

Landfill mining: Development of a theoretical method for a preliminary estimate of the raw material potential of landfill sites

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Abstract

In recent years, the rising need for raw materials by emerging economies (e.g. China) has led to a change in the availability of certain primary raw materials, such as ores or coal. The accompanying rising demand for secondary raw materials as possible substitutes for primary resources, the soaring prices and the global lack of specific (e.g. metallic) raw materials pique the interest of science and economy to consider landfills as possible secondary sources of raw materials. These sites often contain substantial amounts of materials that can be potentially utilised materially or energetically. To investigate the raw material potential of a landfill, boreholes and excavations, as well as subsequent hand sorting have proven quite successful. These procedures, however, are expensive and time consuming as they frequently require extensive construction measures on the landfill body or waste mass. For this reason, this article introduces a newly developed, affordable, theoretical method for the estimation of landfill contents. The article summarises the individual calculation steps of the method and demonstrates this using the example of a selected Austrian sanitary landfill. To assess the practicality and plausibility, the mathematically determined raw material potential is compared with the actual results from experimental studies of excavated waste from the same landfill (actual raw material potential).

Keywords

Landfill mining, raw material potential, gas forecast model, biodegradability, secondary raw materials, sanitary landfill, sorting analysis

Introduction

According to the Austrian Mineral Resources Plan (Weber, 2012), a change in the availability of selected primary raw materials (e.g. ores and coal) could be observed in recent years owing to the raw material demand of emerging economies (e.g. China and India). In addition, the European Union, and thus also Austria, has scarcely any deposits of mineral raw materials, such as iron and steel stabilisers, non-ferrous metals or hydrocarbons (Weber, 2012). To conserve primary raw materials, to reduce Europe's dependence on imports and to achieve an efficiency improvement of raw material, existing recycling technologies must be optimised, but also further developed with new ways of recycling (European Commission – Enterprise and Industry, 2010). A possibility for the conservation of primary resources is represented by 'urban mining', which uses anthropogenically created storage areas (e.g. cities) for the recovery of secondary raw materials. A sub field of urban mining is 'landfill mining', where already landfilled waste is re-excavated, processed, classified and among other things, subjected to impurity and hazardous substance removal in order to obtain the highest possible

amount of potential recyclable materials. Worldwide, about 63 landfill mining projects have been conducted to date (BMBWFT, 1995; Bockreis and Knapp, 2011; Nispel, 2012; van Ommen, 1994). The reason for carrying out landfill mining projects in the past was usually the recovery of landfill capacities, the creation of valuable real estate, contaminated site remediation or the protection of the environment (most importantly the groundwater) (Bockreis and Knapp, 2011; van Ommen, 1994; Zhao et al.,

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2007). The recovery of secondary raw materials, however, was not crucial for the beginning of landfill reclamation in most cases. With the change in waste management to a circular and resource economy (in accordance with European Commission, 2008), science and economics start to focus on landfill sites with regard to their secondary raw material potential. The economic success of a landfill mining project is based on the exact knowledge of the landfill composition and the concomitant potential of available secondary raw material quantities. All waste fractions that can be assigned to a material (i.e. glass, minerals, iron and non-iron metals) and/or energy recycling (i.e. paper, paperboard and cardboard (PPC), plastics, textiles, wood and composite materials) are summarised in the article as secondary raw materials. The sum of these fractions is called 'raw material potential' (RMP).

To obtain detailed data about a landfill, an extensive prior examination of the landfill site must be carried out. In this context, among others, studies to determine the inventory of the landfill as well as rough cost accounting are generated to estimate the cost-effectiveness (DWA, 2012). These studies are often based on field surveys where boreholes and excavations, as well as subsequent sorting and treatment processes of the materials excavated, have already been widely proven (BMBWFT, 1995; Emery, 2011; Nispel, 2012; Wolfsberger et al., 2014). However, these procedures are expensive, time consuming and technically complex, which is why they are usually only used for research or maintenance purposes, or to explore a site before necessary remediation (Bockreis and Knapp, 2011; Nispel, 2012). They are rarely used for detailed investigation or examination of the RMP of a site. As a result, landfills, which may possibly be suitable for a landfill mining project (owing to their RMP), are continuingly operated as active dump sites, causing follow-up costs and posing risks for future generations.

To give landfill owners the opportunity to explore the RMP of their site at an acceptable cost-effective approach, a theoretical method for estimating the secondary raw material amount will be presented in this article. If, as part of this method, a low RMP of the site is assessed, further investigations can be waived, avoiding 'stranded costs' (caused by expensive in-situ preliminary investigations). If a calculated high RMP results, the results provide a basis for more targeted examination steps (e.g. boreholes, excavations). A detailed description of the individual calculation steps of the newly developed method is provided in the section 'Materials and methods'. Furthermore, each calculation step will be demonstrated based on a selected Austrian sanitary landfill (landfill site 1 [LFS 1]). For the examination of the applicability and the plausibility of the method and its principles, the results obtained are compared with results from hand sorting trials of excavated waste from the same landfill. The RMP from the calculations is referred to as the 'theoretical RMP'. The RMP, which results from experimental on-site investigations (i.e. hand sorting), is dubbed the 'actual RMP'. Sample collection and a description of the sorting work can be found in Wolfsberger et al. (2014).

