

# From end-of-pipe to industrial ecology: What is the role of Enhanced Landfill Mining?

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## Abstract

Industrial ecology aims at optimising resource flows throughout society. Landfills and industrial ecology are each other's opposites. The next logical step is that resources dumped into landfills are re-introduced into the material cycles. This article critically reviews whether this recovery of resources out of landfills can currently be realised in a sustainable way and what its role is within an industrial ecology context. The focus is on the evolution in waste management towards Enhanced Landfill Mining, and the impact the different aspects of integrated waste management and Enhanced Landfill Mining have on sustainability. This impact can be assessed by LCC (Life Cycle Costing) and LCA (Life Cycle Analysis). The current economic feasibility of Enhanced Landfill Mining is unfortunately not very sensitive to the recycling possibility of materials, as it is mainly depending on prices of recovered land and on the existing incentives for energy recovery. Most LCA studies on integrated waste management, however, show that recycling is environmentally more beneficial than energy recovery. Although Enhanced Landfill Mining is clearly beneficial from an industrial ecology perspective, the way it can be realised and the choices to be made between Waste to Energy and Waste to Material routes have to be further explored by sound data and improved LCC and LCA models.

## Introduction

It is clear our society and our wealth are built upon materials. The availability of materials however is not unlimited. Some materials such as e.g. Indium used in PV cells, risk to be depleted within only a few years<sup>1</sup> if no proper and efficient recycling route is conceived. The limited resources of some of the most crucial materials and the impact of materials on the environment drive the industry to a more efficient use of resources and to increase recycling rates.

Industrial ecology is concerned about the flows of materials throughout industry and society and the impact of these flows on resources and environment. The way we are nowadays dealing with resources and materials is not sustainable. We urgently need to evolve towards a circular economy, in which materials are reused again and again in a qualitative and energy-efficient way.

Despite major efforts to decrease the amount of waste and despite an increasing awareness to prevent materials to be discarded after a single or even multiple use, the total yearly amount of waste landfilled in Europe is still enormous and only slightly decreasing. In Flanders, where 72% of the MSW is recycled, reused or composted<sup>2</sup>, only 112 ktons were landfilled<sup>3</sup> of the 3,4 Mtons in 2007<sup>2</sup> (*i.e.* 555 kg/inhabitant), while 2,15 Mtons industrial waste was landfilled (*i.e.* 9% of the primary industrial waste after 2 treatments).<sup>4</sup> Thus, the Flemish landfill mass has grown with 2,5 Mtons in 2007, of which about 50% goes to mono landfills. The European Commission expects the amount of waste to increase by 45% between 1995 and 2020. Most EU municipal waste is still sent to landfills (45%) and represents on average

213 kg/person/year (Eurostat). To this one may add a heritage of closed landfills all over Europe. In Flanders, the number of potentially polluted landfills is 1618 of which the average surface is 3,39 ha, being 54,95 km<sup>2</sup> in total or 0,45% of the total surface of Flanders.

At the resource side, the demand for material resources is expected to increase drastically by 2050 by a factor 3 compared to current numbers.<sup>5</sup> This is due to the growth of the world population and of the further development of the BRIC countries and other new economies. This increase in resource use will lead to a further increase in waste, due to inefficient and open materials cycles. Based on macroeconomic data from 30 OECD countries, the OECD states that a 1% increase in national income yields a 0.69% increase in municipal waste amount. The increase in resource demand implies *de facto* that the demand cannot be met by recycled materials, but that fresh material input is indispensable.

One way to partially overcome this increasing demand in resources is to reuse the materials in landfills. For many European countries, this is almost the only source of 'new' materials they have, and hence it can alleviate the high dependency on resources imported from foreign countries and politically instable regions.<sup>6</sup> Of course, this solution is as temporarily as the resources of ores are and has to go hand in hand with a drastic improvement of materials effectiveness and closing of materials cycles.

This article will further focus on the evolution in waste management towards waste mining, and the impact the different aspects of this waste management and landfill mining have on sustainability. The article mainly reviews the findings of waste management system assessments and tries to draw conclusions from these findings for future landfill mining projects.

