Landfill mining: Resource potential of Austrian landfills – Evaluation and quality assessment of recovered municipal solid waste by chemical analyses

Tanja Wolfsberger[1], Alexia Aldrian[1], Renato Sarc[1], Robert Hermann[1], Daniel Höllen[1], Andreas Budischowsky[2], Andreas Zöscher[3], Arne Ragoßnig[4] and Roland Pomberger[1]

Abstract

Since the need for raw materials in countries undergoing industrialisation (like China) is rising, the availability of metal and fossil fuel energy resources (like ores or coal) has changed in recent years. Landfill sites can contain considerable amounts of recyclables and energy-recoverable materials, therefore, landfill mining is an option for exploiting dumped secondary raw materials, saving primary sources. For the purposes of this article, two sanitary landfill sites have been chosen for obtaining actual data to determine the resource potential of Austrian landfills. To evaluate how pretreating waste before disposal affects the resource potential of landfills, the first landfill site has been selected because it has received untreated waste, whereas mechanically–biologically treated waste was dumped in the second. The scope of this investigation comprised: (1) waste characterisation by sorting analyses of recovered waste; and (2) chemical analyses of specific waste fractions for quality assessment regarding potential energy recovery by using it as solid recovered fuels. The content of eight heavy metals and the net calorific values were determined for the chemical characterisation tests.

Introduction

Austria's Raw Material Initiative (Weber, 2012) has observed that the enormous demand of rising-economy countries like China has significantly changed the availability of primary materials (raw materials like ores, or energy resources like coal and gas) in the last 15 years. Additionally, few sources of some mineral raw materials (like iron ore and alloying elements, non-ferrous metals or hydrocarbons) are available in the European Union. These developments may engender lack of raw materials, highly competitive markets and much restricted accessibility of mineral resources. Consequently, the price of raw materials has steadily increased since 2003, the only interruption was the financial crisis of 2008 (Weber, 2012).

Reducing the consumption of primary raw materials, making Europe less dependent on imports and improving the efficiency of resource utilisation, requires promoting the recovery of used or waste materials (European Commission, 2010). Hence, 'urban mining' is gaining significance in addition to classical 'Mining', which is: exploration, extraction and treatment of mineral resources. One branch of urban mining is landfill mining (Buchert et al., 2013), when deposited wastes are retrieved from old landfill sites. A number of landfill mining projects have already been implemented to date. The first was established in Israel in 1953 (Kurian et al., 2003) to extract soil improvers. General reasons for landfill mining have been the reclamation of landfill capacity, the rehabilitation of contaminated sites or groundwater protection (Bockreis and Knapp, 2011; van Ommen, 1994; Zhao et al., 2007). Retrieving recyclables and energy-recoverable materials (REM) from landfills was the purpose in a few cases, except, when a high concentration of REM was expected as a result of waste composition or pretreatment (like metals from slag heaps (Frei, 2005)).

[1]Montanuniversitaet Leoben, Chair of Waste Processing Technology and Waste Management, Leoben, Austria
[2]NUA-Abfallwirtschafts GmbH, Traiskirchen, Austria
[3]AWV Mürzverband, Allerheiligen im Mürztal, Austria
[4]UTC Umwelttechnik und Technische Chemie ZT GmbH, Klagenfurt, Austria

Corresponding author:
Tanja Wolfsberger, Montanuniversitaet Leoben, Chair of Waste Processing Technology and Waste Management, Franz-Josef-Straße 18, 8700 Leoben, Austria.
Email: tanja.wolfsberger@unileoben.ac.at

The recent shift from waste management strategies towards resource management (according to the European Commission (2008)) has placed more emphasis on the recovery of secondary raw materials from sanitary landfill sites, such as metals, plastics or fractions with a high net calorific value (like paper, paperboard and cardboard (PPC), wood, etc.).

Taking this shift of focus into account, the term 'landfill mining' (LFM) is used in this article to describe a procedure for recovering secondary raw materials, excluding any remediation techniques employed at contaminated sites for predominantly environmental reasons. LFM involves excavation, sorting and waste treatment to obtain the highest amount of REM possible. These materials can subsequently be repurposed for material or energy production. Any non-recyclable waste (usually mineral and organic fines) is highly compacted and disposed into the landfill again, saving volume and landfill capacity (Rettenberger, 2010). Referring to the notion of regaining potential secondary raw materials from sanitary landfills, the focus of this study is laid on metals, glass, minerals and fractions with a high net calorific value (like plastics or wood). The entire REM, including metals, glass, minerals, PPC, plastics, wood, leather, rubber, textiles and composites, will hereinafter be called 'resource potential'. Waste fraction fines, problematic or hazardous and some other substances (see the 'Materials and methods' section for a definition) are not believed to possess resource potential. These fractions usually require further treatment and final landfilling (BMBF, 1995; BMLFUW, 2011; Frändegard et al., 2013; Hölzle, 2010).

To maximise the potential output of REM, however, the designated location for a landfill mining assignment must be accurately analysed and assessed. These assessments traditionally refer to historical data (like administration and/or business files, legal permissions, licensing and registration documents, registers or newspapers) or theoretical discussions of waste composition to be derived, for example, from results of past waste-sorting analyses. Data acquired in these surveys allow determining the resource potential, the relative proportion of each REM fraction and the amount of non-recyclables (like fines) by calculating and approximating. Also, hazardous substances or potential risks that can occur in the course of LFM can be identified in advance, and suitable measures be taken to ensure human and environmental safety.

The accuracy of these investigations for estimating the amount of REM in landfills is limited, however, because landfill bodies are persistently subject to chemical and biological degradation. Degradable organic substances (like paper or textile) are under aerobic or anaerobic conditions converted into carbon dioxide, methane and water. These degradation processes may cause a landfill's available resource potential to deviate remarkably from theoretical predictions, as mentioned above. Initial assessment should accordingly include random drilling or test pitting to obtain more reliable data on the current on-site composition and condition of a given landfill, followed by classifying and sorting excavated materials. Then, suitable excavation methods and treatment technologies can be established to maximise the recovery of REM.

Since the issue of landfill mining has been raised in Austria only very recently, little data is available on the actual on-site composition (like Knapp and Bockreis, 2010) and the quality of waste disposed in Austrian landfill sites. There, results of studies concluded elsewhere in Europe were reviewed to gather information on the resource potential. Relevant information on this approach is provided in Wolfsberger et al. (2014). The results of this research revealed a broad variety of REM content, ranging from 20 to 52 wt% (in terms of the original substance (wt%)). An exact estimation of the resource potential of Austrian landfill sites, based on research only, seems accordingly hard to achieve.

This article reports on an investigation of the waste composition of selected Austrian sanitary landfill sites – defined in Austria as 'mass-waste landfills' (BMLFUW, 2008) – by means of sorting analyses of waste after excavation. The investigation sought to answer the following questions.

- Which quantity of REM can be recovered from Austrian sanitary landfill sites?
- Does pretreatment of waste before disposal have any influence on the quantity of detectible REM?

For a precise description of the excavating and sorting procedures, see the 'Materials and methods: Landfill sites and manual sorting' section.

Further chemical analyses were carried out to assess the general quality of excavated REM and to identify how pretreating waste before landfilling affects quality (say, the content of heavy metal) of REM or the resource potential. Since landfill sites seem to contain a high amount of energy-recoverable materials (Hölzle, 2010), the chemical characterisation has focused on waste fractions that may be suitable for energy recovery applications (used as solid recovered fuels (SRF)). The scope of analyses was adapted from BMLFUW (2002), because the European Union does not set limits to contaminants in fuels regarding co-incineration of waste. According to European Commission (2000), the materials may substitute primary energy resources unless critical limit values for emissions are exceeded. In Austria, however, SRF themselves have to meet defined quality criteria, depending on the type of co-incineration plant (see Table 1), which are specified in the Austrian Waste Incineration Directive (BMLFUW, 2002).

In summary, the following issues shall be addressed by this chemical characterisation.

