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Integrating remediation and resource recovery: On the economic conditions of landfill mining

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ABSTRACT

This article analyzes the economic potential of integrating material separation and resource recovery into a landfill remediation project, and discusses the result and the largest impact factors. The analysis is done using a direct costs/revenues approach and the stochastic uncertainties are handled using Monte Carlo simulation.

Two remediation scenarios are applied to a hypothetical landfill. One scenario includes only remediation, while the second scenario adds resource recovery to the remediation project. Moreover, the second scenario is divided into two cases, case A and B. In case A, the landfill tax needs to be paid for re-deposited material and the landfill holder does not own a combined heat and power plant (CHP), which leads to disposal costs in the form of gate fees. In case B, the landfill tax is waived on the re-deposited material and the landfill holder owns its own CHP.

Results show that the remediation project in the first scenario costs about €23/ton. Adding resource recovery as in case A worsens the result to –€36/ton, while for case B the result improves to –€14/ton. This shows the importance of landfill tax and the access to a CHP. Other important factors for the result are the material composition in the landfill, the efficiency of the separation technology used, and the price of the saleable material.

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1. Introduction

Large amounts of potentially valuable materials such as metals, combustibles, and earth construction materials are situated in landfills (cf. [Cossu et al., 1995](#); [Obermeier et al., 1997](#); [Quaghebeur et al., 2013](#); [Frändegård et al., 2013b](#)). With a number of worldwide changes currently underway, e.g. increasing competition for natural resources and raw material prices, stronger incentives for resource conservation and recovery are created (cf. [Kapur, 2006](#); [Halada et al., 2009](#)), which in turn might make the material situated in landfills gradually more interesting to recover.

Landfill mining has recently been defined by [Krook et al. \(2012\)](#) as a process for extracting minerals or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground. This concept can be seen as an alternative method to traditional remediation (i.e., excavate and move the material without including any processes for material extraction) and can have potential advantages if it turns out to be economically justifiable to implement.

Historically, the focus of landfill mining has mostly been on solving local waste management or environmental issues (cf. [Cossu et al., 1996](#)), seeing the landfill as mainly a problem and part of what [Johansson et al. \(2013\)](#) calls the “dump regime”. This corresponds for example to remediation of a landfill to avoid leaching or other future problems or extending the lifetime of a landfill by gaining additional airspace (e.g. [Spencer, 1990](#); [Dickinson, 1995](#); [Cha et al., 1997](#); [EPA, 1997](#)). There are other studies, however, that have a stronger focus on the materials in the landfill and their recovery and use. Examples of this include [Obermeier et al. \(1997\)](#) and [Hull et al. \(2005\)](#), who see landfill mining as a method to secure a high workload of waste fuel for MSW incinerators or cement industries, and [Zanetti and Godio \(2006\)](#), who analyze recovering foundry sands and iron fractions from an industrial landfill from an economic perspective. In spite of this, the emphasis of landfill mining studies so far has mainly been on the material composition of different landfills and on environmental aspects.

In a recent comprehensive landfill mining literature review, [Krook et al. \(2012\)](#) found only two earlier studies that have their main focus on economic issues ([Fisher and Findlay, 1995](#); [van der Zee et al., 2004](#)). Since then, a few more studies have shown economic potential in landfill mining. A case study of a Florida landfill focusing on reclaiming landfill airspace shows prospective

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profit (Jain et al., 2013). Moreover, the Flanders-based Enhanced Landfill Mining (ELFM) project has indicated an economic potential, though relying on the development of innovative waste-to-energy technology and significant governmental support in terms of green energy certificates, tax breaks or the like (Bosmans et al., 2013; van Passel et al., 2013).

Landfilling in Sweden has seen a sharp decline in recent years in favor of energy recovery; less than 1% of municipal solid waste is landfilled while about 50% is used as fuel in combined heat and power plants (SWM, 2010). Sweden has more than 4000 municipal landfills (SEPA, 2008); most are old without the appropriate pollution prevention and control techniques, and in extensive need of remediation. Less than 100 of these are currently operational, and the material that is deposited is mainly inorganic material such as waste incineration ashes, concrete, and insulation material.

These landfills contain materials of interest, combined with potential environmental hazards. According to Frändegård et al. (2013b), at least 450 of Sweden's MSW landfills are currently classified as having high or very high environmental risk, when taking aspects such as the level of contamination and hazardousness, the risk of contamination spreading, and the area's sensitivity and conservation value into account. The owners of the contaminated property/area, municipalities in these cases, are responsible for the remediation (SEPA, 2003). Since many municipalities struggle with constrained finances, it is important for them to investigate ways of reducing costs related to remediation.

Even though recovery of deposited materials and energy resources alone seldom seem to economically justify landfill mining on municipal landfills, previous studies indicate that such a material-focused landfill mining project has the potential to lower the costs of remediation (e.g. Rettenberger, 1995; Prechtai et al., 2008). Given the upcoming need for landfill remediation in Sweden and elsewhere, it is therefore interesting to analyze landfill mining in another context, namely from an integrated approach, where resource recovery (defined as separation and utilization of deposited materials in this study) is added to an already planned remediation project.

The aim of this study is to assess the economic potential of landfill mining for facilitating remediation of municipal landfills and contribute to closing material loops. In doing so, we analyze and compare two remediation scenarios from an economic perspective, one scenario without material separation, and one scenario where material separation is included.

2. Method

To realize the aim we have chosen to construct a hypothetical municipal solid waste landfill, based on the current conditions in Sweden.

Two scenarios are applied to this landfill, firstly a traditional remediation scenario with no material separation, and secondly an integrated remediation and resource recovery scenario including material separation. The reason for including resource recovery in the second scenario is to analyze the potential of how this will alter the project costs and revenues.

In the second scenario, the integrated approach, we set up two cases, A and B, to analyze how different conditions affect the result. Since the hypothetical landfill should be the same in each case, the changed conditions should not be site specific. From a range of possible aspects, such as metal prices, separation technology, or transportation costs, we chose to analyze two previously identified scenario uncertainties related to how the landfill tax is applied and the ownership and capacity of local waste incineration plants (cf. Frändegård et al., 2013b). Both of these factors are interesting to analyze since there are many indications that these will undergo

change in the near future. Swedish waste incineration operators are experiencing an increase in overcapacity, which will probably lead to a larger dependence on import and a possible lack of waste supply, and the Swedish landfill tax is currently being revised to be more beneficial to landfill mining projects with regards to remediation (see Section 2.2.1). Case A is based on the current conditions, while case B is based on future potential.

2.1. The landfill and scenarios

The remediation is taking place in Sweden, on a municipal solid waste (MSW) landfill. According to Hogland et al. (2010), 26% of Sweden's landfills have a volume larger than 100,000 m³ and about 15–20% are considered to be in immediate need of remediation. From a resource recovery point of view, a large and old landfill is believed to have better potential than a smaller, younger one, due to more prospective recyclables, and a larger land area to reclaim (cf. van der Zee et al., 2004). The hypothetical landfill is therefore set at 100,000 m³. It is common for landfills that previously were situated outside a city core to eventually become part of the main urban areas, due to urban expansion (Johansson et al., 2012). The landfill in this study is located in an expansive area in a medium-sized city (100,000 people) and is owned by a municipality.

The landfill has an average depth of 10 meters and using a density of 1 ton per m³ (e.g. Hull et al., 2005) gives a landfill area of 10,000 m² to be remediated. The landfill closed down 30 years ago and is no longer in use, however, in its current condition it is deemed a potential environmental hazard due to lack of appropriate cover and lining systems. The only nearby open landfill is a waste incineration ash landfill, which does not have the capacity to handle this amount of material and does not want to blend its homogenous ash residue with the heterogeneous residues that the remediation project will produce. Since no appropriate landfill site can handle this amount of material, the material in the closed down landfill needs to be excavated and re-deposited while the landfill site is rebuilt according to Swedish standards.