Materials and methods

The method for the assessment of the RMP of landfill sites is presented in this section. The individual steps of the method are described as follows, using the example of compartment (VA) 02 of LFS 1

1. Historical analysis
 - (a) Survey of the deposited waste quantities.
 - (b) Classification of landfilled waste quantities into waste categories by means of sorting analyses from the past.
2. Theoretical calculations
 - (a) Calculation of the degree of degradation of the deposited waste.
 - (b) Survey of the biodegradable proportion of selected waste fractions.
 - (c) Calculation of the theoretical RMP.

Historical analysis

The historical analysis involves the study of administration documents, records of the landfill owner, business registrations and testimonies made by witnesses or documents from archives, as well as a survey of results from waste sorting analyses carried out in the past. The information found in the historical analysis can provide data on the amount and type of waste deposited, as well as their composition and thus prediction about the RMP of a site. For example, the following information was found for LFS 1.

LFS 1 is a sanitary landfill in the form of a mine dump, which was approved in December 1982. The approved capacity amounted to a total of 950,000 m³, where 680,000 m³ was used for landfilling. The site covers a total area of approximately 78,000 m² and is divided into four compartments. Landfilling in VA 02 began in 1991 and ended at the beginning of 2000.

Survey of the deposited waste quantities. According to the historical analysis, municipal solid waste (MSW) and lower amounts of demolition waste constitute the largest proportion on the landfill. Overall, waste of around 141,158 t was landfilled at the VA 02 (Table 1).

Classification of landfilled waste into waste categories by means of sorting analyses from the past. The waste quantity determined from step a) Survey of the deposited waste quantities (see Table 1), must be assigned to waste categories so that the RMP can be estimated. These categories can be variably configured, depending on the application interests of the landfill owner (e.g. separation of scrap materials, manufacture of a fraction with high calorific value, extraction of potential solid recovered fuels). The following 11 waste categories were determined within the scope of this paper: PPC, organics, glass, metals, minerals, textiles and hygiene articles, plastics, wood, problem substances,

Table 1. Deposited waste on the VA 02 of LFS 1.

Waste	Deposited amounts per year (t)									Total
	1991	1992	1993	1994	1995	1996	1997	1998	1999	
Waste from contaminated sites	-	-	-	-	-	6387	9280	172	-	15,839
Used tyres	30	6	3	15	-	93	-	-	-	146
Asbestos cement	-	-	-	-	1	-	2	-	-	2
Demolition waste	-	-	441	311	352	1191	188	29	66	2580
Commercial waste	0	0	1170	1702	2106	1333	1745	280	29	8365
Soil	-	-	-	-	-	-	484	-	16	501
Scrap iron	-	-	-	-	-	0.35	-	0.13	-	0.48
Cemetery waste	-	-	239	98	173	314	249	102	2	1178
Sewage sludge	-	-	-	-	-	-	31	-	-	31
Composting residues	-	-	5342	2799	6311	4623	470	547	36	20,127
Plastic foils	-	-	-	-	1	-	-	-	-	1
Paper, paperboard, cardboard	-	-	-	-	1	1	3	-	-	6
Sand filter contents	-	5	-	-	-	-	-	-	-	5
MSW	12	10	4519	4031	9088	23,525	30,008	6447	948	78,587
Bulky waste	24	-	3821	1929	3547	2067	1978	401	21	13,789
Total	66	*20	15,536	10,885	21,580	39,535	44,438	**7979	1119	141,158

*In 1991/1992, delivered waste was mainly taken to the still existing VA 01 of LFS 1. Only small quantities were deposited at the VA 02. After closure of the VA 01 at the end of 1992, the waste was exclusively deposited at the VA 02, which resulted in an increase in deposit quantities from 20 t (1992) to over 15,000 t (1993).

**From 1998, a part of the waste was moved to the VA 03, which resulted in a renewed reduction of the deposit quantities from more than 44,000 t (1997) to approximately 8000 t (1998) and 1000 t (1999).

MSW: municipal solid waste.

composites and other. Based on the nomenclature, some of the waste shown in Table 1 could be directly assigned to some of the categories mentioned (Table 2).

The fractions 'soil' and 'sewage sludge' could not be assigned to any of the waste categories, which is why they are listed separately later in Table 4. For the assignment of the remaining waste, sorting analyses from the past should be used. Since landfilling in the VA 02 began in 1991 and was completed at the beginning of 2000, the focus was only oriented to sorting analyses that were carried out during this period. It should be noted at this point, that no sorting analyses of bulky waste could be found, which is why this fraction was not assigned to any category and appears separately later in Table 4. It is however, indicated that this waste can contain fractions that may be relevant to the RMP (e.g. metals, wood). For MSW, sorting analyses were collected for the assignment. From the historical analysis, it is known that the waste collection area of the landfill extended mainly to rural areas with low industrial activity, so for simplification and owing to the relatively small quantity of the fraction 'commercial waste' seen in Table 1, the same sorting analyses are used for classification of this waste stream. It is pointed out, that no sorting analyses could be found for MSW from the direct waste collection area of the landfill. For this reason, the sorting results of MSW from other communities with a similar waste management and disposal structure were used. The results of these collected sorting analyses can be found in Table 3.