- What is the quality of REM from landfilled municipal solid waste (MSW) after recovery?
- Does pretreating waste before disposal affect the quality of REM?
- How do contaminants disperse among different REM fractions?
- Can excavated REM be recycled as SRF in Austria?

Table 1. Limit values (mg MJ^{-1} DM (dry matter)) for heavy metal concentration in SRF referring to the net calorific value (BMLFUW, 2002).

Parameter	Limit value					
	Cement plant		Power station		Other co-incineration plant	
	Median	80th percentile	Median ⩽15%*	80th percentile ⩽15%*	Median	80th percentile
Antimony (Sb)	7	10	7	10	7	10
Arsenic (As)	2	3	2	3	1	1.5
Lead (Pb)	20	36	15	27	15	27
Cadmium (Cd)	0.23	0.46	0.17	0.34	0.17	0.34
Chromium (Cr)	25	37	19	28	19	28
Cobalt (Co)	1.5	2.7	0.9	1.6	0.9	1.6
Nickel (Ni)	10	18	7	12	7	12
Mercury (Hg)	0.075	0.15	0.075	0.15	0.075	0.15

*Portion of heat capacity from co-incineration of waste.

Further information on the chemical analyses and the sampling procedure is provided in the 'Materials and methods: Chemical analyses' section. The findings of the excavation and sorting process, the consequences of pretreating waste before landfilling for the resource potential and the evaluation of REM quality, are discussed in the 'Results and discussion' section.

Materials and methods

Two different landfill sites have been selected to determine the influence of waste pretreatment before disposal on the resource potential: One containing non-treated waste and the other, mechanically–biologically treated (MBT) waste. The selection was based on defined criteria (like infrastructure, no surface sealing or good accessibility). Investigations included excavation, sampling and manual sorting of the waste samples. A detailed description of the locations, the examination methods applied and the sorting process is provided in the 'Landfill sites and manual sorting' section. Selected REM fractions were chemically characterised, to assess the availability of excavated waste for use as SRF and to identify how waste pretreatment affects REM quality. Details of the characterisation are provided in the 'Chemical analyses' section.

Landfill sites and manual sorting

Landfill site 1 (LFS 1) is located in Lower Austria and has been used to discharge mainly MSW from 1982 until 2003. The landfill extends across an area of almost 78,000 m^2 and is divided into four compartments. Waste discharged in LFS 1 has not been treated before landfilling. Six locations have been chosen for detailed waste composition evaluation in compartment 2 to explore the area accurately, holding approximately 141,158 t of MSW discharged between 1990 and 2000. Bore holes were driven by a gripper (port diameter of 80 cm) in April 2013, with their depths varying between 7 and 18 m. Samples were taken from every other meter in compliance with ASI (2002). A total of about 3.5 t of waste were collected from 32 samples (their water content varied between 29% and 55%; gravimetric determination compliant with ASI (2007)), with a volume of 240 L each (waste raw density: ~0.5 t m^{-3}) and sieved with a mesh size of 40 mm. Next, sieve oversize and undersize material was manually sorted into the following fractions, corresponding to the Austrian Federal Waste Management Act (BMLFUW, 2011): Iron and non-ferrous metals, glass, minerals (like concrete, stones), PPC, plastics, wood, textiles, composites (like diapers), problematic substances (like batteries), others (like foam materials) and sorting residue (decomposed and unspecified materials that could not be visually identified). Manual sorting was implemented in compliance with ÖNORM S 2097 (ASI, 2005a).

Landfill site 2 (LFS 2) is located in the federal state of Styria and has been in operation since 1979. It has been used mainly for dumping MSW until 2004, followed by mainly landfilling slag and ashes from waste incineration. A significant amount of MSW has been pretreated by a MBT process before dumping at the landfill (about 72 wt% from 1979 to 1984 and 55 wt% from 1985 to 1988). The waste has been shredded in the MBT plant and sieved with a mesh size of 80 mm. Iron has been separated from the waste flow with a magnetic separator. Oversize materials or bulky waste (as received) has been dumped directly. Screen underflow has been mixed with sewage sludge (annual amount: ca. 5 wt% of delivered MSW), subjected to aerobic biological treatment (ca. 24 wt% of delivered MSW between 1979 and 1984 and 18 wt% between 1985 and 1988) and then dumped as MBT-stabilised compost-like material. The landfill body covers an area of approximately 10 hectares, which is divided into four compartments, with compartments 1 and 2 containing MBT and bulky waste deposited between 1979 and 1988. These compartments have been chosen for the survey described in this article. Compliant with ÖNORM S 2121 (ASI, 2002), 50 test pits were excavated in compartments 1 and 2 at a distance of 25 m and a depth of 5–6 m to investigate the area properly and to gain representative waste samples. After excavation, 14 mixed samples (water content between 36% and 50%; gravimetric determination compliant with ASI (2007)) were collected from these 50 test
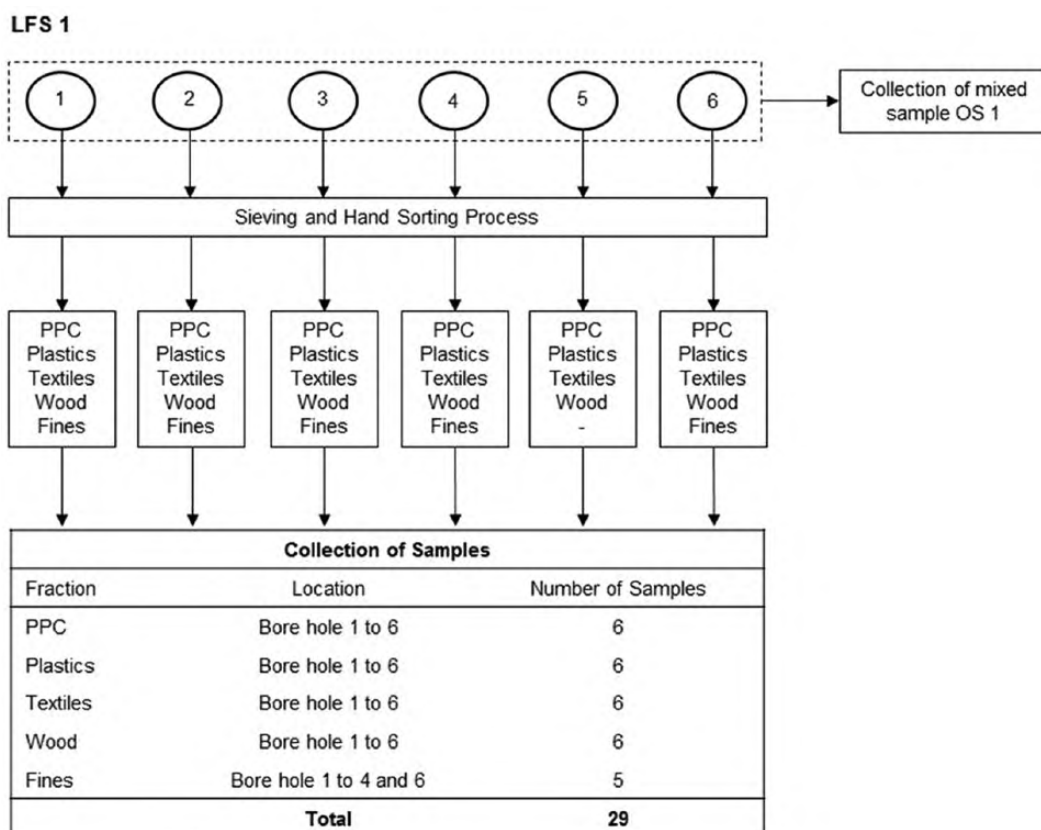
LFS 1

Figure 1. Collection of samples from LFS 1.
LFS: landfill site; PPC: paper, paperboard and cardboard.

pits. Samples from the test pits in a 25×25 m grid have been mixed and quartered with an excavator. About 500 to 700 kg of each mixed sample (8.3 t in total) have been sieved with a mesh size of 40 mm. Sieve overflow (~20 wt%) and sieve underflow (~80 wt%) have been manually sorted afterward. Visual evaluation has yielded a homogenous appearance of the sieve under-flow's composition. Sorting a representative sample seemed therefore sufficient for characterisation. A sample of 1.5 t (6.7 t in total) has been taken and sorted compliant with ÖNORM S 2097 (ASI, 2005a) and the waste separated into the previously mentioned fractions in compliance with the Austrian Federal Waste Management Act (BMLFUW, 2011).