## **Waste management: optimising the end-of-pipe**

### **Waste management in evolution**

Waste management has evolved from landfilling towards landfilling with energy recuperation, incineration, incineration with energy recovery and materials recovery. Since Lansink launched his ladder concept (see other contributions in this volume), representing the hierarchy of waste management options<sup>a1</sup>, the focus gradually shifted from landfilling to material recuperation and recycling (e.g. glass, paper *etc.*) and waste prevention. The Waste Framework Directive of the EC also explicitly mentions a hierarchy of waste operations (taking into account the whole life cycle of products and materials and not only the waste phase) with the objective to save resources, to produce less waste and to use waste efficiently.<sup>7</sup>

Nowadays, the landfill concept itself is also evolving, driven by the potential risk and environmental burden of landfills as well as by the value (in materials and energy) that is contained by landfills. There is a tendency to consider landfills as bioreactors, in which a controlled degradation (dilution and dispersion of contaminants) is allowed in order to guarantee the long term stability of the landfill.<sup>8,9</sup> Another route surpasses the conservative approach of reducing the emissions or potential hazard of a landfill and tries to exploit the resources contained by the landfill, called landfill mining. Classical landfill mining captures and uses the methane for energy generation<sup>10</sup>, but more advanced approaches also have the ambition to recover materials and land<sup>11</sup> or to mine all waste in the landfill and recover materials and energy from it.<sup>12,13</sup>

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<sup>a1</sup> Lansink was the proposer of a motion concerning waste management in the Netherlands, passed unanimously by the Dutch Lower House in 1979.

## **Sustainability assessment of waste management systems**

In the following, a review is made with regard to evaluation tools analysing the best exploitation route for (i) mixed waste, (ii) Waste to Energy (WtE), (iii) Waste to Materials (WtM) and (iv) leaving waste in landfills. In a first section relevant parameters and aspects with regard to the decision between WtE and WtM will be discussed. The next section reveals more detail on the modelling tools used for (integrated) waste management, with special attention to LCC (Life Cycle Costing) and LCA (Life Cycle Analysis) and the pitfalls of this approach.

### **Different modelling approaches and tools**

A general framework for modelling integrated waste management is, amongst others, proposed by Eriksson *et al.*<sup>14</sup> It is evident that there are some essential differences with landfill mining, such as the impact of transport which can be important in an integrated waste management system, the exploitation of the mine itself... With regard to landfill mining, the inputs are only originating from the landfill itself, and not from different waste sources at different sites. However, in most cases the input flows consist of mixed and degraded waste with a variable composition. Whether or not this is a drawback depends of the former landfilling practice (degree of mixing) and the optimisation of the separation process. In order to obtain more homogenous waste streams, it is possible to select sectors of the landfill for mining. Despite these differences, the basics of modelling the environmental impact of landfill mining are similar to other waste management systems.

**Models based on Life Cycle Costing – LCC.** Life Cycle Costing (LCC) is a technique which enables the systematic appraisal of life cycle costs over a period of analysis and is used for evaluating alternatives for equipment and projects.<sup>15</sup> Examples of costs incorporated in LCC are investment costs, operative costs, decommissioning costs, and sales revenues (a negative cost), all discounted to present value.

**Models based on Life Cycle Analysis – LCA.** LCA quantifies the environmental and health impacts resulting from the use of materials, energy consumption or emissions generated to produce products or for carrying out a process or activity. The methodology is standardised (ISO14040), but there are still numerous different ways in which this methodology is put into practice. In general, LCAs are restricted to environmental impacts only. The first step in a LCA is to define the goal and scope of the system(s) under study. The second step is the set up of a life cycle inventory (LCI). The recommended way to report on the LCI for a waste management scheme is: direct burdens, associated with the waste management operations themselves; plus indirect burdens, associated with providing materials and energy to the waste management operations; minus avoided burdens, associated with economic activities which are displaced by materials and/or energy recovered from the waste.<sup>16</sup>

The UN Climate Change Panel (IPCC) portrays LCA as an essential tool for consideration of both the direct and indirect impacts of waste management technologies and policies.<sup>17</sup> Several authors use LCA as a tool to compare different scenarios in waste management on a regional scale.<sup>18,19</sup> This is different from ELFM in so far that the waste is fresh and sometimes partly sorted. In some of the analyses, transport issues are also taken into account<sup>18,14,20</sup> However, land, odour, noise, radiation and casualties are usually not included.<sup>21</sup>

**Models based on Cost Benefit Analysis.** Cost Benefit Analysis (CBA) assesses the positive and negative effects of a set of scenarios by translating all impacts into a common measurement, usually monetary. This means that impacts, which do not have a monetary value, such as environmental impacts, must be estimated in monetary terms.<sup>22</sup> This method is very similar to what is called an environmental LCC,<sup>23</sup> which is an LCC extended with the

monetarised effects such as the impact of emissions and resource use typically described in a Life Cycle Analysis (LCA).