The material composition of the hypothetical landfill is set to a typical composition for municipal solid waste landfills, based on a literature review of previous landfill mining pilot studies from the industrialized part of the world, Table 1 (Frändegård et al., 2013a). This typical composition is divided in ten deposited material types: soil-type material; paper; plastic; wood; textiles; inert materials;

Table 1

Shows estimated material composition (in weight%) of a typical MSW landfill, presented as mean values and absolute standard deviations.

Material type	Mean (%)	St. dev. (%)
Soil-type material	56.3	14.2 ^a
Paper	7.9	6.1 ^a
Plastic	8.1	5.4 ^a
Wood	7.4	4.3 ^a
Textiles	3.3	1.3 ^a
Inert materials	9.7	10.8 ^a
Organic waste	2.7	2.0 ^a
Ferrous metals	3.6	4.1 ^{a,b}
Non-ferrous metals	0.8	0.7 ^{a,b}
Hazardous	0.5	0.1 ^a

^a Based on the following landfill mining studies: Cossu et al. (1995), Hogland et al. (1995, 2004), Hull et al. (2005), Krogmann and Qu (1997), Rettenberger (1995), Richard et al. (1996), Stessel and Murphy (1991) and Sormunen et al. (2008).

^b For ferrous and non-ferrous metals, a special case had to be made, since only a few of the landfill mining cases made a distinction between these two material types; a majority of the cases had just one aggregated material type called "metals." The mean values for ferrous and non-ferrous metals are therefore based on the fact that the accumulated consumption of metals in Sweden over time is around 80% ferrous and 20% non-ferrous, so the mean values for these two material types were calculated proportionally (SEPA, 1996).

organic waste; ferrous metals; non-ferrous metals and hazardous materials.

2.1.1. Remediation scenario

According to SEPA (2012), there are thousands of unlined landfills, and other contaminated areas, in Sweden of immediate need of remediation. The responsibility for this remediation is the owners, generally a municipality. Jain et al. (2013) performed a literature review on landfill reclamation projects and found that the most common objective was to relocate waste from an unlined landfill to a nearby lined landfill. In this scenario, a similar approach is used, with the difference that the unlined landfill will be restructured into a lined landfill where the material will be re-deposited.

Remediation of the landfill follows the recommendations from the Swedish Environmental Protection Agency (SEPA, 2008) and includes installation of low-permeability liner and cover, construction of sloped terraces and setting up a leachate collection system. The material is excavated and sent through a coarse screen that separates the bulky hazardous material, which is transported to a disposal plant, Fig. 1. A star screen is used to separate fines (soil and heavily degraded waste). Since previous studies has shown that this type of material normally meet the legal limits in regards to its content (cf. Cossu et al., 1995), some of the fines material will be used as construction material on the landfill. According to recommendations from the Swedish Waste Management Association (SWM, 2012); two meters of cover material are used per m², which means that 20,000 m³ is used for this purpose. The rest of the material is re-deposited in the new lined landfill.

2.1.2. Integrated remediation and resource recovery scenario

The current larger separation plants in Sweden are working at full capacity. To use landfill mining material as inputs, with generally less valuable materials/metals than normal, probably leads to a loss of income for these plants. Furthermore, the risk of investing large amounts of money in building a new plant for a single landfill is not deemed very likely. We have therefore concluded that the most likely way this scenario would be conducted is using a mobile separation plant based on current and commercial technology. This

separation plant is added to the remediation-only scenario, according to Fig. 2.

Similar to the remediation-only scenario, the excavated material is first dumped over a coarse screen, which separates out bulky hazardous products (e.g. refrigerators and oil barrels) and non-recyclable material. Next, the rest of the material enters the star screen, which separates out “fines” containing heavily degraded waste and cover material. The star screen is attached to three other processes: an air classifier, a magnet, and an eddy current separator (ECS), combined into a state-of-the-art mobile separation plant. The air classifier separates out combustibles such as paper, textiles, and plastic, while the magnet and ECS extract ferrous and non-ferrous metals respectively.

Hazardous materials are transported from the landfill to a disposal facility. The restructured landfill contains a smaller amount of material than the original landfill, and the surface area is therefore decreased from 10,000 m² to around 8200 m². With an average thickness of two meters of cover, around 16,400 m³ of the separated fine materials are used for the reconstruction process, while the rest is re-deposited along with the residual material from the mobile plant separation. The combustible materials are transported to a combined heat and power plant and incinerated. The metals produced by the mobile plant are not clean enough to be recyclable at this stage and are instead transported and sold to a metal processing plant for further refining.

2.1.3. Efficiency of material separation

To establish the separation efficiencies for the separation processes, mass balances for each of the material types were compiled, describing the distribution, in percentages, of each of these materials between the different separated material categories, Table 2. Since the uncertainties of the quality and of the ability for the mobile plant to separate the material in the correct material category, uncertainty interval in the form of mean value and standard deviations are set for each parameter. The values are based on estimates from Stena Metall AB, which also assisted with cost estimates and with setting up the scenarios. Since this data is to a large degree based on Stena Metall AB's own facilities and efficiencies, the actual values are not shown here, but only an illustration of how the values are calculated.

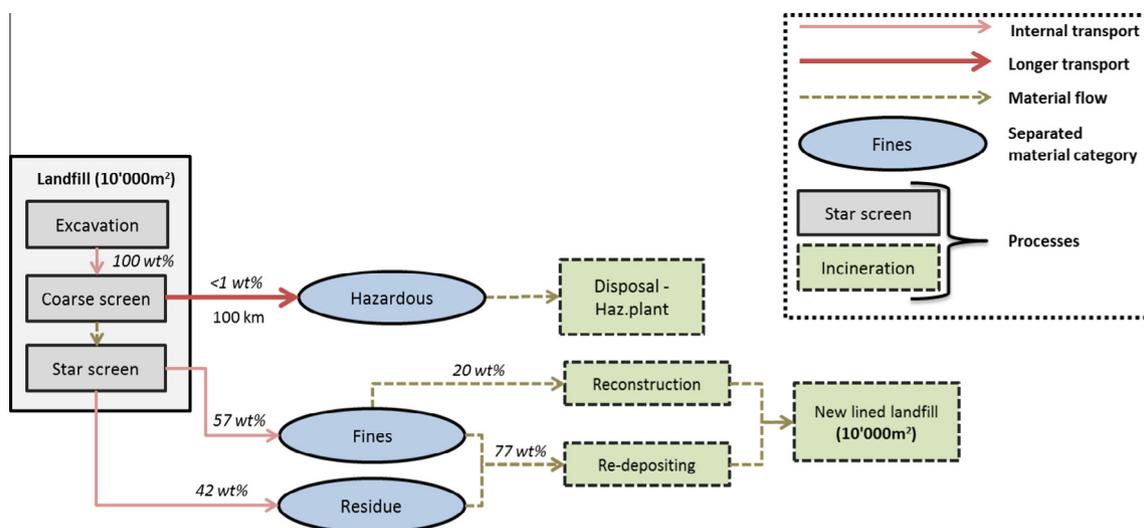


Fig. 1. Overview of the processes, transport distances, material flows and balances, and separated material categories for the remediation scenario. The values show the mean values of the material flows of the material (in wt%), and transport distances (in km). “Material flow” does not have a set distance, it just shows how the material flows between closely placed processes. “Internal transport” is transport within the landfill area, and is set to 10 km, while “Longer transport” is set to 100 km. Twenty wt% of the fines (containing soil and heavily degraded waste) is used for top cover, while the rest of the fine material and the residues are re-deposited in the newly lined landfill.

