Landfill Mining:

Goldmine or Minefield?

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Executive summary

An era of rising consumption has led to resource scarcity across major industries. One way to overcome this challenge and ascertain future supply of resources is recovery of landfilled material. This so-called landfilled mining may valorise previously discarded material streams for a number of purposes and contribute to a circular economy. Across England and Wales, there are more than 20,000 landfill sites of which 90% have been closed before 1996. Besides the general belief that valuable resources can be found within landfills, mining the waste has a number of additional benefits. One stems from the fact that they often lack modern environmental protection technology, which may lead to negative environmental and health impacts. The combination of these facts poses an interesting opportunity for combined resource-recovery and remediation strategies. The report at hand is in place to assess viability and feasibility of landfill mining processes across England and Wales in a step-wise approach.

It starts out with a description of processes and technologies involved in enhanced landfill mining (**ELFM**). This technique aims to fulfil the zero-waste criterion of a circular economy. Here, non-processable waste is stored for future valorisation instead of re-landfilled. We then assess general benefits, such as material and energy recovery from waste, as well as environmental protection. Main limitations to ELFM are of legislative nature, as well as decay within landfilled waste, which may decrease its value. Finally, costs and benefits of landfill mining are determined.

As a starting point, a database of landfill sites in England and Wales is built from GIS data provided by the Environmental Agency, which regulates all landfill sites in England and Wales. The aim of this step is to gather an overview on landfill sites, which can then be filtered to include only the most valuable landfills. The database includes facts such as size of the landfill (in m^2), type of waste included and years of operation. We divide this set of ~20,000 landfill sites into operational (1,694) and closed, or historical (19,670) sites. Only the historical sites are assessed, as mining from operating landfills poses additional risks, which are out of scope of the project. Next, the dataset is filtered to exclude a number of indicators, which make landfill mining unfeasible. These include for example the presence of hazardous waste within the landfill, as it requires additional and costly treatment. Further filtered from the database are datasets without complete information and non-licensed landfills. From the remaining landfills, we filter those with potentially highest values to be used within the next steps. These are sites filled between 1960 and 1990, containing municipal solid, industrial and commercial waste. What remains are 6,146 potentially feasible landfill sites across England and Wales.

In a following step, the datasets are equally divided into three sets based on their size and using the average, a small (12,000 m^2), medium-sized (30,000 m^2) and large (70,000 m^2) landfill are defined. Using specific waste breakdown data from 9 landfills and averaging these, we design a hypothetical

waste breakdown for the three landfill sizes. The main contents within these landfills are plastic, organic waste and paper or cardboard. These different components can be valorised using different techniques. ELFM takes into consideration Waste-to-Material and Waste-to-Energy, where recovered material is either recycled or burnt respectively. Once the land is remediated, it can be used for a different purpose, called Waste-to-Land, while remaining waste that cannot be valorised yet is stored in a temporary storage, called Resource Management. While these different technologies are not taken into consideration within the following Life-Cycle Assessment (**LCA**) due to boundaries defined, they are considered within a subsequent Cost-Benefit Analysis (**CBA**).

A Life-Cycle Analysis (**LCA**) serves to identify differences in emissions between three defined scenarios. In a Do-nothing scenario, leachate and landfill gas from a historical landfill are monitored and collected. The landfill gas is sold to an energy producer for heat and electricity production. Leachate is collected and stored for further treatment. The remaining two scenarios differentiate between on-site and off-site treatment of excavated waste. The On-site process thus involves building a facility, while the off-site includes transport of excavated waste to a nearby (20 km distance) treatment facility. Calculations are done within excel with data from literature and the database 'Ecoinvent 2.0'. This database provides emission specifications for a number of processes in ELFM. Aspects that are left out of consideration as they are out of scope include leachate treatment and water-related processes. Therefore, emissions are calculated in CO_2 with the following assumptions made:

Do-nothing		**On-site/Off-site**
90.92 m^3 gas loaded in truck		45 m^3 waste loaded in truck
0.3 l diesel/km		average waste excavated is 132 tonnes/h
2.67 kg CO_2/l diesel		4.5 l/h for 20 hp
2,532 m^3/day	tot gas produced small LF	25 kW/h per ton of waste excavated
6,330 m^3/day	tot gas produced medium LF	0.4 l diesel/km (100% loaded) 0.3 l diesel/km (empty)
14,770 m^3/day	tot gas produced large LF	2.67 kg CO_2/l diesel

The outcome of the LCA is that the off-site scenario has the highest total emissions compared to the other two scenarios. The difference between the scenarios depends on the size of landfill in consideration. The main difference between the On- and Off-site scenarios in terms of emissions is the CO_2 produced from transport of waste. Therefore, total emissions in the Off-site scenario are 832 tonnes higher than in the on-site one. For the Do-nothing scenario, emissions are only based on transport of landfill gas, with 7 to close to 43 thousand tonnes of CO_2 emitted. A number of boundaries to creation of a full-scale LCA are given. These include variation in physical and chemical properties of waste and insufficient data provision due to competitive markets.

The second-last step in the process is the evaluation of monetary costs and benefits from ELFM. This is done through conduction of a Cost-Benefit Analysis (**CBA**). Through monetary comparison of different alternatives, a CBA can aid decision makers in finding the most valuable scenario. The CBA takes into consideration the same three scenarios and landfill sizes, as well as waste breakdown as given before. A main difference is that the Do-nothing scenario is calculated over a period of 30 years, while the payback period within the On- and Off-site scenarios depend on the size of landfill. Thus, the time of operation is based on an excavation rate of 1,440 m^3 on a 10-hours working day and 250 working days per year. This means a payback period of 4, 5 and 7 years for small, medium and large sites respectively. Cost of transport is based on the same excavation rate and price for gas, insurance and wear. Other capital and operational expenditures are taken from a number of case studies and adapted to the UK where necessary. The biggest capital expense is that of building facilities within the On-site scenario, which is calculated as £30m in total. To offset unforeseen circumstances and to take into consideration that the cost of technology in landfill mining varies significantly, a relatively high contingency of £5m over the first years of operation is included before decreasing to £1m.

The main outcome of the analysis is that mining of larger landfills is more profitable than smaller ones. This is based on higher revenues from waste, as more tonnes can be sold to the market. Therefore, high capital investments may be offset over a longer time frame. Another reason for higher revenues is that a larger area can be sold after remediation. Especially in the UK where the price of land is generally high, this means a high return per additional m^2. While it is possible to yield profits from ELFM on medium and large landfill sites, the Do-nothing scenario will always result in costs.
Once we combined the findings from an extensive literature research with the outcomes of LCA and CBA, we designed a decision matrix. This decision matrix can guide decision-makers towards arriving at the most preferable option. The matrix allows the interested party in considering which scenario to undertake depending on the project's objectives. As possible objectives, we consider Waste-to-Material, Waste-to-Energy, Waste-to-Land and Resource Management. Based on our findings, we decide on five criteria connected to the landfill site in question: Type of waste, operational years, tonnage, surroundings and technology.

It is found that the most important criterion for a viable and feasible ELFM project is the type of waste within the landfill. Hazardous waste for example can increase costs as well as environmental and health risks. Furthermore, the values from different types of waste vary significantly. This is also linked to operational years, not only what is landfilled but also the state of the waste impact values. An example for this is the landfill directive that came into place in 1996, which forced operators to recycle increasingly, which results in lower values within the landfill. The second most important factor to consider when planning ELFM is the technology at hand. Not only the efficiency, but also the cost of technology have to be taken into consideration, as they can distinguish the outcome of a mining project.

The importance of tonnage within the landfill as well as its surroundings can mainly be ascribed to economic reasoning. The capital investments are relatively high and the same for the small, medium and large projects. While they make mining of small landfills unprofitable, in medium and large sites this can be offset through profits from higher tonnage. The surroundings can play an important part in the feasibility and viability as land prices are comparably high in England and Wales. Furthermore, mining close to residential areas may incur high costs for odour and pollution protection, as well as regulatory boundaries.

As a general finding, it can be said that concerning ELFM and its definition with the goal to reduce impact on the environment, an On-site scenario is the most beneficial one. This is due to avoided emissions from transport of waste in comparison to the Off-site scenario. It is strongly advised that every operator interested in ELFM should do a number of site visits prior to the operation. Through visual analysis, the surroundings of a site can be quickly analysed. Furthermore, it is suggested to gather as complete data as possible to anticipate any potential risks and monetary costs and benefits involved. A number of site-samples should be taken to determine the state of waste decay, as well as the type of waste within the landfill. It needs to be kept in mind that future changes within legislation and technology can have a strong impact on the outcome of mining operations. This is especially true as ELFM projects are realised over a number of years. In conclusion, it can be said that under the right circumstances, ELFM may transform a landfill into a goldmine.

