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Landfill mining: A critical review of two decades of research

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ABSTRACT

Landfills have historically been seen as the ultimate solution for storing waste at minimum cost. It is now a well-known fact that such deposits have related implications such as long-term methane emissions, local pollution concerns, settling issues and limitations on urban development. Landfill mining has been suggested as a strategy to address such problems, and in principle means the excavation, processing, treatment and/or recycling of deposited materials. This study involves a literature review on landfill mining covering a meta-analysis of the main trends, objectives, topics and findings in 39 research papers published during the period 1988–2008. The results show that, so far, landfill mining has primarily been seen as a way to solve traditional management issues related to landfills such as lack of landfill space and local pollution concerns. Although most initiatives have involved some recovery of deposited resources, mainly cover soil and in some cases waste fuel, recycling efforts have often been largely secondary. Typically, simple soil excavation and screening equipment have therefore been applied, often demonstrating moderate performance in obtaining marketable recyclables. Several worldwide changes and recent research findings indicate the emergence of a new perspective on landfills as reservoirs for resource extraction. Although the potential of this approach appears significant, it is argued that facilitating implementation involves a number of research challenges in terms of technology innovation, clarifying the conditions for realization and developing standardized frameworks for evaluating economic and environmental performance from a systems perspective. In order to address these challenges, a combination of applied and theoretical research is required.

1. Introduction

In many regions of the world, landfills have long been seen as a final way to store waste at minimum cost. Nowadays, it is a well-known fact that such practices have a number of related implications (Daskalopoulos et al., 1997). Apart from that refined natural resources, in which materials and energy have been invested, are wasted, degradation of organic waste in such deposits generates long-term methane emissions contributing to global warming (Mor et al., 2006; Sormunen et al., 2008). Landfills, especially old ones lacking modern environmental technology, are also well-known sources for local pollution due to leaching of hazardous substances (Flyhammar, 1997). Furthermore, space issues have become increasingly important, especially in densely populated areas, where the location of such deposits sometimes interferes with city expansion (Zhao et al., 2007). In many parts of the world, however, landfilling is still the most common waste disposal method (Eurostat, 2009; Kollikkathara et al., 2009). Even in countries which have developed systems for waste treatment and recycling, this option has often remained important or at least still was as recently as a decade or so ago. Most regions, therefore, involve a large number of old and/or still operational landfills, in which vast amounts of obsolete materials and products have been accumulated over time, some of them more valuable than others (Lifset et al., 2002; Zhao et al., 2007).

Landfill mining has been proclaimed as an innovative strategy to address such implications related to waste deposits (Dickinson, 1995; Hogland, 2002). According to the Oxford Dictionary of English, "landfill" means *"the disposal of waste material by burying it"* or *"a place or process for the disposal of non-hazardous waste, based on burying it in the ground, then compacting it to reduce the volume and finally covering it with soil and landscaping it until it looks like part of the surrounding land"*. The meaning of the word "mining" is, according to the same dictionary, *"the removal of minerals (such as coal, gold or silver) from the ground"* or *"the process of extracting solid natural resources from the shallow parts of the Earth's crust"*. Combining these definitions, landfill mining could be described 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"*.

1.1. Aim and scope

This study involves a literature review on landfill mining, aiming to assess state-of-the-art research in order to identify key

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challenges for realizing resource recovery from such waste deposits. In doing so, we first perform a meta-analysis of the main trends, objectives, topics and findings in 39 selected research papers published during the period 1988–2008. Based on this review, the primary knowledge gaps for understanding the environmental and economic potential of landfills as future resource reservoirs are then identified and discussed.

The review strictly deals with research papers (i.e. articles in scientific journals and proceedings to scientific conferences), which is why so-called gray literature and practitioner knowledge are not accurately addressed. The selected papers were obtained from more than 10 scientific databases using search words such as landfill mining, landfills, remediation, resource recovery, land reclamation, energy recovery and material recycling. In each database, the search phrase ''landfill mining'' was used alone while all of the other words were used in combination with ''landfill mining'' and ''landfills''. Initially, 274 papers were collected; after reading through their abstracts, however, it was concluded that most of them dealt with topics beyond the scope of this review, i.e. different types of disposal and recycling methods for annually generated waste. Most of the 39 selected papers, explicitly dealing with landfill mining, were obtained from the Compendex, Scopus and Science Direct databases.

