an aggregate for road construction or building blocks. Nevertheless, ELFM targets higher value applications. Jones et al. (2013) highlighted that depending on the RDF chemistry and the cooling method applied, the following higher added value products can be developed from plasmastone: glass-ceramic monoliths for use as building materials or glass-ceramic aggregates for use in high-strength concrete; hydraulic binders, pozzolanic binders, or inorganic polymer precursors.

According to the International Energy Agency's (IEA) Greenhouse Gas R&D Program (Hendriks et al., 2000), ordinary Portland cement (OPC) production generates an average world carbon emission of 0.81 kg of CO_2 per kilogram of cement produced. On average, one tonne of concrete is produced each year for every human being in the world (Lippiatt and Ahmad, 2004). Production of alternatives for cement can mitigate this heavy CO_2 burden. So far, fly ash and other by-products of the energy and materials industry, currently disposed of as waste, have been used to produce these alternative products (Huntzinger and Eatmon, 2009; Turgut, 2012; Van den Heede and De Belie, 2012). Machiels et al. (2014) and Iacobescu et al. (2013) explained the possibility of developing binding materials from plasmastone to be used as low-carbon alternatives for OPC in construction applications.

Based on these premises, several valorization routes for plasmastone have been tested at KU Leuven, Belgium, in the framework of the first comprehensive ELFM project ("Closing the Circle" project by Group Machiels, Belgium). These valorization routes mainly include production of inorganic polymer and blended cement products out of plasmastone. To bring ELFM from the conceptual to the operational stage, knowledge about the critical factors of environmental and economic performance of the associated technologies is important. Nonetheless, because of the novelty of the ELFM concept, such evaluations for plasmastone valorization in ELFM have not yet been reported, although several other studies have evaluated the products based on waste materials and by-products. For example, Weil et al. (2009) conducted a detailed life cycle analysis of geopolymers produced both from resource-intensive materials like metakaolin and less resource-intensive materials like fly ash, and McLellan et al. (2011) examined the environmental and economic impacts of the life cycle of geopolymers produced from fly ash. In addition, several studies have discussed the environmental performance of blast furnace slag used in geopolymer production (Habert et al., 2011; Van den Heede and De Belie, 2012). Although these studies explain the possible environmental impacts of transformation of waste materials into alternatives to OPC, a more detailed evaluation is required for plasmastone valorization to identify its usability in ELFM.

This paper addresses the current lack of environmental and economic evaluation for valorization of thermal treatment residues in ELFM. The study comprises life cycle assessment (LCA) and life cycle costing (LCC). The most common valorization route, aggregate production, was compared with two other higher added value applications, inorganic polymer production and blended cement production. This paper identifies and discusses the environmental and economic drivers of plasmastone valorization, analyzes the relative advantages and disadvantages of different scenarios, and suggests possible improvements in design and operating parameters. In addition, a trade-off analysis indicates the most beneficial valorization options to be used in ELFM.

2. Materials and methods

This section describes the studied plasmastone valorization routes and the LCA and LCC methodologies.

2.1. The system studied

The excavated landfill waste is subjected to a series of separation processes to sort different waste fractions. As shown in Fig. 1, the RDF fraction obtained by the separation process is directed to a thermal treatment process. In this study, plasma gasification was the thermal treatment technology considered (Chapman et al., 2010; Bosmans et al., 2013; Taylor et al., 2013a, b). The main products identified were synthesis gas and plasmastone. Synthesis gas can be used mainly for energy production (electrical energy and/or heat), although other valorization options include production of liquid fuels. Plasmastone, which is recovered from the plasma convertor, is fully vitrified, mechanically strong, environmentally stable, and inert. ELFM focuses broader attention on the valorization of all types of landfill wastes, even wastes and by-products generated during processing of landfill waste. Therefore, the obtained plasmastone is subjected to additional various treatments in order to obtain valuable products. Although the entire