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Environmental and economic performance of plasma gasification in Enhanced Landfill Mining

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ABSTRACT

This paper describes an environmental and economic assessment of plasma gasification, one of the viable candidates for the valorisation of refuse derived fuel from Enhanced Landfill Mining. The study is based on life cycle assessment and life cycle costing. Plasma gasification is benchmarked against conventional incineration, and the study indicates that the process could have significant impact on climate change, human toxicity, particulate matter formation, metal depletion and fossil depletion. Flue gas emission, oxygen usage and disposal of residues (plasmastone) are the major environmental burdens, while electricity production and metal recovery represent the major benefits. Reductions in burdens and improvements in benefits are found when the plasmastone is valorised in building materials instead of landfilling. The study indicates that the overall environmental performance of plasma gasification is better than incineration. The study confirms a trade-off between the environmental and economic performance of the discussed scenarios. Net electrical efficiency and investment cost of the plasma gasification process and the selling price of the products are the major economic drivers.

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1. Introduction

During the past 50 years, major paradigm shifts have occurred in waste management in Europe as well as in the rest of the world, both for municipal solid waste (MSW) and industrial waste (Jones et al., 2010). The first shift was the phasing out of uncontrolled landfills due to introducing a number of regulations. Then controlled landfilling has been further developed with an extra care of top and bottom layers and of collection and treatment of landfill gas and leachate. In order to minimise various environmental problems such as global warming, acidification, depletion of the quality of ecosystem and pollution of surface and groundwater mainly due to the long term methane emissions and leachate production (EEA, 2000; Crowley et al., 2003; Mor et al., 2006; Emery et al., 2007; Sormunen et al., 2008; Akinjare et al., 2011; Damgaard et al., 2011) and to reduce the enormous land space required by landfills and the amount of materials to be landfilled, the use of incinerators has been introduced. Nevertheless, in an energy limited world, incineration without energy recovery is an unacceptable practice. Following the EU Waste Hierarchy, as put forward by the Waste Framework Directive (2008/98/EC), waste management has then evolved to a stronger focus on waste prevention, material recovery and recycling. Within this context, an innovative concept called Enhanced Waste Management (EWM) has been introduced in which prevention, reuse and recycling become more important and landfilling as “a final solution” is discarded. More details on EWM can be found in Jones et al. (2010). In this approach landfills become future mines for materials, which could not be recycled with existing technologies or show a clear potential to be recycled in a more effective way in the near future. While reusing and recycling become the first pillar of EWM, the concept of Enhanced Landfill Mining (ELFM) grows into its second pillar. ELFM includes the combined valorisation of the historic waste streams present in the landfills as both materials and energy or in other words Waste-to-Materials (WtM) and Waste-to-Energy (WtE). ELFM approach is clearly distinct from traditional landfill mining where the mining is often limited to reclamation of land, methane and a limited number of valuable metals such as copper or aluminium (van der Zee et al., 2004; Jones, 2008; Prechthai et al., 2008). Jones et al. (2013) explain that in the novel ELFM vision, however, the goal is not to stabilise the materials but to

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fully valorise the various waste streams either as materials or as energy with respect to the environmental sustainability and economic feasibility.

Traditional landfill mining comprises excavation, processing, treatment and/or recycling of deposited materials (Frändegård et al., 2013). Novel ELFM also consists of the same activities but broader attention is given to the valorisation of all types of waste streams such as wastes present in the landfill and even the wastes generated during processing of the landfilled waste. Jones et al. (2013) and Danthurebandara et al. (2015a) explain the major process steps of ELFM including vegetation and top soil removal, conditioning, excavation, separation, transformation of intermediate products and land reclamation. As explained by the authors, the separation process results in many waste fractions such as metals, glass and aggregates which can be sold directly. In addition, intermediate products (fractions that need further treatment steps in order to obtain higher market prices) are also sorted out in the separation process. Refuse Derived Fuel (RDF) is an important intermediate product, which can be valorised in a thermal treatment with energy recovery. Although many existing thermal treatment technologies can be used in processing RDF, it is an objective of the novel ELFM concept to find integrated technologies aiming at "zero waste" processes incorporating recycling, recovery and upgrade of (residue) materials, besides energy production (Spooren et al., 2013).

MSW incinerators offer a large potential source of heat and electricity, especially when combined heat and power (CHP) is applied (Limerick, 2005; BREF, 2006; BREF, 2010). Solid waste incinerators can obtain a significant waste reduction of about 90% (Cheeseman et al., 2003), but because of the risk of leaching heavy metals, a substantial volume of residues must be disposed of mostly in landfills and cannot be recover as material. These facts prove that incinerators have considerable WtE potential, but not a promising WtM potential.

