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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.

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 single-stage design, waste is directly treated with plasma jets; the two-stage design adds plasma cleaning of the produced synthesis gas. High temperatures are reached in plasma gasification, forming high-energy synthesis gas consisting mainly of hydrogen and carbon monoxide. The energy contained in plasma allows low-energy fuels to be treated, such as household waste and industrial waste, which often cannot sustain their own gasification without additional fuel. The resulting synthesis gas is cleaner than conventional gasification process because tar, char and dioxins are broken down. In addition, any inorganic components (glass, metals, silicates) are melted and converted into a dense, inert, non-leaching vitrified slag. The synthesis gas can be used for production of electricity and/or heat and valorised as methanol, methane gas or hydrogen gas.

Residues from the synthesis gas cleaning process (metals, fly ash) can be recycled internally and captured in the slag, which is vitrified to avoid leaching risks. This vitrified slag (plasmastone) has a great potential for rather diverse applications, mainly in the construction materials industry (Jones et al., 2013; Spooren et al., 2013). More details regarding plasmastone valorisation can be found in Danthurebandara et al. (2015b).

Fig. 1 shows how plasma gasification fits in an ELFM system. The RDF fraction obtained by the separation process is directed to plasma gasification. Although the resulted syngas can be valorised in many ways as described, this study examined only electricity production. Plasma gasification offers an intrinsic advantage because of metal recovery. The input RDF contains a minor fraction of metals that cannot be recovered during the separation process and that are melted during the thermal treatment process. In plasma gasification, metals can be separated from the plasmastone when the molten material is discharged into a quenching bath. Produced plasmastone is valorised to achieve the zero-waste goal of ELFM. This study focused only on the subsystem of thermal treatment in ELFM, as highlighted by the dotted line in Fig. 1.

2.2. LCA and LCC methodology

LCA is a technique to quantify the environmental and health impacts associated with producing a durable good or carrying out a process or activity from raw material extraction through materials processing, products manufacturing, distribution, use, repair and maintenance and disposal or recycling (ISO14040, 2006; ISO14044, 2006).

The goal of this LCA study was to evaluate the environmental impacts of the plasma gasification process in the context of ELFM. A comparative LCA model was developed for plasma gasification with different plasmastone valorisation routes. The system function was to reduce environmental impacts and to realise potential resource recovery from landfills. The functional unit was defined as valorisation of 1 tonne of RDF derived from landfilled waste. Also, plasma gasification was benchmarked against incineration, a commonly used thermal treatment method. Based on the system boundary shown in Fig. 1, a simplified comparative LCA model was developed (Fig. 2).

Eight scenarios were proposed depending on the plasmastone valorisation method. The first scenario consists of no valorisation, and the plasmastone is landfilled immediately after the plasma gasification process. Based on the applications of plasmastone described in Danthurebandara et al. (2015b), five scenarios were designed in which plasmastone is used in aggregate production, inorganic polymer cement production, inorganic polymer block production, blended cement production and blended cement block production. Two scenarios were designed to include incineration, one that valorised bottom ash as aggregates in the construction industry and one that did not. Table 1 summarizes the scenarios analysed in this study.

An input–output inventory was made for the plasma gasification process. The input data included the RDF to be processed, energy consumption and auxiliary materials; output data included emissions (to air, water, soil), wastes and products. Auxiliary materials for plasmastone valorisation are described in Machiels et al. (2014), Iacobescu et al. (2013) and Danthurebandara et al. (2015b). Transportation of recovered RDF was not considered in the model because we assumed all processing plants to be situated on the landfill premises. The environmental impact of landfill and processing plant personnel were not considered, and wastewater generated from all processes was directed to relevant treatment methods. We also assumed the produced heat to be used in the process itself (for example, for boilers). The qualities of various other products were:

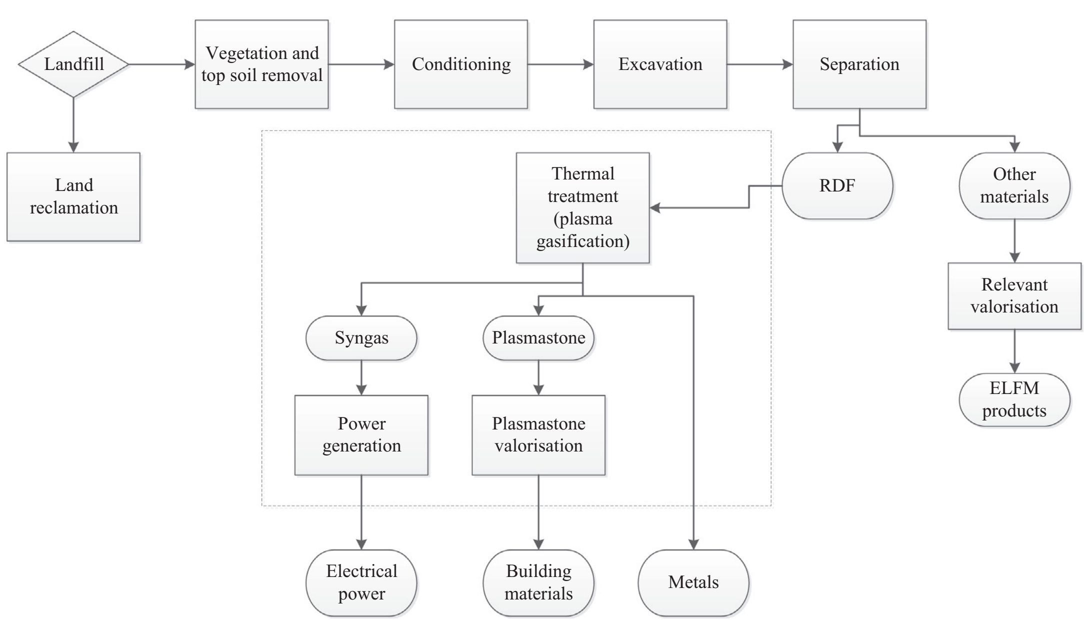

Fig. 1. Interactions of ELFM and the system boundary (indicated by the dotted line).

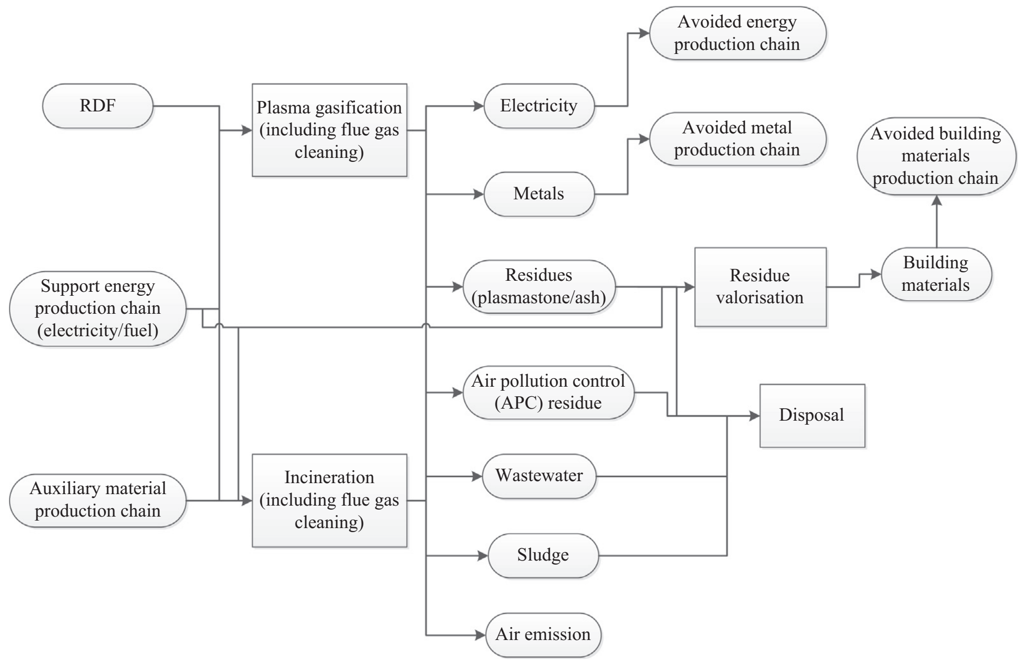

Fig. 2. Overview of the LCA model with the comparison between plasma gasifier and incineration.

Table 1
Summary of the scenarios.

Scenario	Description
Scenario 1	Plasma gasification with landfilling of plasmastone
Scenario 2	Incineration with landfilling of bottom ash
Scenario 3	Incineration with aggregate production out of bottom ash
Scenario 4	Plasma gasification with aggregate production out of plasmastone
Scenario 5	Plasma gasification with inorganic polymer cement production out of plasmastone
Scenario 6	Plasma gasification with inorganic polymer block production out of plasmastone
Scenario 7	Plasma gasification with blended cement production out of plasmastone
Scenario 8	Plasma gasification with blended cement block production out of plasmastone

- Metals recovered have the quality that enables substituting corresponding scrap metals.
- The produced electricity replaces the Belgian electricity mix, which includes 53% nuclear, 40% conventional thermal, 2% hydro and 3% wind energy (Eurostat, 2012).
- Aggregates produced in scenarios 3 and 4 have the quality of gravel that can be used in construction activities (Danthurebandara et al., 2015b).
- Produced inorganic polymer cement in scenario 5 has the quality of OPC, strength class CEM I 52.5 (Danthurebandara et al., 2015b).
- Produced blended cement in scenario 7 has the quality of OPC, strength class CEM II, 32.5 (Danthurebandara et al., 2015b).
- Produced inorganic polymer blocks and blended cement blocks in scenarios 6 and 8 have the quality of commercially available concrete blocks (Danthurebandara et al., 2015b).