2. Landfill mining initiatives over time

According to Savage et al. (1993), landfill mining was first introduced in Israel in 1953 as a way to obtain fertilizers for orchards, but this remained the only reported initiative for several decades. In the 1990s, however, interest in this strategy increased. This is also reflected in the 39 reviewed papers, of which almost 70% originate from this decade, with most from the period 1995–2000 as seen in Fig. 1. Approximately 50% of these papers are from the U.S, while the remainders have been conducted in European (30%) or Asian (20%) contexts.

In the U.S., one of the most important drivers for this revival of interest in landfill mining during the 1990s was, either directly or indirectly, stricter environmental legislation such as the so-called Subtitle D regulations on management of non-hazardous solid waste. Such regulations forced many landfills to close down and also involved tougher requirements on final closure and post management, e.g. long-term monitoring of pollutants (Spencer, 1990; Richard et al., 1996a,b). This took place in a time when landfilling was by far still the most commonly applied waste disposal method in the country and getting permission to develop new landfills was becoming increasingly difficult, primarily due to strong public opposition. Excavation, processing, treatment and recovery of landfilled materials then emerged as a promising strategy to solve the increasing shortage of landfill void capacity and to reduce or postpone costs related to final closure, retrofitting and post-monitoring of the growing number of old landfills reaching end-of-life (Dickinson, 1995; Reeves and Murray, 1996,1997). At the same time, other benefits such as revenue from recovered materials and reclaimed land could be potentially obtained. In Europe and Asia, the situation was somewhat similar although in these regions the growing need for remediation of old landfills and removal of deposits hampering urban development seems to have been important drivers for the increased interest in landfill mining as well (Cossu et al., 1996; Hogland et al., 1995; Hylands, 1998).

Around 2000, the research intensity on landfill mining suddenly decreased; since then, only sporadic initiatives have been reported in the scientific literature. There could be several reasons for this change in activity, such as economic downturns or less demand for landfill space in certain regions of the world due to introduction of more sophisticated waste treatment and recycling programs. One important reason is likely the fact that many feasibility studies from the 1990s found that it was often difficult to obtain high-quality, marketable recyclables from the deposits (e.g. Savage et al., 1993; Krogmann and Qu, 1997). This is critical as it decreases the capacity for creating new landfill space. Furthermore, a ''new'' waste disposal problem might be generated, as well as limiting possible benefits in terms of revenue from recovered materials. Hull et al. (2005) argue that landfill mining is only economically viable under certain conditions: as an alternative option for remediation preferably co-financed from clean-up funds; for removal of deposits hampering urban development; for extraction of supplementary waste fuel in order to secure full working load at waste incinerators; or for creating new landfill space by using existing sites and infrastructure, thereby also facilitating the permitting process.

3. State-of-the-art research

More than 90% of the reviewed papers are either conceptual discussions on landfill mining or, more commonly, pilot-scale

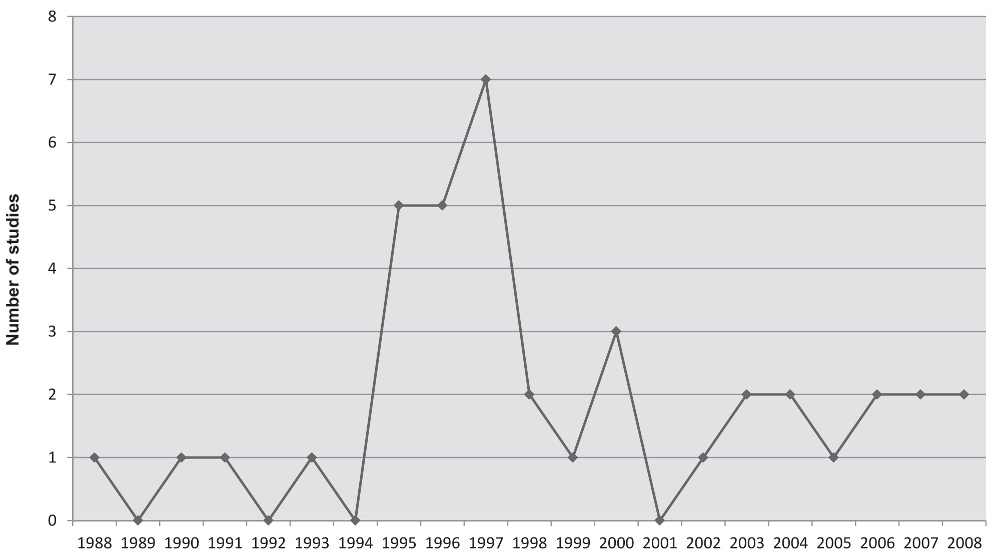

Fig. 1. Research intensity on landfill mining during the years 1988–2008 presented as number of published papers per year. The total number of papers included in the figure is 39.