Abbreviations

CBA Cost-Benefit Analysis

ELFM Enhanced Landfill Mining

EA Environment Agency

GIS Geographic Information Systems

IW Industrial Waste

LFG Landfill Gas

LCA Life Cycle Assessment

MSW Municipal Solid Waste

NPV Net Present Value

WEEE Waste Electrical and Electronic Equipment

WtE Waste-to-Energy

WtL Waste-to-Land

WtM Waste-to-Material

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1. Introduction

Strongly increased consumption linked to growing global population has led to a steady rise in production and thus large amounts of resources being used up to a point of resource scarcity (Rockstrøm et al., 2009).This issue of resource needs has come to the forefront of the debate over recent years, partly due to considerable concern over supply shortage and the need of primary and secondary raw materials.

Considering the increasing scarcity and raising prices of resources, such as metals and minerals, the recycling and recovery of these materials from landfill sites, is of great relevance. One source for material recovery is mining of landfilled waste. Recent research has demonstrated that landfill sites could offer a high potential of primary and secondary raw materials rather than just represent contaminated land.

With close to 20,000 landfills spread across England and Wales (EA, 2015) the recovery of the landfilled materials and land reclamation no longer represents an unrealistic scenario. The improved techniques and technologies and the shortage of materials and space, suggest that landfill sites could become an alternative solution to this challenge rather than a risk.

The potential recovery of materials burried in the landfills, without compromising human and environmental health, is only possible by using complex techniques and modern technologies, therefore the feasibility of such projects are highly bounded to the quality and price of recovered materials in the market. It is important to mention the new economical and productive tendency towards a Circular Economy. The main objective for this new trend is to close the extraction-production-disposal cycles and reintegrate the materials considered as waste into the productions streams.

The project reviews innovative and integrated methods for enhanced landfill mining in England and Wales. The aims of this project is to develop a database of all landfill sites in England and Wales. Using this database as a support, a decision matrix will be design with the goal to provide guidance to parties considering landfill mining towards assessment of suitability of a particular landfill according to our findings. A Life Cycle Analysis (LAC) and a Cost-Benefit Analysis (CBA) will be carried out based on three hypothetical landfill sites built from the gathered data. This in order to evaluate the technical and financial feasibility of undertaking in situ and ex situ landfill mining.

The report is divided into seven sections. The next section provides a brief review of the history of landfill mining projects done around the world in the last decades. The third section presents the regulations and necessary authorisations that need to be considered before any landfill mining activity takes place. The next chapter shows the importance to consider environmental and health impact assessment during the whole mining process. The fifth section describes the methodology followed to gather the data needed and the criteria used to select the potential landfill sites for mining activities and, also the steps and assumptions to carry out the life cycle and cost-benefit analysis for three hypothetical landfill sites are explained. The sixth section presents the results and findings regarding the gathering and construction of the database, the life cycle and cost-benefit analysis and, the objectives and parameters considered for the matrix decision design which could provide guidance for the selection of landfill sites in future mining projects. The final section discusses there results and provides insight into the strengths and weaknesses for landfill mining activities. This section also highlights the parameters that should be consider to ensure a positive outcome of any landfill mining project.

2. History of landfill mining

This part of the report briefly describes the origin and concept of landfill mining, making reference to different projects that have been carried out in the past. Also, a differentiation is made between conventional and enhanced landfill mining with benefits and limitations to the latter. Different available technologies for landfill mining are mentioned; and the importance of the attachment to legislations to be able to start mining projects is pointed out. Finally, a concise description of LCA and CBA is done as they are essential for the results of the report.
The first reference to landfill mining was made about sixty years ago concerning a site in Tel Aviv, Israel in 1953 (Savage *et al*., 1993). Since then, about fifty projects have been realised, with the majority focusing on solving local concerns such as conservation of landfill space, remediation and other traditional waste management challenges (US-EPA, 1997; Van der Zee *et al*., 2004). Only few of the reported landfill mining projects were done with an emphasis on resource recovery (Rettenberger, 1995). An overview on the history of documented landfill mining from 1953 to 2001 can be found within Table 1.

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 (Krook *et al.*, 2012; Van der Zee *et al.*, 2004). A newer perspective on landfill mining includes valorisation of materials as well as temporary storage for future recovery, called enhanced landfill mining.

Table 1. History of landfill mining sites (*cf*. Claire *et al*., 2008).

Year	Country	Location	Primary Purpose
1953	Israel	Tel Aviv	Recovery of soil
1989	India	Deonar, Mumba	Pilot study to investigate use of organics as compost
1988	USA	Collier County, Florida	Demonstration project by New York Energy Research and Development Authority
1990	USA	Edinburg, Texas	Reduce groundwater contamination; soil recovery; recovery of landfill capacity
1991-1993	USA	Lancaster County	Soil recovery; energy from waste
1992	USA	Bethlehem	Avoid groundwater contamination; recovery of landfill capacity
1992	USA	Thomson, Connecticut	Recovery of landfill capacity
1993	USA	Nashville, Tennessee	Contamination issues; recycling soil and ash for road base
1993	USA	Newbury, Mass	Avoid groundwater contamination; recovery of landfill capacity.
1994	USA	Hague, NY	Reclaim land: re-use site as recreational space
1994	Canada	McDougal, Ontario	Avoid groundwater contamination
1993	Germany	Berghof	First European site: recycling; recovery of landfill capacity 1994
1994	Sardinia		Recovery of landfill
1994	Sweden	Filborna	Pilot test
1998	Sweden	Gladsax	Energy recovery and recycling
2001	Netherlands	Arnhem	Reclaim land
2001	Netherlands	Heiloo	Recovery of landfill

2.1. Conventional vs. Enhanced Landfill Mining

In conventional landfill mining, recovery is limited to methane collection and an incomplete extraction of valuable materials and/or land reclamation and restoration (Prechthai, 2008). While traditional landfill mining has a long history, enhanced landfill mining (**ELFM**) has come into focus recently as a way to increase recovery rates from material excavation. The two processes, including in-and outputs are depicted within Figure 1:

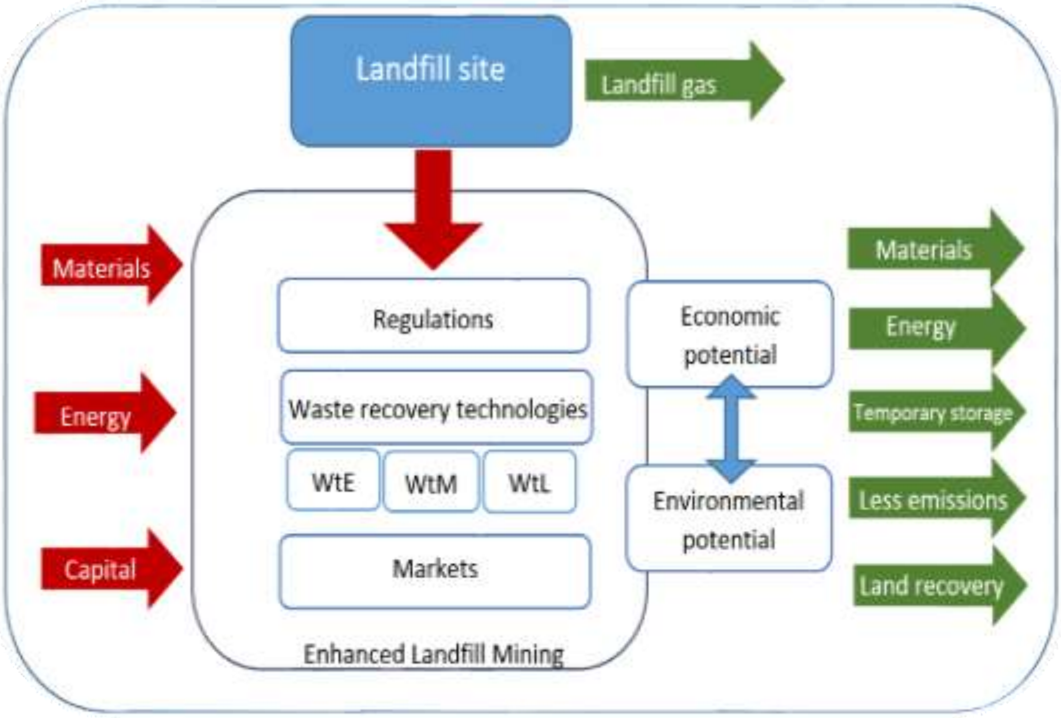

Figure 1: Landfill mining and ELFM process

ELFM mainly differs from conventional mining through optimised valorisation of different types of materials extracted from landfill sites, for example through increased energy recovery from waste, aiming to reduce the amount of re-buried waste to almost zero (Danthurebandara *et al.*, 2015). Another goal of ELFM is to mitigate greenhouse emissions from landfill sites and landfill mining activities to the atmosphere (*ibid.*), using various technologies which make waste streams considerable for different valorisation techniques.