To get a cross-section over the entire deposit period, the resulting averages were calculated from the sorting analyses apparent in Table 3 and used for the assignment of waste into

Table 2. Direct assignment of waste quantities to waste categories.

Waste	Waste Category
Used tyres, plastics foils	Plastics
Demolition waste, sand filter contents	Minerals
Asbestos cement	Problem substances
Scrap iron	Metals
Cemetery waste, composting residues	Organics
Paper, paperboard and cardboard	PPC

categories in accordance with Formula 1 (illustrated by the example of PPC):

$$PPC = M_{MSW} * MW \quad (1)$$

where PPC is the amount of PPC in MSW (t), M_{MSW} is the amount of MSW (t) and MW is the proportion of PPC to MSW (%).

As seen in Table 3, the sorting of waste was not carried out consistently in the different communities. So, for example, the group 'minerals' is only named for 1998. Results for the 'wood' fraction could only be found for 1994, 1995 and 1996. Therefore, it is assumed that these groups were assigned to the 'other' fraction during the hand sorting of the remaining years. For a better comparability of the sorting analyses, the proportions of the fraction 'wood' in 1994 (1 or 0.6%), in 1995 (1%) and in 1996 (2.4%), as well as the proportion of the fraction 'minerals' in 1998 (8%), were also added to the proportion of the fraction 'other'. The result of this summary is reported separately in

Table 3. Composition of MSW.

Substance group	1990 ^a (w%)	1994 ^b (w%)	1994 ^c (w%)	1995 ^d (w%)	1996 ^e (w%)	1998 ^f (w%)	Mean (w%)
PPC	11.2	13.4 ^g	14.1	7	17.5	12	13
Organics	38	45.9 ^h	46.2	13	8.7	35	31
Glass	4.1	2.5	3.2	3	2	5	3
Metals	3.9	3.2	3.7	4	2.9	3	3
Textiles	2.2	4.6	3.3	5	3.5	6	4
Plastics	8.3	9.9	7.9	10	10.9	9	9
Hygiene products	7.8	8.9	6.0	13	0	10	8
Problem substances	1.5	0.8	1	0.5	0.2	2	1
Composites	3.2	2.1	2.1	11	7.2	8	6
OWM ⁱ	19.9	9.1	12.6	33	47.2	10	22
Other	19.9	8.1	12.0	32	44.8	2	–
Wood	0	1	0.6	1	2.4	0	–
Minerals	0	0	0	0	0	8	–
Total	100	100	100	100	100	100	100

^aLÖ (1999).

^bIUT (1994): Average urban 1993–1994 with compost bin.

^cIUT (1994): Average urban 1993–1994 without compost bin.

^dTB Hauer (2002).

^eSattler (personal communication, 29 July 2014).

^fA14 (2014).

^gIncludes beverage carton packaging

^hIncludes materials <40 mm.

ⁱOther/wood/minerals.

OWM: other/wood/minerals; PPC: paper, paperboard and cardboard.

Table 3 as a fraction ‘other/wood/minerals’ (OWM). It is anticipated that this will reduce the theoretical RMP of the site because the proportions of the potentially to be materially recycled fraction minerals and energetically recycled fraction wood are not included in the estimation. The results of the classification of the waste quantities to waste categories (equation (1)) can be found in Table 4.

Theoretical calculations

The data found during the historical analysis provides initial findings about the RMP of a site. However, owing to organic components, conversion processes take place in landfills that can reduce the RMP. Therefore, the degree of degradation of the waste must be considered. This degree depends on the storage duration and composition of the waste, as well as the prevailing environmental conditions within the landfill. It should also be noted that not all waste fractions can be decomposed up to 100% by micro-organisms within a few decades, or are only partially accessible to biodegradability. So, for example, wood (owing to the lignin) or paper waste (owing to the coating and filler content) may not be fully converted by micro-organisms and are not degraded correspondingly. This is why an accurate estimation should also include the actually biodegradable proportion of each waste fraction. To reflect this in the estimation of the RMP of the VA 02 of LFS 1, the theoretical calculation steps ‘Calculation of the degree of degradation of the deposited waste’ and ‘Survey of the biodegradable proportion of selected waste fractions’ are explained more closely in this section. Based on the results found in these two steps, the third calculation step ‘Calculation of the theoretical RMP’ is to follow and analyse.

Table 4. Deposited quantities at the VA 02 of LFS 1 according to assignment of the waste quantities to waste categories.

Waste category	Quantity (t)
PPC	12,889
Glass	3392
Plastics	9741
Metals	3547
Composites	5757
Textiles and hygiene articles	12,044
OWM ^a	25,164
Bulky waste	13,789
Problem substances	1030
Sewage sludge	31
Soil	501
Organics	53,273
Total	141,157

^aIncluding proportions of wood and minerals.