investigations exploring the feasibility of mining specific deposits. Although a few success stories from the 1990s are frequently referred to in the literature (e.g. in Dickinson, 1995), more detailed descriptions of such projects that have been realized on a large scale are rare.

Characterization of deposited material is the most studied main topic within landfill mining research (e.g. Cossu et al., 1995; Hogland et al., 1995; Godio et al., 1999; Bernstone et al., 2000; Kurian et al., 2007). In fact, almost 50% of the reviewed papers involve such pilot-scale investigations, in which waste from landfills of different age and from different regions has been excavated and analyzed in terms of its material composition and/or physical and chemical characteristics, as seen in Fig. 2. This research has provided essential knowledge for evaluating the feasibility of mining landfills, often demonstrating variations in waste composition between different landfills and even within specific sites (Hogland, 2002; Kurian et al., 2003; Hull et al., 2005). Such a condition adds uncertainty to the conceivability of landfill mining and indicates that site-specific investigations always are a necessity. Still, there are also some recurring patterns regarding the composition of waste deposits in the literature. Typically, municipal landfills consist of about 50–60 weight percent of a soil-type material (cover material and heavily degraded waste), 20–30 weight percent combustibles (e.g. plastic, paper and wood), 10 weight percent inorganic materials (e.g. concrete, stones and glass) and a few weight percent of metals (mainly ferrous metal). This is often the case even when considering landfills situated in totally different parts of the world (cf. Cossu et al., 1995; Krogmann and Qu, 1997; Prechthai et al., 2008). Several studies, therefore, also stress the potential for resource recovery, both in terms of recycling of earth construction materials and metals, and energy recovery of combustibles (Cobb and Ruckstuhl, 1988; Obermeier et al., 1997; Hogland et al., 2004; Kurian et al., 2007). The presence of hazardous waste in the deposits has generally been found to be low, often comprising far less than one weight percent.

Most of the waste composition studies also address environmental and safety issues, although primarily as a sub-topic. Emphasis has been on local risks related to the excavation of landfills, i.e. leaching of hazardous substances, slope stability issues and risks for formation of explosive and poisonous gases (Hogland et al., 1995; Cossu et al., 1995; Zhao et al., 2007; Prechthai et al., 2008). Most of the studies conclude that the risks for occupational health impacts are generally low, although on some occasions the generation of, for instance, landfill gas was temporarily found to be significant, especially at the bottom layers of the landfill. As a consequence, it is anticipated that authorities will in most cases plausibly require an approved safety and health plan involving procedures for management of hazardous waste, systematic monitoring of air quality, trained and well-equipped workers and so on (Cossu et al., 1996). Nonetheless, knowledge about exactly what administrative, regulatory and safety demands that such initiatives will involve, and how in the end they will influence feasibility, is still lacking. There is also insufficient information available in the reviewed literature regarding pollutant emissions taking place after the landfill has been excavated; i.e., what are the long-term effects of landfill mining?

The second most commonly addressed main topic is technology for excavation and materials processing (e.g. Cobb and Ruckstuhl, 1988; Rettenberger, 1995; Reith and King, 1997; Cha et al., 1997; Hino et al., 1998; Chang and Cramer, 2003). This is because beneficial implementation of landfill mining virtually always relies on the fact that a large share of the excavated waste can be separated out and then recovered in some way, preferably off-site (cf. Fisher and Findlay, 1995). So far, emphasis has been on separating the soil-type material from the waste by using mobile screening equipment, sometimes also including an air knife and a magnet (Stessel and Murphy, 1991; Savage et al., 1993; Krogmann and Qu, 1997; Hogland, 2002). The reason for this approach is the anticipation that soil, in contrast to waste, will be fairly easily recovered. Several studies, including a few demonstration projects, have also demonstrated that a large share of the soil-type material, often containing low contamination levels, can be recovered as landfill cover material or for offsite use as filler material (Dickinson, 1995; Reeves and Murray, 1997; Kurian et al., 2003; Zhao et al., 2007). Such mobile technologies, however, have generally been far less efficient for obtaining other recyclables of a marketable quality, although there are a few cases in which recovery of ferrous metals and waste fuel also have been reported (e.g. EPA, 1997; Krogmann and Qu, 1997).

