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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 ELFM research that has been performed in 2009–2012 with respect to the Closing the Circle (CtC) project in Houthalen-Helchteren,

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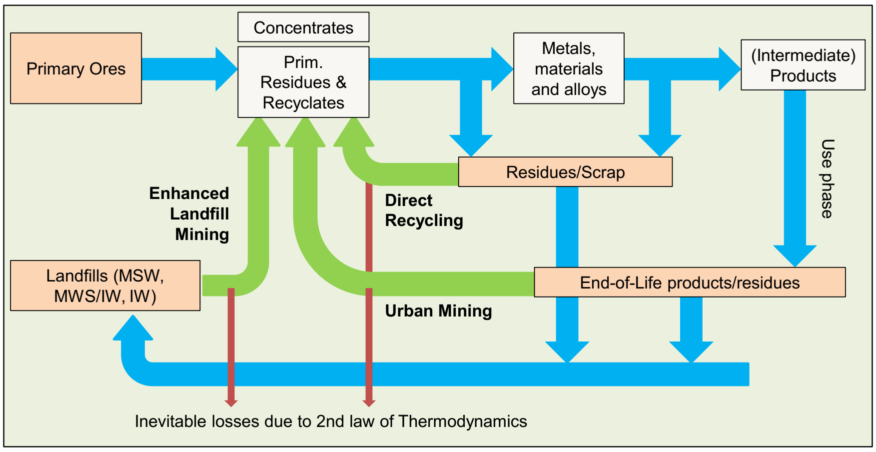

Fig. 1. Different ways to close materials loops in a circular economy: (1) direct recycling of preconsumer scrap and residues (e.g. slags), (2) urban mining of End-of-Life consumer goods and other products, (3) landfill mining of historically landfilled pre-consumer and post-consumer waste streams. Reproduced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

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 pre-treatment 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 technologies to prepare a Solid Recovered Fuel (SRF) that can be processed in a Waste-to-Energy installation, thereby generating

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Table 1
Distinct landfill mining/management concepts that are under development.

Concept	Type of resource recovery	Definition	Main references
Enhanced Landfill Mining (ELFM)	*Ex situ*	Addresses the combined and integrated valorization of distinct landfilled urban waste streams as both materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE), while meeting the most stringent ecological and social criteria.	(Jones and Tielemans, 2011) – focus of the present paper
Enhanced biodegradation (& Bio-reactor)	*In situ*	Especially developed as cost-effective remediation measure for contaminated soils and groundwater bodies. Both contaminant plume and source areas are treatable. With respect to landfills, there is limited experience on old and abandoned sites.	(Hoekstra et al., 2005; Hoekstra and Langenhoff, 2007; Read et al., 2011; Rich et al., 2008)
Sustainable landfill	*In situ*	Refers to methods to minimize the pollution potential of landfills, by *in situ* remediation within the timeframe of one generation with, a.o., using the bioreactor concept, on modern managed landfills. Pollutants are broken down to harmless substances, flushed out or immobilized in the landfill. This risk reduction can be accomplished together with methane extraction, organic content stabilization and specific land use.	(Woelder et al., 2007; Cossu et al., 2011)
Natural cap/catch	*In situ*	Concepts which use the properties of natural organic material to isolate contaminated waste (natural cap) and prevent contaminated leachate from spreading (natural catch). The goal is to create a gradual, functional replacement of the standard landfill cover (soil and synthetic foil) by a natural layer of living, organic material. The principle of natural catch is to improve the conditions for natural attenuation in the seepage zone of waste dumps by the restoration or (re)construction of wetlands.	(Clemens et al., 2010; Dijcker et al., 2011)
Temporary storage place	*In situ and ex situ*	Provides the link between the *ex situ* ELFM and the *in situ* resource recovery concepts. The temporary storage concept is 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* materials recovery. The temporary storage place has to be applicable to a wide range of landfill types.	(Jones and Tielemans, 2011)

energy (and heat) and residues (e.g. bottom ash, air pollution control residue, plasmarok slag). The fractions that are not directly recoverable, are sent to temporary storage. Concurrently, as shown in Fig. 3, the still embryonic temporary storage concept is also relevant for future waste streams from the technosphere. As is the case for currently non-recoverable fractions from the WtM plants these new streams (e.g. crushed lamps, asbestos) can also be stored in view of future valorization, whenever technologies are mature and/or economic viability for the resource recovery procedure is ascertained. The degrees of freedom for the design of future waste storage places are higher than for old and abandoned landfills which are transformed into temporary storages.