Table 2 shows inflow–outflow energy, solid waste generation from the processes, auxiliary materials required mainly for flue gas cleaning and emission data considered in the life cycle inventory. The start-up energy required for the system was taken from Belgium's average country electricity grid. The data for plasma gasification were based mainly on a pilot experiment performed for RDF obtained from the case study landfill of the first comprehensive ELFM project in Belgium (Tielemans and Laevers, 2010). Zaman (2013), Indaver (2012) and BREF (2006, 2010) provided necessary data for the incineration process. Note that plasma gasification requires a considerable amount of oxygen, in contrast to incineration. Because carbon dioxide is a combination of biogenic and fossil carbon, the proportion of each had to be identified to calculate the environmental burden. Although the Ecoinvent database showed that MSW contributes 60.5 percent of biogenic carbon, a 47 percent share of biogenic carbon dioxide was used in this study because that is the fixed share used in Flanders, Belgium (Van Passel et al., 2013).

For the environmental impact assessment of this study, the ReCiPe endpoint method (Hierarchist version, H/A) was selected because it includes a variety of impact categories. These are: (i) climate change on human health, (ii) climate change on ecosystems, (iii) ozone depletion, (iv) terrestrial acidification, (v) freshwater eutrophication, (vi) human toxicity, (vii) photochemical oxidant formation, (viii) particulate matter formation, (ix) terrestrial ecotoxicity, (x) freshwater ecotoxicity, (xi) ionising radiation, (xii) agricultural land occupation, (xiii) urban land occupation, (xiv) natural land transformation, (xv) metal depletion and (xvi) fossil fuel depletion (Goedkoop et al., 2013).

LCC is a tool to determine the most cost-effective option among different competing products/processes, when each is equally appropriate to be implemented on technical grounds. To perform LCC for the selected scenarios in Table 1, we considered a hypothetical processing plant with a processing capacity of 100,000 tonnes RDF/year and a 20-year lifetime. A cash flow model was developed with necessary costs and revenues associated with the scenarios. The cash-flow model was extended for 20 years with a 15 percent discount factor. For the incineration process, we used 40 €/t RDF in investment costs and 60 €/t RDF in operational cost (Ducharme, 2010); all the other costs and revenues were similar to those applied in Danthurebandara et al. (2015a,b). The net present value (NPV) was used as the major economic indicator. To examine how the NPV varies when the values of uncertain assumptions are modified, a Monte Carlo simulation approach was used, as

Table 2
Life cycle inventory.

Parameter	Scenario 1 (plasma gasification)	Scenario 2 (incineration)
Energy and residue data		
Start-up energy (kW h/t RDF)	269[a]	78[b]
Calorific value of RDF (MJ/kg RDF)	20[a]	20[a]
Net electrical efficiency (%)	27[a,d]	22[c]
Solid residue generation (apart from APC residues) (t/t RDF)	0.17[a] (valorisation of this fraction is considered in scenarios 4–8)	0.228[b] (this fraction is considered to be landfilled in scenario 2 and to be valorised in scenario 3)
APC residues (t/t RDF)	0.024[a]	0.043[b]
Metal recuperation (t/t RDF)	0.01[a]	–
Auxiliary materials data		
Oxygen (t/t RDF)	0.55[a]	–
$NaHCO_3$ (kg/t RDF)	4[a]	–
Activated carbon (kg/t RDF)	0.2[a]	0.5[b]
NaOH (kg/t RDF)	0.8[a]	–
H_2O_2 (kg/t RDF)	0.4[a]	–
Urea (kg/t RDF)	1.2[a]	3.5[b]
Limestone (kg/t RDF)	–	6.7[b]
Quicklime (kg/t RDF)	–	4.4[b]
Emission data		
Carbon dioxide (kg/t RDF)		
Biogenic	689[a]	789[b]
Fossil	776[a]	889[b]
Carbon monoxide (kg/t RDF)	0.02[a]	0.09[b]
Particulates (kg/t RDF)	0.2[a]	0.014[b]
Nitrogen oxides (kg/t RDF)	0.43[a]	1.49[b]
Sulphur dioxide (kg/t RDF)	0.08[a]	0.019[b]
Hydrogen chloride (kg/t RDF)	0.02[a]	0.003[b]
Dioxins (kg/t RDF)	–	8×10^{-8}[b]
Mercury (kg/t RDF)	–	1.6×10^{-6}[b]
Heavy metals (kg/t RDF)	–	0.052[b]

[a] Industrial reference.
[b] Indaver (2012).
[c] BREF (2006, 2010).
[d] UCL (2014).

explained by Van Passel et al. (2013). This approach helps to identify the uncertainties of the input parameters as well as their importance.