There are quite different possibilities to monetarise externalities (externalities can be described as the “external costs and benefits that arise when the social or economic activities of one group of people have an impact on another, and when the first group fails to account fully for their impact”<sup>24</sup>), such as the estimated cost for replacing resources and neutralising emissions, the willingness-to-pay for ecological benefits or to avoid a cost, the estimated (future) taxes on emissions and resource use. Reich<sup>23</sup> comments that resource valuation is still very difficult to deal with (as it is in LCA), unless market values are accepted. It has to be noted that weighing methods are biased by the fact that they are expressions of personal values and thus normative.

**Integrated models.** Most models for integrated waste management combine elements of Life Cycle Analysis with Life Cycle Costing. Examples of software packages for integrated waste management are:

- ORWARE: this is a Swedish computer-based model for calculation of substance flows, environmental impacts, and costs of waste management.<sup>14,25</sup> The ORWARE model is built using MATLAB with its graphical interface SIMULINK. The ORWARE software only takes the amount of substances in the input into account, not their context, and does not include toxicity effects.
- MSW-DST (USA) models costs based on a full cost accounting (FCA) approach.
- IWM2: Procter & Gamble: Integrated Waste Management2 (UK).<sup>26</sup> Neither DST nor IWM2 include some non-toxic environmental effects.
- The WISARD model of Ecobilan developed in France by the Ecobilan group.<sup>27</sup> WISARD database is limited to the types of recovery facilities available, as well as the recycling processes available under each recovery category. WISARD is quite rigid, while a more general and flexible software tool with a broader database would be preferable.
- EASEWASTE is another, more recent model developed at the Technical University of Denmark for LCA on waste management systems: Environmental Assessment of Solid Waste Systems and Technologies<sup>28,29</sup> in which the landfill hazard is better taken into account by estimating the contents of the leachate.

All models describe input flows of waste in terms of waste fractions, with only minor differences in characterisation (mainly organics, metal, glass, plastic, paper, incineration ashes), which is very different from the mixed waste input of a landfill. The level of detail differs from model to model and - important for the proposed project - the models are developed for different regional characteristics. They will not easily allow adjustments to other regions or other situations like landfill mining.<sup>14</sup>

Finally, Emery *et al.*<sup>20</sup> remark that no computer software waste management tool currently integrates all sustainability aspects (*i.e.* ecological, economic and social), and hence progress can be made by integrating more sustainability dimensions and by supporting policy makers on both company and government level.

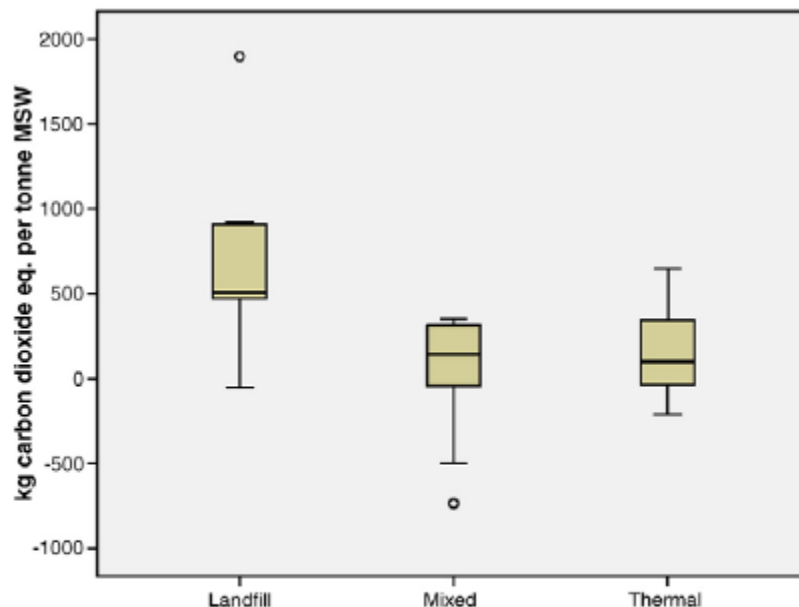
### **Validity and pitfalls of LCC and LCA**