Another frequently occurring main topic involves theoretical discussions about possible benefits of landfill mining (e.g. Savage et al., 1993; Reith and Salerni, 1997; Murphy, 2000). In fact, virtually all of the reviewed papers touch upon this issue, although often briefly. According to Van der Zee et al. (2004), for instance,

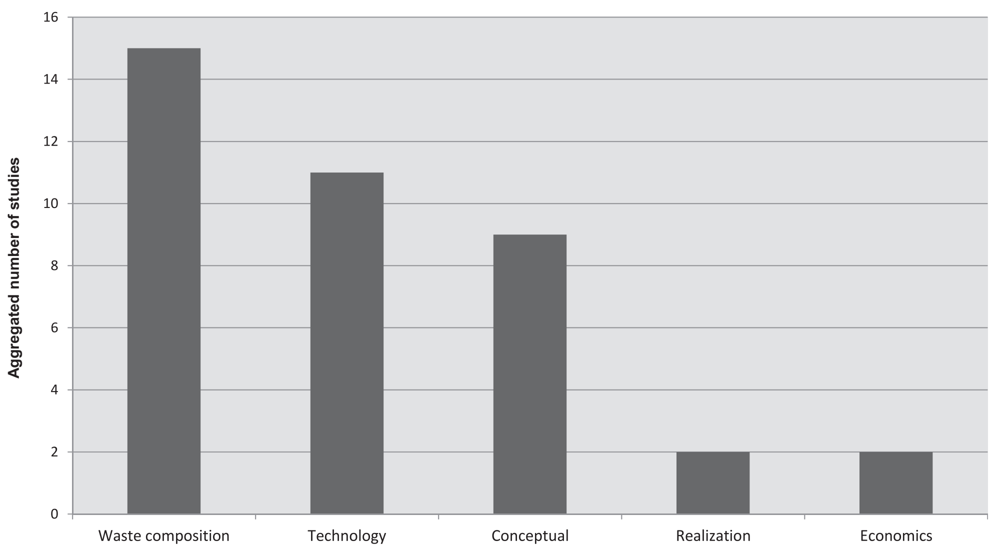

Fig. 2. Categorization of the 39 reviewed papers regarding which main topic they address. For simplicity, only one main topic has been attributed to each of the papers although they also often touch upon other sub-topics. This is further described in the text.

landfill mining *"is a process of excavating a landfill using conventional surface mining technology to recover e.g. metals, glass, plastics, soils and the land resource itself"*. This, however, is not a typical definition of landfill mining. In most of the research, a much broader and partially different view on this strategy is applied. A typical example of a frequently recurring definition in the literature is given by Cossu et al. (1996), in which landfill mining is defined as *"the excavation and treatment of waste from an active or inactive landfill for one or more of the following purposes: conservation of landfill space, reduction in landfill area, elimination of a potential contamination source, mitigation of an existing contamination source, energy recovery from excavated waste, reuse of recovered materials, reduction in waste management system costs and site re-development"*. Here, much more emphasis is placed on landfill mining as a way to solve traditional management issues related to waste deposits, while resource recovery of deposited material is simply outlined as one possible benefit among others (see also e.g. Spencer, 1990; Dickinson, 1995; Cha et al., 1997; Krogmann and Qu, 1997; Prechthai et al., 2008). So, although virtually all initiatives on landfill mining have involved some efforts to recover deposited resources, i.e. primarily cover soil material, such constituents have so far been largely subordinated to other objectives. There are, however, a few exceptions in terms of projects that primarily explore possibilities for recovery of specifically valuable materials from waste deposits such as metals (Hino et al., 1998), foundry sand (Zanetti and Godio, 2006) and waste fuel for energy generation (Rettenberger, 1995; Obermeier et al., 1997).