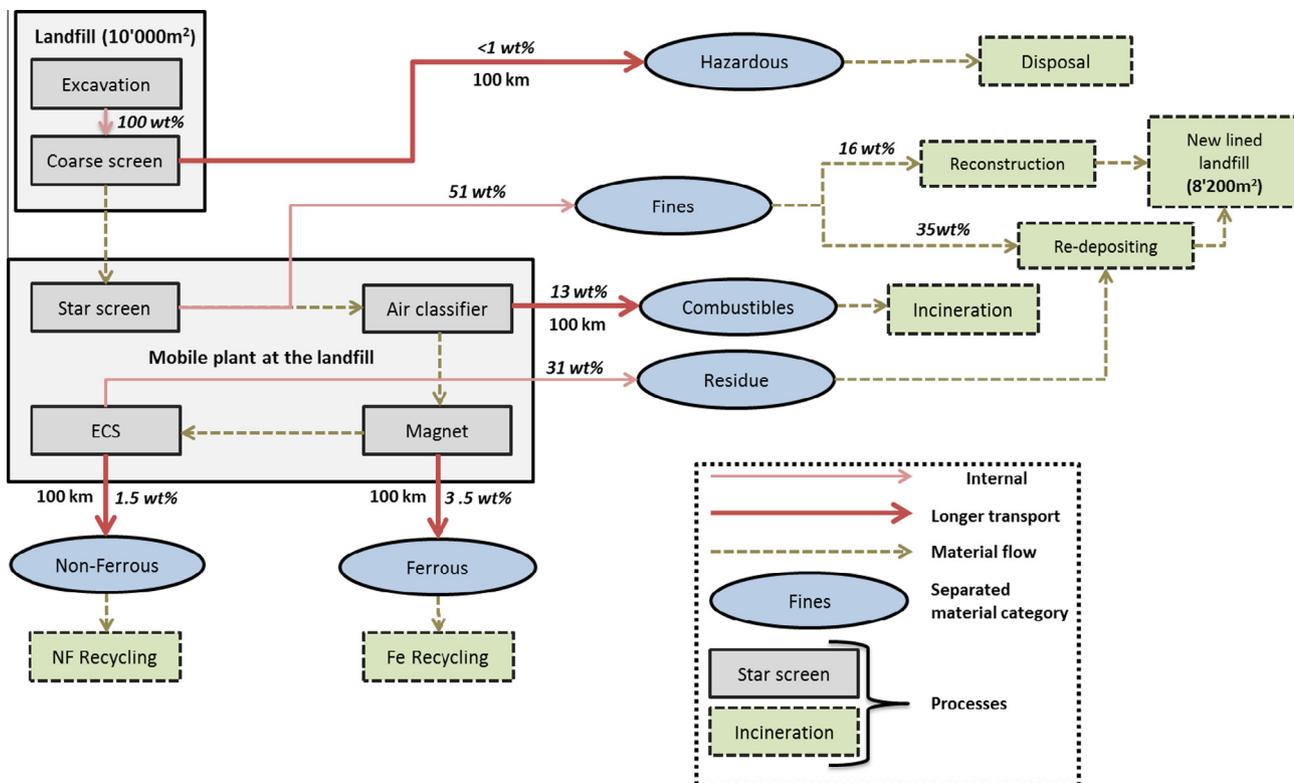


Fig. 2. Overview of the processes, transport distances, material flows and balances, and separated material categories for the integrated remediation and resource recovery scenario. The values show the mean values of the material flows of the material (in wt%), transport distances (in km), and area of the landfill (in m²). “Material flow” does not have a set distance, it just shows how the material flows between closely placed processes. “Internal transport” is transport within the landfill area, and is set to 10 km, while “Longer transport” is set to 100 km. Sixteen wt% of the fines (containing soil and heavily degraded waste) is used for top cover, while the rest of the fine material and residues are re-deposited in the newly lined landfill.

Table 2
Illustration of how the mass balances between the deposited material types and the separated material categories have been calculated, in weight percent. Comb = Combustible material, NF = Non-ferrous, Fe = Ferrous, Constr = Construction material, Res = Residue, Haz = Hazardous material.

Material type	Separated material category								
	Fines	Comb	NF	Fe	Constr	Plastic	Res	Haz	
Soil	a1(%)	a2(%)	a3(%)	a4(%)	a5(%)	a6(%)	a7(%)	a8(%)	$\sum_{i=1}^8 a_i = 100\%$
Paper	b1(%)	b2(%)	b3(%)	b4(%)	b5(%)	b6(%)	b7(%)	b8(%)	$\sum_{i=1}^8 b_i = 100\%$
Plastic									
Wood									
Textiles									
Inert materials									
Organic waste									
Ferrous metals									
Non-Fe metals									
Hazardous									

2.2. Economic analysis

Studying complex systems such as landfill mining inherently leads to the need for simplifications and assumptions. A common way to simplify the analysis is to assign single best estimate values to each parameter in a defined model and hence end up with a

single value as result. However, this has the possibility of failing to capture the inherent uncertainties when analyzing landfill mining. Since the values of the input parameters are highly uncertain, presenting the result as a single value might be misleading.

Another way of conducting an evaluation of a system with uncertainties is to include these uncertainties in the analysis, e.g.

by using stochastic modeling, setting up scenarios or using fuzzy data sets (cf. Lloyd and Ries, 2007). Clauvrel et al. (2013) discuss the problems with not distinguishing between stochastic and epistemic uncertainties in analyzing complex systems. If the area of study has not been explored to a high degree, which is the case with regards to landfill mining due to the lack of large projects (cf. Krook et al., 2012), it would generally be better to use a stochastic model.

Since the analysis focuses on direct variable costs from a landfill owner's perspective and does not include investment costs, using, for example, the real option method (cf. D'Alpaos, 2012) or a more basic NPV method does not apply here. Due to the type of data available, and the way the analysis is set up, stochastic modeling in the form of Monte Carlo simulation is chosen in this study. All the different input parameters in this study, e.g. material composition, separation efficiencies, costs, etc., have a set distribution, in the form of mean value and standard deviation. The simulation works by generating numerous randomized results based on these parameters' respective sample space. These results are then aggregated into a probability distribution curve, which can be graphically presented and analyzed. For a more in-depth description of MCS, see for example Metropolis and Ulam (1949) or Kalos and Whitlock (2008).

2.2.1. Scenario uncertainties

The uncertainties in landfill mining (and other concepts with a deficit in empirically based data) can be split between scenario uncertainties and parameter uncertainties (Huijbregts et al., 2003). Parameter uncertainties are those mentioned in the previous paragraph, e.g. the amount of non-ferrous metals in the landfill or the separation efficiency of combustible materials. Scenario uncertainties are comprised of all the uncertainties within the assumptions and choices made in order to build the scenarios.

When performing this and previous studies (e.g. Frändegård et al., 2013b), two aspects of the scenarios were deemed challenging, namely how to deal with costs and benefits for the municipality related to the landfill tax on re-deposition of non-recyclable materials and waste incineration of extracted combustibles.

Another very important scenario uncertainty is how the actual reference case is set up. The size of the landfill, its material composition, the separation technology used, and the estimated and/or collected operating costs and revenues all have a substantial impact on the economic result. These factors are mainly handled by using probability ranges instead of single values for each parameter in the simulation, which is used to show how different values for different parameters influence the result. The parameters found to be most important are also subjected to a thorough sensitivity analysis. The choice of reference case, for example if the materials are re-deposited in the same landfill site or moved to another one, also affects the importance of specific economic factors, which is discussed in Section 3.1.

2.2.1.1. Landfill tax. The present Swedish landfill tax is approximately EUR 50 (SEK 435, SFS 2005:962) per ton deposited material. If material is re-deposited during a remediation project, no landfill tax has to be paid. However, it is unclear if integrated remediation and resource recovery projects are exempt with the present tax code. The Swedish landfill tax code is currently under revision, which strongly indicates that integrated projects will be exempt in the future, but no decisions have yet been made (SEPA, 2013). Moreover, it is unclear whether the tax has to be paid in projects that solely or mostly focus on resource recovery, where the remediation of the landfill is not obvious or the main driver behind the project. Since the code is under revision, without any final decision, it is interesting to include the potential economic impacts of this factor in the study.