OWM: other/wood/minerals; PPC: paper, paperboard and cardboard.

Calculation step 1 – Calculation of the degree of degradation of the deposited waste. Microbial degradable carbon compounds (such as paper) are converted, among others, to water and carbon dioxide under aerobic conditions and into methane and carbon dioxide under anaerobic conditions within a landfill body. The emissions released during this conversion process are discharged mainly in the form of landfill gas. For this reason, gas forecast models are used for the calculation of the degree of degradation in the course of the presented method. In this context, several approaches already exist in literature that can be found in Fellner et al. (2003). Theoretically 22.414 L of standard landfill gas may be created from 12 g carbon through anaerobic

processes, regardless of how much methane or carbon dioxide accumulates. This results in a landfill gas accumulation of 1.868 L for the degradation of 1 g carbon. This correlation can be represented mathematically as (LUBW, 1992):

$$G_e = 1.868 * C_{org} \quad (2)$$

where G_e is the total gas quantity ($\text{m}^3 * \text{t}_{\text{waste}}^{-1}$) and C_{org} is the biodegradable organic carbon content ($\text{kg C} * \text{t}_{\text{waste}}^{-1}$).

A formula was derived from these theoretical considerations by Tabasaran and Rettenberger in 1987 (LUBW, 1992), which allows the calculation of the gas amount formed if the biodegradable organic carbon content is known. The formula takes into account the influence of the landfill body temperature as well as the temporal course of landfill gas formation:

$$G_t = M_A * 1.868 * C_{org} * (0.014 * T + 0.28) * (1 - 10^{-k * t}) \quad (3)$$

where G_t is the landfill gas quantity for the period t (m^3), C_{org} is the introduced biodegradable carbon content (kg/t), M_A is the deposited waste quantity (t), T is the temperature ($^{\circ}\text{C}$), k is the degradation constant (a^{-1}) and t is time (a).

The time-dependent landfill gas formation follows an exponential function, which reaches its half-life in about 7–8 years (LUBW, 1992). It should be taken into account that the model simulates ideal environmental conditions inside a landfill body, and factors like actual water or nutrient content as well as its distribution in the landfill are not included. The model therefore provides findings that are higher than according to experience (Fellner et al., 2003). In practice, the calculation model by Tabasaran and Rettenberger (UBA, 2003) has nevertheless proved itself, which is why it is used in the present calculations for the estimation of the amount of landfill gas. For the survey of the parameters necessary for the calculation, equation (3), the procedure was as follows.

Time span (t). To determine the time span t , 1991 was set as the starting value based on the commissioning of VA 02. Since the results obtained from the newly developed method should be compared with the results of on-site hand sorting at the end, the year of the conducting of these sortings (2013) was chosen as the endpoint of the consideration period.

Temperature in the landfill (T). The temperature range in landfills can be assumed in most cases to be 30°C – 35°C (LUBM, 1992). To take into account both, the ‘best case’ (low degree of degradation) as well as the ‘worst case’ (high degree of degradation), the temperature T for the LFS 1 landfill is set to the average of the two temperatures (32.5°C) for the entire period considered.

Degradation constant (k). Measurements of the speed of the degradation in landfills yielded plausible k -values ranging from 0.035 – 0.045 a^{-1} (Fellner et al., 2003; LUBM, 1992). For the same reason as in the determination of the temperature, the k value with the average of the two specifications (0.040 a^{-1}) is used.

Table 5. Time series of the C_{org} in MSW (UBA, 2003).

Year	C_{org} ($\text{kg} * \text{t}_{05}^{-1}$)
1991	190
1992	180
1993	170
1994	160
1995	150
1996	140
1997	130
1998	130
1999	120

Introduced biodegradable carbon content (C_{org}). The C_{org} is the most important parameter for the landfill gas forecast model. It should be noted here, that for estimating the quantity of landfill gas and the degree of degradation, only the readily and medium biodegradable carbon (e.g. organics, textiles made from natural fibres, paper) is crucial. The degradation of poorly biodegradable waste (such as plastics) is therefore not involved. For MSW, the following C_{org} values can be used in Austria for the years 1991 to 1999 (cf. Table 5).

As presented in Table 5, the C_{org} in MSW continuously decreases over the years, which is attributed to the introduction of the separate collection of biogenic waste in large parts of Austria at the beginning of the 1990s. According to a personal communication (9 February 2015), this separate collection was also already selectively introduced in the waste collection area of LFS 1 at the beginning of 1990 and implemented in all municipalities of the waste collection area by 1992. It should be noted at this point that no C_{org} values were found for other types of waste containing biogenic components and which are shown in Table 1 (e.g. waste from contaminated sites). Hence, the values indicated in Table 5 were also used for these types of waste.

Deposited waste quantity (M_A). For the survey of the parameter M_A , the quantities indicated in Table 1 were drawn on as initial values. Because only waste with a readily and medium biodegradable organic proportion leads to the release of landfill gas, only waste of an organic nature was considered for the calculation. The sum of these waste quantities yields the M_A values determined for each year (Table 6) and provides an accurate estimation of landfill gas quantities released per year dependent on the C_{org} converted annually.