3. Results and discussion

3.1. Environmental performance

Fig. 3 indicates the characterisation data for the study's basic scenario: plasma gasification of 1 tonne of RDF with landfilling of

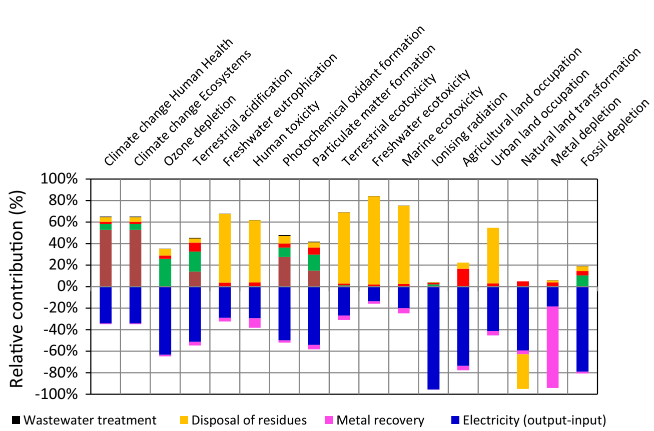

Fig. 3. Environmental profile of scenario 1 (characterisation results).

plasmastone. To get a better view of the relative contributions, the total environmental impact on each impact category was set at 100%. The total environmental impact for a specific impact category is a summation of all the environmental burdens minus all the benefits. The environmental burdens are expressed as positive values and the benefits are indicated as negative values.

As the figure indicates, electricity production yields an environmental benefit in all impact categories. Next to that, a significant benefit can be seen on metal depletion impact category due to metal recovery. Major burdens are caused by disposal of solid residues, flue gas emission and oxygen usage. As a result, flue gas emission dominates the climate change impact category. The graph indicates that half of the burden in this impact category could be compensated by the avoided burden due to electricity production. However, the impact of the thermal treatment process was derived from a comparison with the Belgian electricity generation mix in which nuclear energy has a share of 53% (Eurostat). The environmental impact of production of nuclear energy is lower compared to the other energy production methods. Hence the replaced impact is also lower when the Belgian electricity mix is used as the substituted product of the thermal treatment process.

The process can be extended through the use of flue gas in local horticulture, because flue gas contains higher amounts of CO_2 and lower temperature waste heat. CO_2 acts as a plant fertiliser, while the residual heat warms greenhouses, avoiding the use of primary fossil fuels; therefore, the burden of flue gas could be mitigated (Jones et al., 2013). The burden of oxygen mainly results because of the energy source used in the entire production process. Using renewable energy sources for oxygen production can further reduce the impact of plasma gasification. In addition, investigating the possibility of using air instead of pure oxygen in plasma gasification is worthwhile from an environmental point of view.

Disposal of solid residues contributes considerably to the burden yield in the impact categories of freshwater eutrophication, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and urban land occupation. Scenario 1 assumed that solid residues (plasmastone) are landfilled, and therefore, higher volumes of inert residues impose a higher burden on the environment. However, various studies have shown that inert residues could be used as construction materials (Iacobescu et al., 2013; Pontikes et al., 2013; Spooren et al., 2013; Machiels et al., 2014), thus eliminating the burden of solid residue disposal. This possibility is discussed in the other scenarios. The benefit yielded by disposal of solid residues on the impact category of natural land transformation is due to the indirect benefit caused by transformation of landfills (in where the residues are disposed of) into vegetation areas.

Normalisation was performed on a European level in order to make the impacts in different categories comparable with each other (PRéConsultants, 2010). Fig. 4 presents the normalised comparison of the environmental profile of valorisation of 1 tonne of RDF (scenario 1). In the same graph, the normalised results of the incineration process (scenario 2) are presented for better comparison with the plasma gasification process.

Normalisation shows that for both scenarios the contribution to climate change and fossil depletion is very important. In addition, the contribution to human toxicity also is substantial. The impact on metal depletion impact category is significant only for plasma gasification because the process offers intrinsic advantage for the recovery of minor amounts of metals in the RDF. Particulate matter formation is also slightly significant only in plasma gasification. Important to notice is the insignificance of other impact categories for both plasma gasification and incineration.