Chemical analyses

As already mentioned, chemical characterisation has focused on energy recovery from particular REM (use as SRF) according to Austrian legislation. Hence, to gain a first impression of the land-fill sample's quality (a mixture of all sorts of waste), mixed samples from LFS 1 (OS 1) and LFS 2 (OS 2) have been analysed, compliant with BMLFUW (2002), and the following parameters determined: Net calorific value (NCV), antimony (Sb), arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), cobalt (Co), nickel (Ni) and mercury (Hg).

The waste fractions of PPC, plastics, wood, textiles and fines (smaller than 20 mm) have been chosen for detailed examination

to learn more about the dispersion of heavy metals in the exca-vated mixed sample (OS 1 and OS 2) and to see whether SRF could be recovered from REM. Total Organic Carbon (TOC) values of fines have been additionally examined to obtain infor-mation about the degree of degradation.

The samples have been taken in compliance with ÖNORM S 2127 (ASI, 2011). With regard to LFS 1, samples of PPC, plastics, wood, textiles and fines have been individually taken from each bore-hole (except for the fines) after sieving and manual sorting (see Figure 1), resulting in six samples of the fractions PPC, plas-tics, wood and textiles (from bore-holes 1 to 6) and five samples of fines (from bore-holes 1 to 4 and 6), or 29 samples altogether.

Concerning LFS 2, four laboratory samples of the fractions PPC, plastics, wood, textiles and fines had to be gained from the 14 mixed samples (see Figure 2). The individual fractions gained from sieving and manual sorting of the mixed samples 1 and 2 (MPA) 3, 4 and 5 (MPB) 6, 7, 8 and 9 (MPC) as well as 10, 11, 12, 13 and 14 (MPD) have been combined for this purpose (20 samples in total).

Two mixed samples have been prepared for the analyses of OS 1 from LFS 1 and OS 2 from LFS 2 (see Figure 1 and 2), consisting of material from bore-holes 1 to 6 (LFS 1) and MPA to MPD (LFS 2). Heavy-metal contents have been assessed in com-pliance with ASI (2005b) using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). To establish comparability with the requirements of the Austrian Landfill Directive (BMLFUW,
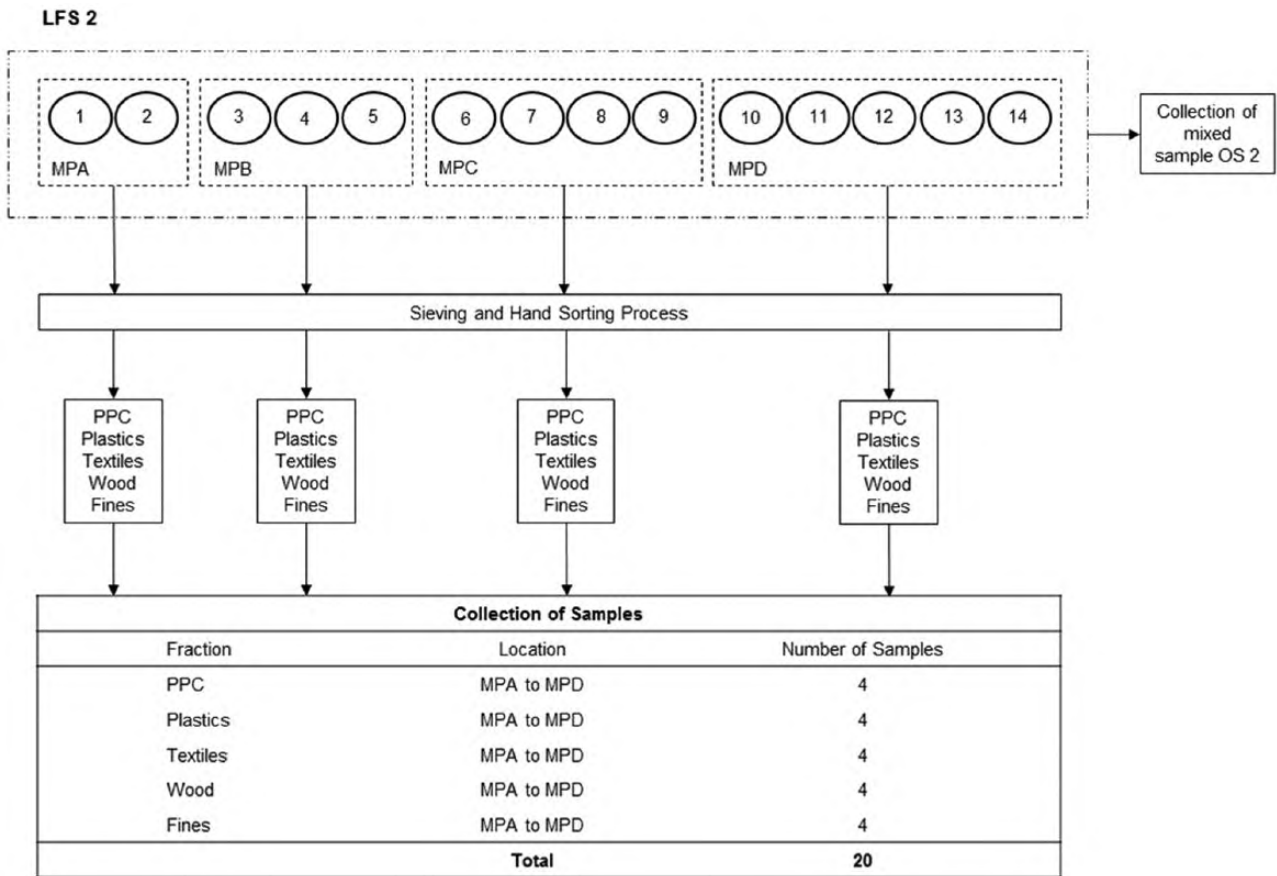
Figure 2. Collection of samples from LFS 2.
LFS: landfill site; PPC: paper, paperboard and cardboard.

2008), heavy metal contents of fines have been analysed in compliance with ASI (2005c) applying ICP-MS. TOC values have been examined in compliance with ASI (2001) using a TOC analyser (combustion unit with infrared-detection). Net calorific values have been calculated according to GIS (2000) by applying bomb calorimetry.

To assess whether the materials may suit as SRF, the measurements achieved have subsequently been compared with the limit values shown in Table 1. Each parameter determined has been recalculated for this purpose and related to its NCV as in equation (1):

$$Content_{NCV} = \frac{Content}{NCV} \qquad (1)$$

where $Content_{NCV}$ is the heavy metal content related to the NCV (mg MJ^{-1} DM) and $Content$ is the heavy metal content according to analysis (mg kg^{-1} DM).

Two specifications from BMLFUW (2002) have been further considered to compare the results with the limit values.

1. Austrian law stipulates that median and 80th percentile have to be calculated if more than five measuring values of any waste are available (to take account of statistic deviations). Both median and 80th percentile must stay below the limit values provided in BMLFUW (2002) and shown in Table 1 if the waste is supposed to be used as SRF.

2. Determine the arithmetic mean value if there are less than five measuring values available. Legal provisions stipulate that this mean value shall not exceed the limit value of the median nor shall any measuring value exceed the limit of the 80th percentile.

Observing these specifications, median and 80th percentile have been calculated based on the analysis of PPC, plastics, wood, textiles and fines from LFS 1 (six measurements altogether) for each waste fraction. As for LFS 2, four measurements have been taken (MPA to MPD); the mean value has been generated and compared with the limit values.