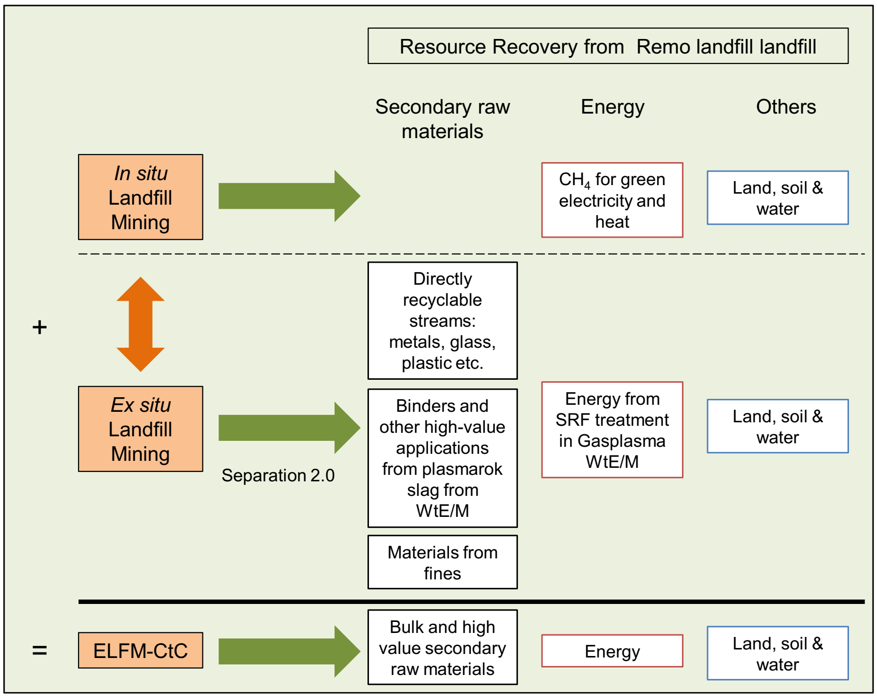

Fig. 2. Resource recovery from *in situ* and *ex situ* landfill mining – the double arrow indicates that for the Closing the Circle (CtC) project an *in situ* LFM phase (on landfill cells that are not excavated yet) can be combined with *ex situ* LFM (on landfill cells that are excavated).

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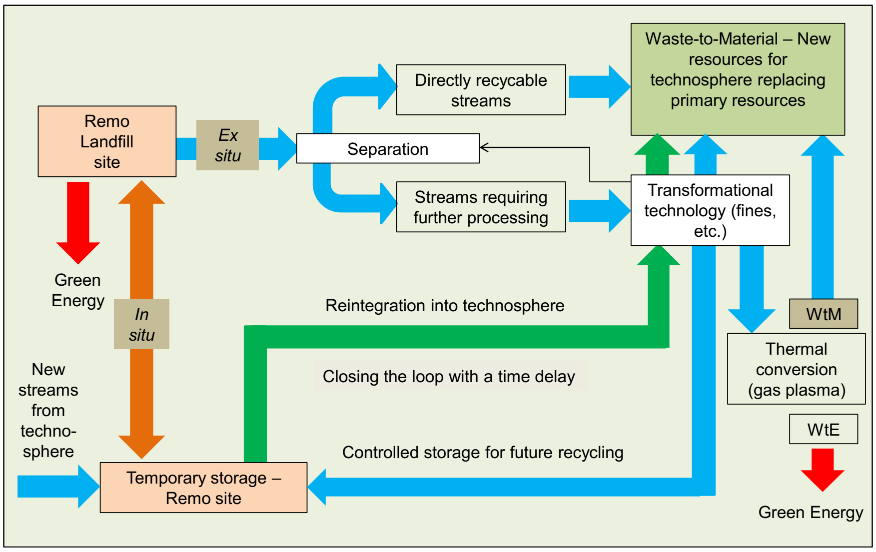

Fig. 3. Flow sheet for the REMO Closing the Circle project, which combines *in situ* with *ex situ* landfill mining, with a view on maximum resource recovery.

2.3. *Enhanced Landfill Mining*

The focus now goes to *ex situ* ELFM, its link with the temporary storage concept and the need for innovative separation and transformation technologies. The ELFM concept has been under development since 2008 by the Flemish ELFM Consortium. This transdisciplinary consortium of experts was established in Flanders (Northern part of Belgium) to integrate landfilling in an integrated, systemic resource recovery practice. The Consortium brings together academic experts (from materials, civil and chemical engineering, metallurgy, geology, psychology, environmental economics, law and biomonitoring science), the company Group Machiels, the Flemish Public Waste Agency (OVAM), and representatives of the local communities. Currently, ELFM is defined as the "*the safe conditioning, excavation 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*". The "integrated" aspect refers to a maximum valorization of materials and energy, rather than a cherry picking approach. With respect to the innovative character of the involved technologies, the ELFM consortium is investigating the potential of, in particular, the Gasplasma™ WtE technology (Bosmans et al., in this issue; Chapman et al., 2011a). As part of the sustainable approach ELFM incorporates the goal to sequester, use and/or offset a significant fraction of the CO_2 arising during the energy valorization process. Concurrently, the landfill zone can be reclaimed for new societally beneficial usages (Van Passel et al., 2011).

As the definition highlights, the ELFM concept is relevant for both historic and future landfills. In the latter case, landfills become future mines for materials, which cannot yet be (economically) recycled with existing technologies or show a clear potential to be recycled in a more effective way in the near future. Indeed, for certain waste streams, incineration eliminates the possibility of its reuse as a material. The net results are increased material costs and decreased welfare, with respect to a direct materials recycling process. To make sure more materials find their way to recycling instead of incineration or dumping, the 'temporary storage' concept (instead of a permanent landfill) becomes worthwhile. The landfill owner, the landfill operator and/or the waste producer will have to take into account that the landfill needs to be mined after a short, intermediate or longer period.

3. The Closing the Circle ELFM-project

The 'Closing the Circle' project (CtC) is the first case-study for the ELFM Consortium to investigate the opportunities and barriers for ELFM in the REMO landfill site in Houthalen-Helchteren. CtC was initiated in 2007, ending its concept phase at the end of 2008. Valorization tests, engineering and more detailed elaboration of the project was performed in the period 2009–2012. These tests were intended to validate the assumptions made during the concept phase and are described in this paper. From 2013 onwards, the project will enter a pilot-scale phase. Subsequently, the full-scale WtE and WtM plants are to be constructed, allowing the resource recovery to start by 2017. Next to the electricity/heat generation plant, up to 50 ha of greenhouses are planned, fuelled with the steam and part of the CO_2 coming from the electricity generation plant. The CtC project requires an investment of ~230 M€ and would employ up to 800 people. The WtM and WtE plants will be operational for 20 years. Over that period the landfill site will be gradually developed into a sustainable nature park.