The calculations regarding landfill tax in this study are only relevant for material, i.e., fines and residues, re-deposited in the landfill, but not for the separated fines used as cover material. For residual material generated in later processes, located outside the boundaries of the landfill site, e.g. waste incineration ash that is deposited, landfill tax is already included in the cost (gate fee) that the municipality pays.

2.2.1.2. Waste incineration. Currently Sweden is experiencing a growing shortfall of waste to match the capacity of the country's 32 waste incineration facilities. While the amount of generated municipal solid waste has decreased in recent years, the number of CHPs has grown. This overcapacity has led to an increasing import of waste from other European countries, mainly Norway. In 2009, about 10% of the capacity was used for imported waste from Norway (SEPA, 2012).

If an actor wants to perform the integrated scenario described in this study without having access to a combined heat and power plant themselves, they would have to pay to be relieved of the combustible material. This cost can be quite large, since the current fee in Sweden is about 40 €/ton (SWM, 2012). If the combustible material has to be disposed of in the integrated scenario, and this "gate fee" has to be paid, the cost for this could be over EUR 0.5 million. However, if the landfill owner in this study has their own CHP and can benefit from selling heat and electricity produced by the excavated combustible materials, the combustible materials would instead produce revenues. Moreover, if the CHP does not need any additional fuel and has its supply covered, there might be a cost associated with using the combustible material from the landfill, which might not be up to the same standard and produce the same quality product (in regards to heat/electricity) as the regular fuel. The CHP will furthermore lose some revenue since it will not receive payment in the form of gate fees in addition to having to use sub-standard fuel.

Uncertainties in regards to landfill tax and waste incineration are handled by creating two different cases, A and B, for the integrated remediation and resource recovery scenario.

In case A, the CHP (owned by a different actor than the municipality) used for the excavated combustible materials is assumed to be running at 90% of its capacity based on regular fuel obtained from the source separation program, and handles this problem by importing waste from other countries. This leads to the CHP owner receiving gate fees from those foreign actors paying to dispose of their waste. Hence, for the CHP owner not to lose money by using the waste produced from the municipal landfill mining project, the municipality will pay a gate fee for all extracted combustible materials. The municipality will also pay landfill tax on material that is re-deposited in the landfill in the integrated scenario.

In case B, the municipality owns a CHP and pays no landfill tax for re-deposition of exhumed masses in either of the scenarios. Moreover, in this case we assume that the current CHP has the same overcapacity when using locally produced waste, but uses the excavated material from the landfill as supplementary fuel for obtaining a full workload. This is a similar approach to landfill mining mentioned in Hull et al. (2005) and Obermeier et al. (1997).

2.2.2. Relevant costs and revenues for each scenario

The economic analysis is done from the perspective of the landfill-owning municipality, with each scenario divided into several types of costs and revenues, see Table 3.

Costs for planning, excavation, material separation, landfill reconstruction, transport, disposal of hazardous material were collected from Stena Metall AB (2013). Many of these specific costs are only shown in aggregated form in the calculations due to confidentiality agreements.

Table 3
List of the different type of costs (C) and revenues (R) included in the economic analysis. Remediation-only (RO) and Integrated remediation and resource recovery (IR&RR). “X” = cost/revenue is included in the scenario, “–” = cost/revenue is not included in the scenario, “X=” = cost/revenue is the same for both scenarios, “X–” = cost/revenue is lower for IR&RR-scenario, “X+” = cost/revenue is higher for IR&RR-scenario.

Type of cost/revenue	C/R	Unit	Case	RO	IR&RR	Source
Planning	C	€/project	A/B	X	X=	Stena Metall AB (2013)
Excavation	C	€/ton	A/B	X	X=	Stena Metall AB (2013)
Material separation	C	€/ton	A/B	X	X+	Stena Metall AB (2013)
Landfill reconstruction	C	€/ton	A/B	X	X–	Stena Metall AB (2013)
Transport	C	€/ton km	A/B	X	X+	Stena Metall AB (2013)
Disposal fee – Hazmat	C	€/ton	A/B	X	X=	Stena Metall AB (2013)
Gate fee	C	€/ton	A	–	X+	SWM (2012)
Landfill tax	C	€/ton	A	–	X+	SFS (2005:962)
Waste incineration	C	€/MJ	B	–	X+	SEMI (2013)
Waste incineration	R	€/MJ	B	–	X+	SEMI (2013)
Material sales	R	€/ton	A/B	–	X+	LME (2014) Stena Metall AB (2013)
Land reclamation	R	€/m ²	A/B	–	X+	van Passel et al. (2013)

All the costs have a set mean value and a distribution in the form of a standard deviation. As some processes and data are better known than others, the standard deviation varies accordingly. For example, since calculating costs related to excavation and transport is common practice, the standard deviations for these costs are set to a relatively low value of 10%. The standard deviation for metal prices and land values however, which have a much higher uncertainty, is instead set to 30%.

Planning costs includes all fixed costs related to initiating a landfill mining/remediation project and consists to a large degree of administrative costs. This cost type includes costs for preliminary investigations of the landfill site, preparation of and application for permits, planning for the project and setting up the required machinery. *Excavation* costs incorporate both the actual digging with an excavator and the use of wheel loaders and dumper trucks to transport the material internally on the landfill. *Material separation* includes costs related to the use of the star screen situated at the landfill for the remediation-only scenario, while for the integrated scenario the processing cost for the mobile separation plant is also added.

Landfill reconstruction consists of costs for constructing terraces, installing bottom lining and top cover system, according to the description in Section 2.1.2. These costs are actually lower for the integrated scenario than in the remediation-only scenario, since material is transported away from the landfill site, which means a smaller area to reconstruct. Subsequently, using separated fines material as construction material leads to an avoided cost in procuring cover material externally, even though this cost is comparatively minuscule in the studied system. Another related and more significant factor which is relevant in case A is the avoidance of landfill tax for separated fines material used for the construction of top cover. In both case A and B, for the remediation-only scenario, the area to reconstruct is 10,000 m², while in the integrated scenario the area is about 8200 m², reclaiming 1800 m² of land.

The revenue from *land reclamation* is very site-dependent and hard to give a general estimate on. The Dutch landfills in a study by van der Zee et al. (2004), located closer than 500 m from a built-up area, have an estimated land value of €50–€300 per m². The calculations by van Passel et al. (2013) result in a weighted average of €40/m² for general land value in Flanders. Since the landfill in this study is located close to an urban area while being in a less densely populated country than Belgium and the Netherlands, €40/m² seems like a good mean value to use in the simulations, since it also corresponds well to the mean value of industrial land in medium-sized cities sold by Swedish municipalities (SKT, 2010). This means a total value of the reclaimed land of about €72,000.

Transport involves costs for moving the material on the landfill site, as well as longer transport from the landfill to a hazardous

material disposal facility. For the integrated scenario, there is also material transported to the metal processing facility and to the combined heat and power plant (CHP). *Disposal fee* include the costs of disposing of hazardous material at a hazardous material disposal facility. The average cost for disposing hazardous material has been estimated at about 200 €/ton, although this varies a lot depending on the type of material.

The costs and revenues from *waste incineration* of the separated combustible material in the integrated scenario are calculated based on data from the Swedish Energy Markets Inspectorate (SEMI, 2011, 2013). The costs, which are a calculated average based on three of Sweden's CHPs and are calculated based on all costs related to the energy/heat generation for those companies, are approximately 120 €/GJ of electricity generation and about 9 €/GJ of produced heat. The revenues from waste incineration are close to 150 €/GJ of electricity generation and 17 €/GJ of produced heat.

Prices of non-ferrous metals were collected from LME (2014), and the price of ferrous metal was received from Stena Metall AB (2013). The revenues for the municipality from *material sales* were based on the need for valorization of the separated metal categories from the landfill, which led to setting the revenue for the municipality selling the material at 70% of the market price, according to discussions with Stena Metall AB (2013).