Different options for recovery comprise Waste-to-Material (**WtM**), which is the re-valorisation of recovered waste and its reuse as potential materials, as well as Waste-to-Energy (**WtE**) (Jones *et al.*, 2013) - linked to energy that can be gathered from landfilled material, either as electricity or heat (OVAM, 2013). Besides WtM and WtE, Van Passel (*et al.*, 2010) also considers Waste-to-Land (**WtL**), describing the creation of space at the location of the landfill site, as well as assignment of a new land use to the remediated landfill site (OVAM, 2013). Furthermore, Resource Management is taken into account, defined as "*the temporary storage of waste with a view to a later valorisation and use of this waste*" (OVAM, 2013).

ELFM seeks to form a fully closed loop material system (Stahel, 2013). The Ellen MacArthur Foundation (2015) describes a circular economy as "*restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times,* *distinguishing between technical and biological cycles".* The 'Closing the Circle' project was a concrete case of ELFM developed in the Group Machiels at the Houthalen-Helchteren landfill site (Tielemans, 2010) in Belgium (*cf*. Appendix 7.2.2). According to the author, more than 16 million tonnes of mixed municipal solid waste (**MSW**) and industrial waste (**IW**) were stored at the site in Belgium. Merit to the information well documented regarding the type, amount and location of the waste at the site, it was calculated that approximately 45% of the waste could be recovered as valuable materials. The recycling residue could be valorised as energy from waste or sold to plasma technology companies. Just a very limited amount of mined waste was identified as non-valuable material due to the fact that its potential is not yet identified, and therefore will have to be sent to temporary storage for possible valorisation in the future.

2.2. Technology in ELFM

The ELFM process involves different steps such as excavation, segregation techniques, withdrawing wastes previously disposed, and reuse of waste and the land for financial and environmental advantages (Carter, 2011). Recycling and recovery of materials is in most cases only a second purpose, which has resulted in a standstill in development of specialised mining technologies although landfilled waste has special features, such as being strongly compacted (Ford *et al*., 2013). A number of technologies are readily available in the market with different characteristics and for different stages of the process (*ibid.*), some of which can be found within Table 2.

Depending on the efficiency and development of technologies involved, different waste streams can be excavated and valorised (Ford *et al*., 2013), leading to varying benefits from the operation. Furthermore, a number of limitations to ELFM may arise from suitable or unsuitable technology, as further explored within the following segment.

Table 2: Different technologies involved in ELFM (*cf*. Ford *et al*., 2013)

Process	Technologies	Description	Separated waste stream
Removal of moisture from the waste mass, the collection and extraction of landfill gas	• Bioreactor	In situ. Stabilisation of biological waste activity in a short time.	-
Excavation/waste removal	• Trackhoe and backhoe excavators • Bulldozers • Grappling Hoes	Ex situ. Waste is removed from the landfill in order to be processed.	-
Size reduction	• Hammermills - vertical and horizontal shaft • Shear shredder • Rotary, guillotine and scissors-type shears • Grinders - roller, disc-mill, ball mill • Flail mill • Wet pulper • Knife mill	Ex situ. Facilitation of subsequent material handling and sorting.	-
Screening	• Trommel • Vibrating • Disc/star	Ex situ. Waste is separated by size by passing through one or more screens.	Soil
Air technologies	• Windshifter • Drum separators • Air classifiers • Air knife	Ex situ. Separation of waste.	Paper and plastic (light fraction) Wood, organic and textile (medium fraction) Glass, stones (heavy fraction)
Metal separation	• Overband magnets • Drum magnets • Head pulley magnets • Eddy current separators	Ex situ. Removal of ferrous and non-ferrous metals.	Ferrous metals Non-ferrous metals
Temporary storage		In situ and ex situ. Environmentally safe place where the materials which cannot be treated in the present moment are disposed. Permits in situ recovery of energy, soil, groundwater, land and nature, and possible future materials recovery.	-

2.3. Benefits and limitations

There are a number of social and environmental benefits as well as certain limitations that have been mentioned surrounding enhanced mining practices. An overview of these is given within this chapter.

2.3.1. Benefits

According to Rettenberger (1995), the three basic benefits of ELFM include: Extraction potentials, energy recovery, hazards reduction and use of reclaimed land. Below is a brief summary:

- Materials recovery: Materials which are considered to be valuable are extracted from old landfill sites. This is primarily due to the urgent need for more sustainable use of natural resources.
- Waste-to-Energy: Recovered waste materials are incorporated with fresh waste sources as feedstock and used to generate heat and electricity. This initiative is gaining popularity across European countries like Sweden, Norway among others.
- Reduction of potential hazards and utilisation of regained land space.

It is strongly believed that recovered materials from landfill sites could provide high economic revenues; their value will depend on the amount and quality of the recovered fractions and the market, which the following subchapter will further explore.

The amount of waste that could potentially be recovered principally depends on physical and chemical conditions of the landfill and the efficiency of equipment and technology used (Møller, 2009). According to the World Resource Foundation (Strange, 1998), purity of the excavated waste can vary between 70 and 90%, with recovery rates for material that has been landfilled being:

- Soil: 85-95%
- Metals (ferrous): 70-90%
- Plastic: 50-75%

A high amount of plastics can be found in landfills, but according to Kurian (2008), his research concluded that it is not viable to reuse it due to its highly diminished quality. Quaghebeur (2013) agrees, stating that excavated plastic, textile, paper/cardboard and wood do not have the required quality for recycling and reintegration in the production market. Therefore, the best valorisation route for these types of waste is WtE.

It has been found that the highest economic potential from resource recovery lies within landfills operated and closed between 1960 and 1995 (Møller, 2009), as after these years many of the EU countries established waste separation programmes. At the same time, the 1960s marked a period of consumer society, which is thcae reason why landfills that were closed before 1960 should contain a lower amount of valuable materials, due to the waste produced by society prior to this era (*ibid.*). Furthermore, industrial landfill sites could contain very valuable materials, e.g. sites operated by the electronics and car industries (*ibid.*). Besides potential benefits from landfill mining, a number of limitations have been specified in the literature, laid out in the following part.

2.3.2. Limitations

Due to the complexity of landfill mining activities, Fornaseri (2014) identifies three main limitations and concerns:

- Mechanical instability of waste: Materials like plastic, textiles and metals provide a good structure for landfill allowing deep excavations. This heterogeneity can hide weak areas and zones filled with leachate and gases.
- Presence of Biogas: The anaerobic reactions in landfill sites produce below others methane and carbon dioxide. This could represent a risk to workers due the probability of explosions, and it could increase odour and pollution.
- Hazardous waste: This type of waste can be dangerous, especially in historical landfill sites where regulations were not yet implemented.

Møller (2009) identifies as a major limitation of ELFM the great amount of machinery and manpower required. Like Fornaseri (2014), he also identifies odour and gas emissions as limitations. Excavation and reclamation activities could shorten the lifespan of equipment due to the amount of waste being handled; the high particulate content and corrosive nature of recovered material can also have negative effects on the equipment (*ibid.*). Additionally, uncertainties of knowing the components of the buried waste can raise health and environmental safety issues through exposure to leachate and hazardous material or pathogens.

Furthermore, as could be seen in 1995 when the landfill directive came into place, legislation may play a major role in landfill operation and viability of mining. Existing adequate incentives for the mitigation of environmental threats through landfill mining, and a suitable legislative framework may make the difference for feasibility and viability (Van Passel *et. al*., 2012). The following chapter will thus take a look at current legislation within the EU and UK.

3. Legislation EU and UK

As laid out in chapter 2, ELFM projects within England and Wales have not yet been deeply developed. Therefore, information on the legislative framework and regulations to be followed is not readily available. It can be stated though, that necessary authorisations and implications will be particular to specific landfill sites and mining projects (Ford *et al.*, 2013).