The REMO landfill site has been operational since the early 1970s. The landfill site covers an area of 130 ha and is situated in the direct vicinity of the villages Heusden-Zolder, Helchteren and Houthalen. The landfill site is surrounded by an old coal mine slag heap, a military training area and one of the main nature reserves in Flanders. The latter clarifies the strong interest in developing nature on the landfill site during and after the ELFM activity. The amount, the type and the location of the various waste streams stored in this landfill have been closely documented. Based on these data, over the years, 18 million metric tons of waste (as-received) has been stored in the REMO landfill. Roughly 11.8 million tons (as-received) is MSW and comparable industrial waste. Almost 6.3 million tons (as-received) is industrial waste such as shredder material from the car industry, metallurgical slags, bottom ashes from waste incineration, industrial sludges and contaminated soil. Almost 1.5 million tons of sand (part of the industrial waste) was used as intermediate cover. The data of the log book provided a first estimate of the value of materials in the landfill. The mass of the different waste fractions was recalculated to estimate the dry weight currently present in the landfill. The moisture content and degradation of organics over time was taken into account resulting in an estimated total dry mass of 13 million tons currently present in the landfill including the soil used as intermediate cover. Based

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on the data, 50 wt% (dry mass) is of a combustible nature (paper/cardboard, plastics, shredder, wood, textile, organics…). Approximately 25 wt% (dry mass) are fines, i.e. mainly soil and sludge and a small amount of fly ash. Construction and demolition waste, metallurgical slags, metals and glass account for the remaining 25 wt%.

4. Synthesis Closing the Circle research

4.1. Research methodology

The main objective of the remainder of this paper is to demonstrate the conditions for which ELFM is feasible. This is performed by synthesizing a number of conducted and on-going research subprojects related to CtC. Most of these studies have been reported in Conference Proceedings papers or peer-review Journals, while others are internal confidential reports. Firstly, characterization studies of excavated landfilled waste (Quaghebeur et al., 2010, in this issue) were performed to verify the quality of the available data (log book) of the materials in the landfill. Secondly, validation studies of the envisaged material recuperation (Chapman et al., 2011a) and the energetic valorization technologies (Helsen and Bosmans, 2011; Bosmans et al., 2010, in this issue) were conducted. Thirdly, nature conservation analyses (De Vocht, 2009; De Vocht and Descamps, 2011) assessed the environmental impact and the envisaged integration of the site in a nearby nature reserve. Finally, the establishment of the project's carbon footprint (de Gheldere et al., 2009) within a larger environmental economics study (Van Passel et al., in this issue) was conducted to demonstrate the advantage of landfill mining compared to a do-nothing scenario. More conceptual (Jones et al., 2011), societal (Craps and Sips, 2011) and legal background (Wante and Umans, 2011) studies have been published in the 1st Enhanced Landfill Mining Symposium book (Jones and Tielemans, 2011). All studies were performed by research teams from the ELFM Consortium and other, related research institutes. The synthesis discusses the key technological and non-technical challenges that have been or are being addressed. Wherever possible reference is made to existing literature. Nevertheless, as indicated by the review paper of Krook et al. (2012), the landfill mining literature is immature: in a 20 year period only 12 articles were published in peer reviewed journals.

4.2. Characterization of the landfilled waste

The REMO landfill consists of 7 main sections, corresponding to different time periods. The landfill zones are divided in separate cells with industrial waste (IW), construction and demolition waste and municipal solid waste (MSW), originating from both households and companies. The amount and type of waste stored in the landfill is currently registered by means of the EURAL waste code. Based on the as-received waste data stored in the log book, a first estimation of the amount and type of waste was made. The valorization potential was subsequently determined by regrouping the waste categories from the landfill registry (EURAL code, log book) in 25 valorization (utilization) categories, including plastics, metals, glass, textiles, organics, sludge, slags, sand, etc. For most categories of IW regrouping solely based on waste category is feasible. For MSW, regrouping is not straightforward since this type of waste is typically composed of a mixture of materials. For MSW produced by households, regrouping was therefore done using the records of the composition of fresh MSW over time as determined by manual separation tests (OVAM, 2008; Quaghebeur et al., 2010, in this issue). To obtain more information about the composition of MSW produced by companies, a sampling campaign and subsequent manual separation test was performed on 25 trucks of fresh MSW produced by companies (data Group Machiels – not public).

The analysis of the log book data resulted in an estimate of 18 million metric tons of waste initially received at the landfill. Corrections were then made for the as-received moisture content over time to estimate the materials actually present in the landfill. The actual dry waste mass was calculated using the moisture contents of various waste types available from the Phyllis database (Phyllis, 2011). To take into account the degradation of the fractions rich in organic carbon (paper, cardboard, textile and the organic fraction in MSW), the assumption was made that 50% of the material degraded during storage in the landfill. This corrections resulted in an estimate of around 13 million metric ton dry weight currently available in the landfill. More than 5 million metric ton of this mass is classified as industrial waste. Shredder material (>40 wt%) and sludge (~20 wt%) constitute the two major fractions. More than 7.5 million metric tons is MSW generated by households or companies. In this category construction and demolition waste (~25 wt%) and plastics (20 wt%) are the most important fractions by weight.

Although analysis of the log book provided a first estimate of the valorization potential of the landfill, the evaluation is dependent on the log book data and records available in literature. In addition, the evaluation does not allow to take into account changes in composition and characteristics of the waste over time caused by burial or storage in the landfill. An exploratory field test was therefore carried to verify the quality of the register and the conversion to categories meaningful for valorization. The characterization was based on 6 trial excavations. The 6 locations were selected based on the age and type of waste (industrial or MSW). 4 locations in the zones containing MSW and 2 locations in zones containing industrial waste were studied. Excavation was performed from the top of the landfill down to the bottom using a cactus grab crane. The maximum depth was 18 m. Waste samples were taken every metre and subsamples were analyzed through manual sorting. During these sorting tests the samples were dried and screened at 10 mm. Manual sorting was applied to separate the waste in 8 distinct fractions. The amount of wood, paper/cardboard, textile, plastics, metal, glass, ceramics, aggregates and 'unidentified' were determined for every fraction >10 mm. Also the weight of the fraction below 10 mm was recorded. The individual fractions were subsequently sampled and analyzed. The calorific value, the ash content, the elementary composition and the halogens were determined. A full description is provided by Quaghebeur et al. (in this issue). Here the main conclusions are summarised.