Results and discussion

Sorting analyses

The results obtained for waste originating from LFS 1 (summarised for all 32 investigated samples) and from LFS 2 (shown separately for compartment 1 and 2) are provided in Table 2.

Materials >40 mm (i.e. sieve overflow) constitute approximately 32 wt% for LFS 1 and 16–23 wt% for LFS 2. Hence, the portion of materials <40 mm (i.e. sieve underflow) can be established at around 68 wt% (LFS 1) and 77–84 wt% (LFS 2), respectively. The higher content of fines (<40 mm) in LFS 2 can be explained by the mechanical–biological pretreatment of waste before disposal.

Table 2. Summarised results on the composition of sieve overflow and underflow fractions of deposited materials at LFS 1 and 2 (wt%).

Waste material	LFS 1 Compartment 2			LFS 2 Compartment 1			LFS 2 Compartment 2		
	Coarse	Fines	Total	Coarse	Fines	Total	Coarse	Fines	Total
Minerals	3.4	6.6	5.6	5.0	1.7	2.2	12.3	4.4	6.2
Glass	0.3	1.4	1.0	0.6	0.5	0.5	0.2	0.8	0.7
Metals	10.8	1.9	4.7	6.1	1.8	2.5	3.1	2.1	2.3
Wood, leather, rubber	16.9	5.9	9.4	7.7	1.5	2.5	7.8	1.9	3.3
Plastics	32.2	11.6	18.2	40.2	12.5	16.9	40.0	19.5	24.2
PPC	3.5	3.0	3.2	7.1	1.1	2.1	4.9	1.0	1.9
Textiles	13.8	1.9	5.7	12.6	1.4	3.2	13.8	3.2	5.6
Composites	9.9	1.0	3.8	8.3	0.3	1.6	9.3	0.7	2.7
Problematic substances	0.1	0.1	0.1	0.3	0.2	0.2	0.5	0.0	0.1
Others	2.0	1.1	1.4	7.8	0.1	1.3	5.0	0.3	1.4
Sorting residue	7.0	65.6	46.8	4.2	79.1	67.1	2.9	66.0	51.5
Resource potential (REM)	91	33	52	88	21	32	91	34	47
Non-recyclables	9	67	48	12	79	68	9	66	53
Further information									
Sieve size	40 mm			40 mm			40 mm		
Fines (w%)	68			84			77		
Period of filling	1990–2000			1979–1984			1985–1988		
Maturity of waste (years)	13–20			24–30			25–29		

LFS: landfill site; PPC: paper, paperboard and cardboard; REM: recyclables and energy-recoverable materials.

The investigation has found that the resource potential (i.e. the sum of REM) in the coarse fraction of LFS 1 is approximately 91 wt% vs. 88–91 wt% for LFS 2. In both landfills it consists mainly of textiles and plastics. Regarding the influence of pretreatment of waste before disposal on the resource potential, no significant differences have been observed between the portions of minerals, glass, plastics, PPC, textiles and composites in the coarse fractions. There are disparities for iron and non-ferrous metals, as well as for wood, which can be attributed to the magnetic separation and biological treatment implemented on LFS 2.

The amount of REM in the fines was measured as 33 wt% for LFS 1 and 21–34 wt% for LFS 2, indicating a much lower resource potential than those for coarse fractions. No significant variations (and therefore no influence of pretreatment) in the portions of particular waste have been detected by comparing results from LFS 1 and LFS 2.

The portion of non-recyclables (i.e. sum of the problematic substance, others and sorting residue fractions) adds up to ca. 9 wt% in the coarse fraction and 67 wt% in fines for LFS 1 and 9–12 wt% in the coarse fraction and 66–79 wt% in fines for LFS 2; it is mainly composed of sorting residue. With regard to the high amount of non-recyclables in both landfills, the total resource potential (i.e. the total REM in the coarse fraction and fines) is 52 wt% for LFS 1 and 32–47 wt% for LFS 2. Observing that especially PPC, plastics, wood, leather, rubber, textiles and composites seem suitable for incineration or co-incineration (SFR), about 40 wt% from LFS 1 and 26–38 wt% from LFS 2 might be used in energy recovery (see Figure 3). A total of 11 wt% (LFS 1) and 5–9 wt% (LFS 2), respectively, seem to be suitable for material recovery (adding up the minerals, glass and metals fractions).

Chemical analyses

The findings of the chemical analyses of OS 1 and OS 2 are shown in Table 3.

The results obtained for OS 1 and OS 2 show a high degree of heavy metal contamination for both landfills. However, materials pretreated before disposal that were extracted from LFS 2 seem to contain even higher portions of heavy metals (mg kg^{-1} DM) than the untreated materials from LFS 1. The results of lead, cadmium and mercury in OS 2 exceed the findings for OS 1 by more than twice as much. By contrast, the nickel content of untreated materials from LFS 1 is more than three times higher than the content found in LFS 2. Since nickel is often used in alloys, its presence is presumably owed to the higher amount of iron in LFS 1 (magnetic separation on LFS 2 before landfilling). Lead has been used in many products like glass, accumulators, paintings, foils, cable sheathings, plastics or electronic devices (Stahl, 2002; UBA, 2009). Cadmium can be found in batteries and was also utilised in colour pigments and as a stabiliser in plastics (Stahl, 2002; UBA, 2009). Mercury is a common part of electrical equipment, thermometers, porcelain or disinfectants (Stahl, 2002). Since both landfill sites contain MSW, however, the variations in lead, cadmium and mercury mentioned above cannot be attributed to different landfill content
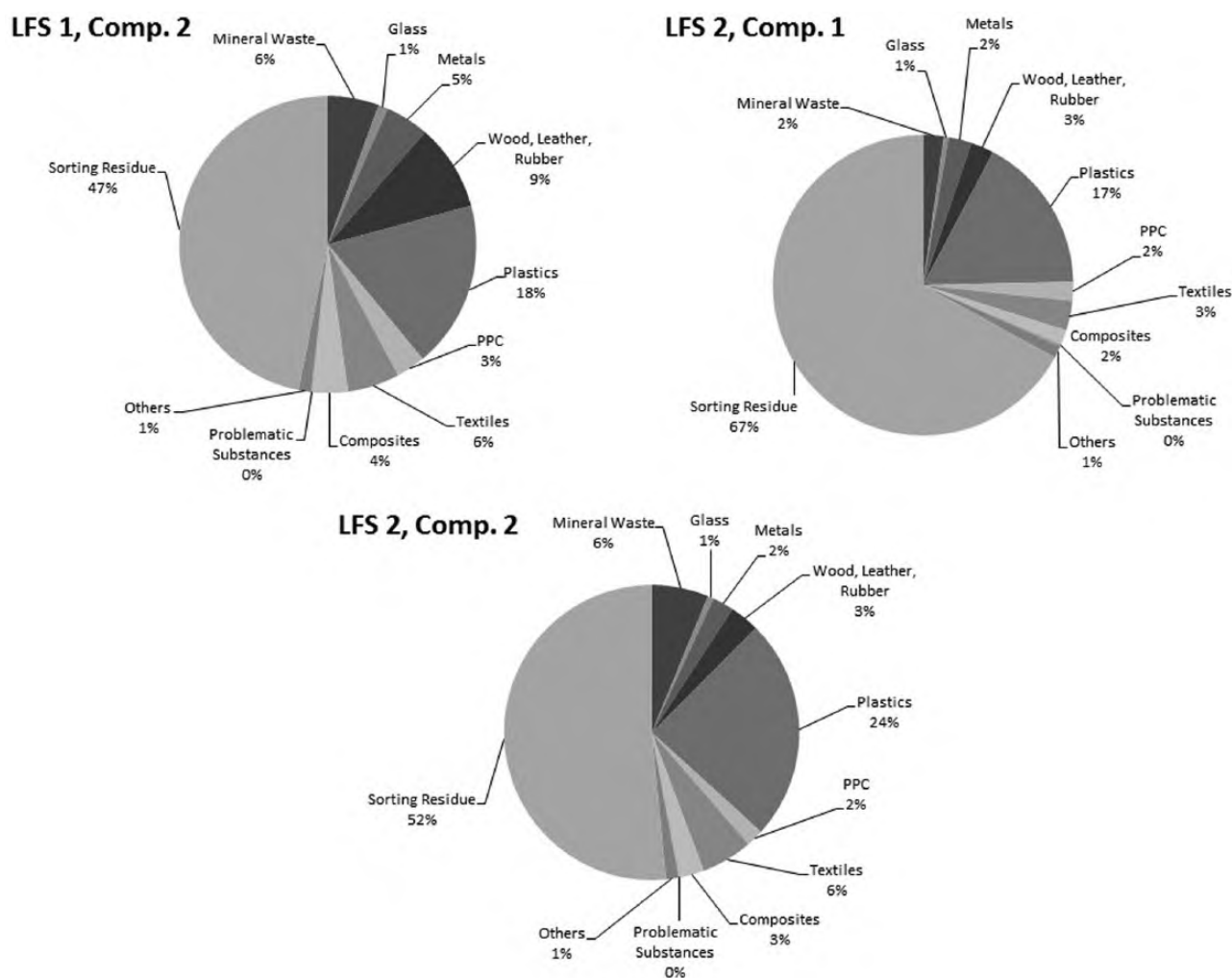
Figure 3. Composition of LFS 1 (compartment 2) and LFS 2 (compartment 1 and 2) including fines.
LFS: Landfill site; PPC: paper, paperboard and cardboard.