The essential objective of England and Wales' regulations and EU directives relating to waste management should be the protection of human health and the environment against harmful effects caused by waste management (UK Gov, 2016). The activities must be undertaken in a manner to achieve environmental and human health protection, and should also avoid nuisance (*ibid.*). Environmental permitting in UK and Wales is primarily legislated by the 'Environmental Protection (England and Wales) Regulations 2016' and 'The Waste (England and Wales) Regulations 2011' (*ibid.*). The directives that have to be followed are:

- COUNCIL DIRECTIVE 1999/31/EC of 26 April 1999 on the landfill of waste, the main objective of this directive is making sure that operational and technical requirements on the waste and landfills are in order, provide for measures, procedures and guidance to prevent and/or reduce negative effects on the environment, especially surface and ground water, soil and air pollution, it also includes the greenhouse effect emissions, as well as any possible risk to human health, during the entire life-cycle of the landfill.
- DIRECTIVE 2006/12/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 April 2006 on waste, the main objective of this directive is to offer guidance relating to waste management and it focuses on the protection of human health and the environment against harmful effects caused by the collection, transport, treatment, storage and tipping of waste. It also provides consistent rules that should be applied on waste disposal and recovery, subject to exceptions. The recovered materials as raw materials should be encouraged in order to conserve natural resources. It may be necessary to adopt specific rules for re-usable waste.
- DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives, "this directive presents measures to protect the environment and human health by preventing or reducing the negative impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use."
- DIRECTIVE 2008/1/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 January 2008 concerning integrated pollution prevention and control, the main purpose of this directive is to prevent and control the pollution arising from the activities. It presents measures to prevent or to reduce emissions in the air, water and land from waste management activities among others, in order to achieve a high level of protection of the environment.
- DIRECTIVE 2014/52/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 April 2014 this directive was created to amend Directive 2011/92/EU on the assessment

of the effects of certain public and private projects on the environment. It presents "the principles for the environmental impact assessment of projects by introducing minimum requirements, with regard to the type of projects subject to assessment, the main obligations of developers, the content of the assessment and the participation of the competent authorities and the public, and it contributes to a high level of protection of the environment and human health."

According to Ford (*et al.*, 2013), the general parameters to follow in order to apply for the appropriate permits include:

- A description of the activities and the method to be used for each type of operation including: inputs and outputs, resources, infrastructure and equipment a justification of the selected equipment
- A description of the types and quantities of waste that may be treated
- A conceptual model for the identification of the potential hazards and risks, potential receptors and possible pathways
- The safety and precautionary measures to be taken
- Monitoring and control operations
- Closure and after-care plans

As environmental and health impacts play a major role within the legislative framework surrounding landfill mining, the following chapter gives a deeper insight into this topic.

4. Environmental and health impact assessment

Although ELFM has recently become the new method for the reduction of waste and recovery of land in the waste industry, some concerns have been raised such as the hollow left behind after the excavation of waste (Denafas, 2014). As mining projects may have a permanent impact, environmental and health effects have to be considered, risks assessed and precautions and control measures put in place through a life cycle assessment (*ibid.*).

A project carried out by Cambridge University (Barlow, *et. al.*, 1990) and another research by Vijayaraghavan (2011) also identified the process as:

- A control measure for toxic material leaching into the groundwater due to the vulnerability to failure by the initial use of a single liner between the pit and the ground
- A way to reduce landfill gas (**LFG**) emissions into the atmosphere, which its compounds are mainly methane, carbon dioxide and volatile organic compounds

- Reuse of discarded wastes
- Re-purposing landfills for other uses such as real estate.

According to Ford (*et al.*, 2013), hazardous wastes are most likely to be prevalent at older landfills that were in operation at a time when waste disposal practices and waste acceptance criteria were not as robust or well-regulated as in the present day. Such waste may be subject to special handling and disposal requirements to mitigate risk to the environment and human health of workers and/or nearby residents (*ibid.*). Furthermore, old sites often lack modern leachate and gas control technologies (Flyhammar, 1997).

Mining landfills within residential areas will pose a very significant health risk to residents. Depending on the management option, some gases could be released of which some are not pungent yet harmful like methane. Methane forms as a result of decomposition of waste, released into soil and atmosphere (Boardman, *et. al* 2004). Williams (2013) and Carter (2011) stated that one gram of methane has 23 times the impact of a gram of carbon dioxide over a 100 years period and it constitutes between 40% and 60% of landfill gas. Breathing in high levels of the gas can cause agitation, nausea, slurred speech, vomiting, facial flushing and headache and sometimes in severe cases heart complications, coma and death (Bull, 2010). This could be the case for on-site workers and/or nearby residents. Because of possible ailments and nuisance that could be caused by landfill mining activities, the importance of a health and environmental impact is pointed out in order to prevent and mitigate negative consequences.

5. Methodology

5.1. Database criteria selection and development

All historical- as well as operational landfill sites in England and Wales are regulated by the Environment Agency (**EA**). In order to construct a database of landfills within these regions, Geographic Information Systems (**GIS**) data provided by the EA (2016) was used to construct the tool within Excel. According to this database, 1,694 sites are permitted and 19,670 are historical, comprising:

- 91% closed without a permit before 1994
- 3% closed before the landfill directive (licensed up to closure) between 1994-2001
- 4% closed under the landfill directive after 2001
- 2% operational

These landfill sites are further classifiable into 5 different categories, defined as follows:

- Inert: The waste suffers no alteration once it has been buried (e.g. glass, concrete, bricks, soil).
- Household: Waste from different sources (e.g. houses, caravans, houseboats, schools).
- Commercial: Waste originated from activities such as trade, business, sports, entertainment.
- Special: Hazardous waste (e.g. flammable, irritant, toxic materials).
- Industrial: Waste produced from industry or factories, excluding mine, quarries and agricultural wastes.

Landfill sites usually contain:

- 56% of inert waste
- 33% of industrial waste
- 28% of commercial waste
- 28% of household waste
- 5% of special waste
- 11% is composed of liquid/sludge and unknown materials.

As generally more than one type of waste can be found within a landfill, the values add up to more than 100%.

Of the ~20,000 landfills, not all are suitable for ELFM, which is why they were not considered from the database.

A filtered Excel spread sheet was used for the deletion of landfill sites that did not meet the requirements that were stablished (Figure 2). These requirements include complete data available and were the permits were updated or not. Selection of the sites follows with the exclusion of datasets through SPSS statistical analysis to increase viability of the dataset. In subsequent application of qualitative (type of waste, first and last input) and quantitative (size and tonnage) criteria, further unviable landfill sites have been excluded. An example for those deleted from the sample in the process are sites containing hazardous waste, as this should increase costs to a point where the project is not feasible (Danthurebandara *et al*., 2015; Quaghebeur *et al*., 2013). In accordance with Gusca (2015), another goal of the database modification is the classification of landfills into different sizes to assess whether the size of landfill makes a difference in feasibility. The selective criteria that have been applied to the database are shown in table 3.

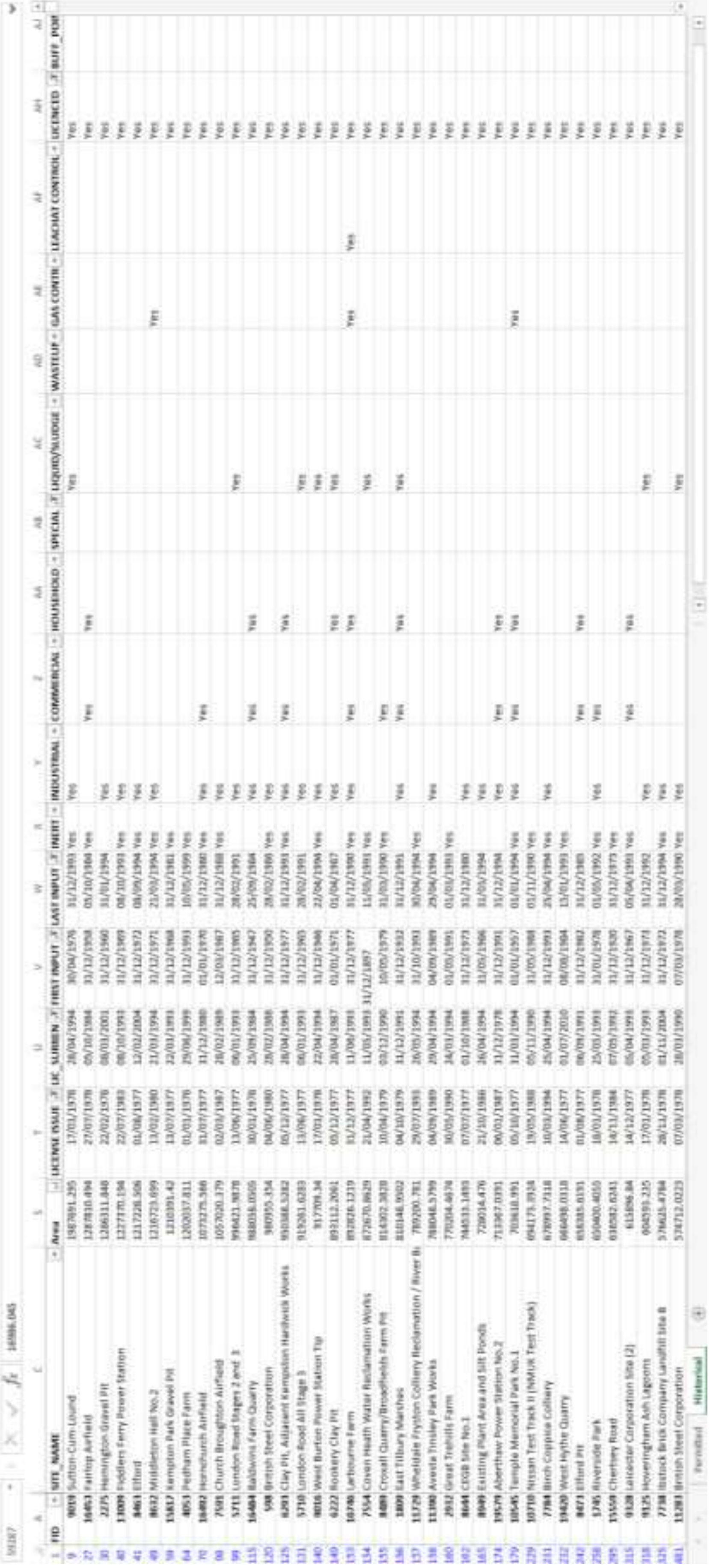

Figure 2 Filtered Excel spread sheet used for landfill site selection

For further detail on the selection process the following link can be accessed: https://drive.google.com/open?id=0B9Q7PKoFFkA3N0duMjN6REhjWnM