Revenues and costs are then summed up and presented as cumulative probability distribution charts for each scenario and case.

3. Results and discussion

3.1. Economic analysis

The remediation project costs EUR 1.5–3 million to undertake, with an expected (average) cost of about EUR 2.3 million, or €23/ton, Fig. 3. This cost per ton is higher than what is seen in for example a Swedish remediation project carried out in 2005 on an inactive area of the Stentippen landfill in Helsingborg. In that project, focused on contaminated soil, about 340,000 m³ was excavated and the remediation cost was €13/ton (Johansson et al., 2012). The project, which was simpler in its setup than the scenario described in this study, consisted of the following main components: the material was excavated, screened with an XRF analyzer, and depending on contamination level the material was re-deposited, used as cover material, or deposited into another active landfill nearby owned by the same actor. Just as in case B of the remediation scenario in this study, no landfill tax was paid in the Stentippen project. Additionally, no new landfill had to be constructed which, according to our results, costs about €12/ton, which clearly explains the big disparity between the result of the

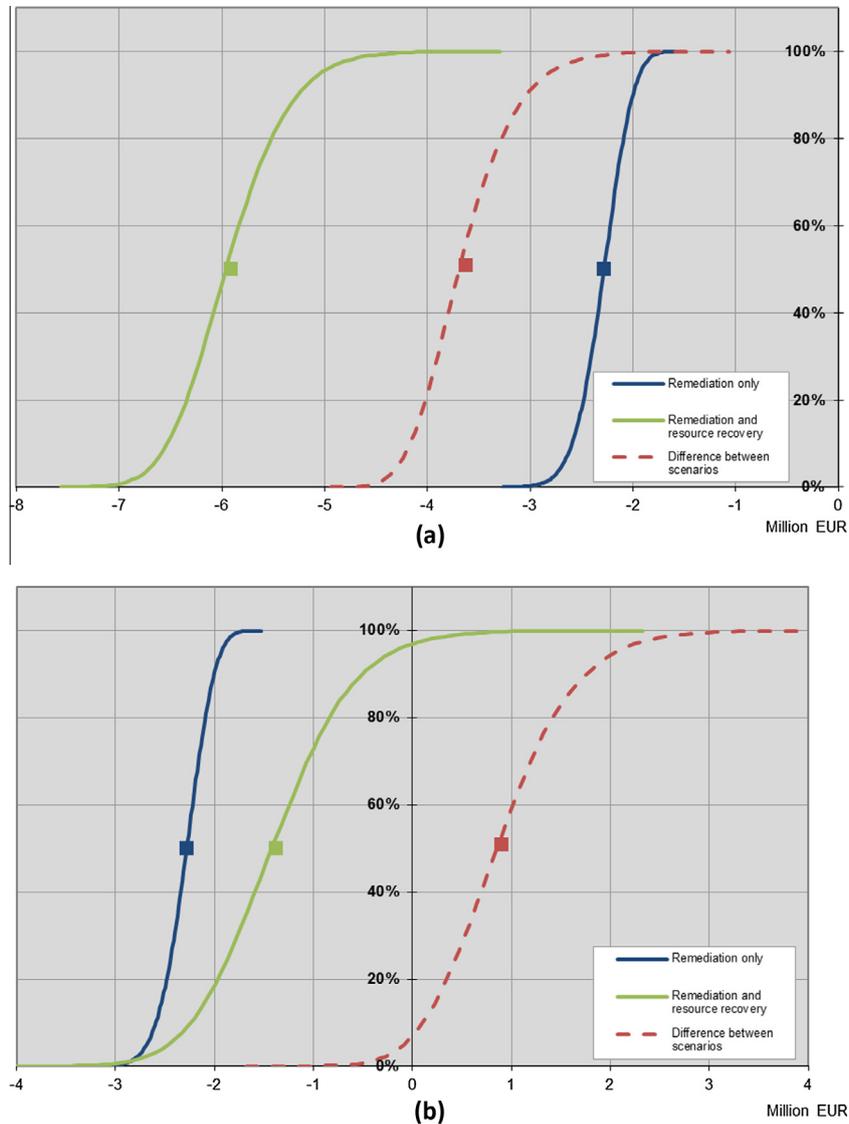


Fig. 3. The chart shows the cumulative probability distribution of the net result (in million euros) for the two scenarios in case A (a) and case B (b); remediation only and integrated remediation and resource recovery, as well as the difference between the two. Results are based on a 30,000-sample Monte Carlo simulation. The square on each curve illustrates the most probable result, the expected value for each scenario. The x-axis of the result charts describes the net result, which can be either positive (profit) or negative (deficit). If the entire range of possible outcomes, i.e., the curve, is located to the left of the y-axis, the scenario only produces results with deficit, and vice versa. When scenarios have a result curve that lies on both sides of the y-axis, the point where the curve crosses the y-axis determines the probability of a deficit.

Stentippen case and the remediation scenario analyzed in this study.

The remediation project has the same costs for both cases. With the addition of resource recovery in case A, including the costs of landfill tax and gate fees for combustible materials, the result worsens considerably. Adding resource recovery to the remediation project in case A increases the costs by about EUR 2–5 million, with an expected value of EUR 3.6 million, or €36/ton, Fig. 3a.

However, for the integrated scenario there are big differences. With the addition of resource recovery in case B, the result is still negative to a large degree, but the expected cost is decreased to about EUR 1.4 million, or €14/ton, Fig. 3b. There is about 5% probability for the integrated remediation and resource recovery project to show a net profitable result. Even though the expected value is higher for the integrated scenario, the range of possible outcomes is wider, ranging from around EUR –3.5 to +2.0 million. However, as seen by the curve showing the differences between scenarios, the risk of worsening the result by including resource recovery is small, with a probability of less than 1%.

This type of comparison between the scenarios is sensitive to the setup of the reference case, so as a comparison, we have simulated what it would cost if the remediation project was done by simply excavating all the material and transporting it to another landfill not owned by the municipality. The costs involved would be costs for planning, excavation, transport, and re-depositing at the new landfill, but no costs for material separation or landfill reconstruction. The revenue of about €350,000 for cleaning up the whole landfill area would only be a small fraction of the net loss of EUR 10 million, or €100/ton, whereby the majority of the result can be derived in this scenario from the cost of depositing in another landfill site, owned by another actor. The depositing cost is estimated to be about €90/ton, including landfill tax. However, it is not clear from a legal standpoint if this material is taxable, since it is in relation to a remediation project, even though the material has left the landfill site. If tax is excluded from the calculations, the total result is then lowered to EUR 5 million, or €50/ton. If the depositing fee is disregarded completely the result is around €10/ton, comparable to the previously mentioned

Stentippen case, and case B in this study (excluding landfill construction costs).

When using this alternative reference case for the integrated scenario, all the residual material, i.e. everything except the separated combustible, ferrous, and non-ferrous material, is transported and re-deposited in another landfill. Since all the material leave the old landfill site, the whole area can be considered for other construction. This leads a project result of –€6.5 million (including landfill tax). Hence, the integrated scenario shows an improved result by €3.5 million compared to the remediation-only scenario also when using this reference case.

3.1.1. Which processes matter most?

Furthermore, to expand on the analysis of each scenario, the expected (mean) values of revenues and costs for each scenario and case respectively have been divided into several types of processes according to Table 3. It is important to remember, however, that these values only give part of the picture, since each cost and revenue varies according to the preset probability range for each parameter. For the processes in this study, the larger the expected value, the larger the variability is generally for that specific process.

The remediation-only scenario is similar for both cases, and includes no direct revenues, with the exception of the negligible avoided cost of buying construction material, Fig. 4. The largest costs relate to the processes included in the reconstruction of the landfill, comprising about half the scenario's costs. Excavation of the material, separation using the star screen and costs for disposal of hazardous material together cover about 40% of the cost, while material transport and project planning are relatively small factors.