Pyrolysis produces a combustible gas that can be used in steam turbines, gas turbines, gas engines and even in fuel cells, but is feasible only for specific homogeneous feed materials, such as tires and electronic waste, and does not offer a complete alternative to MSW incineration (Bosmans et al., 2013). Pyrolysis also has the major environmental disadvantage of requiring disposal of solid residues in landfills (Young, 2010) and it is an endothermic process.

Gasification has several advantages over traditional combustion of MSW: Only a fraction of the stoichiometric amount of oxygen necessary for combustion is required, and the formation of dioxins, SO_2 and NO_x is limited and the volume of process gas is low, which results in smaller, less expensive gas cleaning equipment (Bosmans et al., 2013). The syngas generated by gasification can be used in combined cycle turbines, gas engines and potentially in fuel cells for electricity and heat generation, or as a chemical compound to produce methanol. Gasification also offers WtM potential if a slagging gasifier is used (Hirschfelder and Olschar, 2010; Arena and Di Gregorio, 2013).

Although the application of plasma-based systems for waste management is a relatively new concept, many studies revealed that plasma technology is an attractive waste treatment option in ELFM compared with other processes. Plasma-based systems offer flexibility, fast process control and more options in process chemistry, including the possibility of generating valuable products (Ray et al., 2012; Bosmans et al., 2013; Taylor et al., 2013). Bosmans et al. (2013) recently analysed and compared several thermal treatment technologies including incineration, gasification, pyrolysis, plasma technologies and their combinations for their suitability in ELFM. One of their conclusions is that plasma gasification/vitrification is a viable candidate for combined energy and material valorisation in the framework of ELFM.

In order to bring ELFM from the conceptual to the operational stage, the knowledge about the critical factors of environmental and economic performance of selected technologies is important. As the previous studies point out that thermal treatment (plasma gasification) is one of the most contributing processes in ELFM with respect to the environmental and economic impact (Danthurebandara et al., 2015a), a more detailed environmental and economic analysis is required to identify the possible improvements of the technology. The objective of this work is to analyse the environmental and economic performance of plasma gasification in ELFM framework. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have been performed to quantify the environmental and economic impacts of the plasma gasification. Additionally, the plasma gasification is benchmarked against a commonly used thermal treatment in waste processing such as incineration. Moreover, the relative advantages and disadvantages of different scenarios are analysed and suggestions are made regarding some possible improvements in design and operating parameters.

2. Materials and methods

This section describes the plasma gasification process, system boundaries and the LCA and LCC methodologies.

2.1. Process description

Plasma is known as the fourth state of matter. The presence of charged gaseous species makes the plasma highly reactive and cause it to behave significantly differently from other gases, solids or liquids. Plasma is generated when gaseous molecules are forced into high-energy collisions with charged electrons, which generated charged particles. The energy required to create a plasma can be thermal or carried by either an electric current or electromagnetic radiations (Bosmans et al., 2013). More details on main groups of plasmas can be found in Huang and Tang (2007) and Tendero et al. (2006).

Plasma offers a number of advantages to waste treatment processes (Heberlein and Murphy, 2008). The high-energy densities and temperatures that can be achieved in plasma processes enable high heat and reactant transfer rates, which can reduce the size of the installation for a given waste throughput and can melt materials at high temperature, increasing the overall waste volume reduction. Plasma-based systems also have the important advantage of being able to crack tars and chars, and therefore, the efficiency of conversion to high-quality syngas is much higher compared with non-plasma systems (Spooren et al., 2013). Since electricity is used as the energy source, heat generation is decoupled from process chemistry, which increases process controllability and flexibility (Bosmans et al., 2013).

Heberlein and Murphy (2008) described the categories of plasma technologies for waste treatment: plasma pyrolysis, plasma gasification, plasma compaction and vitrification of solid wastes, and the combinations of these three. Plasma pyrolysis installations treat polymer, medical waste and low-level radioactive waste (Guddeti et al., 2000; Nema and Ganeshprasad, 2002; HTTC, 2009); however, no information is available on industrial plasma pyrolysis facilities for processing MSW or RDF, the type of solid waste that is the focus of this study (Bosmans et al., 2013). Hence, Bosmans et al. (2013) noted that plasma gasification and vitrification is the preferred plasma-based technology for solid waste treatment.

More often plasma gasification is combined with vitrification to treat solid waste containing high amounts of organics. Plasma gasification systems may be either single or two-stage. In the

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