Important is to clearly define the boundary of inquiry. In the case of landfill mining the system boundaries can be established without major problems. Within these boundaries, the impacts arising from all activities or process steps must be identified. One of the major difficulties in analysing indirect environmental impacts is to establish what, if anything, is replaced (avoided burden), when something is recovered from the waste management system.<sup>30</sup> A good definition of the avoided burden (avoided production of virgin materials and energy by

using the recycled materials and recovered energy of the landfill) will be crucial to estimate the environmental benefits of landfill mining. Another problem in LCC and LCA is the allocation of burden or costs: how to link the costs of the landfill mining activities with the broad variety of output flows (materials and energy)? This can be done based on several principles such as physical and chemical causation or economic value, or on an arbitrary choice of a physical parameter such as energy or mass.<sup>31</sup>

Another difficulty is related to the conversion of impacts into monetary terms. This requires a.o. adjustment for inflation, and for shadow prices. For example, prices do signal scarcity of resources, but only when markets are functioning perfectly. Therefore, in certain cases, market prices can be corrected for government intervention, imperfect competition and externalities.

A recent and comprehensive overview of modelling the waste hierarchy by LCA is given by Cleary.<sup>32</sup> Cleary studies the reliability of LCA by statistically analysing 20 different LCA studies on municipal solid waste. He concludes that it is difficult to compare LCA results, since there are differences in the definition of the system boundaries between the studies. Figure 1 shows as example a comparison of global warming potential of municipal waste management systems.



**Figure 1:** Statistical overview of 20 different LCA studies on MSW management systems. Mixed means recycling combined with incineration of the residual fraction.<sup>32</sup>

### Modelling aspects of some subsystems of landfill mining

**Modelling of incineration.** Only a few authors take account of the environmental burden of incineration in the waste management models.<sup>33</sup> Modelling of different incineration technologies and differentiating the impacts per incinerated material/product is done by Khoo<sup>34</sup> and Mendes *et al.*<sup>35</sup> Some authors consider valorisation routes for fly ashes after incineration and incorporate a possibility to make pavement bricks from them.<sup>36</sup>

**Modelling recycled materials impact.** Castro *et al.*<sup>37</sup> point to the fact that recycling concerns mixed materials streams and that it is not sufficient to take the mass balance of substances into account in the analysis, since contaminations of one material by another can have huge effects on the quality. This loss of quality after recycling should be taken into

account. Castro *et al.*<sup>37</sup> propose the use of exergy to describe the loss of quality due to recycling.

**Modelling the impact of landfilling.** The effect of landfilling (or avoiding the effects by landfill mining) primarily depends on the type of landfill.<sup>29</sup> In practice, it may sometimes be difficult to model the burden of the landfill due to lack of data on emissions from landfills. Furthermore, emissions from landfills can continue for very long time periods, thousands of years or longer<sup>38</sup>, and the environmental impact of the pollutants might be different if they are emitted slowly. The used barrier systems – inertisation, solidification, sealing sheets *etc.* – degrade and have a limited functional lifetime. Caps and liners *e.g.* could only last for 50 to 100 years.<sup>39</sup> Whether or not long-term emissions are accounted for can have a significant influence on the results of a sustainability assessment. In fact, not taking the long term effects of landfills into account, can result in a shift of burden to future generations.

Leachate generation, *i.e.* one type of emissions, in terms of amount of leachate per ton of waste landfilled, depends on climatic factors, cover design and on the geometry of the landfill. The deeper the landfilled material pile, the less annual leachate generation per ton of waste there will be. Leachate composition will depend on the type of waste landfilled, the product alloys and molecular composition, and not directly on the chemical composition of the actual waste.<sup>40</sup>

### Deciding on WtE versus WtM

The question whether waste should be incinerated, recycled, composted or landfilled has many dimensions – economic, technical, social, and environmental – so there will never be a simple answer. Björklund *et al.*<sup>41</sup> evaluated a number of studies on the assessment of waste management systems and they basically found four key factors with a significant influence on the ranking between recycling, incineration, and landfilling:

- The type of recycled materials;
- The type of materials avoided by recycling;
- The energy sources avoided by energy recovery from incineration;
- The time perspective of landfills.