Integrating remediation with resource recovery for case A produces some revenues, but also additional costs, Fig. 5. The landfill tax becomes almost half of the total cost, which clearly shows its impact and importance.

Even though most of the cost parameters in the integrated scenario are seen in the remediation-only scenario, with the exception of costs for waste incineration, most of them are changed. The integrated scenario leads to an avoided cost of EUR 0.3 million in landfill reconstruction, due to 1800 m² less landfill area that needs to be reconstructed by recovering a share of the material. Since more material needs to be transported off the landfill site due to the separation processes, costs for transports are increased by EUR 0.2 million. Costs for material separation increase a lot, from EUR 0.4 to 1.3 million, by adding the processes for separating combustible material and metals.

Including resource recovery in the remediation project for case B produces more revenues, and decreases some of the costs. Revenues from producing heat and generating electricity are the

dominant factor in this scenario, and comprise over 70%, or EUR 2.8 million of the potential revenue streams, Fig. 6. Material sales are also important however for the net result, while the value of the land reclamation is a small fraction of the total revenue using land value of €40/m³. However, if instead the highest land value from van der Zee et al. (2004) is used, €300/m³, the revenue from land reclamation is over EUR 0.5 million, which shows that the location of the landfill can have a large impact on the result.

3.1.2. Further analysis of important factors

The difference between the revenues and costs in case B is about EUR 1.4 million. To reach a profitable result, three factors are analyzed in more detail, all related to the revenues from material sales, i.e., metal content in the landfill, separation efficiency, and metal prices.

Examining the calculations on which the scenario results are based, the average amount of metals in the landfill is about 4.4%, where 3.6% is ferrous, and 0.8% is non-ferrous. The composition of the landfill in this study is based on an average of municipal solid waste landfills in the industrialized part of the world, an average landfill that does not seem to consist of enough metals to make their separation currently profitable. What would contribute to a more positive result would be to find a landfill with more recyclable metals, as mentioned above, perhaps by following the funnel methodology proposed by van der Zee et al. (2004). Another, more long-term solution is to increase the efficiency in the separation technology. With the standard equipped mobile technology on which this study is based, about half of the ferrous metals and about one-third of the non-ferrous metals can be extracted (Frändegård et al., 2013b). Combining ferrous and non-ferrous metals, the average separation efficiency is around 40%. If these fractions could increase, the economic result would increase as well. The third main factor for determining the income from material sales are the actual prices of metals. This factor is hard to predict, and has varied widely in recent decades. Using the figures and metal composition in the simulation, the average price per ton is about €500/ton, even though ferrous metals are much less expensive than non-ferrous metals.

To reach profitability, one, or a combination of these three factors need to increase by a total of 150%, i.e., metal composition needs to be at least 11%, separation efficiency needs to be 100%, or the average price of metals needs to increase to about €1300/ton. These figures might seem overwhelming and unrealistic, but what should also be pointed out is that instead of one factor increasing with by 150%, it is enough if all of them, on average, increase with by at least 35%. This means that the metal composition needs to be around 6%, separation efficiency needs to be 54% and the average price of metals needs to be €700/ton. The composition and the efficiency changes are only viable if the amount of non-ferrous metals are is at least 20% of the total amount of metals, which is typical for municipal landfills.

In regards to the landfill composition, there are several landfill mining cases reporting a high metal content. Several specific cases of municipal landfills with a metal content higher than 6% have been reported (cf. Sormunen et al., 2008; Prechtai et al., 2008). If industrial landfills, or municipal landfills with a high degree of industrial waste, are included, the metal content can be even higher. For example, one industrial landfill in Sweden has been estimated to consist of over 10% scrap metals, of which more than half are non-ferrous metals (Alm et al., 2006). One way of increasing the separation efficiency is to use a larger separation facility off-site, instead of a mobile plant on-site. According to Frändegård et al. (2013a), this can increase the separation to close to 60%. However, a problem with these types of separation facilities is that they are constantly running at near full capacity, and it can be difficult to make room for excavated material from a

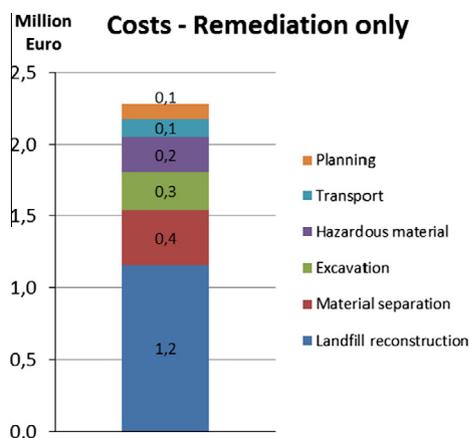


Fig. 4. Result divided into expected values of different cost types for remediation-only scenario.

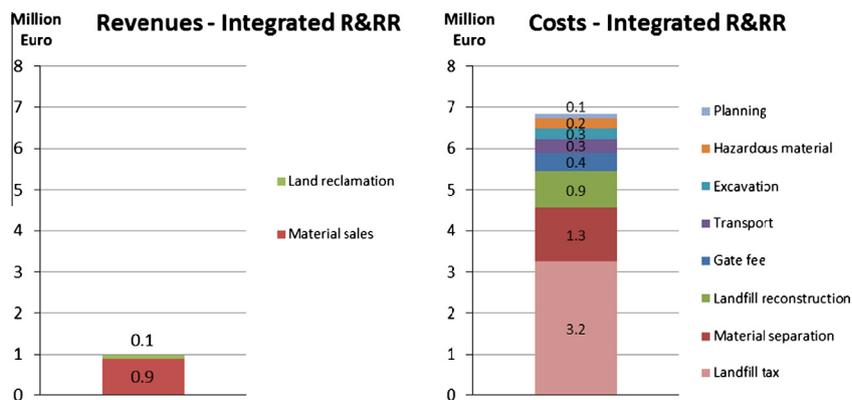


Fig. 5. Result divided into expected values of different cost and revenue types for the integrated remediation and resource recovery scenario (case A).

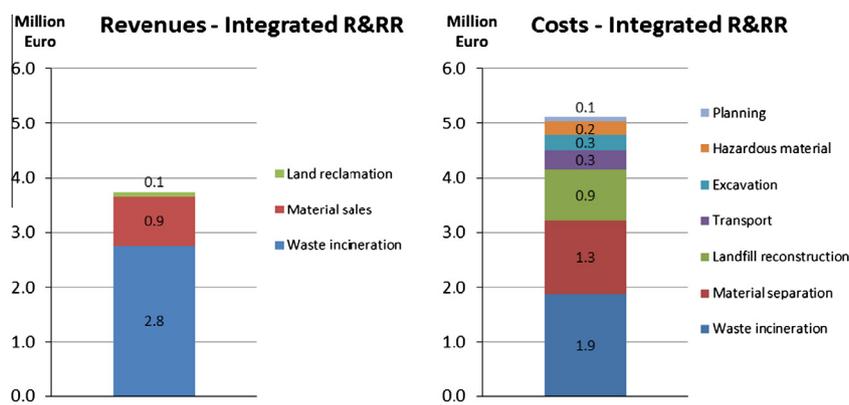


Fig. 6. Result divided into expected values of different cost and revenue types for the integrated remediation and resource recovery scenario (case B).

landfill. Moreover, this might lead to lower revenues for the facility owner since the metal content generally is lower than in the usual input material. Finally, large changes in metal prices are common. For example, copper prices have been very volatile during the last 10 years, fluctuating wildly between €2000/ton and €7000/ton, with some increases and decreases in price of over 100% in only a year (LME, 2014).