In order to reach three different sizes of landfills (small, medium and large), the final data sample of around 6,000 landfills is used. This data is divided into three equal fractions with respect to their size in m^2. Afterwards, the median of each of these is taken, which yields the final size of landfills. The data provided by the EA informs on m^2 instead of m^3 or tonnage, which is for example needed for calculations on excavation. Thus, it is assumed that the depth of a landfill is 15 m and that the waste density is 1.15 t/m3. Linking these findings and assumption together leads to the following hypothetical landfill sizes and tonnages:

- Small: 12,000 m2; 207,000 tonnes
- Medium: 30,000 m2; 517,500 tonnes
- Large: 70,000 m2; 1,207,000 tonnes

When compared with literature (Danthurebandara et al., 2015; Quaghebeur, (2013); Tielemans, 2010; Van Passel, 2013), it quickly becomes obvious that the remaining samples are much smaller than those in case studies. Throughout the project, this has a big influence, for example on costs of benefits and years of operation.

Table 3. Criteria used for modification of the database 'Landfills in England and Wales'

		Selection criterion	**Selection**
Step 1	EA database	Complete data	Complete information
			Licensed
Step 2	Qualitative indicators	Type of waste	Without hazardous waste
		First and last input	Before 1960; after 1990
Step 3	Quantitative indicators	Size (Tonnage)	Small < 17,000 m^2 (< 293,250 tonnes)
			Medium 17,000 m^2 – 58,000 m^2 (293,250 - 1,000,500 tonnes)
			Large > 58,000 m^2 (> 1,000,500 tonnes)

To achieve the construction of an accurate database and the matrix decision tool, 15 landfill operator companies were approached and asked for specific data regarding the sites under their operation. The information required included:

- Waste breakdown
- License status
- Volume

As this data could not be obtained, the waste breakdown was designed from files supplied by one landfill operator, as well as supporting literature research. The following chapter gives an insight into the information provided by the operator.

5.2. Waste breakdown – 9 landfills

The operator's data was gathered for nine landfills across England and Wales including information on tonnage and waste breakdown, as well as status of operation, which can be found in table 4. Within the classification at hand, all of them were categorised as small landfills.

Table 4: Total content, waste breakdown and status of operation.

Landfill	Total tonnage	Waste breakdown (%)												Status
		P/c	P	T	W	G	O	M	WE	H	R	S	F	
LFS1	12,702	15	20	4	6	3	26	3	2	0	17	1	1	Closed
LFS2	3,749	21	21	5	3	4	21	4	1	1	17	0	1	Opened
LFS3	7,155	17	22	7	7	2	19	3	1	1	17	1	3	Opened
LFS4	7,878	11	19	7	11	1	15	3	1	2	27	0	3	Closed
LFS5	4,070	19	19	6	7	2	24	3	2	2	15	0	0	Opened
LFS6	3,141	20	19	5	5	1	16	6	2	1	22	1	3	Opened
LFS7	4,384	11	18	7	10	3	26	3	1	2	18	1	0	Closed
LFS8	3,712	29	21	3	8	2	17	5	1	1	13	0	1	Closed
LFS9	3,909	24	22	6	5	1	19	3	1	1	15	1	2	Closed
P/c=Paper/cardboard; P= Plastic; T= Textile; W= Wood; G= Glass; O= Organic waste; M= Metal; WE= WEEE; H= Hazardous; R= Rest; S= Soil; F= Fines.														

From this data and supported by literature research, waste breakdown of a hypothetical landfill site in England and Wales was constructed, while a number of assumptions needed to be made, as discussed within the following subchapter.

5.3. Assumptions and scenarios considered

As data on a number of facts was still missing such waste break-down and tonnage, some information was assumed. It is estimated that the depth of a typical hypothetical landfill in England and Wales is 15 m (Ford *et al.*, 2013), while the density of waste landfilled is 1.15 t/m^3 in accordance with Hull (*et al.*, 2005). These assumptions alongside previously mentioned provided data aided in calculation of tonnage of landfills. This was necessary based on the fact that the EA's GIS files supply the area of the landfill, rather than tonnage or volume.

From above mentioned collected and assumed data, it was possible to build a hypothetical waste breakdown. Using this as a base, one hypothetical landfill was constructed each for small, medium-sized and large sites.

The waste breakdown for the hypothetical small, medium-sized and large landfills has to be based on information provided for 9 landfills. This is due to an unavailability of waste breakdown data from more landfills. The tonnages for each landfill provided are averaged between all nine. They are then transformed into percentages of total waste within the 9 landfills. This yields the following waste breakdown:

- Plastic 20%
- Organic waste 20%
- Paper/cardboard 19%
- Rest 18%
- Wood 7%
- Textile 5%
- Metal 4%
- Glass 2%
- Fines 2%
- WEEE 1%
- Soil 1%

These percentages are then applied to the tonnages of the three landfills previously estimates, yielding tonnes of type of waste for each landfill size. This breakdown aids in calculation of LFG production and calorific value of material in further steps.

Three scenarios have been considered as shown in Table 5.

Table 5: Table showing the Goal Scope and Boundary of the Scenarios

Scenarios	Boundary conditions	Goal and scope	Functional unit
Do-nothing	Biogas monitoring and collection	Monitoring and capturing LFG	Kg CO_2/l diesel
ELFM MSW	Cradle to Gate	Excavation and processing of waste on-site	Kg CO_2/ton waste
ELFM MSW	Cradle to Gate	Excavation and processing of waste off-site	Kg CO_2/ton waste

The Cradle to gate boundary conditions imply that recovered materials are going to be used as inputs to a refining and materials recycling plant and sold to potential buyers (Quantis, 2014). For a cradle to cradle boundary, the extracted materials would further be refined and processed into finished goods and transported to consumers (European Commission, 2010).

Some aspects were not considered due to limited data available. These include:

- Water used for industrial mining process
- Water footprint for washing and treating the soil
- Waste discharged from the process
- CO_2-emissions from leachate treatment

Other major challenges encountered included selection of the type, size and energy requirement of equipment during mining process.

1) Do-nothing scenario

The Do-nothing scenario is used as a ground score indicator as there are few operations carried out. The scenario assumes that there is no mining operation carried out on the landfill site. What is done is monitoring and collection of LFG, as well as leachate control. Monitoring of gas production and depletion is carried out for 30 years. Technology and data concerning leachate and gas control are based upon Damgaard (*et al*., 2011), with LFG collected being sent to facilities for production of either electricity or heat at 30% and 80% efficiency respectively. In terms of leachate measures installed, a system for collection is assumed to be installed alongside a bottom liner, taking into consideration a possible decay over time. It is then directed to a collection pond, where it is pumped and stored for further treatment.

2) On-site scenario

Mining operations were carried out on this site using excavators, waste screening and sorting equipment as depicted within the ELFM process description. Valorisation of waste and treated waste material occurred on-site, building respective facilities as taken from SLR (2016).

3) Off-site scenario

This excavation in this scenario is similar to the On-site scenario, with the main change being that the excavated waste was transferred via trucks to a waste management facility 20 km from the landfill site.

5.4. Life Cycle Assessment

The LCA was used to determine the environmental impact of the valorisation of total wastes present in the three typical hypothetical landfills (small, medium-sized and large). For each process the environmental impact was calculated and related to the tonnes of wastes. After that, the individual results were combined to evaluate the total amount of CO_2.

Valorisation of all materials present in the landfill is one of the main objective of ELFM. Following these, we selected a series of technologies in order to reach these objective. The figure 3 shows the process and technology considered.

The following assumptions were made:

- The environmental impact of the infrastructure was considered to be very low because of its long service life and for this reason not taken into account.
- Solid waste treatment impact is counted for the process that causes the waste.
- The distance taken into account between landfill and processing plant is 20 km for Off-site scenario.
- Leachate treatment is not included as it is common to all scenarios.

The equivalent carbon emissions were calculated from the amount of diesel consumed per tonne of excavated material.