The results of the field test confirmed differences in the composition and characteristics of the waste materials with regard to type of waste (MSW versus IW) but also reveal differences related to the period during which the waste was stored. For MSW changes in the amount of plastics and metals over time can be attributed to changes of fresh MSW initially landfilled over time, while changes in content of organic waste and paper/cardboard were mainly governed by degradation of the material during landfilling. Degradation of MSW could be described reasonably well with a first order decay curve:

$$C(t) = C_0 \cdot e^{-kt} \quad \left(R^2 = 0.98, C_0 = 42\%, k = 0.0269 \text{ year}^{-1}\right) \qquad (1)$$

where k is the first order rate constant reflecting the rate at which the degradation of carbon-rich material occurs. The factor C_0 represents the concentration of Total Organic Carbon in the MSW at the time of burial. A more accurate determination of the degradation resulted in a slightly lower amount of waste (average 12.5 million ton, from excavation data) with respect to the value

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based on the register (13 million ton). Another advantage of the field test is that the composition of the waste is measured, allowing a more accurate evaluation of the valorization potential for the samples excavated. The drawback of the field test is its cost, limiting the amount of samples that can be analyzed in detail. The records for the industrial waste works with completely different material categories, such as residues from recycling processes, residues from soil cleaning, shredder material, bottom ash, metallurgical slag etc. Assessment of the valorization potential with regard to traditional recycling markets (metals, plastics, paper/cardboard, wood, ...) is therefore more difficult.

Table 2 shows the average results and standard deviations for the different waste fractions from MSW. Two calculations methodologies are compared. The first is based on the log book data combined with literature data, while the second uses the results from the excavations. Overall the MSW composition using the two methods compares relatively well. For some fractions, however, differences are observed. The amount of fines is underestimated using the log book method compared to the excavation method. Also for degradable fractions (wood, textile, paper/cardboard, organic fraction), variations are observed that can be attributed to the fact that when using the log book data, the assumption that 50% of the materials degrade during storage in the landfill is not correct.

4.3. Material separation and WtM/WtE utilization

Taking into account the data from the excavations, it is clear that the fines fraction is higher than initially thought, while the combustible fraction is lower than expected. It is assumed that the main reason for this is that a certain part of the initial, combustible fraction gets attached to the fines. The high amount of fines found in the landfill is in accordance with literature data (Perdido Landfill, 2009; RenoSam, 2009). Krook et al. (2012) reported a 50–60 wt% soil-type material as a generic average for municipal landfills. Hence, the fines fraction (<10 mm) forms a major part of the total amount of landfilled waste. Finding valorization opportunities for these fines is a challenge for ELFM. Likewise, construction and demolition waste is a major fraction to be valorized. Specifically for CtC, the utilization of the metallurgical (stainless steel) slag fraction in the landfill is also a key challenge. The register indicates the presence of more than 1 million metric ton of chromium and nickel containing stainless steel slags, together with ashes from waste incineration. The slag fraction was not included in Table 2 as no slag samples were taken during the excavation field trials. The cactus grab crane could not penetrate through the metal containing slag layers. Based on present experience, a significant part of these slags will have to be recovered as fines, which will require innovative techniques for cleaning, metal recovery and slag valorization. Similarly, the total metal content in the industrial fines can be up to 30 wt% (Quaghebeur et al., 2010). This is considerably higher than the metal content (1–5 wt%) in the fines originating from the municipal solid waste fraction.

Table 2
Waste fractions (including standard deviations based on excavation samples) in wt% dry mass for municipal solid waste calculated from the registry and from excavated samples.

Wt% dry mass	MSW (log book)	MSW (excavation)
Paper/cardboard	11	7.5 (6.0)
Textile	0.6	6.8 (6)
Plastics	20	17 (10)
Metals	2.1	2.8 (1)
Glass/ceramics	1.7	1.3 (0.8)
Aggregates	34	10 (6)
Wood	2.7	7 (5)
Fines	12	44 (12)
Organic fraction	7.5	–
Unidentified	8.4	3.8 (4)

Although the amount of plastics was lower than expected, the total amount of combustibles from the municipal solid waste in the REMO landfill is still 38.1 wt%. For the industrial waste this is only 14.5 wt% (Quaghebeur et al., in this issue). In order to valorize the combustible materials sound separation flow sheets need to be developed, which are able to liberate this fraction (for WtE) from the materials to be valorized through WtM routes. For CtC an industrial-scale separation trial was performed to assess the distribution of the various material fractions and the quality of the obtained Solid Recovered Fuel (SRF), fines and other materials. Two batches (MSW and IW, respectively) of approximately 400 tons of material – from a plot of 10 by 10 m along the full depth of the landfill cells (15 m) – were excavated and treated in a separation plant to produce different materials fractions, including SRF. The excavations were performed in the same zones where also the samples for the characterization study were taken (Quaghebeur et al., in this issue). The different process steps of the separation plant are:

- Drum screen;
- Screen;
- Wind shifter;
- Washer;
- Dense medium separation in barrels.