Only two papers deal with the realization process of landfill mining as a main topic. One of them discusses selected technical, economic and political factors that could influence the choice between using traditional closure of landfills or landfill mining (Bryden, 2000). The other briefly describes a general framework outlining five steps that have to be taken in order to realize landfill mining projects in the U.S.: (1) Conduct a site characterization study; (2) Assess potential economic benefits; (3) Investigate regulatory requirements; (4) Establish a preliminary worker health and safety plan; and (5) Assess project costs (EPA, 1997). A reason for this lack of interest in how to actually proceed in order to realize such projects is presumably that most of the initiatives thus far have been fully occupied by addressing the initial step of such a process, i.e. site-specific characterization studies.

Even though almost 40% of the reviewed papers touch upon economic aspects (e.g. Cobb and Ruckstuhl, 1988; Savage et al., 1993; Krogmann and Qu, 1997; Bryden, 2000), there are only two studies that strictly focus on this issue as their main topic (Fisher and Findlay, 1995; Van der Zee et al., 2004). Accordingly, there is no common framework for how landfill mining actually should be evaluated, e.g. which economic aspects should be accounted for and how should these different parameters be calculated. Instead, there is more or less a consensus within the reviewed literature that every landfill mining project has its unique set of conditions and objectives influencing its economic feasibility. Reported estimates on landfill mining costs therefore vary by as much as one order of magnitude, i.e. from 10 to 100 US$ per metric ton of processed material (Savage et al., 1993; Cossu et al., 1996; Krogmann and Qu, 1997). An important reason for this large variance is probably that these studies refer to largely different types of initiatives, involving different objectives, technologies, actors, and so on. Unfortunately, there is often a lack of transparency when it comes to describing such underlying conditions, making it more or less impossible to evaluate and compare cost estimates from different studies.

Due to the shortage of reported full-scale projects in the reviewed literature, comprehensive cost-benefit analyses of landfill mining are rare. Back in the 1990s, however, studies both in Europe and the US concluded that landfill mining aiming to create new landfill space could be an economic option, mainly due to avoided costs for re-siting a new landfill (e.g. Rettenberger, 1995; Fisher and Findlay, 1995). Recent changes in waste management in these regions, involving a substantially decreased need for landfill void capacity, makes it unclear if such a conclusion still is valid. As pointed out previously, several of the reviewed studies also stress reclamation of land as a possible economic driver for landfill mining, especially in densely populated regions where the value of land can be significant (Van der Zee et al., 2004; Hull et al., 2005). An overall conclusion in many of the reviewed papers is that projects solely focusing on recovery of deposited resources from landfills are seldom economically justified. An exception is an Italian study, presenting a positive cost-benefit analysis for the recovery of foundry sand and iron fractions from an industrial landfill (Zanetti and Godio, 2006).

As outlined by Van der Zee et al. (2004), there are many possible costs (e.g. site preparation, regulatory compliances, labor, hauling, and purchase of technology) and benefits (e.g. increased disposal capacity, revenues for recyclables, land value and avoidance of future remediation costs) that may or may not appear in landfill mining projects. In their economic model, a step-wise procedure is used for identifying high-potential landfills for mining in a region. Although this model is largely based on hypothetical assumptions regarding, e.g., how the age, size and location of landfills influence economic aspects of mining, it could still provide valuable input to the development of a more standardized framework for economic evaluation of such projects.

4. Discussion

4.1. Landfill mining in the past

Developing a common understanding of the meaning of a concept or strategy is fundamental, since it influences how such initiatives will be planned and realized, and within what context they will finally be evaluated. The tentative definition of landfill mining derived from the Oxford Dictionary of English at the beginning of this article solely emphasizes resource recovery from landfills. This definition does not, however, accurately describe how this strategy thus far has been applied in practice, Fig. 3. In the reviewed papers, the three most commonly stated main objectives for landfill mining projects have been extension of landfill lifetime, consolidation of landfill area facilitating final closure and remediation (e.g. Spencer, 1990; Dickinson, 1995; Cha et al., 1997; Krogmann and Qu, 1997; Prechthai et al., 2008). The employed technology, therefore, has typically involved simple excavation and screening equipment, often making it possible to extract and recover a large share of the soil-type material and thereby contributing to the core objectives above (Fisher and Findlay, 1995). As mentioned previously, such technologies have often proved to be ineffective in obtaining marketable recyclables from the deposited resources.