Furthermore, estimating emissions from transportation was based on kilometres travelled during mining activities. Similar calculations were carried out on sieving and sorting equipment by imputing the amount of energy consumed by machinery. The amount of electrical power consumption and emissions per kilowatt of treated waste was used with the database 'Ecoinvent 2.0' filling gaps where data was not readily available. The LCA takes into consideration the three scenarios defined afore, and is based on the ISO 40440:2006 standards (Finkbeiner *et al.*, 2006), as well as similar LCA projects by Gusca (*et al.*, 2015) and Danthurebandara (*et al*., 2013).

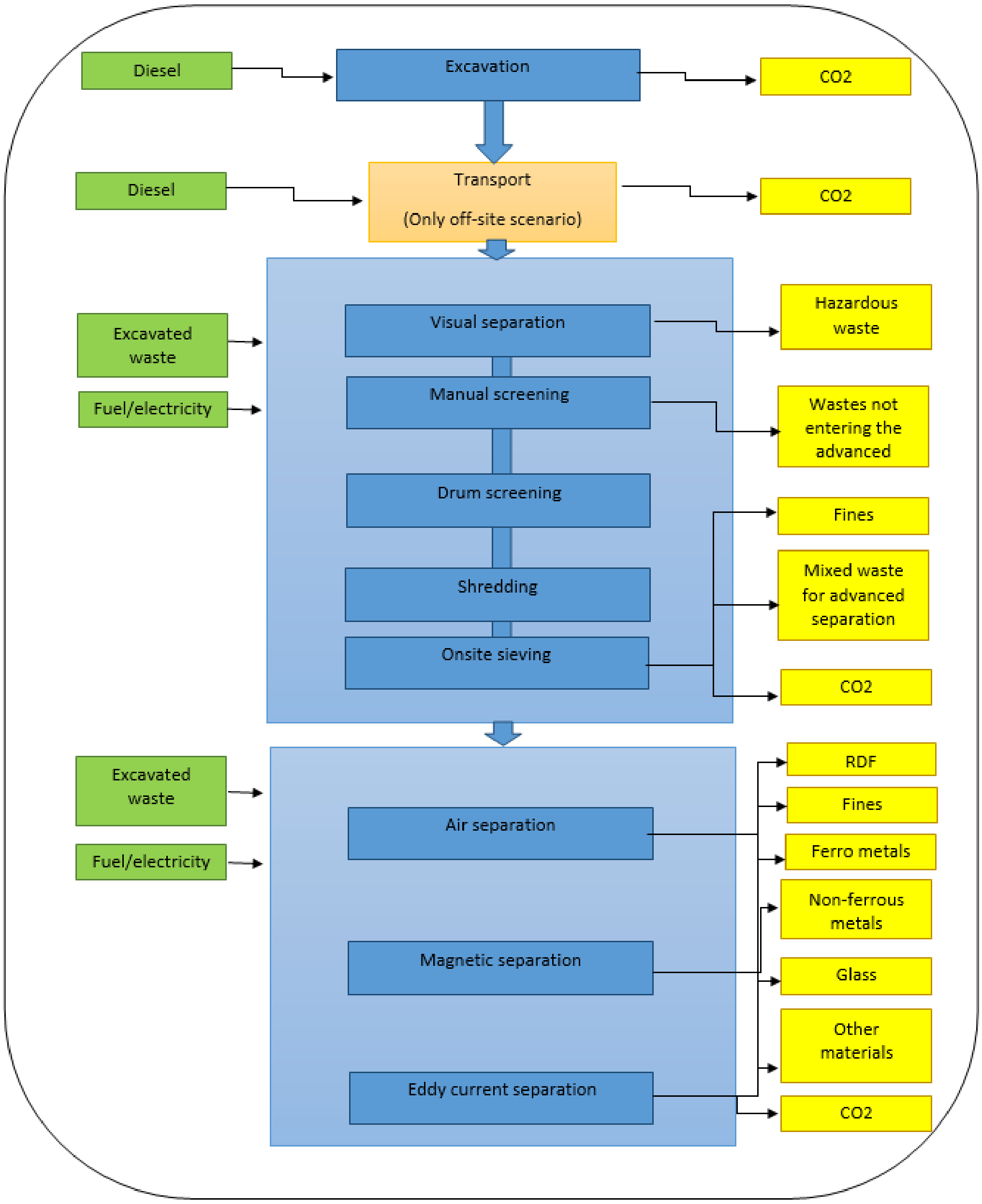

Figure 3: Process flow diagram of LCA

For each of the processing stages, energy and material use is calculated. It is important to note that the LCA includes emissions from excavation, as well as equipment and mining activities. This allows quantifying of the total amount for both equipment and site emissions to achieve a more comprehensive result. Assumptions in equipment power capacity were made and equipment used was in the medium duty capacity (Painesis, 2011). For most mining processes, energy is sourced from diesel (17%) and electricity (40%) (DOE, 2007), assumed to be from the UK National Grid medium power mix. Some further assumptions have been made in order to fill information gaps. A summary of these can be found in Table 6.

Table 6: Assumptions made for the LCA (IEEP, 2009)

Do-nothing		**On-site/Off-site**
90.92 m^3 gas loaded in truck		45 m^3 waste loaded in truck
0.3 l diesel/km		average waste excavated is 132 tonnes/h
2.67 kg CO_2/l diesel		4.5 l/h for 20 hp
2,532 m^3/day	tot gas produced small LF	25 kW/h per ton
6,330 m^3/day	tot gas produced medium LF	0.4 l diesel/km (100% loaded) 0.3 l diesel/km (empty)
14,770 m^3/day	tot gas produced large LF	2.67 kg CO_2/l diesel
		20 km distance to the facility

For further detail on the LCA process the following link can be accessed: https://drive.google.com/open?id=0B9Q7PKoFFkA3N0duMjN6REhjWnM

5.5. Cost-benefit analysis

For the CBA, the same scenarios designed, assumptions made and boundaries defined as within the LCA are taken into consideration. As the Do-nothing scenario spans over 30 years, it is divided into constant annual fractions for the calculation at hand. The period of ELFM operation for On- and Off-site scenarios is based on total volume of each landfill (in m3), excavation per hour (1,440 m3 as assumed for the LCA) and working days per year (250 without working weekends). This means a payback period of 4, 5 and 7 years for small, medium and large sites respectively.

Operating cost for waste treatment is taken from Van Passel (et al., 2013), who estimates £ 17.2 per tonne processed. This is rounded up to £20 to incorporate higher prices in the UK compared to the case study from Belgium. Costs for building the facilities are £20 m for waste treatment, and £10m for the energy production (Fitzgerald & Themelis, 2009). WtE operation costs are estimated as £0.5m per year (cf. Rodriguez & Themelis, 2007).

Prices for material in £/ton have been taken from Ford (*et al.*, 2013) as follows:

- Paper & Card 5
- Dense plastic 30
- Glass 0
- Ferrous metal 140
- Non ferrous metal 2850
- WEEE 0
- HHW 0

Cost of transportation is based upon tonnes excavated per day (1,440 m3) and km driven to the facility (20 km per trip). The cost per km (£1.01) includes insurance and wear, as well as petrol used. A contingency is incorporated to offset possible unforeseen circumstances such as additional trucks to transport the waste within years with highest excavation numbers. Additionally, a probable rise in petrol prices over the next years has thus been taken into account. The contingency is relatively high compared to the size of operation. In part, this is done as technology used within the LCA and CBA is not further specified due to strongly carrying costs and unavailable data.

Despite this contingency, it is important to note that costs may strongly differ from one site to another, which is why site specific CBAs should be done before undertaking the project. For example excavation of waste from a deeper landfill should imply higher costs, due to an increased need of transportation from deeper areas, and possibly additional technology (Ford et al., 2013). This agrees with Van der Zee (et al., 2004), mentioning that landfills differ in features such as size and contents, as well as the location, which will ultimately result in variation of mining costs and benefits.

5.6. Decision matrix

The matrix decision provides guidance in order to classify whether a landfill site is suitable or not for landfill mining activities. For its design, different objectives and key parameters were considered. The objectives are WtE, WtM, WtL and Resource Management. Key parameters included within the decision matrix are type of waste, operational years, the landfills tonnage and its surroundings, as well as technology available.

Based upon literature research and the report's findings, each parameter is assigned a certain value, from 1 being not applicable to 4 with high relevance to the outcome of a certain objective. These are then combined into a decision matrix, aiding with the decision whether or not to invest, based upon the objective of a specific ELFM project.

6. Findings

6.1. Database

Figure 3 depicts the amount of landfills that have been found as either not suitable, suitable or uncertain for ELFM.