The setup of the separation plant was designed to produce a combustible SRF fraction (38%). Other fractions coming out of the separation flow sheet are metals (6 wt%), fines (39 wt% dry mass) and a heavy fraction coming from the bottom of the dense media separation barrels. The results from these separation tests show a lower amount of fines with respect to the results from the second sampling campaign. On average, the SRF constitutes 38 wt% (dry mass), which matches the value previously observed for MSW. The main reason for the lower amount of fines compared to the data from the second sampling campaign is that the screening in the industrial scale trial occurred at 0–4 mm, while the second campaign used a screen of 0–10 mm. Based on these results, a material separation and recuperation flow sheet has been developed (Fig. 4). After the visual separation and milling, crushing or shredding, a series of drum screens separate materials based on size. Subsequently, for the fines fraction lower than 10 mm, wet separation is performed using the density separation principle. Fines are further washed and sieved. The fraction in excess of 10 mm is treated with dry separation steps, including air, magnetic and eddy current separation.

4.4. Energy recuperation and plasmarok valorization

The second sampling study found a lower amount of combustibles (i.e. 38 wt%) than was calculated from the landfill registry (50 wt%). The characterization of the materials obtained with the cactus grab crane showed that the direct use of these fractions is not an option for efficient energetic valorization. The average gross calorific value of MSW varies between 6.6 MJ kg^{-1} to 11 MJ kg^{-1} depending on the age (Quaghebeur et al., 2010). The calorific value of Industrial waste is even lower and ranges from 5.3 to 6.9 MJ kg^{-1} (Quaghebeur et al., 2010). However, the calorific values of the different (manually) separated CtC fractions show a gross calorific value for plastics of 19–28 MJ kg^{-1} (Quaghebeur et al., 2010). No systematic difference was observed correlated to age or type (IW or MSW) of waste. This is lower than what the literature indicates for plastics (35.4 MJ kg^{-1} dry ash free) (Phyllis, 2011). The Phyllis

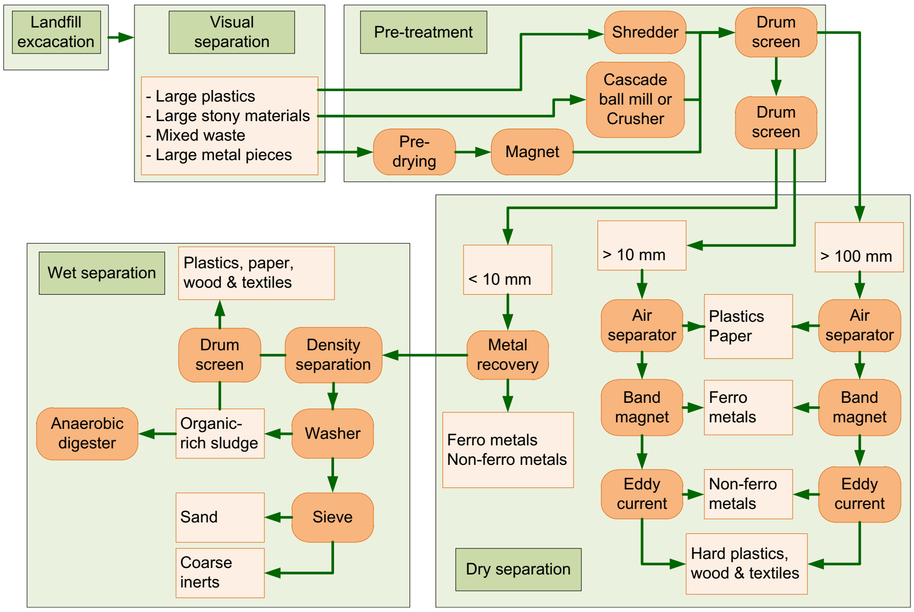

Fig. 4. General flow sheet of the intended material recuperation process within the CtC project.

database indicates an ash content of plastics of 1 wt%. However, in the case of the SRF recovered from the CtC project, an ash content of 29 ± 7 wt% was measured for the plastics fraction. The average gross calorific value for wood, paper/cardboard is, respectively, 18 MJ kg^{-1} and 11 MJ kg^{-1} (Quaghebeur et al., 2010). For wood, this is similar to the data in the Phyllis database (Phyllis, 2011). The ash content is 14.2 wt% and 41 wt% respectively. The calorific value of paper/cardboard is relatively low compared to the Phyllis database (18 MJ kg^{-1}) due to the high ash content (41 wt% compared to 10 wt %). Based on these data and the content of these waste fractions from the REMO landfill, an average gross calorific value for the combustibles was calculated as 19.4 MJ kg^{-1} (16–22 MJ kg^{-1}) and an ash content of 29 wt%.

The SRF produced from the separation of the excavated waste batches of 400 kg was analyzed as well. Relatively clean SRF was produced. Measurements by Bosmans et al. (2010) and Bosmans et al. (in this issue) show that the Gross Calorific Value of the SRF ranged between 19 and 25 MJ kg^{-1} dry matter or between 17 and 22 MJ kg^{-1} at a moisture content of 12 wt%. This corresponds with a net electrical efficiency of 16–21 MJ kg^{-1}. The net electrical efficiency is a measure of conversion of solid waste to net renewable electricity generated by the process and is defined as follows:

$$\text{Net Electrical Efficiency}(\%) = 100*(\text{Net power output from process})/(\text{Net energy content of the fuel fed to the system}) \quad (2)$$

The ash content of these fuels ranged between 20 and 33 wt% dry matter (Bosmans et al., 2010). Theoretical calculations performed with HSC Chemistry for Windows (Outokumpu Research Oy, Finland) allowed to calculate a net electrical efficiency of 25%–30% for a full scale operation (operated at thermodynamic equilibrium).