Using the indicated parameters T , k , C_{org} and M_A , the theoretical landfill gas quantity (G_t) formed within a specified time period can be calculated using equation (3). If it is assumed that 1.868 L of landfill gas are formed per gram of carbon, the portion of degraded carbon (equation (4)) can then be concluded and the degree of degradation (equation (5)) estimated:

$$C_{org,de} = \frac{G_t}{1.868} \quad (4)$$

$$D = \frac{C_{org,de}}{C_{org,tot}} * 100 \quad (5)$$

Table 6. Quantity of waste with organic components deposited annually at the VA 02 (M_A).

Year	Type of waste considered	M _A (t)
1991	MSW, bulky waste	39
1992	MSW	9
1993	Commercial waste, cemetery waste, MSW, composting residues, bulky waste	15,093
1994	Commercial waste, cemetery waste, MSW, composting residues, bulky waste	10,562
1995	Commercial waste, cemetery waste, composting residues, PPC, MSW, bulky waste	21,226
1996	Wastes from contaminated sites, Commercial waste, cemetery waste, PPC, composting residues, MSW, bulky waste	38,249
1997	Wastes from contaminated sites, commercial waste, cemetery waste, PPC, composting residues, MSW, bulky waste	43,723
1998	Wastes from contaminated sites, commercial waste, cemetery waste, PPC, composting residues, MSW, bulky waste	7948
1999	Commercial waste, cemetery waste, composting residues, MSW, bulky waste	1036

PPC: paper, paperboard and cardboard; MSW: municipal solid waste.

where $C_{org, de}$ is the degraded carbon content (kg C), $C_{org, tot}$ is the total introduced biodegradable carbon in time t (kg C) and D is the degree of degradation (%).

The results of this first theoretical calculation step are shown later in Table 8.

Calculation step 2 – Survey of the biodegradable proportion of selected waste fractions. As already mentioned, even biodegradable substances do not usually consist of 100% biodegradable proportions. To take this into consideration, the biodegradable proportion of selected waste was surveyed. For this, analyses, which had already been carried out in the past and found in literature, were used. The results of the analyses found are summarised in Table 7.

As shown in Table 7, a broad range of the biodegradable proportion of a waste fraction is assumed according to the literature values. For this reason, the average was obtained from the literature values and used in the estimation of the RMP. Owing to the, in part, low data basis, the calculation of the median was waived at this point.

Calculation step 3 – Calculation of the theoretical raw material potential. The results shown in Table 4 provide the initial value of waste quantity in each waste category for the calculation of the theoretical RMP. The amount of each waste fraction has been multiplied by the calculated degree of degradation (Table 8) as well as the respective average of the biodegradable proportion (Table 7), allowing the already-degraded proportion of the respective waste fraction to be estimated:

$$DW = I * D * b \quad (6)$$

where DW is the degraded waste (t), I is the initial value (t), D is the degree of degradation (%) and b is the biodegradable proportion (%).

The waste quantity still stored in the landfill was then calculated by subtracting the degraded waste DW from the corresponding initial value I . The sum of the amounts of glass, iron, non-iron, PPC, plastics, textiles and composite materials obtained using this formula gives the secondary RMP of the site (Table 9).

Comparison of the theoretical and the actual RMP

To verify the applicability of the method presented, the results obtained were compared with data from hand sorting trials (Table 10). It is noted that the hand sorting had been conducted on the basis of the current Austrian Federal Waste Management Act, (BMLFUW, 2011), which is why the classification into waste categories may vary from those listed in Table 4. Here, however, the fractions ‘organics’, ‘soil’ and ‘sewage sludge’ can be compared with the quantity of ‘sorting residues’ listed in Table 10. For a better comparability of the theoretical with the actual RMP, the proportions of ‘minerals’ (5.5%) and ‘wood’ (9.4%) found during the hand sorting were assigned to the fraction ‘other’.

Results and discussion

Historical analysis

As described in the section ‘Material and methods’, the amount of waste (Table 1) that was found through the historical analysis and deposited at the landfill has been assigned to waste categories (Table 4) using the sorting analysis averages listed in Table 3. The results presented provide information on the amount of waste that was delivered to the VA 02 of the landfill and deposited. But it does not allow an exact statement of which quantities were actually still available in 2013 (see selected period of consideration) or what quantities were already degraded by microbial conversion processes.

Theoretical calculations

To be able to consider the degree of degradation in the estimation of the RMP, it was calculated by means of a chosen gas forecast model. The results of this first theoretical calculation step are shown in Table 8. Accordingly, the amount of landfill gas formed over the designated period (1991–2013) amounts to 21.9 million m³. Therefore, a degraded C_{org} of about 11.7 million kg of C can be concluded. If this is viewed in relation to the $C_{org, tot}$ (around 19.6 million kg C), the degree of degradation for the VA 02 of

Table 7. Biodegradable proportion of selected waste fractions.