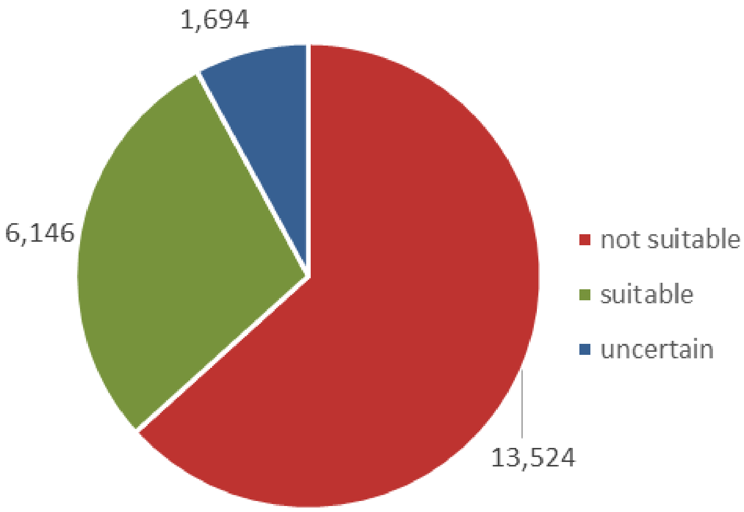

Figure 4: Landfills sorted as not suitable, suitable or uncertain for ELFM

As can be seen, the majority of landfills have been classified as not suitable, for example due to the type of waste inside the landfill, while the category ‘uncertain’ is based upon missing data. Of the ~20,000 landfills across England and Wales, just above 6,000 have been found to be potentially viable and feasible and were used within subsequent steps of the project.

6.2. The hypothetical landfill

As the waste breakdown of the final samples was not readily available, the hypothetical landfill was established from data of 9 landfill sites. The landfill site created is shown within Figure 4:

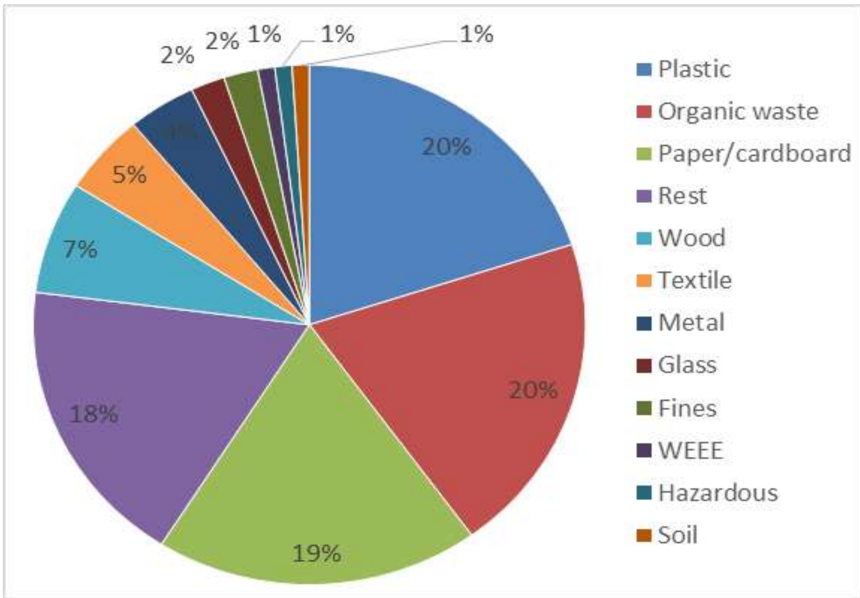

Figure 5: Breakdown of the hypothetical landfill in England and Wales

It can be seen that more than half of the waste within the hypothetical landfill is made up of plastic, organic waste and paper or cardboard. It needs to be kept in mind though, that the composition of waste within specific landfills may differ based on the landfills age and its location. Total tonnages for the small, medium and large landfill have been calculated as around 200 thousand, 500 thousand and 1.2 million tonnes respectively.

6.3. LCA

The LCA's findings for the three scenarios, as well as small, medium-sized and large landfills can be found within the following figure, depicting CO_2-emissions from each process within ELFM, subject to assumptions and boundaries defined.

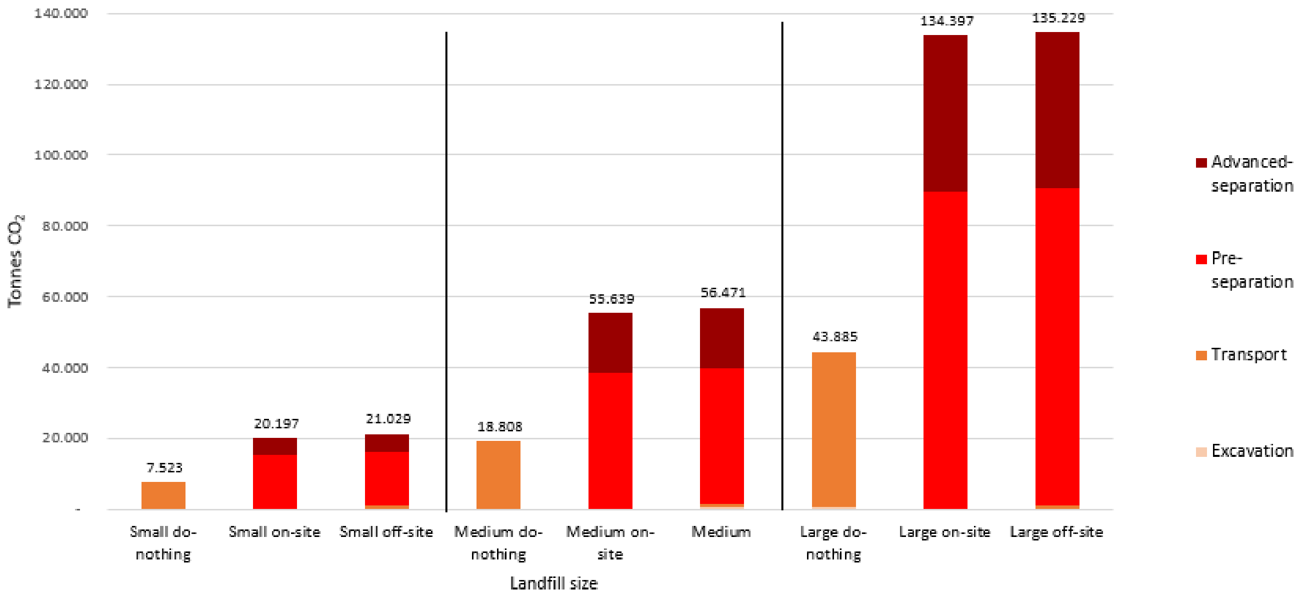

Figure 6: Total emissions of CO_2 for each scenario

It was found that the on-site operations have a lower environmental impact than off-site ones. Increased emissions in the latter are based upon use of diesel in transportation of recovered materials off-site for further treatment and valorisation. Gusca (2015) demonstrates that there can be a 28% higher impact from sorting waste off-site against recycling at the landfill site.

Factors that make it a challenge in understanding landfill mining equipment energy consumptions and emissions include:

- Deciding on the appropriate type and size of electric motor on drills, conveyors and crushers.
- Difficulty in gathering emission data on equipment.
- Variation in physical and chemical properties of waste materials being processed.
- Inconsistency in mining operations and process setups for operators (link between processes such as excavation, transportation of materials and resources). Different operations require different plant setups.
- Companies not providing sensitive data due to competitive markets (Gusca, 2015).

As the LCA mainly aims at understanding emissions, the economic point of view is analysed within the following CBA.

6.4. CBA

The CBA's most important finding is that mining of larger landfills is more profitable than smaller ones (Figure 6), which is in good agreement with Ford (et al., 2013). This can be based upon higher tonnage of waste within the landfill with possible revenues through revalorisation, or on a larger area in terms of m2 to be remediated and sold for a new purpose. Small landfills being unprofitable is often based upon high capital investments which cannot be recovered with the values from low tonnages within the landfill.