It is clear from the results that the amount of combustible materials in the landfill is of high importance for the economic outcome. Depending on the project owner's access to a CHP, and their need for and access to supplementary fuel sources, the result differs a lot. An actor investigating the potential of integrating resource recovery into its remediation project has to take the amount of combustible materials in the landfill into account. If this actor owns a CHP running on overcapacity, the amount of combustible materials in the landfill directly affects the result, i.e., more material leads to higher revenues. Still, this might not be completely realistic since the result is based on the preconditions for the scenario regarding overcapacity, and a lack of supply through import. Sweden has an ongoing overcapacity on its waste incinerators, but solves this currently by importing waste from Europe. This is currently preferable since the waste incinerator owner receives gate fees that cover their operating costs, which in turn leads to increased profits and is therefore seen as a more attractive option compared e.g. to extracting waste fuel from their own landfills.

However, this solution may be seen as somewhat questionable in the long run, since more countries will try to implement policies to move up in the waste hierarchy (prevent, reuse, recycle) and decrease the amount of waste produced. Meanwhile, there is continuous expansion of waste incineration facilities throughout

Europe that increase the demand and thus the competition for waste fuel, which will make it more costly, or let us say less profitable, to import. Hence, landfills might eventually become a suitable alternative or at least a supplement to import.

If the owner does not have access to a CHP, which is true for most landfill owners today, more combustibles only produce more costs, even though the ongoing trend points at decreasing gate fees. There are also different types of methods for turning waste into energy, in addition to incineration that is used in this study. Bosmans et al. (2013) discusses the different technologies, i.e., incineration, gasification, pyrolysis, plasma, and combinations thereof, and suggests that plasma gasification would be an efficient choice when dealing with municipal solid waste. This technology is part of what makes the ELM project seem to have economic potential (Jones et al., 2013; van Passel et al., 2013). Even though the commercial performance of this technology is unclear at this date, it might lead to changes in the economic potential of landfill mining.

4. Conclusion

The main conclusion that can be drawn from this study is that integrating resource recovery with a remediation project can be profitable, or more realistically decrease the project cost, under certain conditions. Primarily, it is important to know whether the landfill tax has to be paid for the re-deposited material, since according to this study this cost can make up half the project's total cost. The latest draft for a revised landfill tax code in Sweden points toward re-deposited material being exempt from tax when it is performed within a remediation project (SEPA, 2013). However, the final revised code has not yet been decided. Another important

factor is whether the handling of the combustible materials incurs additional costs or revenues, i.e., if the landfill owner has to pay to be relieved of the separated combustibles or if profits can be made from the waste incineration process. This in turn depends on the situation regarding ownership of a CHP, current and future overcapacity, and the potential supply from imports or other sources. Depending on what type of material is sought after, the selection of the right landfill is also important. Studies has shown that older landfills contain a higher amount of metals than newer ones, due to more efficient pretreatment for the recently deposited waste, while newer landfills contain a higher amount of plastics and combustible materials than older ones (e.g. Hull et al., 2005; Krook et al., 2012; Krook and Baas, 2013).

At least two of the previously mentioned aspects, the revenues from metal separation and the question of owning a CHP, could be facilitated by cooperation. Municipal landfills might not be optimal from a resource recovery point of view, while specific industrial landfills, related for example to the metalworking industry, might potentially have a much higher metal content. An industrial landfill owner without a CHP might cooperate with a CHP owner and decide to share the project's costs, as well as the revenues. Other possible types of landfills that might be of interest for landfill mining could include landfills containing waste incineration ash. This material is more homogenous than the usual MSW or industrial landfill and it might thus be easier to choose optimal separation technologies and increase the efficiency.

There could also be mutual benefits from including a recycling company in the analysis, assisting with the separation and recycling processes, and giving some of its increased profits back to the landfill owner. Depending on the situation, there could also be an opportunity to include other actors, perhaps neighboring companies looking to expand but lacking suitable land, or construction companies willing to build on this newly remediated land. Different types of profit-sharing setups with different actors would be of interest for future studies.

The knowledge of how to best optimize separation processes for material that has been deposited in a landfill for decades, and thereby reduce the amount of residual material that needs to be re-deposited, is generally lacking. This study has used a mobile plant for material separation, located at the landfill, which may seem like a reasonable choice for a small municipality-owned landfill, and has been the way most previous landfill mining projects have been setup. However, there are stationary separation plants that could be considered due to their higher separation efficiencies (e.g. Frändegård et al., 2013b), even though they might need to be improved to suit landfilled material. Using a separation technology with higher efficiency leads to less residual material, which is important both in regards to environmental and economic potential.

Finally, this study has only considered direct economic costs and revenues. A landfill owner would gain more advantages than the directly economic ones, though, in the form of indirect benefits. These are usually hard to quantify, but should be included in the discussion surrounding a project like this. A landfill-owning municipality, for example, would probably see the benefits in increased societal values by transforming an environmentally unfriendly landfill to a prosperous and safer area. These benefits can be addressed, for example, by using the contingent valuation method (cf. Ayalon et al., 2006; Marella and Raga, 2014). Other indirect costs not covered in this article are the potential savings that could be gained by remediating the landfill and installing safe lining and cover systems, instead of waiting until the local environment becomes damaged. Additionally, landfill mining may lead to a reduction in the carbon footprint by recycling previously landfilled material and/or replacing conventional energy generation by less carbon-emitting combustibles. If landfill mining is a

concept that governmental bodies would like to support, it would be important to make these external societal benefits internal revenues for the landfill mining initiator, by introducing governmental grants or subsidies. The importance of this is shown, for example, in the study by van Passel et al. (2013), where the possibility to receive green electricity certificates is one of the key factors for the positive economic result.