Table 3. Results of the chemical characterisation for OS 1 (LFS 1, compartment 2) and OS 2 (LFS 2, compartment 1 and 2).

Parameter	OS 1	OS 2	OS 1	OS 2
	mg kg^{-1} DM		Mg MJ^{-1} DM	
NCV (kJ kg^{-1} DM]	10,900	10,750	–	–
Sb	22	33	2	3
As	13	33	1.2	3.1
Pb	250	1,420	23	132
Cd	4.9	13.5	0.45	1.26
Cr	150	360	14	33
Co	10	21.5	0.9	2.0
Ni	580	157.5	53	15
Hg	0.4	7.65	0.037	0.712

DM: dry matter; NCV: net calorific value.

entirely. It is known, however, that contaminants concentrate on small substances, owing to their higher specific surface area. Higher heavy metal contents in OS 2 may presumably be ascribed to the mechanical–biological treatment applied before disposal that increased the portion of fines in LFS 2 accordingly.

The measurements of OS 1 and OS 2 have been recalculated (see equation (1)), to superficially assess whether excavated MSW is applicable as SRF, referred to their NCV and compared with limit values depicted in Table 1. Note that this comparison does not clearly indicate suitability, because only one sample per landfill site has been analysed, leaving no chance to detect statistical deviations (such as median, 80th percentile). The measurements of both landfill materials exceed the specified limits. Especially in OS 2, the measurement exceeds nearly all limit values (except for antimony) so that OS 2 cannot be used as SRF in cement, power or other co-incineration plants. Owing to a high content of nickel in OS 1, the limit value for cement, power and other co-incineration plants that would be compliant with BMLFUW (2002) cannot be observed. The analytical results of OS 1 indicate that the limit values of other co-incineration plants are also exceeded: Both the lead and cadmium values for use in cement, power and other co-incineration plants and the cobalt value for power and other co-incineration plants.

Results obtained for the PPC, plastics, wood, textiles and fines fractions are summarised in Table 4 and Table 5, shown for

Table 4. Results of the chemical characterisation of selected waste fractions from sample 1 to 6 from LFS 1.

Parameter	LFS 1 (compartment 2)												Median	80th percentile
	1	2	3	4	5	6	1	2	3	4	5	6	Mg MJ^{-1} DM	
	Mg kg^{-1} DM (NCV in kJ kg^{-1} DM)						Mg MJ^{-1} DM							
PPC														
NCV	14,500	10,200	13,100	16,100	9500	9200	–	–	–	–	–	–	–	–
Sb	21	12	22	4	7.2	6.4	1	1	2	0	1	1	1	1
As	4.6	9.4	5.5	2.7	9	8.8	0.3	0.9	0.4	0.2	0.9	1.0	0.7	0.9
Pb	140	220	61	42	130	170	10	22	5	3	14	18	12	18
Cd	3.2	1.3	0.69	0.99	1.2	0.92	0.22	0.13	0.05	0.06	0.13	0.10	0.11	0.13
Cr	61	95	80	20	100	110	4	9	6	1	11	12	8	11
Co	6.3	10	5.8	2.1	9.1	7.8	0.4	1.0	0.4	0.1	1.0	0.8	0.6	1,0
Ni	82	55	45	16	40	51	6	5	3	1	4	6	5	6
Hg	5	0.76	<0.25	<0.25	<0.25	0.3	0.345	0.075	0.019	0.016	0.026	0.033	0.075	0.075
Plastics														
NCV	19,700	18,000	21,300	19,500	29,500	22,800	–	–	–	–	–	–	–	–
Sb	22	12	22	11	16	24	1	1	1	1	1	1	1	1
As	7.1	8.9	8	9.1	5.1	8.9	0,4	0,5	0,4	0,5	0,2	0,4	0.4	0.5
Pb	190	600	200	180	310	350	10	33	9	9	11	15	10	15
Cd	1.1	1.2	2	8	1	2	0.06	0.07	0.09	0.41	0.03	0.09	0.07	0.09
Cr	78	130	120	87	65	150	4	7	6	4	2	7	4	7
Co	7.7	7.9	8.4	16	7.5	11	0.4	0.4	0.4	0.8	0.3	0.5	0.4	0.5
Ni	23	51	63	170	160	72	1	3	3	9	5	3	3	5
Hg	0.63	2.2	0.37	1.2	3.5	0.54	0.032	0.122	0.017	0.062	0.119	0.024	0.062	0.119
Wood														
NCV	19,000	18,700	23,300	16,600	17,000	17,200	–	–	–	–	–	–	–	–
Sb	3	2.1	3.5	4.7	4.4	3.5	0	0	0	0	0	0	0	0
As	3.9	5	3.9	3.4	3.3	5	0.2	0.3	0.2	0.2	0.2	0.3	0.2	0.3
Pb	90	98	430	110	260	130	5	5	18	7	15	8	7	15
Cd	0.83	0.56	< 0.50	5	1.1	1	0.04	0.03	0.01	0.30	0.06	0.06	0.06	0.06
Cr	37	53	76	38	77	100	2	3	3	2	5	6	3	5
Co	2.9	4.6	3.5	3.1	3.7	3.8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ni	13	30	26	32	23	43	1	2	1	2	1	3	1	2
Hg	<0.25	0.36	<0.25	0.32	0.25	0.25	0.013	0.019	0.011	0.019	0.015	0.015	0.017	0.019
Textiles														
NCV	23,900	25,000	21,400	19,100	17,200	15,600	–	–	–	–	–	–	–	–
Sb	1.8	28	4.5	3.6	73	92	0	1	0	0	4	6	1	4
As	<2.5	7.4	4.7	4.3	6.1	11	0.1	0.3	0.2	0.2	0.4	0.7	0.3	0,4
Pb	58	210	120	81	200	530	2	8	6	4	12	34	7	12
Cd	0.74	2	1.3	2.7	3.4	8.4	0.03	0.08	0.06	0.14	0.20	0.54	0.11	0.20
Cr	23	120	58	48	65	95	1	5	3	3	4	6	3	5
Co	1.6	9.3	4.5	6.4	8.1	9.8	0.1	0.4	0.2	0.3	0.5	0.6	0.4	0,5
Ni	6.8	64	40	69	62	46	0	3	2	4	4	3	3	4
Hg	1.8	1.8	<0.25	<0.25	0.45	0.59	0.075	0.072	0.012	0.013	0.026	0.038	0.055	0.072
Fines (<20 mm)														
NCV	9000	4400	5700	4700	–	5000	–	–	–	–	–	–	–	–
Sb	3	4	6.1	3.6	–	3.1	0	1	1	1	–	1	1	1
As	16	21	23	21	–	18	0.7	0.8	1.1	1.1	–	1.2	1.1	1.2
Pb	240	140	570	230	–	110	10	6	27	12	–	7	10	20
Cd	1.6	4.8	2.5	3.4	–	0.84	0.07	0.19	0.12	0.18	–	0.05	0.12	0.19
Cr	130	140	170	150	–	170	5	6	8	8	–	11	8	10
Co	6.6	12	17	11	–	13	0.3	0.5	0.8	0.6	–	0.8	0.6	0.8
Ni	45	51	60	45	–	52	2	2	3	2	–	3	2	3
Hg	0.54	0.42	0.4	0.43	–	0.6	0.023	0.017	0.019	0.023	–	0.038	0.023	0.031