Plasma gasification process is more efficient than conventional incineration in converting the energy content of the waste to electricity (27% vs 22%). Therefore, although both processes give rise to

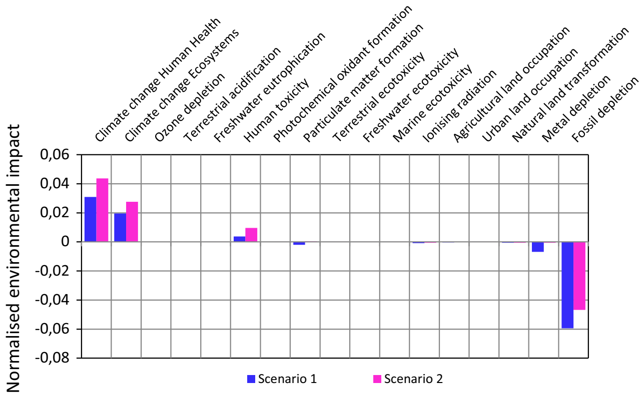

Fig. 4. Normalised environmental profile of scenario 1 and 2.

the direct emissions of carbon dioxide, particulate matters, etc. from the waste conversion plant, plasma gasification process displaces more conventional electricity generation and is therefore associated with significantly lower lifecycle environmental burdens. Moreover, recovery of metals from the residues is higher than in incineration due to intrinsic advantage of metal recuperation capacity of plasma gasification process, further reducing the environmental burdens by replacing primary metal production. Incineration shows a higher environmental burden and lower environmental benefit compared with the plasma gasification process, mainly due to the lower net electrical efficiency of the incineration plant.

To investigate the sensitivity of the environmental profile of plasma gasification we replaced landfilling of plasmastone in scenario 1 with higher added-value applications of plasmastone, as explained in Table 1. Fig. 5 illustrates the comparative environmental profiles of the scenarios applying various plasmastone valorisation methods. In addition, the impact of incineration, with valorisation of bottom ash as aggregates (scenario 3), is also shown. Only the most significant impact categories were included in the figure.

Fig. 5 indicates that the environmental burden of plasma gasification on the climate change impact category varied considerably when plasmastone is valorised. The impact on both climate change on human health and on ecosystems decreased by 12%, 41%, 23% and 24% respectively when plasmastone is used in aggregate production, inorganic polymer cement production, inorganic polymer block production and blended cement production. These decrements are due to replacement of conventional gravel production and OPC-based products, which have higher greenhouse gas emissions.

In contrast, the use of plasmastone in blended cement block production results in a 12% increased burden in the same impact categories. As previously explained, in both inorganic polymer cement/block production and blended cement/block production processes, traditional Portland cement/concrete with a heavy CO_2 burden is replaced. However, in blended cement production, Portland cement is used as an input material, which explains the difference in environmental impact between the two valorisation techniques. The impact of these valorisation technologies on global warming potential (GWP) can be found in detail in Danthurebandara et al. (2015b).

Importantly, the burden on human toxicity impact category become a benefit when the above higher added value valorisation applications are introduced to the process. Moreover, benefits in the categories of particulate matter formation, metal depletion and fossil depletion also increased with various valorisation technologies. As shown in Fig. 5, blended cement block production is more beneficial for metal depletion than other valorisation methods. Based on this method's individual environmental profile, this benefit can be attributed to avoidance of steel usage in the construction of the concrete production plant. Also, this benefit is significantly higher in blended cement block production than in inorganic polymer block production because five times more blended cement blocks than inorganic polymer blocks can be produced from 1 tonne of plasmastone (Iacobescu et al., 2013; Machiels et al., 2014).

When the impact assessment method of IPCC 2007 GWP 100a (Goedkoop et al., 2013) is used, the net CO_2 equivalent emission of plasma gasification process with the least value plasmastone valorisation method (aggregate production) is 0.5 t CO_2 equivalent/t RDF. This finding is nearly two times less than the CO_2 equivalent emission of traditional incineration with bottom ash valorisation (scenario 3), and aligns with UCL's (2014) recent comparative LCA study performed for plasma gasification and traditional incineration. The comparison can alternatively be framed to show that an incineration plant must achieve at least 29% net electrical efficiency to display the same environmental GWP impact (i.e. kg of CO_2 eq per kg of RDF treated) as the plasma gasification. Such high efficiencies of more than 30% are also reported with the improvements for energy recovery (Van Berlo, 2010). However it was not reported whether the plant is continuously operating under full load.

The results obtained for the various scenarios in the impact assessment phase were aggregated to a single environmental score (single score) in order to have an indication of the overall environmental performance of each (see Fig. 6).

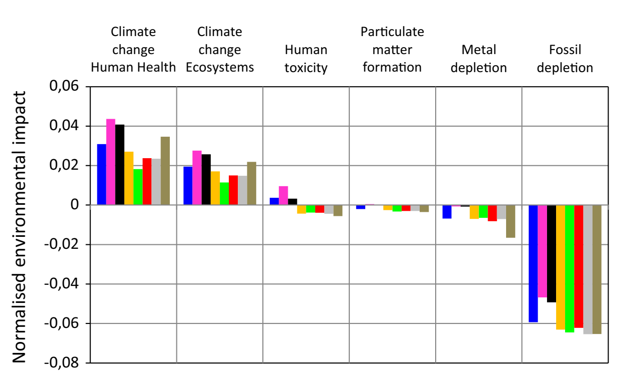

Fig. 5. Normalised environmental profile of different scenarios.