References

- Alm, J., Christéen, J., Collin, G., 2006. Landfill Mining at Stena Gotthard's Landfill in Halmstad – an Environmental and Economic Evaluation. Master's thesis, Linköping University, Linköping, Sweden.
- Ayalon, O., Becker, N., Collin, G., 2006. Economic aspects of the rehabilitation of the Hiriya landfill. *Waste Manage.* 26, 1313–1323.
- Bosmans, A., Vanderreydt, I., Geysen, D., Helsen, L., 2013. The crucial role of Waste-to-Energy technologies in enhanced landfill mining: a technology review. *J. Cleaner Prod.* 55, 10–23.
- Cha, M.C., Yoon, B.H., Sung, S.Y., Yoon, S.P., Ra, I.W., 1997. Mining and remediation works at Ulsan landfill site, Korea. In: *Proceedings Sardinia '97, Sixth International Landfill Symposium*, vol. 4, pp. 553–558.
- Clauvrel, J., Guyonnet, D., Tonini, D., Christensen, T.H., 2013. Stochastic and epistemic uncertainty propagation in LCA. *Int. J. Life Cycle Assess.* 18, 1393–1403.
- Cossu, R., Motzo, G.M., Laudadio, M., 1995. Preliminary study for a landfill mining project in Sardinia. In: *Proceedings Sardinia '95, Fifth International Landfill Symposium*, vol. 3, pp. 841–850.
- Cossu, R., Hogland, W., Salerni, E., 1996. Landfill Mining in Europe and the USA. *ISWA Year Book*, pp. 107–114.
- D'Alpaos, C., 2012. The value of flexibility to switch between water supply sources. *Appl. Math. Sci.* 6, 6381–6401.
- Dickinson, W., 1995. Landfill mining comes of age. *Solid Waste Technol.* 9, 42–47.
- EPA (United States Environmental Protection Agency), 1997. *Landfill Reclamation*. Washington, DC.
- Fisher, H., Findlay, D., 1995. Exploring the economics of mining landfills. *World Wastes* 38, 50–54.
- Frändegård, P., Krook, J., Svensson, N., Eklund, M., 2013a. A novel approach for environmental evaluation of landfill mining. *J. Cleaner Prod.* 55, 24–34.
- Frändegård, P., Krook, J., Svensson, N., Eklund, M., 2013b. Resource and climate implications of landfill mining – a case study of Sweden. *J. Ind. Ecol.* 17 (5), 742–755.
- Halada, K., Ijima, K., Shimada, M., Katagiri, N., 2009. A possibility of urban mining in Japan. *J. Jpn. Inst. Met.* 73, 151–160.
- Hogland, W., Jagodzinski, K., Meijer, J.E., 1995. Landfill mining tests in Sweden. In: *Proceedings Sardinia '95, Fifth International Landfill Symposium*, vol. 3, pp. 783–794.
- Hogland, W., Marques, M., Nimmermark, S., 2004. Landfill mining and waste characterization: a strategy for remediation of contaminated areas. *J. Mater. Cycles Waste Manage.* 6, 119–124.
- Hogland, W., Hogland, M., Marques, M., 2010. Enhanced Landfill Mining: Material recovery, energy utilisation and economics in the EU (Directive) perspective. In: *Proceedings of the International Academic Symposium on Enhanced Landfill Mining, Houthalen-Helchteren, Belgium*, pp. 209–222.
- Huijbregts, M.A.J., Gilijamse, W., Ragas, A.M.J., Reijnders, L., 2003. Evaluating uncertainty in environmental life-cycle assessment. A case study comparing two insulation options for a Dutch one-family dwelling. *Environ. Sci. Technol.* 37 (11), 2600–2608.
- Hull, R.M., Krogmann, U., Strom, P.F., 2005. Composition and characteristics of excavated materials from a New Jersey landfill. *J. Environ. Eng.* 131, 478–490.
- Jain, P., Townsend, T.G., Johnson, P., 2013. Case study of landfill reclamation at a Florida landfill site. *Waste Manage.* 33, 109–116.
- Johansson, N., Krook, J., Eklund, M., 2012. Transforming dumps into gold mines. Experiences from Swedish case studies. *Environ. Innov. Soc. Transit.* 5, 33–48.
- Johansson, N., Krook, J., Eklund, M., Berglund, B., 2013. An integrated review of concepts and initiatives for mining the technosphere: Towards a new taxonomy. *J. Cleaner Prod.* 55, 35–44.
- Jones, P.T., Geysen, D., Tielemans, Y., van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., Hoekstra, N., 2013. Enhanced landfill mining in view of multiple resource recovery: a critical review. *Journal of Cleaner Production* 55, 45–55.
- Kalos, M.H., Whitlock, P.A., 2008. *Monte Carlo Methods*. Wiley-VCH, Weinheim, Germany.
- Kapur, A., 2006. The future of the red metal: discards, energy, water, residues and depletion. *Prog. Ind. Ecol. – Int. J.* 3, 209–236.
- Krogmann, U., Qu, M., 1997. Landfill mining in the United States. In: *Proceedings Sardinia '97, Sixth International Landfill Symposium*, vol. 4, pp. 543–552.
- Krook, J., Baas, L., 2013. Getting serious about mining the technosphere: a review of recent landfill mining and urban mining research. *J. Cleaner Prod.* 55, 1–9.
- Krook, J., Svensson, N., Eklund, M., 2012. Landfill mining: a critical review of two decades of research. *Waste Manage.* 32, 513–520.
- Lloyd, S.M., Ries, R., 2007. Characterizing, propagating, and analyzing uncertainty in life-cycle assessment – a survey of quantitative approaches. *J. Ind. Ecol.* 11 (1), 161–179.

- LME (London Metal Exchange), 2014. <<http://www.lme.com>> (accessed February 2014).
- Marella, G., Raga, R., 2014. Use of the contingent value method in assessment of a landfill mining project. *Waste Manage.* 34, 1199–1205.
- Metropolis, N., Ulam, S., 1949. The Monte Carlo method. *J. Am. Stat. Assoc.* 44 (247), 335–341.
- Obermeier, T., Hensel, J., Saure, T., 1997. Landfill mining: energy recovery from combustible fractions. In: *Proceedings Sardinia '97, Sixth International Landfill Symposium*, vol. 4, pp. 569–578.
- Prechtai, T., Padmasri, M., Visvanathan, C., 2008. Quality assessment of mined MSW from an open dumpsite for recycling potential. *Resour. Conserv. Recycl.* 53, 70–78.
- Quaghebeur, M., Laenen, B., Geysen, D., Nielsen, P., Pontikes, Y., Van Gerven, T., Spooren, J., 2013. Characterization of landfilled materials: screening of the enhanced landfill mining potential. *J. Cleaner Prod.* 55, 72–83.
- Rettenberger, G., 1995. Results from a landfill mining demonstration project. In: *Proceedings Sardinia '95, Fifth International Landfill Symposium*, vol. 3, pp. 827–840.
- Richard, D., Ambrosie, R., Zavoral, P., Zimmerman, R., 1996. Fargo takes a second look at the old landfill site. In: *Proceedings of the 19th International Madison Waste Conference*, University of Wisconsin-Madison/Extension, pp. 197–205.
- Swedish Energy Markets Inspectorate, 2011. *Analys av fjärrvärmeföretagens intäcks- och kostnadsutveckling*. [Analysis of district heating companies revenue- and cost development] Eskilstuna, Sweden: Swedish Energy Markets Inspectorate.
- Swedish Energy Markets Inspectorate, 2013. <<http://www.ei.se>> (accessed January 2013).
- SEPA (Swedish Environmental Protection Agency), 1996. *Metaller – materialflöden i samhället*. [Metal – material flows in society.] Stockholm, Sweden.
- SEPA (Swedish Environmental Protection Agency), 2003. *Om ansvar för miljöskulder i mark och vatten*. [About responsibility for environmental debt of soil and water.] Stockholm, Sweden.
- SEPA (Swedish Environmental Protection Agency), 2008. *National Inventory Report Sweden*. Stockholm, Sweden.
- SEPA (Swedish Environmental Protection Agency), 2012. *Från avfallshantering till resurshållning*. [From waste management to resource management] Stockholm, Sweden.
- SEPA (Swedish Environmental Protection Agency), 2013. *Översyn av deponiskatten*. [Revision of the landfill tax] Stockholm, Sweden.
- SFS 2005:962 *Skatt på avfall*. [Waste tax] Stockholm: Justitiedepartementet.
- SKT, 2010 (Swedish Association of Municipal Engineers). *Prisundersökning för kommunal mark, 2009–2010*. [Survey of the prices of municipal land, 2009–2010] Stockholm, Sweden.
- Sormunen, K., Ettala, M., Rintala, J., 2008. Detailed internal characterisation of two Finnish landfills by waste sampling. *Waste Manage.* 28, 151–163.
- Spencer, R., 1990. Landfill space reuse. *Biocycle* 31, 30–33.
- Stena Metall AB, 2013. Personal communication with Hitomi Lorentsson, project manager, Stena Metall AB.
- Stessel, R.I., Murphy, R.J., 1991. Processing of material mined from landfills. In: *Proceedings of the National Waste Processing Conference*, Detroit, MI: ASME, pp. 101–111.
- SWM (Swedish Waste Management), 2010. *Svensk avfallshantering 2010*. [Swedish waste management 2010.] Malmö, Sweden, Swedish Waste Management.
- SWM (Swedish Waste Management), 2012. *Avfall Sverige Deponihandbok*. [Landfill Guide by Swedish Waste Management.] Malmö, Sweden, Swedish Waste Management.
- van der Zee, D.J., Achterkamp, M.C., de Visser, B.J., 2004. Assessing the market opportunities of landfill mining. *Waste Manage.* 24, 795–804.
- van Passel, S., Dubois, M., Eyckmans, J., de Gheldere, S., Ang, F., Jones, P.T., van Acker, K., 2013. The economics of enhanced landfill mining: private and societal performance drivers. *J. Cleaner Prod.* 55, 92–102.
- Zanetti, M., Godio, A., 2006. Recovery of foundry sands and iron fractions from an industrial waste landfill. *Resour. Conserv. Recycl.* 48, 396–411.