The research on landfill mining has been primarily conducted to this point within the waste management community, in which a traditional research topic has been to analyze ways to achieve more efficient operation of waste deposits. In fact, over the last 20 years, little has happened regarding the research focus, but the prevailing topic is still landfill composition. This view on landfill mining as a strategy for solving traditional waste management issues has also largely influenced how such initiatives have been evaluated. For instance, the economic feasibility of landfill mining has been considered only in relation to narrowly defined alternative costs, for example traditional closure and post management and remediation (Spencer, 1990; Fisher and Findlay, 1995; Dickinson, 1995; Murphy, 2000). In the U.S., several initiatives

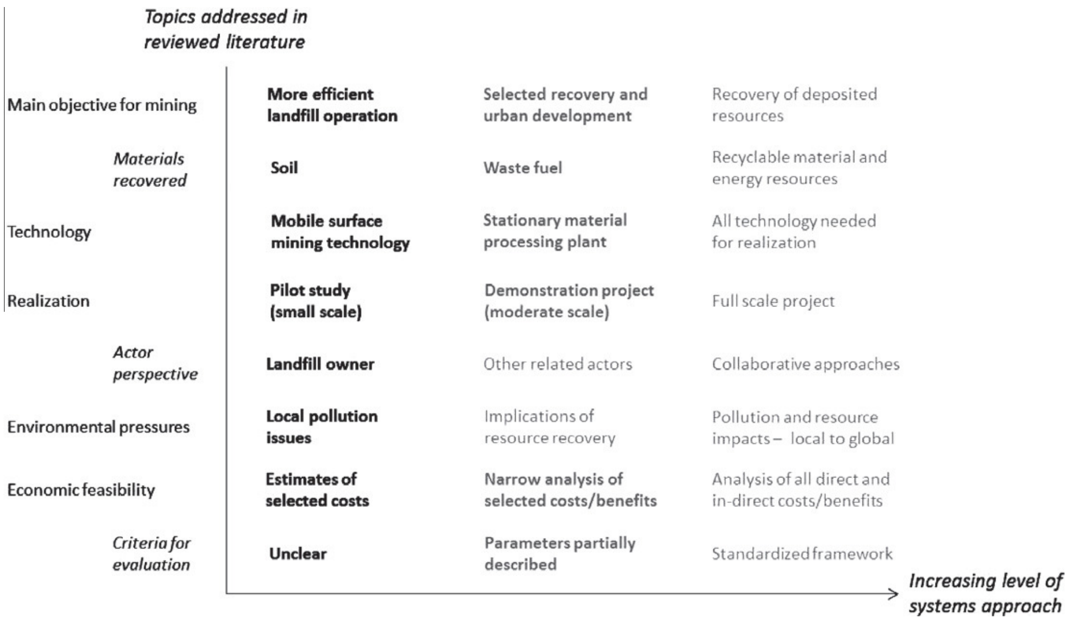

Fig. 3. Matrix of topics which are addressed in the reviewed literature and at what level of systems approach they have been carried out. Black font means main focus point, mid-gray some focus and light gray means that they are omitted in the reviewed articles. See text for further explanations.

during the 1990s were reported to be economically justified solely by extending the service life of existing landfills, thereby avoiding costs for re-siting a new landfill. Nevertheless, despite strong optimism about the potential of landfill mining in the literature, the lack of reported large-scale projects indicates that within such a waste management context this strategy has, in many cases, not yet been an economic option (cf. Bryden, 2000; Hull et al., 2005).

4.2. Landfill mining as a resource extraction strategy

At present, there are several worldwide changes underway that are likely to make resource extraction from alternative sources a more and more viable option such as rapidly growing competition for resources, increasing raw material prices, the large-scale environmental problems we now face and the fact that the natural reservoirs for many valuable resources are rapidly declining (Kapur, 2006; Halada et al., 2009). At the same time, several studies belonging to the research field of Industrial Ecology show that in many regions of the world massive amounts of strategically important materials such as metals have accumulated in landfills (Lifset et al., 2002; Kapur and Graedel, 2006; Müller et al., 2006). On a global level, for instance, the amount of copper situated in such deposits (i.e. 393 million metric tons) has been estimated as comparable in size to the present stock in use within the technosphere (i.e. 330 million metric tons). Ongoing research in Sweden also indicates that apart from metals, the amount of potential waste fuel situated in municipal landfills is enough to cover the district heating demand in the country for 10 years (Krook et al., submitted for publication). Such findings challenge the current view on landfills as final storage locations for waste and indicate the emergence of a new perspective on landfill mining, primarily as a strategy for extracting valuable material and energy resources. Related to this new perspective on landfills is enhanced landfill mining, primarily emphasizing intentional storage of currently non-recyclable material and energy resources in such a way that future valorization is facilitated (Hogland et al., 2010; Jones et al., 2010). This concept strives to integrate landfilling as a more sustainable waste management practice, and could also involve resource recovery from operational as well as closed landfills.