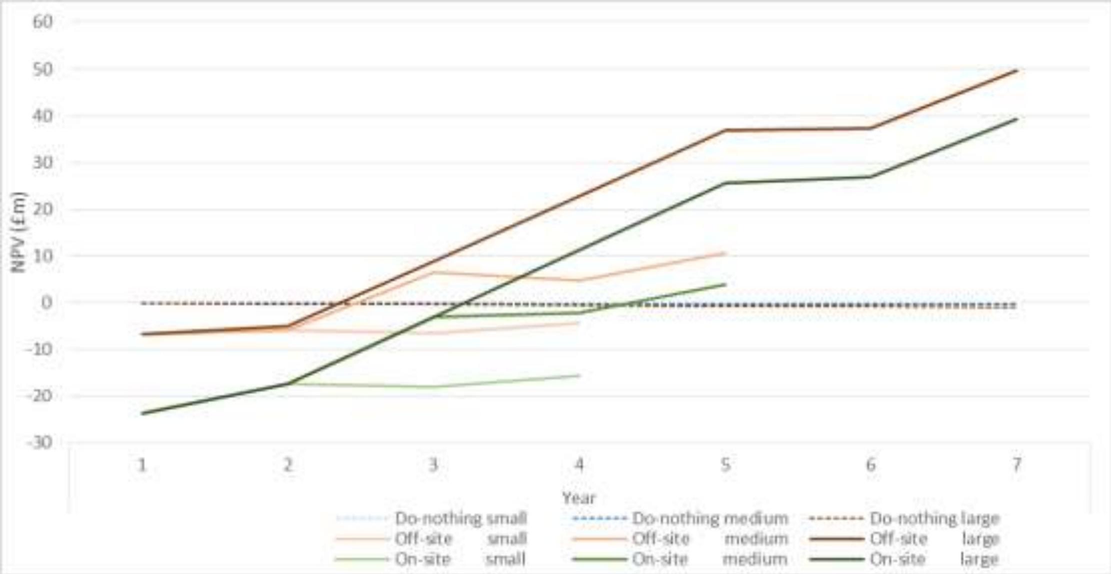

Figure 7: CBA of 3 scenarios over a 7-year period

Comparing economic feasibility of the On-site and Off-site scenarios, it can be found that the Off-site one may yield higher profits, especially during the first years. This is mainly due to higher investment costs within the On-site scenario, where the costs of building mobile facilities need to be recovered before a profit can be made. Thus, the starting point is a different one.

As can be seen from the figure, the Do-nothing scenario can only result in costs, even though a small profit can be made from the sale of LFG, but this fraction is not sufficient to offset costs of transport and technology.

6.5. Decision matrix

With the findings of literature research, database selection, LCA and CBA, the decision matrix was filled as can be seen within figure 7:

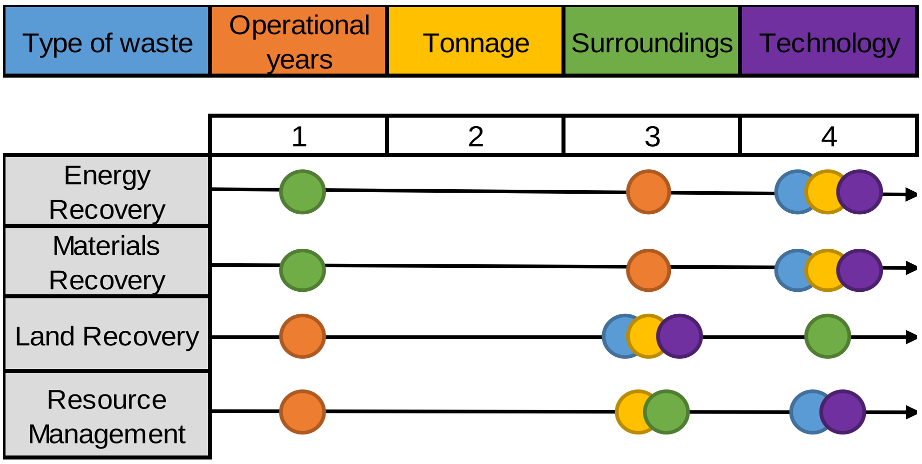

Figure 8: Decision matrix for ELFM projects; subject to boundaries and assumptions (1 = not applicable; 2 irrelevant; 3 important; 4 very important)

It can be taken from the decision matrix that the main influencing factors for feasibility and viability of an ELFM project are type of waste within the landfill as well as the technology available and used.

The type of waste within the landfill plays a major role in the decision whether to mine or not, as for example presence of hazardous waste within a landfill may not only increase health and environmental risks before, during and after mining, but also significantly drive up the cost of a project towards infeasibility. Furthermore, the value of waste that can be mined from within a landfill is highly dependent on its type. While for example electronic waste is marked by high value, its presence within landfills – especially younger ones – is improbable, due to the landfill directive forcing companies to increasingly recycle these. Additionally, waste that is not yet recyclable needs to be temporarily stored for future valorisation and may thus involve costs.

Another factor which may strongly influence the outcome of an ELFM project in terms of operative success and feasibility is the year span within which the landfill was operated. Although older landfills should show a higher potential for valuable material – especially between the years 1960 and 1990 – it may be possible that the quality of recovered material is substantially diminished due to decay. Further based on this is the danger of increased environmental and health risk during the mining, as well as inappropriate leachate and gas control measures at the site, possibly resulting in injury and pollution.

In terms of tonnage, it has been found that the higher the amount of landfilled material, the higher a project's possible profit and IRR. This stems from the fact that it is possible to regain generally high capital expenditure over a longer time span and with more material recoverable. At the same time it needs to be kept in mind that excavation of a deeper and/or larger landfill may lead to increased challenges and costs as more specialised technology is needed, such as additional conveyor belts. Furthermore, higher amounts of recovered material may need bigger facilities and more space for temporary storage.

An additional potentially beneficial factor closely linked to tonnage is the size of the landfill, with the finding that the larger the area that is reclaimed and can be valorised through assigning to it a new land-use, the higher the potential economic feasibility of the project. The possible benefit highly depends on the landfill sites surroundings though, as areas with higher prices per m^2 can yield a significantly higher profit from the sale of remediated land. Simultaneously, a higher price per m^2 can be a negative factor if Resource Management is necessary, as the land that needs to be acquired for facilities may decrease profits. Surroundings play an additional role when ELFM is to be undertaken close to a residential area. If this is the case, the costs to install control measures for nuisance and odour, as well as legislative issues and necessary risk management may lead the decision-maker towards rejection of mining plans. Furthermore, the proximity to sorting and/or valorisation facilities plays into the significance of a site's surroundings, based upon differences in emissions from and costs for transport of material.

The importance of technology stems from the fact that 34% of variation in a project's IRR can be explained by the efficiency of technology (Van Passel, 2013). It is stated that higher efficiency results in a higher IRR, making technology efficiency – especially of WtE processes - one of the key objectives for feasibility of ELFM projects. Especially important is also the emission status of technology involved, where newer and/or more developed technology may make a considerable difference to a project's environmental and health impact, on the one hand due to mitigated emissions from LFG and on the other hand from lower output during operation. Considering resource management, technology may play an important role in the possibility to valorise excavated materials and thus increase profit, as well as decrease environmental and health risks and need for storage.

A more general finding from the development of the report is that there is a significant knowledge gap for landfill site operations before 1996. This gap is for example based upon not requiring to specify breakdown of waste that was landfilled before the EU directive came into legislation in 1990 with a few additional years for transformation of reporting processes. Therefore, companies could not provide all the required information, leading to a number of assumptions made. This may strongly impact the viability and feasibility of ELFM projects, as well as the safety of workers and residents.

7. Discussion and recommendations

A number of recommendations can be drawn from the project at hand, one of the most important ones for decision-makers being that ELFM is potentially beneficial from an environmental as well as economic point of view. In order for this statement to be true, a number of parameters need to be taken into consideration, which can be found within the decision matrix tool.

Recognising emissions saved in the On-site scenario in comparison to the Off-site scenario, and linking it to the definition of ELFM which aims at reducing environmental and health impact, it can be concluded that the On-site scenario is preferable for an operator interested in ELFM, although the economic benefit may be lower. One factor which makes ELFM especially feasible in the UK is the reclamation of land, as land prices throughout the country are general high. The decision for one landfill or another may be impacted solely based on land prices in the surrounding areas.

Before starting an ELFM project, an interested operator is always advised to do a site visit in order to fill knowledge gaps concerning the specifics. This is not only due to missing data attainable from a number of sources, but also changing conditions of the landfill and its surroundings. It is advised to do waste samplings so that one may decrease uncertainty arising from type of waste and age of material landfilled, as these can strongly increase costs, as well as health and environmental risks.

What needs to be furthermore taken into account before engaging in ELFM are current and local regulations and legislation in place. It should be kept in mind that these can change over time and throughout the operation, with possible effects to the outcome, especially as landfill mining of large sites – the most profitable ones - is often done over a time period of many years. Another finding linked to this is that the regulatory framework needs to be clearer and easier accessible for parties interested in ELFM projects. In general, changes in frameworks as well as markets over time need to be anticipated, as for example increased resource scarcity may lead to rising prices within markets for recovered material.

For the machinery used within ELFM, efficiency depends on the currently available technology. New models should have higher efficiencies than older equipment, resulting in lower emissions (Fallis, 2013). For the electrically powered machinery, the motor should be replaced with specific duty type designs and allow power switching during variable waste sorting. By having low voltage supply when lighter waste streams are fed, energy can be saved rather than having a constant energy supply throughout the separation process. For older equipment, good maintenance can improve the machines’ performance and suppresses pollution factors. Future development of machines can not only increase efficiencies and decrease emissions, but also drive down prices of currently available technology, which should be taken into consideration in terms of planning of ELFM.

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