Fraction	Water content (%)	Biodegradable proportion (% ₀₅)					
		BLU (2003)	Dehoust et al. (2002)	IPCC (2006) ^b	LM (2003)	Pommier et al. (2010)	Nelles (1998)
PPC	21	78	40	100	43	–	65
Organics	60	40	20	100	–	–	53
Hygiene products	60	36	24	–	–	–	30
Composite	19	49	–	–	–	–	49
Textiles	14	56	24	–	–	–	40
Fine fraction	28	50	–	–	–	–	50
Wood	14	86	43	–	–	–	65
Rubber and leather	6	–	39	–	–	–	39
Bulky waste	–	–	–	50	–	–	50
Glass	1	–	–	–	–	–	0
Plastics	16	–	–	–	–	–	0
Metals	2 ^a	–	–	–	–	–	0
Minerals	2	–	–	–	–	–	0
Sewage sludge	75 ^c	–	–	–	–	9	9

^aNispel (2012).

^bValues from the literature are specified relative to the dry matter. To improve comparability with the other literature sources, these are converted using the specified water levels in accordance with BLU (2003) on the wet substance.

^cNelles (1998).

LFS 1 can be estimated at approximately 60%. The survey of the biodegradable proportion of selected waste fractions was already described in the section ‘Material and methods’ and the average used for the calculation of the theoretical raw material potential per waste fraction can be found in Table 7. Based on the historical analysis and the calculated degree of degradation and biodegradable portion, the theoretical RMP was ascertained in the third step of the calculation (Table 9).

As shown in Table 9, the theoretical RMP of the VA 02 of LFS 1 is around 35% according to the method developed. If it is assumed that mainly glass, iron and non-iron metals are suitable for material recycling, of these, about 6% could be supplied for material recovery. Based on their high calorific value, the fractions PPC, plastics, textiles and composites seem to be suitable for energy recovery. Based on the results, 29% of the landfill content could thus be used for energy supply.

Comparison of the theoretical and the actual raw material potential

For the comparison of the theoretical and actual raw material potential, the results, which were obtained during the on-site hand sorting trials were summarised (Table 10). Additionally, the absolute deviation of the theoretical results that were collected by the method presented (Table 9) from the results gained from hand sorting is represented.

According to the hand sorting, the actual RMP is approximately 37%. Of this, ca. 6% could be used for material (deviation from the method <1%) and approximately 30.8% for energy supply (deviation from the method ~2%). The calculated total deviation of the actual from the theoretical RMP can, with great

probability, be specified at approximately <5%. (Note: In the present case, this is ~1%.)

Conclusion

As could be shown by comparing the theoretical and actual RMP, the presented, newly developed method can be used for estimating the potential of secondary raw material quantities of a landfill site and therefore as a decision-making tool for landfill owners. Costs that would be incurred through a preliminary exploration using drilling and mining, as well as hand sorting, can thus be saved.

In this method, however, as clearly illustrated in the article, the conversion processes taking place in landfill bodies must be considered. The calculations show that for the determination of the degree of degradation, gas forecast models can be used; the model by Tabasaran and Rettenberger has proven successful. It should be noted that this model usually provides higher than actual findings and the degree of degradation is thus estimated too high, resulting in distortions in the calculation of secondary raw materials potential. The comparison of the theoretical (about 35.2%) to the actual RMP determined from the hand sorting trials (36.5%), however, showed a good consistency of the results (deviation of approximately 1%), which is why suitability of the gas forecast model is assumed for the calculation of the degree of degradation.

As the comparison of the results from Table 9 and Table 10 has shown, partly higher deviations can be observed with individual waste fractions. For example, the theoretically determined amount of plastics was approximately 9%, while the hand sorting trials showed an amount of around 18%. These variations can be

Table 8. Result of the degree of degradation according to the gas forecast model of Tabasaran and Rettenberger.