DM: dry matter; LFS: landfill site; NCV: net calorific value; PPC: paper, paperboard and cardboard.

Table 5. Results of the chemical characterisation of selected waste fractions from sample MPA to MPD from LFS 2.

Parameter	LFS 2 (compartment 1 and 2)									
	MPA	MPB	MPC	MPD	Mean	MPA	MPB	MPC	MPD	Mean
	Mg kg^{-1} DM (NCV in kJ kg^{-1} DM)					Mg MJ^{-1} DM				
PPC										
NCV	12,600	12,800	12,800	14,800	13,250	–	–	–	–	–
Sb	12	15	9.4	5.8	11	1	1	1	0	1
As	15	14	19	5.6	13.4	1.2	1.1	7.5	0.4	1.0
Pb	540	680	900	290	603	43	53	70	20	45
Cd	3.3	9	5.1	2.3	4.9	0.26	0.70	0.40	0.16	0.37
Cr	120	110	700	550	370	10	9	55	37	28
Co	11	14	34	7.7	16.7	0.9	1.1	2.7	0.5	1.3
Ni	57	51	73	40	55.3	5	4	6	3	4
Hg	1.2	1.2	2.6	1	1.5	0.095	0.094	0.203	0.068	0.113
Plastics										
NCV	18,900	18,000	13,000	12,500	15,600	–	–	–	–	–
Sb	15	26	41	52	34	1	1	3	4	2
As	28	29	30	23	27.5	1.5	1.6	2.3	1.8	1.8
Pb	880	1320	830	1300	1083	47	73	64	104	69
Cd	14	39	19	24	24.0	0.75	2.17	1.46	1.92	1.54
Cr	260	400	490	380	382.5	14	22	38	30	25
Co	15	15	19	29	19.5	0.8	0.8	1.5	2.3	1.3
Ni	120	92	130	370	178	6	5	10	30	11
Hg	2.5	2.8	2.2	1.9	2.4	0.132	0.156	0.169	0.152	0.151
Wood										
NCV	15,200	15,600	14,100	16,000	15,225	–	–	–	–	–
Sb	7.3	2.6	13	8	8	0	0	1	1	1
As	17	7.9	12	8	11.2	1.1	0.5	0.9	0.5	0.7
Pb	370	380	250	130	283	24	24	18	8	19
Cd	2.8	3	8.7	1.6	4.0	0.18	0.19	0.62	0.10	0.26
Cr	58	45	70	90	66	4	3	5	6	4
Co	7.2	4.8	7.8	4.9	6.2	0.5	0.3	0.6	0.3	0.4
Ni	67	32	41	30	42.5	4	2	3	2	3
Hg	0.84	0.61	0.66	0.93	0.8	0.055	0.039	0.047	0.058	0.050
Textiles										
NCV	12,700	11,300	14,900	15,500	13,600	–	–	–	–	–
Sb	42	28	31	32	33	3	2	2	2	2
As	31	38	29	19	29.3	2.4	3.4	1.9	1.2	2.2
Pb	460	560	780	480	570	36	50	52	31	42
Cd	9.2	6.2	7.3	7.5	7.6	0.72	0.55	0.49	0.48	0.56
Cr	2000	500	1060	320	970	157	44	71	21	71
Co	15	16	17	12	15.0	1.2	1.4	1.1	0.8	1.1
Ni	91	110	86	85	93	7	10	6	5	7
Hg	2.5	2	2	2	2.1	0.197	0.177	0.134	0.129	0.156
Fines (<20 mm)										
NCV	4500	4600	4000	3900	4250	–	–	–	–	–
Sb	57	27	26	25	34	4	2	2	2	2
As	40	38	35	32	36.3	3.1	3.4	2.3	2.1	2.7
Pb	2280	1500	3300	1000	2020	180	133	221	65	149
Cd	12	18	4.7	5	9.9	0.94	1.59	0.32	0.32	0.73
Cr	320	230	270	370	298	25	20	18	24	22
Co	23	21	24	36	26.0	1.8	1.9	1.6	2.3	1.9
Ni	170	130	150	180	158	13	12	10	12	12
Hg	9.2	3	1.7	2	4.0	0.724	0.265	0.114	0.129	0.292

DM: dry matter; LFS: landfill site; NCV: net calorific value; PPC: paper, paperboard and cardboard.

LFS 1 and LFS 2 each, to provide information about the distribution of heavy metals in OS 1 and OS 2, respectively.

The measurements allow deducing on an even distribution of heavy metals for materials from LFS 1, with the exception of cadmium and lead whose highest concentrations have been found in the plastics, textiles and fines fractions. The distribution of lead in textiles was confirmed by Stahl (2002) who stated that the concentration of lead in textiles was three times higher than those in other waste fractions of MSW. Results similar to those of Stahl (2002) can be obtained for the concentration of cadmium in plastics. By contrast, Stahl (2002) states that the content of lead in plastics is low.

Findings in materials extracted from LFS 2 suggest a heterogeneous distribution of antimony, arsenic, nickel and mercury, as well as cadmium and lead, showing the highest concentrations in plastics and fines, while PPC and wood have lower contamination levels. Chromium seems to be concentrated in textiles because the result of the analyses indicates values that are more than twice as high as those of other fractions.

Comparing the findings (see Figure 4) reveals that the heavy metal results of the PPC, plastics, textiles and fine fractions in LFS 2 are many times higher than those of LFS 1. Significant variations can be observed in the concentration of lead. The wood fractions of both landfill sites appear to be least contaminated, whereas the fines fraction seems to be one of the most contaminated (especially in LFS 2). Fines, in turn, adhere to other waste fractions as impurities (as has been noticed during manual sorting). Hence, contamination of all waste fractions can be observed, decreasing the quality of excavated materials. Since fines seem to strongly affect the quality of REM, this fraction has been closer examined. One possible explanation of the high difference in heavy metal content of fines from LFS 1 and LFS 2 is higher degradation in LFS 2 owing to biological treatment in the MBT plant and the age of the waste. In this case, the TOC value for fines from LFS 2 would have to be much lower than for LFS 1. However, the analysis results show TOC values between 10% and 20% for fines from LFS 1 and ca. 10–16% for fines from LFS 2. Slightly higher TOC values can be found for fines in LFS 1 only. This high deviation of the heavy metal content cannot be entirely explained by a higher degree of decomposition in LFS 2. Therefore, the analysis results suggest that pretreating waste before disposal has produced additional heavy metal mobilisation in the examined landfill because leaching processes have been promoted by mechanical comminution (more waste has been available). These heavy metals may have accumulated on fines (high specific surface area), leading to stronger contamination of materials from LFS 2. There is an influence of sewage sludge on the heavy metal concentration in the MBT-stabilised, compost-like material deposited in the examined landfill. However, heavy metal content of sewage sludge that had been transported to LFS 2 in the period from 1979 until 1988 has not been analysed in this article.