A short landfill time perspective in principle covers the decomposition of easily degradable materials like *e.g.* biodegradable organics. Most landfill models assume the landfilled material to be basically inert after this time frame (Finnveden<sup>42</sup>). This review shows that in general recycling has the lowest impact on total energy use and global warming potential (GWP) in most cases. Cherubini<sup>43</sup> confirms that independently of the applied methodology (LCA or another Environmental Impact Assessment), significant environmental savings are achieved from undertaking any type of recycling. The conclusions of Björklund<sup>41</sup> are summarised in Table 1.

The study of Eriksson<sup>44</sup> shows more generally that reduced landfilling in favour of increased recycling of energy and materials leads to lower environmental impact, lower consumption of energy resources, and lower economic costs. One of the remarkable results of this study is that from the 8 defined scenarios, the scenario in which the highest fraction is recycled is best performing with respect to the overall CO<sub>2</sub> emissions, acidification and energy consumption. A major obstacle for recycling is, however, the price uncertainty of recycled materials.<sup>45</sup>

**Table 1:** Overview of the potential use of waste management options for different categories of materials.

General conclusion	Exceptions
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Non-renewables (metal, glass, plastic)	Both total energy use and GWP are in general lower for recycling than for incineration or landfilling of non-renewable materials.	<ul style="list-style-type: none"> <li>Recycled plastics to replace wood-derived products</li> <li>Feedstock recycling of plastics need high energy use (However, the performance is also increased in some cases)</li> </ul>
Renewables (paper, cardboard)	Total energy is in most cases smaller in case of recycling than for incineration/combined recycling. For GWP, recycling and incineration are almost the same.	<ul style="list-style-type: none"> <li>Depends on the current energy mix that is replaced by the energy generated by waste incineration</li> </ul>

Finally, not all authors come to the same conclusion. Emery *et al.*<sup>20</sup> showed in their LCA analysis that the incineration option can be preferred compared to the landfill and recycling/composting options. However, economic modelling showed that incineration options have higher operational costs and lower associated jobs compared to the other options such as recycling. These complex trade-off issues between economic, social and environmental issues, demonstrate the need for a clear and integrated decision tool.

## The ELFM system

### ELFM from an industrial ecology perspective

Cohen-Rosenthal<sup>46</sup> defines the goal of industrial ecology “to reintroduce materials and energy back into productive reuse with the minimum energy required and the least waste of material in the process.” He states that the ultimate question is not whether we can alter the structure of materials we use (and hence waste), but towards what purpose, with what technologies and at what costs. In this view, landfill mining is the farthest closing point of materials cycles, and is viable when the ‘cost’ (economic, environmental and social) is comparable or less than other options. The question is then how this ‘cost’ can be assessed and compared with other waste management routes.

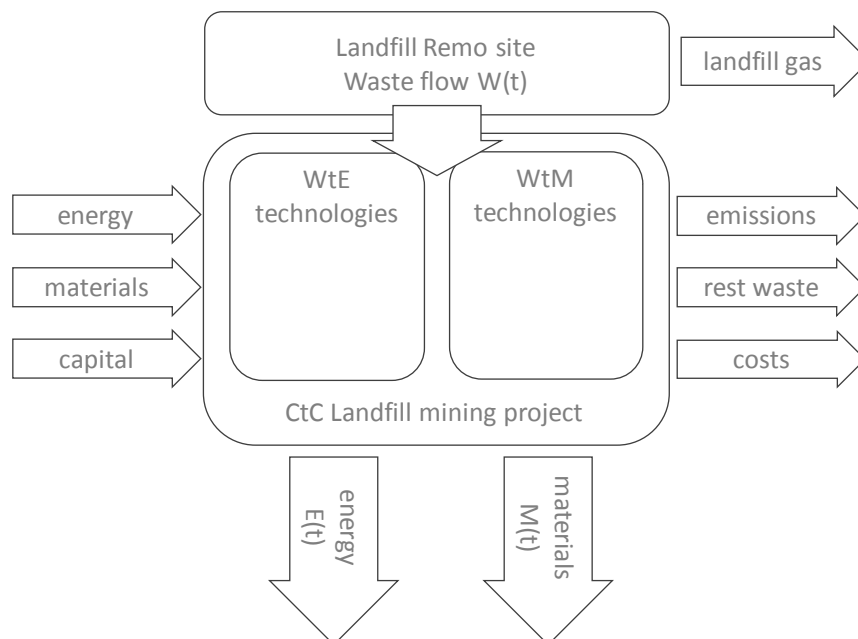
It is clear that first materials efficiency has to be improved and that recycling and recovery schemes need to be optimised. However, mixed waste streams and new waste types (such as all kind of composite materials, bio- and nanomaterials...) will exist and temporary storage of waste in anticipation of better recycling technologies will be needed. The way landfills are managed or mined may not be seen separately from the integral waste management system or even broader: Sustainable Materials Management. As explained by Jones *et al.*<sup>13</sup> in this volume, Enhanced Landfill Mining is part of the more general, innovative concept of Enhanced Waste Management, in which prevention, reuse and recycling are predominant and landfills are discarded as final solutions. Enhanced Landfill Mining as mining of historical landfill sites is also important to get acquainted with technologies to treat very complex waste and will deal with the development of new valorisation routes for waste flows which are complex, new or just difficult to valorise (economically) with current recycling technologies (see examples given in Van Gerven *et al.*<sup>47</sup> in this volume)