Pilot trial runs were performed in cooperation with Advanced Plasma Power in which the produced SRF was fed into the Gasplasma™ process to produce synthetic gas (syngas), which was fed into an engine for electricity production. Fig. 5 shows the summary flow sheet of this two-stage Gasplasma™ process (Chapman et al., 2011a,b; Bosmans et al., in this issue). The pilot test was performed to assess the theoretical efficiencies and to assess the stability of the operation. Two test campaigns were performed. Both SRFs are the recycling residue of a combination of MSW and IW obtained from the REMO landfill. As obtained through the characterization study of the landfill waste, they are representative for the intended WtE process for SRF from REMO. Net electrical efficiencies of 20% (campaign 1, SRF1) and 23% (campaign 2, SRF2) were obtained. The stability of the process was proven by longer runs (up to 75 h). Higher energy conversion efficiencies (cf. HSC calculations) are expected to be possible in future plasma converter designs (see also Chapman et al. (in press)).

The advantage of the plasma system is not only the production of clean syn gas and a good burnout. The residual ash resulting from the high ash content of this SRF is in a molten state at the temperature of the plasma converter (~1400 °C). The converter design allows that approximately 90% of the ash from the SRF will be captured in the slag bath. Cooling of the slag after tapping results in a dense and vitrified material. From the analysis of the vitrified slag through two-stage leaching tests (BS EN 12457-3) for granular materials, it is concluded that the material is safe to be used as an aggregate/gravel replacement (Chapman et al., 2011b). Nevertheless, the ELFM Consortium targets higher value applications. As plasmarok is produced from a melt this permits a high degree of flexibility. Depending on SRF chemistry and the cooling method applied, the following products can be developed: glass-ceramic monoliths for use as building materials or glass-ceramic aggregates for use in high strength concrete (controlled cooling in both cases), hydraulic binders (composition close to blast furnace slag, granulation required), pozzolanic binders or inorganic polymer precursors (lower CaO/SiO_2 basicity, granulation required). Depending on the target composition, the melt chemistry can be

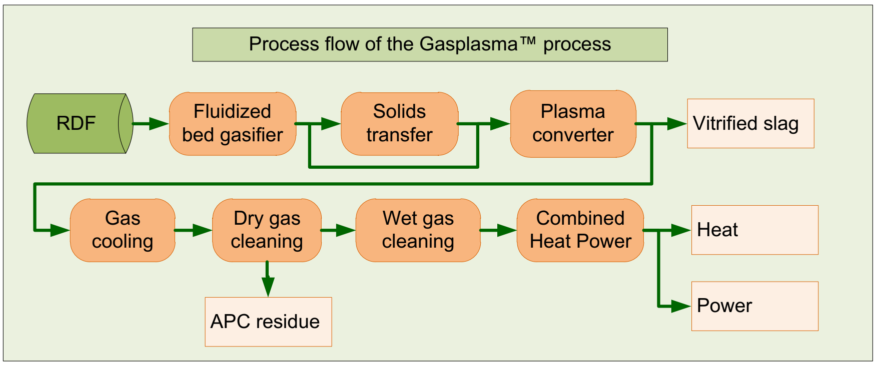

Fig. 5. Overview of the Gasplasma™ WtE/M process (RDF = Refuse Derived Fuel = SRF = Solid Recovered Fuel, Vitrified slag = plasmarok, APC = air pollution control).

corrected via additions of 'fines' or other sources. The fines to be produced during melting (a type of 'fly ashes', not to be confused with the fines from separation) can be re-introduced in the plasma reactor. On-going research has indicated the feasibility of the suggested techniques for several metallurgical residues (Kriskova et al., 2011, in press; Pontikes et al., 2011).

4.5. Overall CtC flow sheet

By combining all results an integrated flow sheet was developed for CtC (Fig. 6), including WtM, WtE, valorization of waste heat and CO_2 in greenhouses (Energy-to-Culture, EtC) and CO_2 emission reduction measures. Apart from the *ex situ* approach for the