To answer the question whether excavated waste may substitute primary energy resources, the analytical results have been correlated with the limit values (see Table 1). In view of BMLFUW (2002) requirements, the limit values for SRF usage of LFS 1 materials (PPC, plastic, wood, textiles and fines) in cement or power plants have not been exceeded. Slight transgression of the limit value in arsenic has to be considered when assessing the usage of fines in other co-incineration plants.

Regarding the results for materials from LFS 2 (see Table 5), almost no value measured complies with the regulated limits according to Table 1. The waste fractions of PPC, plastics, textiles and fines display high transgressions of lead, cadmium, chromium, cobalt and mercury so that none of these materials from LFS 2 seem suited for application as SRF. The wood fraction is least contaminated while lead and cadmium values exceed the limits insignificantly. It is assumed that the lead content in this fraction (wood from LFS 2 and LFS 1) can be ascribed to white lead, which has been commonly used as wood protection agent in the past (Falk et al., 2005). Since the measurements do not meet the median, however, nor do the results for the sample MPC comply with the legal 80th percentile, wood cannot be allocated to SRF usage, either.

Conclusion

Results obtained from sorting analyses reported in this article indicate that the average resource potential of sieve overflow materials (cut-off point at around 40 mm) of Austrian sanitary landfill sites may be estimated at approximately 88 to 91 wt%. It was further shown that the resource potential of fines (<40 mm) is much lower than the amount of REM in the coarse fraction. Sieving to separate fines is therefore advisable. The results have shown that pretreatment of waste before disposal did not significantly affect the amount of minerals, glass, plastics, PPC, textiles or composites. Iron, non-ferrous metals and wood vary, which can be attributed to magnetic separation and the MBT procedures applied on LFS 2.

In comparison, a pretreatment of waste before disposal seems to affect the heavy metal mobilisation in a particular landfill, as shown by chemical characterisation of excavated waste samples (OS 1 and OS 2) and selected waste fractions (PPC, plastics, wood, textiles and fines) from LFS 1 and LFS 2. Materials from LFS 2 display contamination levels that are more than twice as high as those found in waste fractions from LFS 1. The likeliest reason may be that higher heavy metal content of fines in LFS 2 has been generated by mechanical–biological treatment. Fines, in turn, adhere to other waste fractions, hence, contamination of all waste fractions has been observed. It seems that waste pretreated before landfilling evinces a lower quality after excavation. This was confirmed by comparing analytical results with legal requirements to the co-incineration of REM as SRF in Austria. Based on the results acquired, materials from LFS 1 could be used to substitute primary energy resources. Waste from LFS 2, however, does not meet the legal limit values, owing to high concentrations of lead, cadmium, chromium, cobalt and mercury.
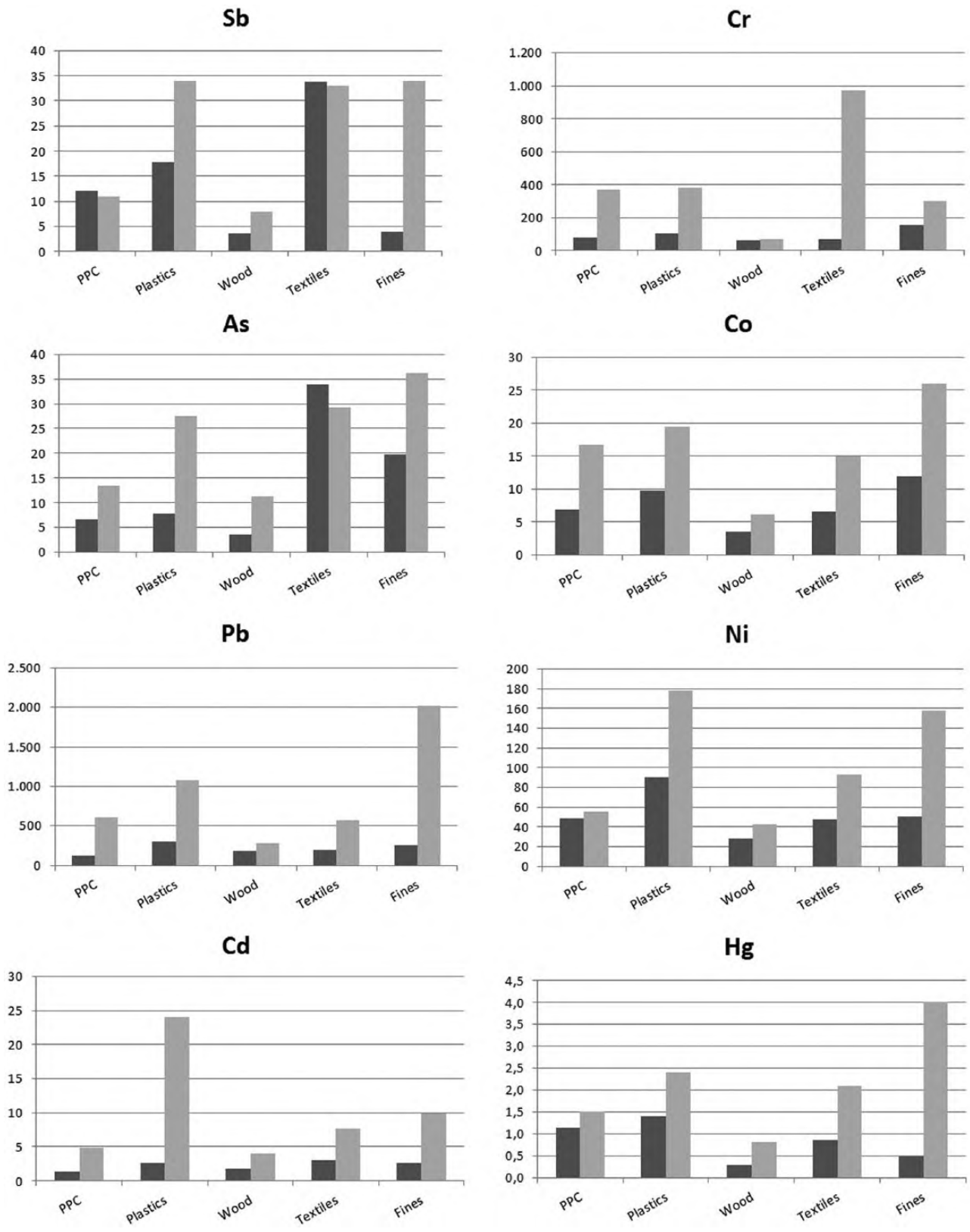
Figure 4. Heavy metal content of selected waste fractions from LFS 1 (left column) and LFS 2 (right column) in mg kg^{-1} DM (arithmetic mean values).
PPC: paper, paperboard and cardboard.

Ultimately, further theoretical investigations (Excel-based software simulations to assess the efficiency of various stages of material recovery with regard to quality and amount of REM) and practical examinations are needed to address the following questions that have arisen during the objective examination.

- What are the sources of heavy metals (especially in LFS 2) and how do they attach to excavated waste fractions?
- Can different treatment methods (like drying or leaching) be applied before waste excavation to decrease the concentration of heavy metals in specific waste fractions?
- To what extent does the degree of decomposition of excavated waste affect the usability of REM?
- How can the quality of excavated waste materials be improved after excavation and sieving?
- Are there other waste recycling or recovery paths (besides co-incineration) available for REM?

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References

ASI (Austrian Standard Institute) (2001) ÖNORM EN 13137 Charakterisierung von Abfall – Bestimmung des gesamten organischen Kohlenstoffs (TOC) in Abfall, Schlämmen und Sedimenten [Characterization of waste – Determination of total organic carbon (TOC) in waste, sludge and sediments]. Vienna, Austria: ASI.

ASI (Austrian Standard Institute) (2002) ÖNORM S 2121 Probenahme von Böden für die Durchführung einer Abfalluntersuchung [Sampling of soil for analysing waste]. Vienna, Austria: ASI.