Period under consideration	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total	C _{org} degraded	C _{org} introduced	
	Quantity of gas formed											(kg C*a ⁻¹)	
	[m ³ *a ⁻¹]												
1991	826	-	-	-	-	-	-	-	-	-	826	442	6827
1992	754	196	-	-	-	-	-	-	-	-	949	508	1620
1993	687	178	309,969	-	-	-	-	-	-	-	310,835	166,400	2,565,810
1994	627	163	282,695	204,155	-	-	-	-	-	-	487,639	261,049	1,689,920
1995	572	148	257,821	186,191	384,639	-	-	-	-	-	829,371	443,989	3,183,900
1996	521	135	235,135	169,809	350,795	646,906	-	-	-	-	1,403,302	751,232	5,354,860
1997	475	123	214,446	154,867	319,928	589,986	686,668	-	-	-	1,966,494	1,052,727	5,683,990
1998	434	113	195,577	141,241	291,778	538,073	626,248	124,823	-	-	1,918,287	1,026,920	1,033,240
1999	396	103	178,368	128,813	266,105	490,729	571,145	113,840	15,019	-	1,764,517	944,602	124,320
2000	361	94	162,674	117,479	242,691	447,550	520,891	103,823	13,697	-	1,609,259	861,488	0
2001	329	85	148,360	107,142	221,336	408,170	475,058	94,688	12,492	-	1,467,662	785,686	0
2002	300	78	135,306	97,715	201,861	372,256	433,258	86,356	11,393	-	1,338,523	716,554	0
2003	274	71	123,401	89,117	184,100	339,501	395,136	78,758	10,390	-	1,220,748	653,505	0
2004	250	65	112,543	81,275	167,901	309,629	360,368	71,828	9476	-	1,113,335	596,004	0
2005	228	59	102,640	74,124	153,127	282,385	328,660	65,508	8642	-	1,015,374	543,562	0
2006	208	54	93,609	67,602	139,654	257,538	299,741	59,744	7882	-	926,032	495,734	0
2007	189	49	85,372	61,654	127,366	234,878	273,367	54,487	7188	-	844,551	452,115	0
2008	173	45	77,861	56,229	116,159	214,211	249,314	49,693	6556	-	770,240	412,334	0
2009	157	41	71,010	51,281	105,938	195,363	227,377	45,320	5979	-	702,467	376,053	0
2010	144	37	64,762	46,769	96,617	178,173	207,370	41,333	5453	-	640,657	342,964	0
2011	131	34	59,063	42,654	88,116	162,496	189,124	37,696	4973	-	584,287	312,787	0
2012	119	31	53,866	38,901	80,362	148,198	172,483	34,379	4536	-	532,876	285,265	0
2013	109	28	49,127	35,478	73,291	135,158	157,307	31,354	4137	-	485,988	260,165	0
									Total		21,934,218	11,742,087	19,644,487
													59.8 %
													Degree of degradation

Table 9. Theoretical RMP of the VA 02 of LFS 1.

Waste category	Quantity	
	(t)	(%)
*PPC	7862	7.0
*Glass	3392	3.0
*Plastics	9741	8.7
*Metals	3547	3.2
*Composites	5756	5.1
*Textiles and hygiene articles	9153	8.2
OWM ^a	25,165	22.4
Bulky waste	9652	8.6
Problem substances	1030	0.9
Sewage sludge	30	0.0
Soil	501	0.4
Organics	36,332	32.4
Total	112,160	100
*Theoretical raw material potential	39,452	35.2

^aIncluding portions of wood and minerals.
OWM: other/wood/minerals.

attributed to the data basis used for the method. As already mentioned, the method presented in this article is based on historical data and sorting analyses from the past (i.e. historical analysis). Since these form the initial values for the theoretical calculations, they represent the most important input parameters for the assessment of the RMP. In the case of the historical analysis, the conditions of a site, such as waste collection area, population density or separating behaviour of the population, must therefore be included in addition to a thorough data search on waste deposit amounts and types.

The sorting analyses applied to the classification of the waste into the waste categories appear to have great influence on the final results. As already mentioned, no data on the composition of MSW could be found in the waste collection area of LFS 1, which is why sorting analyses of communities with a similar waste management and disposal structure were used. These however do not exactly reflect the conditions of LFS 1, which may lead to a distortion of the proportions of individual waste fractions. As shown in Table 10, the deviations of individual fractions to one another in most cases however, are under 10% (exception: sorting residues), which is why the methodology explained in the article is still judged to be sufficiently plausible.

It should be taken into account however, that the method allows no statement on the quality and the subsequent suitability of potential secondary raw materials for an actual recovery, but it represents a tool for the estimation of RMP quantities. A precise characterisation and assessment of the quality of waste excavated can only be done by test drilling or digging with subsequent laboratory or small scale sorting/examination and chemical analyses of the obtained materials. If the decision is made to excavate the site based on the theoretical RMP determined with the method, such investigations must then be subsequently performed.

Table 10. Results of on-site hand sorting trials.

Waste category	Quantity (%)	Deviation theoretical/actual raw material potential (%)
*Iron	3.8	1.5
*Non-iron	0.9	
*PPC	3.2	3.8
*Plastics	18.1	9.4
*Glass	1.0	2.0
*Composite	3.8	1.3
*Textiles	5.7	2.5
OWM ^a	16.3	6.1
Sorting residues	47.0	14.2
Problem substances	0.1	0.8
*Actual raw material potential	36.5	1.3

^aIncluding portions of wood and minerals.
OWM: other/wood/minerals.

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References

- A14 (Amt der steiermärkischen Landesregierung, A14 Wasserwirtschaft, Ressourcen und Nachhaltigkeit, Referat Abfallwirtschaft und Nachhaltigkeit) (2014) Restmüllzusammensetzung auf einen Blick [Composition of MSW]. Available at: <http://www.abfallwirtschaft.steiermark.at/cms/beitrag/10168259/4336659/> (accessed 15 January 2015).
- BLU (Bayerisches Landesamt für Umweltschutz) (2003) *Zusammensetzung und Schadstoffgehalte von Siedlungsabfällen [Composition and contaminant content of municipal solid waste]*. Augsburg, Germany: Bayerisches Landesamt für Umweltschutz.
- BMBWFT (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie) (1995) *Abfallwirtschaftliche Rekonstruktion von Altdeponien am Beispiel der Deponien Schöneiche und Schöneicher Plan [Reconstruction of old landfills shown by the examples of Schöneiche and Schoeneiche plan]*. Berlin: Projektträger Umweltbundesamt, Abfallwirtschaft und Altlastensanierung, Endbericht.
- 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.
- Dehoust G, Gebhardt P and Gärtner S (2002): Der Beitrag der thermischen Abfallbehandlung zu Klimaschutz, Luftreinhaltung und Ressourcenschonung [The contribution of thermal waste treatment to