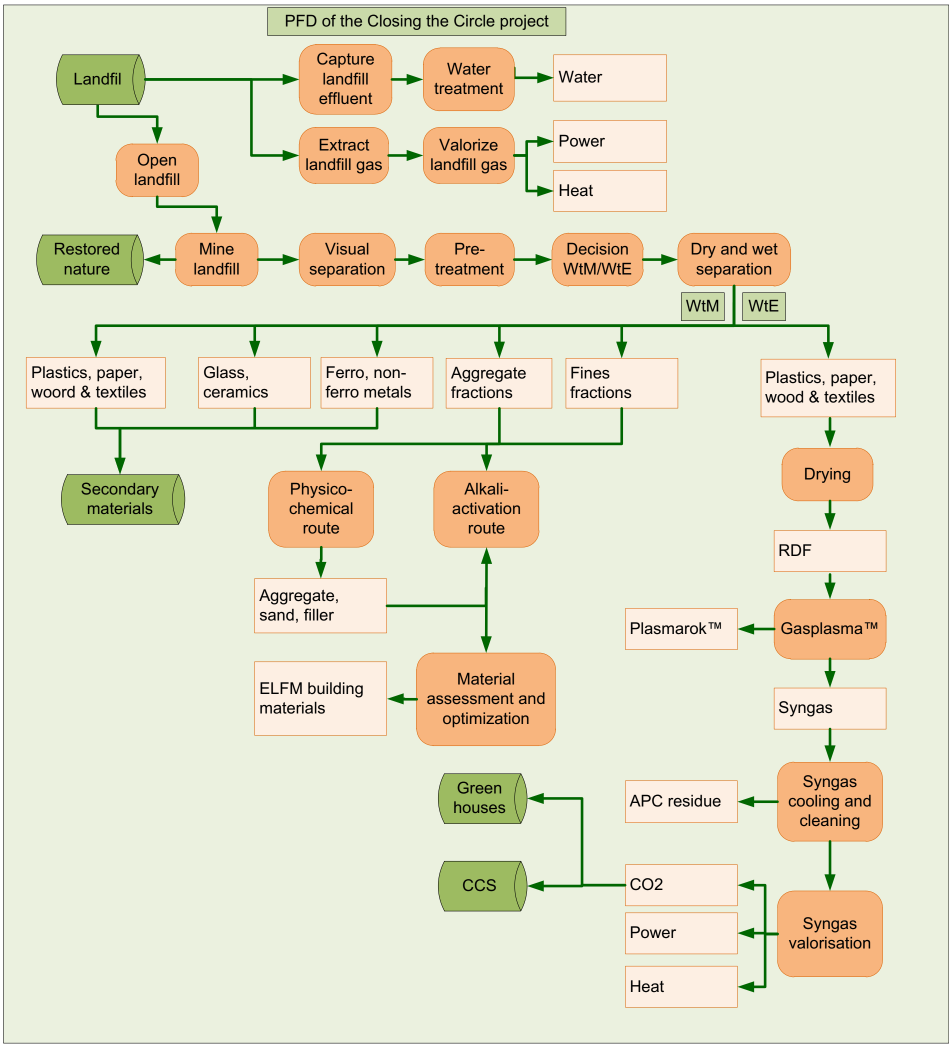

Fig. 6. General ELFM process flow diagram for the Closing the Circle project (RDF = SRF = Solid Recovered Fuel).

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landfills cells that are excavated, the flow sheet also shows the concurrent *in situ* CH_4 extraction for the other cells.

4.6. Environmental impact

De Vocht and Descamps (2011) have argued that an Environmental Impact assessment (EIA) of an ELFM project should be wide in scope and in time. A systems perspective is required, as corroborated by Udo de Haes et al. (2000) and Finnveden and Moberg (2005). The negative local effects must be evaluated against not only the positive local environmental impacts but also the off-site effects. De Vocht and Descamps (2011) and De Vocht (2009) have quantified the biodiversity related environmental impacts of CtC. Apart from the impact of noise, light, visual disturbance on animal populations and the eutrophication effects of nitrogen and sulphur deposition from the WtE plant, landfill mining will result in the partial loss of ecosystems. The REMO landfill site currently consists of dry siliceous grassland, dry heath and wooded heathland ecosystems, which have gradually developed after completion of the landfilling activities. Future landfill mining will therefore lead to the temporary loss of habitat, which has been estimated as a loss of 2.2–14.4 ha in time periods of 5 years (De Vocht, 2009). However, gradual ecosystem restoration is possible after the landfill mining activity (De Vocht, 2009). Habitat surface can vary in function of the targeted conservation goals. When a 75% open landscape is aimed for, 162 ha of dry heath can be restored (De Vocht, 2009).

Furthermore, CtC generates several positive, off-site environmental effects. Although the quantification of these impacts can be difficult, this step is indispensable (Lenzen et al., 2003). In CtC CO_2 and low temperature heat ($\sim$40–60°) arising from the WtE plant will be used in local horticulture (EtC) to, respectively, fertilise the plants and heat the greenhouses, avoiding the use of primary fossil fuels. A second, key example is related to the production of secondary raw materials through WtM. This not only saves energy (Ayres, 1997) but also has an influence on land occupation elsewhere. During a 20 year period CtC is expected to produce approximately 1.3 million metric ton of inert aggregates. As these aggregates can substitute gravel in construction applications (e.g. concrete), CtC will have an off-site impact upon local gravel extraction. The annual production of gravel for the local market in the Belgian province of Limburg is 1.9 million metric ton, which corresponds to approximately 12.4–37.3 ha of arable land that annually has to be converted for extraction (De Vocht, 2009). Replacing granulate production will reduce this type of land occupation by 0.4–1.3 ha each year.

4.7. Carbon footprint

As described above, the implementation of CtC goes hand in hand with a reduced use of fossil fuels for the production of electricity, heat and virgin materials, leading to an improved net carbon balance. A carbon footprint study was performed by de Gheldere et al. (2009), using the Bilan Carbone approach, which compares the carbon balance of the ‘do-nothing’ with the CtC scenario. The Bilan Carbone method is designed to estimate the greenhouse gas emissions (CO_2-equivalent or CO_2(eq)), wherever they may occur. The difference in energy and materials that are not produced by the CtC scenario will be produced on the market in the do-nothing scenario (which for this site already includes *in situ* CH_4 mining, see Fig. 2). With respect to the ‘do-nothing scenario’ the *ex situ* ELFM approach shows a net CO_2(eq) advantage of 1 million metric ton over a period of 20 years (de Gheldere et al., 2009). This result is obtained without taking into account any of the routes to sequester (e.g. through Enhanced Coal Bed Methane recovery, cf. Laenen and Van Tongeren, 2011), use (as in greenhouses) or offset (as in alternative binders replacing Ordinary Portland Cement) the produced CO_2 emissions from the WtE plant.

5. Non-technical barriers for CtC

Despite the many positive spill-overs, a number of ‘non-technical barriers’ need to be overcome. Wante and Umans (2011) and Hogland et al. (2011) have studied the ELFM concept with respect to the European Waste Framework (2008/98/EC) and Landfill (99/31/EC) Directives. They state that the provisions foreseen in connection with temporary storage are not suitable for CtC/ELFM. Indeed, the Waste Framework Directive considers ‘temporary storage’ either as preliminary storage of waste for the purposes of transport or as preliminary storage prior to recovery (code R13). In this case storage should be limited to three years (EU Landfill Directive). This implies that the storage of waste in ELFM sites needs to be considered as disposal, when storage exceeds a period of three years. Wante and Umans (2011) conclude that it is advisable to develop a dedicated legal framework for temporary landfills. On the other hand, the mining of old existing landfills seems to be less problematic from a legal point of view. Wante and Umans state that, although no provisions have been foreseen for this kind of activity, there are no specific barriers in the EU Waste Framework Directive that prevent Member States from performing this. Nevertheless, Wante and Umans (2011) advise to develop a specific framework that can be used as a legal basis for granting environmental permits.