ASI (Austrian Standard Institute) (2005a) ÖNORM 2097 Sortieranalyse von Abfällen [Sorting analysis of waste]. Vienna, Austria: ASI.

ASI (Austrian Standard Institute) (2005b) ÖNORM EN 15411 Feste Sekundärbrennstoffe – Verfahren zur Bestimmung des Gehaltes an Spurenelementen [Solid recovered fuels - Methods for the determination of the content of trace elements] (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, Tl, V und Zn). Vienna, Austria: ASI.

ASI (Austrian Standard Institute) (2005c) ÖNORM EN ISO 17294–2 Wasserbeschaffenheit – Anwendung der induktivgekoppelten Plasma-Massenspektrometrie (ICP-MS) – Teil 2: Bestimmung von 62 Elementen [Water quality – Application of inductively coupled plasma mass spectrometry (ICP-MS) – Part 2: Determination of 62 elements]. Vienna, Austria: ASI.

ASI (Austrian Standard Institute) (2007) ÖNORM EN 14346 Charakterisierung von Abfällen – Berechnung der Trockenmasse durch Bestimmung des Trockenrückstandes oder des Wassergehaltes [Characterization of waste – Calculation of dry matter by determination of dry residue or water content]. Vienna, Austria: ASI.

ASI (Austrian Standard Institute) (2011) ÖNORM S 2127 Grundlegende Charakterisierung von Abfallhaufen oder von festen Abfällen aus Behältnissen und Transportfahrzeugen [Basic characterization of waste heaps or solid waste from containers and transport vehicles]. Vienna, Austria: ASI.

BMBF (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie) (1995) Abfallwirtschaftliche Rekonstruktion von Altdeponien am Beispiel Schöneiche und Schöneiche Plan [Reconstruction

of old landfills shown by the examples of Schöneiche and Schöneiche Plan]. Berlin: Projektträger Umweltbundesamt, Abfallwirtschaft und Altlastensanierung, Endbericht.

BMLFUW (Bundesministerium für Land-und Forstwirtschaft, Umwelt und Wasserwirtschaft) (2002) BGBl. II Nr. 389/2002 Verordnung des Bundesministers für Land-und Forstwirtschaft, Umwelt und Wasserwirtschaft und des Bundesministers für Wirtschaft, Familie und Jugend über die Verbrennung von Abfällen (Abfallverbrennungsverordnung – AVV) [Waste Incineration Directive]. Vienna, Austria: BMLFUW.

BMLFUW (Bundesministerium für Land-und Forstwirtschaft, Umwelt und Wasserwirtschaft) (2008) BGBl. II Nr. 39/2008 Verordnung über Deponien (Deponieverordnung – DVO) [Landfill Directive]. Vienna, Austria: BMLFUW.

BMLFUW (Bundesministerium für Land-und Forstwirtschaft, Umwelt und Wasserwirtschaft) (2011) Bundesabfallwirtschaftsplan 2011 [Federal Waste Management Act], Band 1, Vienna, Austria: BMLFUW.

Bockreis A and Knapp J (2011) Landfill Mining – Deponie als Rohstoffquelle [Landfill mining – Landfills as depot for raw materials]. In: ÖWAV 3–4/2011, 2011.

Buchert M, Ustohalova V, Mehlhart G, et al. (2013) Landfill Mining – Option oder Fiktion [Landfill mining – Chance or fiction]. From Öko-Institute.V. (Institute for Applied Ecology), Publications (2013). Available at: http://www.oeko.de/oekodoc/1802/2013–479-de.pdf (accessed 2 May 2014).

European Commission (EC) (2000) Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. Brussels, Belgium: European Commission.

European Commission (EC) (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Brussels, Belgium: European Commission.

European Commission (2010) Enterprise and Industry. Improving Framework Conditions for Extracting Minerals for the EU – Abridged report of the ad-hoc Working Group on Exchanging Best Practice on Land Use Planning, Permitting and Geological Knowledge Sharing, Raw Materials Supply Group, Brussels, Belgium: European Commission – Enterprise and Industry.

Falk R, Janowiak J, Cosper S, et al. (2005) Remilling of salvaged wood siding coated with lead-based paint. Part I Lead exposure. *Forest Products Journal* 55: 76–80.

Frändegard P, Krook J, Svensson N, et al. (2013) A novel approach for environmental evaluation of landfill mining. *Journal of Cleaner Production* 55: 24–34.

Frei U (2005) Ist der Elbisgraben eine Goldgrube? [Is Elbisgraben a gold mine?]. *Bau- und Umwelt-Zeitung* 50: 1. Available at: http://www. netzwerk-umwelt.ch/userfiles/file/Veranstaltungen/Ist_der_Elbisgraben_ eine_Goldgrube_Artikel_in_der_Bau_und_Umwelt-Zeitung.pdf (accessed 13 August 2014).

GIS (German Institute for Standardization) (2000) DIN 51900–1 Prüfung fester und flüssiger Brennstoffe – Bestimmung des Brennwertes mit dem Bomben-Kalorimeter und Berechnung des Heizwertes – Teil 1: Allgemeine Angaben, Grundgeräte, Grundverfahren [Testing of solid and liquid fuels – Determination of gross calorific value by the bomb calorimeter and calculation of net calorific value – Part 1: Principles, apparatus, methods].

Hölzle I (2010) Vom Deponierückbau bis zum landfill mining – eine Synthese internationaler Untersuchungen [From landfill deconstruction to landfill mining – a synthesis of international examinations]. *Österreichische Wasser- und Abfallwirtschaft* 62: 155–161.

Knapp J and Bockreis A (2010) Potential of recoverable wastes in Tyrolean landfills. In: *Proceedings of the ISWA World Congress 2010*, Hamburg, 15–18 November 2010.

Kurian J, Esakku S, Palanivelu K, et al. (2003) Studies on landfill mining at solid waste dumpsites in India. In: Christensen TH, Cossu R and Stegmann R (eds) *9th international waste management and landfill symposium*, S. Margherita di Pula – Cagliari, Sardinia, Italy, 6–10 October 2003, CISA, Cagliari, Italy.

Rettenberger G (2010) Deponierückbau: Technik, Wirtschaftlichkeit, Perspektiven [Landfill deconstruction: Technique, economics, prospects]. In: Deponietechnik 2010, Band 35, Hamburg: Verlag Abfall aktuell.

Stahl T (2002) Matrixspezifische Analytik für organische und anorganische Schadstoffe im Restmüll – Anorganische Analytik mittels Röntgenfluoreszenzanalyse [Analytics for organic and inorganic contaminants in MSW – Analyses of inorganic contaminants via X-ray fluorescence analysis]. In: *Bayrisches Landesamt für Umwelt Fachtagung 2002*, Augsburg, Germany, 5 December 2002, pp.50–67.

UBA (Umweltbundesamt) (2009) Schwermetalldeposition in Österreich erfasst durch Biomonitoring mit Moosen [Deposition of heavy metals in Austria by means of moss biomonitoring] (Aufsammlung 2005). Available at: http://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0201.pdf (19 August 2014).

van Ommen HC (1994) Bericht aus den Niederlanden: Erfahrungen der Grontmij Gruppe [Report from the Netherlands: Experiences of the Grontmij Group]. Kommunale Umwelt-Aktion U.A.N., Schriftenreihe Heft 19.

Weber L (ed.) (2012) Der österreichische Rohstoffplan [Raw Material Initiative of Austria] – Archiv für Lagerstättenforschung, 26, Geol. B.-A., Vienna.

Wolfsberger T, Höllen D, Sarc R, et al. (2014) Landfill mining – case study: Characterization and treatment of excavated waste from Austrian sanitary landfill sites and estimation of the resource potential. In: *ISWA World congress*, Sao Paulo, Brazil, 8–11 September, Sao Paulo, Brazil.

Zhao Y, Song L, Huang R, et al. (2007) Recycling of aged refuse from a closed landfill. *Waste Management & Research* 25: 130–138.