- climate protection]. Available at: <http://www.oeko.de/oekodoc/75/2002-013-de.pdf> (15 December 2014).
- DWA (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall) e.V. (2012) *Rückbau von deponierten Abfällen [Landfill mining of deposited waste]*. Hennef: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall.
- European Commission (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 – Enterprise and Industry (2010) 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.
- Emery R (2011) Mining of waste from landfill in a developing country for beneficiation (re-use/recycling): is it a viable and sustainable opportunity? Insight to a trail study in South Africa. In: *13th international waste management and landfill symposium*, Sardinia, Italy 3–7 October 2011.
- Fellner J, Schöngrundner P and Brunner P (2003) Methanemissionen aus Deponien – Bewertung von Messdaten (METHMES) [Methane emissions from landfills – Assessment of Measurements]. Available at: <http://www.bmlfuw.gv.at> (accessed 20 December 2014).
- IPCC (Intergovernmental Panel on Climate Change) (2006) Draft 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available at: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/> (accessed 23 December 2014).
- IUT (Innovative Umwelttechnik GesmbH) (1994) *Endbericht über die Ergebnisse der Restmüllanalysen 1993/1994 in der Steiermark* [Report of the results of sorting analyses of municipal solid waste 1993/1994 in the Federal State of Styria]. Seebenstein: IUT.
- LM (Lebensministerium) (2003) Österreichische Strategie zur Verringerung der zur Deponierung bestimmten, biologisch abbaubaren Abfälle, Bericht an die Kommission gemäß Art. 5 Abs. 1 der Richtlinie über Abfalldeponien (1991/31/EG) [Austrian Strategy for the reduction of biological degradable waste designated for landfilling]. Available at: <http://www.bmlfuw.gv.at/> (accessed 13 August 2014).
- LÖ (Landesregierung Oberösterreich) (1999) LGBl. No. 104/1999 Verordnung der Oö. Landesregierung, mit der ein Abfallwirtschaftsplan für das ganze Landesgebiet erlassen wird (Oö. Abfallwirtschaftsplan 1999) [Waste Management Act of the Federal State of Upper Austria]. Available at: <http://www.ris.bka.gv.at> (accessed 3 January 2015).
- LUBM (Zentraler Fachdienst Wasser-Boden-Abfall-Altlasten bei der Landesanstalt für Umweltschutz Baden-Württemberg) (1992) Der Deponiegashaushalt in Altablagerungen – Leitfaden Deponiegas [Landfill gas in old landfills – Guideline Landfill Gas]. Available at: <http://www.lubw.baden-wuerttemberg.de> (accessed 25 November 2014).
- Nelles M (1998) Mechanisch-biologische Restabfallbehandlung zur Umsetzung der Deponieverordnung [Mechanical-biological waste treatment for the implementation of the landfill Ordinance]. Doctoral Dissertation, Montanuniversität Leoben.
- Nispel J (2012) Ressourcenpotential von Hausmülldeponien am Beispiel der Kreismülldeponie Hechingen [Resource potential of sanitary landfills based on the example of the landfill site Hechingen]. Schriftenreihe zur Bodenkunde, Landeskultur und Landschaftsökologie Band 59.
- Pommier S, Manas Llamas A and Lefebvre X (2010) Analysis of the outcome of shredding pretreatment on the anaerobic biodegradability of paper and cardboard materials. *Bioresource Technology* 101: 463–468.
- TB Hauer (Technisches Büro Hauer Umweltwirtschaft) (2002) Restmüllanalysen in Niederösterreich 2002/2002 [Analyses of municipal solid waste of the Federal State of Lower Austria]. Available at: http://www.tbhauer.at/Berichte/noe_rmanalysen2001.pdf (accessed 15 January 2015).
- UBA (Umweltbundesamt) (2003) *Biologisch abbaubarer Kohlenstoff im Restmüll [Biological degradable carbon content in municipal solid waste]*. Vienna: Umweltbundesamt GmbH.
- van Ommen HC (1994) Report from the Netherlands: Erfahrungen der Grontmij Gruppe [Report from the Netherlands: Experiences of the Grontmij Group]. Kommunale Umwelt-Aktion U.A.N., Schriftenreihe Heft 19.
- Weber L (2012) Der österreichische Rohstoffplan [Raw Material Initiative of Austria]. Archiv für Lagerstättenforschung, 26, Geol. B.-A., Vienna, Austria.
- 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.
- Zhao Y, Song L, Huang R, et al. (2007) Recycling of aged refuse from a closed landfill. *Waste Management & Research* 25: 130–138.