## Sustainability assessment of ELFM

Due to the innovative aspect of the Enhanced Landfill Mining concept, there is no literature available yet on assessing the best recovery route for waste originating from a landfill. However, there is certainly a parallel with existing models for assessing the most appropriate waste management options (in general: incineration, recycling or landfilling) before waste is landfilled. The complex interaction between economic costs and returns and environmental considerations requires an integrated approach to enable landfill managers to exploit landfills in an optimal way, maximising economic return and minimising environmental impact. Moreover, such tools can also help policy makers to design tailored policy measures with regard to ELFM on a regional level.

An Enhanced Landfill Mining sustainability assessment differs from the integrated waste management systems in the literature (which themselves all show their particularities and shortcomings) in the following aspects:

- Landfill mining is exploiting a large stock of waste. This means choices can be made with respect to which part of the landfill is exploited first, while current waste management has to deal with the currently available waste streams. The combination of a long term and a short term approach is typical for landfill mining: long term includes e.g. opting for landfill mining or postponing landfill mining, technology choices and investment costs, whereas short term decisions are e.g. related to directing the daily exploitation to either WtM or WtE, linked to current market prices and operational costs.
- Operation costs (and risks) of landfills are different from waste management systems, e.g. transport costs and impacts are limited to the site.
- The input flows are extremely mixed and can also be degraded, but can on the other hand be scheduled in function of the needs of the landfill mining system.
- This all requires a flexible system that can optimise inputs and outputs in function of variations in time due to economical (market prices, regulation) and operational reasons (quality of input, availability and capacity of processing units...). The general flows are sketched in Figure 2 for an ELFM case study site.



**Figure 2:** Illustration of the general logic behind the decision model



- Other aspects of landfill mining which do not play a role in waste management systems are: regaining land, lowering the maintenance and/or reclamation costs and risks of landfills, site sanitation, recovering soil material, better control of hazardous wastes when uncovered during the landfill mining of old sites...<sup>48</sup>

## Conclusions

This paper has placed Enhanced Landfill Mining in an industrial ecology framework. ELFM has to be seen in the broader perspective of Enhanced Waste Management, in which the focus is on improved recycling and reuse of materials. ELFM is needed to reintroduce materials in the material cycles and to recover energy from a quite large and urban stock of resources held in landfills. The question, however, is not *if* but rather *when* ELFM is economically and environmentally feasible. Concurrently, what are the most sustainable exploitation routes? Assessing the sustainability of a landfill mining exploitation can be inspired on the Life Cycle Costing and Life Cycle Analysis models built for integrated waste management. Nevertheless, there are also important differences between ELFM and integrated waste management assessments. Land recuperation is e.g. a significant parameter for ELFM, while transport costs are not. It is clear that the feasibility of landfill mining projects will increase with market prices of materials and energy. The decisions to be made which fractions should follow WtE and WtM routes are similar for ELFM as for integrated waste management. For the latter, several studies corroborate that for non-renewables, on average, WtM is more environmentally desirable than WtE. This is less the case for renewables. The effect of degradation (and hence time dependency) of renewables in landfills is not understood yet. Current incentives stimulate WtE and have a large effect on the profitability of landfill mining. Finally, Enhanced Landfill Mining is not only important to revalue previously dumped materials but will also stimulate the development of technologies and new valorisation routes for waste flows which are complex, new or just difficult to valorise (economically) with current recycling technologies.

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