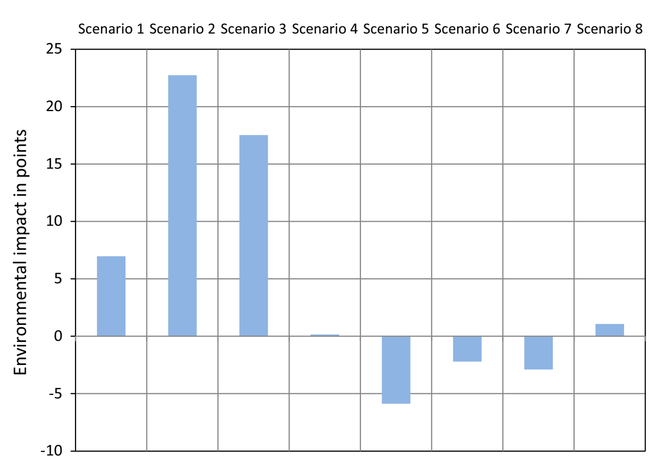

Fig. 6. Environmental profile of different scenarios in single environmental score.

As shown in Fig. 6, the basic scenario of plasma gasification (scenario 1) shows a better environmental performance compared with incineration process (scenario 2). The overall environmental impact (burden) of incineration is more than three times higher than that of the basic scenario of plasma gasification. When various plasmastone valorisation methods are introduced, the total impact of plasma gasification is reduced further. For scenario 4 (aggregate production out of plasmastone), the net impact is almost neutral, while it becomes beneficial for the scenarios that employed inorganic polymer cement/ block and blended cement production. For the scenario using blended cement block production (scenario 8), the environmental impact is more than six times less than the basic scenario of plasma gasification. In fact, as the graph suggests, plasma gasification is not only a WtE process but also a WtM process that addresses the key objective of ELFM: a combined valorisation of landfilled waste as both WtM and WtE that maximises economic returns and minimises environmental burdens. According to the review of Bosmans et al. (2013), plasma gasification/vitrification is a viable candidate to achieve ELFM's technological goals. Next to that, this LCA study indicates that plasma gasification is capable of realising the environmental goals of ELFM through both WtE and WtM.

3.2. Economic performance

Figs. 7 and 8 show the relationship between the economic and environmental impact of the various scenarios formulated for RDF valorisation, including plasma gasification and incineration. The total environmental impact was calculated for the hypothetical treatment plant described in Section 2.2 (100,000 t RDF/year of treatment capacity and a 20-year lifetime). In Fig. 7, the environmental impact is indicated in points: the output of ReCiPe endpoint method delivered as a single environmental score. Because both thermal treatment methods and the developed residue valorisation options directly contribute to global warming potential, Fig. 8 illustrates the environmental impact in kilograms CO_2 equivalent. In both graphs, the economic impact is expressed in NPVs, with positive values of NPV implying economic profits and negative values of environmental impact indicating environmental benefits. At first glance, none of the scenarios appear viable both environmentally and economically. Danthurebandara et al. (2015b) concluded that plasmastone valorisation by inorganic polymer cement production, inorganic polymer block production and blended cement production yield both environmental and economic profits. Nevertheless, when plasma gasification is coupled with those plasmastone valorisation scenarios, the overall economic impact is negative. The benefit on CO_2 equivalent observed by previous authors for these same three scenarios also is a burden when plasma gasification and plasmastone valorisation processes are combined (Fig. 8). However, when a variety (ReCiPe method) instead of a single impact category (GWP method) is considered, the net environmental impacts of the scenarios remain beneficial (Fig. 7). Only plasma gasification with blended cement block production out of plasmastone (scenario 8) yields an economic benefit. The NPV is five times less when blended cement block production (scenario 8) is substituted with inorganic polymer block production (scenario 6). Aggregate production (scenario 4) results in a 45% decrease in NPV compared with scenarios with blended cement and inorganic polymer cement production (scenarios 7 and 5). Economic analysis reveals that the NPV of plasma gasification is higher when the higher added-value applications for plasmastone are considered. In addition, as Figs. 7 and 8 imply, blended cement is the economic driver of the plasma gasification process. It is important to notice that the lowest environmental and economic profit is obtained when the scenario includes incineration and landfilling of residues (scenario 2). In contrast to this study, the recent analysis of Winterstetter et al. (2015) shows better environmental performance in incineration than in plasma gasification. However, the percentage difference of efficiencies of incineration and plasma gasification that Winterstetter et al. used is only 7% (30% for incineration and 32% for plasma gasification) while the present study used a 23% difference (22% for incineration and 27% for plasma gasification). Residue valorisation and emission levels for incineration and plasma gasification are also not reported in Winterstetter et al. Furthermore, Winterstetter et al. considered the substitution of marginal Belgian electricity produced by natural gas instead of Belgian average energy mix used in this study. Nevertheless, both studies highlight that none of the scenarios offers CO_2 equivalent saving as well as positive NPVs.