Secondly, potentially affected communities might react negatively towards the plans of performing ELFM in their neighbourhoods. As broad public support is essential to proceed with ELFM, the ELFM Consortium employs a multi-actor collaboration approach (Craps and Sips, 2011). This involves participation in the local CtC Sounding Board and a series of interactive workshops to connect with local civil society representatives. Concurrently, national workshops are organized with industry, government, academics and civil society actors, which lead to the co-creation of a holistic ELFM approach.

A third non-technical barrier is related to the economics of ELFM. In line with the conclusions of Krook et al. (2012), economic benefits must simply outweigh the costs to make landfill mining feasible for individual companies. At present this is often not the case. As discussed by Van Passel et al. (in this issue) an ELFM project cannot be initiated if the (positive) externalities are not internalized in the private return. Government intervention is vital. The existence of external benefits of ELFM – *i.e.* reduced global footprint, land reclamation, avoided land use for primary mining, sustainable material and energy production – justify support mechanisms. An integrated decision tool to analyze the complex trade-off between economic, social and environmental aspects is therefore needed. The ELFM Consortium is developing a Life Cycle Assessment/Life Cycle Costing (LCA/LCC) based ELFM model (Van Passel et al., in this issue; Van Acker et al., 2011) to contribute to the much needed standardization frameworks for evaluating performance (Krook et al., 2012). Moreover, such a decision tool can support public actors to develop a tailored ELFM support scheme, including incentives for distinct combinations of material recycling, energy utilization and nature restoration.

6. Conclusions and outlook

In order for CtC/ELFM to mature, continuous technological innovation with respect to cost-effective separation and WtM/E transformation technologies is essential. The breakthrough of a process such as the Gasplasma system will depend on its ability to operate smoothly and apply the best system for energetic

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conversion of the syngas. A main challenge is the control of tar and the production of a high quality slag. Apart from the technological challenges also the non-technical barriers need to be addressed appropriately. Therefore, future EIAs should be wide in scope both spatially as in time, thereby realistically evaluating the many positive local and off-site effects against potentially negative, local short term effects on habitat size and quality.

Extrapolation calculations corroborate the economic, environmental and social potential of ELFM in Europe and beyond. As Europe has 150,000–500,000 landfills, the full implementation of ELFM would generate a CO_2 equivalent savings of 15–75 million metric ton CO_2(eq)/year during 20–30 years. This extrapolation is based on the CtC potential (de Gheldere et al., 2009) and the average size of the 150,000–500,000 EU landfills (8.000 m^2/landfill, Hogland et al. (2011)), with respect to the REMO landfill mass (18 million metric ton). Secondly, the full implementation of ELFM in Europe would generate a significant stream of secondary raw materials, thereby improving the EU's materials autonomy. Based on the values of Hogland et al. (2011) and Vossen (2005), related to the amount of landfills and the average amount of materials per landfill, the total amount of materials in landfills older than 1995 is in the range of 3.300–11.000 million metric ton. A value of 11.000 million metric ton of materials from landfills constitutes up to 5% of the yearly EU-27 Domestic Materials Consumption (8200 million metric ton in 2007) (Eurostat, 2010) for non-energy, non-food materials and minerals for the next 25 years.

Thirdly, apart from contributing to renewable and/or green energy production, Gasplasma™ WtE entails the production of major quantities of plasmarok slag. In case ELFM would be implemented on a European scale 250-840 million metric ton of plasmarok can be produced (extrapolation from CtC data to EU landfills). In the most ideal case plasmarok can be used as a direct substitute for cement. If one can manage to duplicate the blast furnace chemical composition (Kriskova et al., 2011), then the cement substitution can theoretically be as high as 95 wt% (Cement class: CEM III/C, EN 197-1 Cement Composition). Assuming a 50% replacement of cement, the produced plasmarok could, hypothetically, replace 125–420 million metric ton of cement in EU-27 (i.e. full potential for a total of 20–30 years). As per ton of cement an average of 0.65 ton of CO_2 is produced (Ecofys, 2009) this corresponds to a further reduction of CO_2 emissions of 3–11 million metric ton CO_2(q)/year in the EU-27.

Fourthly, Van Passel et al. (in this issue) conservatively estimated the long term (economic) potential for land reclamation from *ex situ* ELFM at more than 20 km^2 in Flanders only. Once more, this figure can be extrapolated to the EU level delivering a value of 6.000 km^2. Hogland et al. (2011) estimated the land reclamation in EU-27 to be between 2.800 and 4.000 km^2. If one includes the surrounding areas which are impacted by contaminants then one obtains a figure which roughly corresponds with the extrapolation from the Flemish situation. Finally, CtC is expected to create up to 800 jobs (i.e. 200 extra jobs for operating the WtE plant and up to 600 additional jobs in EtC horticulture). Using the same (0.2%) factor as for the CO_2 equivalent balance and the plasmarok production, one comes to a hypothetical figure of up to 0.24–0.8 Million (direct) new jobs (for a period of 20–30 years) in the EU-27.

To conclude, by combining (future) valorization of materials with energy production and land re-use, cost efficient resource recovery of landfills will generate economic, environmental and social spill-overs. As primary resources become more scarce and external costs of primary resources are internalized, ELFM will become more feasible. However, strategic policy decisions and tailored support systems for ELFM – underpinned by standardized LCA frameworks – will be indispensible to remove the remaining non-technical barriers.

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