4.3. Challenges and future directions for landfill mining

Although the potential for resource recovery from landfills appears significant, facilitating the realization of such a new perspective on landfill mining also involves a number of challenges. For any emerging strategy, the issue of uncertainty is often an overall factor prohibiting implementation since it makes it difficult for companies to foresee the outcome of such initiatives. One such critical uncertainty related to resource recovery from landfills is the performance of technology, i.e. which materials can actually be separated out from deposited waste and, perhaps even more important, at what quality levels. There are a few studies that have demonstrated that it might be technically possible to extract high-quality metals (both ferrous and non-ferrous) and waste fuel from landfills if more sophisticated semi-mobile or stationary processing plants are applied (Rettenberger, 1995; Obermeier et al., 1997; Hino et al., 1998; Zanetti and Godio, 2006). Even so, much more applied research is needed demonstrating the efficiency, capacity and suitability of different technologies for landfill mining in practice. In some projects, it might only be justified to use mobile equipment whereas in others more advanced stationary processing plants could be an option. However, one thing is for certain: if the core objective is resource extraction, the conventional surface mining technologies that have been used in the past will not be sufficient.

In order for landfill mining to be feasible for individual companies, economic benefits must simply outweigh the costs. So far, this type of project has mainly been initiated, funded and operated by local authorities, i.e. owners of landfills, aiming to solve a specific issue of relevance for their region such as lack of landfill space (Dickinson, 1995; Van der Zee et al., 2004). Initiatives emphasizing extraction of valuable resources from deposits on commercial grounds are however something significantly different. First of all, such projects should at least not solely be evaluated from a waste management perspective but also within a broader resource management context, where the feasibility is compared to alternative costs for extracting the resources from their natural reservoirs. Furthermore, it is not likely that landfill owners on their own are in the position of meeting the technical, economic and legislative conditions that will follow such activities. Binding different types of expert knowledge to the projects by developing closer collaboration with actors belonging to different lines of business might therefore be necessary, e.g. materials companies, energy producers, metals recyclers and so on.

Developing such partnerships could in fact have direct economic consequences for landfill mining. In Sweden, for instance, it is prohibited to landfill combustible materials, and waste incinerators often have a monopoly status on the local market. Waste producers, therefore, do not have many alternatives other than to deliver their waste to the local incinerator at a cost which varies from 53 to 106 € per metric ton (The Swedish Waste Association, 2007). For a landfill mining practitioner, such a fee may be detrimental due to the generally large amount of combustibles situated in waste deposits, while the revenues for the produced heat and electricity go exclusively to the incinerators. This implies that either actors that own incinerators should perform resource recovery from landfills, or else a close collaboration between landfill mining practitioners and incinerators has to be developed, possibly involving the sharing of costs and benefits. Such business agreements could also be interesting for incinerators in order to secure a full working load for their plants in the years to come. Waste incinerators in Sweden, as well as in Germany and the Netherlands, have now experienced overcapacity for the first time ever, a trend that is expected to continue (e.g. Profu, 2010).

Here, research could play an essential role by clarifying the underlying conditions for realization through, for instance, reviewing previously conducted landfill mining projects. Based on such knowledge, alternative business models for how to organize and manage landfill mining initiatives could be developed, e.g. which actors should be involved and how they should collaborate and share costs and benefits in order to facilitate realization.