The trade-off line of the RDF valorisation scenarios indicates the economic benefit that must be forfeited to obtain the environmental benefit. In both Figs. 7 and 8, the trade-off line starts from plasma gasification with blended cement block production (scenario 8), passes plasma gasification with inorganic polymer block production (scenario 6), then reaches plasma gasification with blended cement production (scenario 7), and ends at plasma gasification with inorganic polymer cement production (scenario 5). Implementation of scenario 8 is favorable from the view point of financial investor of

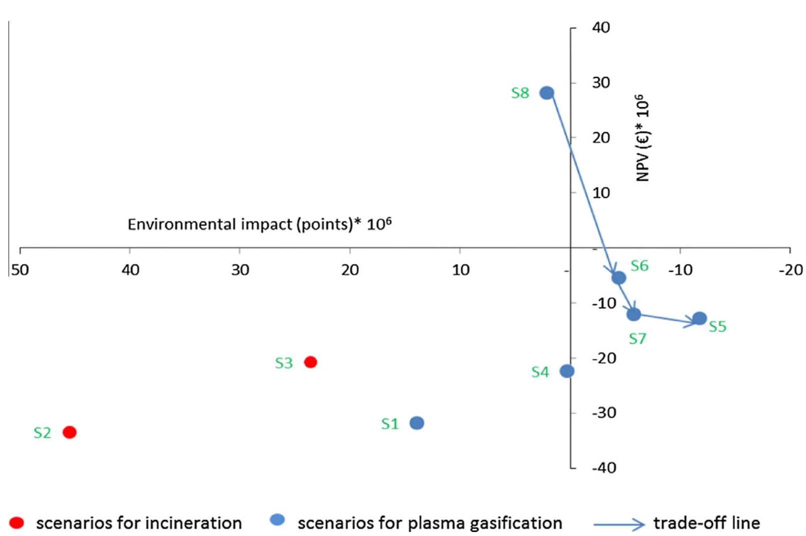

Fig. 7. Trade-off analysis between NPV and overall environmental impact of different RDF valorisation scenarios.

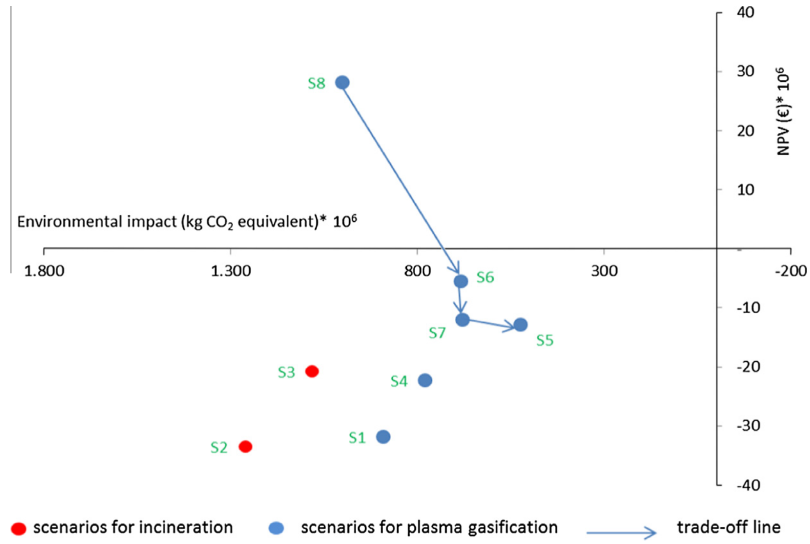

Fig. 8. Trade-off analysis between NPV and GWP of different RDF valorisation scenarios.

ELFM project. However, the government may introduce extra taxes to compensate the environmental burden associated with this scenario. On the other hand, if the government stresses to implement scenario 5 instead of scenario 8, higher subsidies for green certificates and higher electricity prices should be offered. The price of green certificates should be increased from 117 €/MW h to minimum 147 €/MW h in order to implement scenario 5 with economic profits. Moreover, the electricity price is needed to be increased by 20% to obtain economic profits from scenario 5.

Monte Carlo simulations show that the following parameters have an important impact on economic performance: (i) the net electrical efficiency of the thermal treatment system, (ii) the calorific value of RDF, (iii) the price of electricity, (iv) the price of green certificates, (v) the green energy fraction and (vi) the investment and the operational costs of the thermal treatment system. Prominently, these parameters were the most influencing parameters of a full-scale ELFM project, as discussed in Danthurebandara et al. (2015a)

Table 3 illustrates the contribution of the different parameters to explain the variation in NPV obtained from Monte Carlo simulations using triangular distributions. An increase in the NPV with an increase of a parameter is indicated as a positive contribution and the opposite situation is presented as a negative contribution. Only the most sensitive parameters are included in Table 3. The table shows that the increments of the net electrical efficiency yield higher NPVs; however, the improvement of efficiency may conceive significant growths in investment cost, which affects NPV negatively. Hence, a careful control of these two parameters is necessary to make plasma gasification an economically viable candidate in RDF valorisation. In addition to these parameters, the selling price of the higher-value products obtained from plasmastone becomes an important parameter for scenarios 5–8. This positive contribution of the product's selling price is significantly high for scenarios associated with blended cement production; an average of 41.2% and 15.8% for product price ranges of 90–110 €/t and 45–55 €/t respectively. This finding suggests that high-quality

Table 3
Most sensitive parameters to the NPV.

Parameter	Minimum value	Maximum value	Contribution to the variance of NPV in different scenarios (%)							
			S1	S2	S3	S4	S5	S6	S7	S8
Net electrical efficiency of the plasma gasification system (%)	24 (+)	30 (+)	26.6 (+)			26.5 (+)	25.7 (+)	25.8 (+)	19.5 (+)	22.0 (+)
Net electrical efficiency of the incineration system (%)	20 (+)	24 (+)		22.9 (+)	23.5 (+)					
Calorific value of RDF (MJ/kg)	18 (+)	22 (+)	25.8 (+)	22.8 (+)	22.5 (+)	25.7 (+)	24.5 (+)	25.4 (+)	17.9 (+)	21.9 (+)
Price of electricity (€/MW h)	60 (+)	76 (+)	10.0 (+)	7.4 (+)	7.8 (+)	9.4 (+)	9.9 (+)	9.4 (+)	4.8 (+)	7.7 (+)
Price of green certificates (€/MW h)	110 (+)	124 (+)	4.4 (+)	4.6 (+)	4.5 (+)	5.3 (+)	4.7 (+)	4.7 (+)	3.2 (+)	4.4 (+)
Green energy fraction (%)	42 (+)	52 (+)	4.2 (+)	4.2 (+)	4.0 (+)	5.1 (+)	5.2 (+)	4.6 (+)	2.5 (+)	4.6 (+)
Investment cost of plasma gasification system (€/t RDF)	45 (+)	55 (+)	25.7 (–)			24.4 (–)	24.0 (–)	25.5 (–)	17.2 (–)	21.1 (–)
Operational cost of plasma gasification system (€/t RDF)	57 (+)	77 (+)	3.0 (–)			3.4 (–)	3.4 (–)	3.6 (–)	2.2 (–)	2.8 (–)
Investment cost of incineration system (€/t RDF)	35 (+)	45 (+)		35.1 (–)	34.1 (–)					
Operational cost of incineration system (€/t RDF)	50 (+)	70 (+)		2.6 (–)	2.3 (–)					
Selling price of inorganic polymer cement (€/t)	135 (+)	165 (+)					2.0 (+)			
Selling price of inorganic polymer cement block (€/t)	63 (+)	77 (+)						0.7 (+)		
Selling price of blended cement (€/t)	90 (+)	110 (+)							41.2 (+)	
Selling price of blended cement block (€/t)	45 (+)	55 (+)								15.8 (+)

products will increase the economic performance of the plasma gasification because higher quality eventually yields a higher selling price.

4. Conclusions

This paper includes the results of an environmental and economic evaluation performed to identify the capability of plasma gasification process to be used in the novel concept of ELFM. Besides energy production, plasma gasification is capable of producing building materials out of its residues, which contributes to the WtM component of ELFM. The study concludes that the environmental burdens created by the process decrease when the plasmastone is subjected to various valorisation methods instead of landfilling. Similarly, environmental benefits also increase, because of the replacement of OPC-based products, which are associated with higher greenhouse gas emissions.

The economic analysis supports the production of blended cement as the economic driver of plasma gasification, and further analysis confirms that net electrical efficiency and investment costs of the plasma gasification system should be controlled carefully to obtain positive NPVs. In addition, the selling prices of the higher-value products obtained from plasmastone positively affects the NPV. Because the product's quality directly determines its selling price, improvements in product quality could expand the economic benefits of the process.

Among the discussed scenarios, traditional incineration obtains the lowest economic and environmental profit. A clear trade-off exists between economic and environmental performances of the scenarios; nevertheless, the results indicate that plasma gasification has a great potential to maximise the economic and environmental profits with cautious handling of certain parameters (net electrical efficiency, investment cost, product quality). Although this study considered only power generation, the produced syngas from plasma gasification could be used in many other applications. Finally, a detailed analysis of all possible syngas valorisation technologies would be required to have a straightforward and broad knowledge of the maximum contribution of plasma gasification within ELFM.

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