In order to realize any project of considerable size, it is becoming increasingly important to demonstrate its environmental performance, not the least for facilitating the permitting process. As described in this study, however, landfill mining research has thus far dealt exclusively with local risks such as pollutant emissions during excavation. Although this has been a useful and necessary approach, it is also insufficient because resource recovery from landfills will also generate environmental consequences on a regional and global scale. According to Cohen-Rosenthal (2004), for instance, "*a 50 acre* (20.3 hectares) *landfill might contain as much as 240,000 tons* (217,680 metric tons) *of steel and 20,000 tons* (18,140 metric tons) *of aluminum*". Recycling such amounts of metal, and thereby replacing virgin production, will lead to large energy savings and avoidance of many kinds of environmental pollution (Ayres, 1997). Furthermore, the amount of combustibles in landfills that potentially could be used for energy recovery is typically several orders of magnitude larger. At the same time, the extraction, processing, transportation and recycling of deposited materials will require both material and energy resources, which might generate significant negative impacts.

There is also an obvious risk that landfill mining might lead to an increased dispersal of unwanted substances such as heavy metals, especially if the applied technologies fail to separate out the dispersed hazardous materials in the landfill (Krook et al., 2007). Efficient separation technologies for hazardous waste are in fact critical, since they largely determine the usability of the produced recyclables. Thus, in order to address the environmental performance of this new perspective on landfill mining, there is a need for research applying a systems approach (e.g. Life Cycle Assessment), enabling the balancing of positive and negative impacts taking place on the local, regional and global scales (cf. Udo de Haes et al., 2000; Finnveden and Moberg, 2005).

As future resource reservoirs, landfills also call for a more proactive approach in terms of prospecting for the most profitable landfills to mine. In many countries, there are thousands of landfills (cf. SEPA, 1986; Van der Zee et al., 2004), which vary with respect to ownership, location, composition and age – site-specific factors, any of which might influence the feasibility of mining. Some, for example, might contain large amounts of valuable materials such as metals, almost no hazardous waste and be located close to waste treatment and recycling plants, while for others the conditions for mining may not be as favorable. In this case, it could be useful to learn how such implications have been dealt with in other lines of business, such as within the traditional mining industry.

However, in order to develop such landfill mining prospecting tools, knowledge about the critical factors for economic and environmental performance must first be developed. As pointed out previously, there are many possible benefits, costs and environmental impacts that may or may not occur in such projects, dependent on e.g. objectives, applied technologies and recycling options, regulatory requirements, actors' constellations and site-specific factors such as the age, location and composition of landfills. Therefore, developing standardized frameworks for evaluating critical factors for performance of different kinds of landfill mining initiatives is an essential research challenge for facilitating implementation of this promising, but so far largely theoretical strategy.

5. Conclusions

It can be concluded that although valuable research on landfill mining has been conducted for more than two decades, the field is still somewhat immature when it comes to standards and common principles for realization and evaluation. This is also indicated by the fact that only about 35% of the reviewed research papers (i.e. just 12 articles total during a twenty-year period) have been published in scientific journals. Instead, the majority of research occurs in forums such as conferences or trade journals with far less standardized measures for validating scientific quality and thus trustworthiness. In these publications, there is generally alack of transparency regarding, for instance, how reported projects have been setup, which parameters have been actually included in evaluations of technical and economic feasibility, and exactly how these parameters have been addressed. Without such a common understanding about basic frameworks and principles, it is more or less impossible to compare results from different studies and develop a common knowledge base within the field.

This immaturity of the landfill mining research field also implies that there might be significant amounts of valuable practitioner knowledge available in gray literature and in organizations which have conducted such activities in practice – information sources that have not been accurately addressed by this study. Therefore, we strongly urge other researchers to perform such complementary reviews by using broader search tools and qualitative methods such as interviews.

From this review, it can be concluded that facilitating implementation of resource recovery from landfills involves three main research challenges: technology innovation, addressing the underlying conditions for realization and developing standardized frameworks for evaluating performance. Applied research such as demonstration projects, reviews of experiences from previously conducted projects and interviews with societal actors (e.g. legislators and authorities) is essential for understanding the capacity of technology and conditions for realization. For example, how much of the deposited resources can actually be transformed into marketable recyclables, and how will current environmental legislation, taxes and subsidies apply to landfill mining? Theoretical research is useful for assessing possible alternative business models for how landfill mining initiatives can be organized and managed. Such research is also needed for developing standardized frameworks for evaluating critical factors for economic and environmental performance – frameworks necessary for decreasing the uncertainties that currently prohibit implementation. In order to avoid sub-optimizations, we believe that these frameworks must be developed by applying a prominent systems approach combining tools such as Life Cycle Assessment and Cost-Benefit Analysis.

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