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EMPHASIZING THE ROLE OF E-WASTE IN THE FINANCIAL PROFITABILITY OF LANDFILL MINING PROJECTS

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Abstract

The Landfill Mining (LFM) concept refers to the process of excavating, and sorting solid waste from operating or closed landfills in order to recycle or produce energy from recovered materials, conserve landfill space, and rehabilitate/redevelop contaminated land. Although LFM offers a wide range of environmental and social benefits, LFM projects need to be, at the same time, economically feasible. The latter is heavily influenced from the composition of the waste excavated from the landfill, the quality of recovered materials and the recycling market conditions. This paper aims specifically at exploring the role of e-waste in the profitability of LFM projects and filling this gap in the literature. For the purposes of the analysis, a "typical" Greek landfill site is examined forming different alternatives with respect to the objectives of e-waste recovery and processing and, consequently, the cost and benefits of the LFM operations, based on the findings of the first pilot project of LFM carried out in Greece, at Polygyros landfill. The results of the study show that the presence of e-waste improves the profitability indices. However, it seems that the adoption of more complex recycling and recovery processes leads to no gain in the financial results. These findings are supported by the uncertainty analysis conducted, which reveals that the price and concentration of plastics are the most significant factors, followed by the non-ferrous metal price and concentration. The conclusions of the study should be seen with caution, however. As the international experience shows, the financial success of LFM projects is site-specific and is not assured in all cases. Therefore, it should be clear that further research efforts in the field are warranted to definitely answer the question.

Keywords

Landfill Mining, WEEE, Financial Analysis, Sensitivity Analysis, Monte Carlo Simulations

1. Introduction

Nowadays, there exist hundreds of thousands of uncontrolled and controlled landfills. For instance, Wagner & Raymond (2015), citing the findings of Krook, Svensson & Eklund (2012) and Ratcliffe, Prent & van Vossen (2012) point out that in the EU alone there are an estimated 150,000-500,000 closed and active landfills containing around 30-50 billion m^3 of waste. In Greece, for example, the amount of municipal solid waste (MSW) landfilled, in 2010, was equivalent to 81% of the total generated MSW, i.e. 4.2 million tonnes (Bakas & Milios, 2013). Moreover, up to 2011, 109 illegal dumping sites all over Greece were in operation despite the ruling of the European Court of Justice of 2005 (Bakas & Milios, 2013). These landfills occupy valuable land near urban centers and in some cases constitute sources of environmental contamination and nuisance; at the same time, however, they are regarded as valuable repositories of materials and energy (e.g. Quaghebeur et al., 2013; Hermann et al., 2014). During recent decades, efforts have been made to deal with the environmental implications of waste disposal sites and the exploitation of valuable materials contained within them in the context of Landfill Mining (LFM), i.e. the process of excavating, and sorting the unearthed materials from operating or closed solid waste landfills for recycling, processing, or for other dispositions (Krook et al., 2012; Marella & Raga, 2014; Zhou, Gong, Hu, Cao, & Liang, 2015). In general, the LFM process helps to: eliminate potential contamination sources; recover energy and useful materials; conserve landfill space; reduce waste management costs; and rehabilitate and redevelop landfill sites (Hogland, Marques, & Nimmermark, 2004; Damigos, Menegaki & Kaliampakos, 2016b).

Although offering many benefits, LFM projects, apart from the cases where wastes need to be moved either for serious environmental reasons or other purposes, have to be economically feasible. Yet, until today, the economic feasibility of LFM projects from a private point of view has been studied little and with conflicting results. For instance, Van Vossen & Prent (2011) examined a typical landfill of 500,000 tonnes and found that revenues from extracted metal would offset mining costs by 8.2% if full separation of the waste occured and by 18% if only ferrous metal were separated. Jain, Townsend, & Johnson, (2013) considered a landfill reclamation project that entailed the excavation of approximately 371,000 in-place m^3 of unlined landfill airspace. The cost of the project was US$3.09 million (i.e. US$8.33 per in-place m^3 airspace) and resulted in a gross monetary benefit of approximately US$6 million, since the airspace recovered was valued at over US$9 million. Zhou et al. (2015) analyzed a typical old landfill in China under four different landfill mining scenarios. They concluded that the LFM project could provide a net positive benefit between US$1.92 million to US$16.63 million, but the results were sensitive to the benefits of land reclamation and electricity generation. Danthurebandara, Van Passel, Vanderreydt, & Van Acker (2015) examined a hypothetical open waste dump site of 1,000,000 tonnes of waste in an urban area considering two scenarios for the use of the RDF fraction (i.e. direct selling of RDF and thermal treatment of RDF for electricity production). The results showed that, none of the scenarios were judged to be economically beneficial. Wagner & Raymond (2015) proved that landfill mining projects can be profitable. They estimated that the mean cost per Mt for extracting and recovering metals at an ashfill was US$158, while the minimum revenue was US$216, respectively. Further benefits came from extending the ashfill's life. These findings proved that LFM can be profitably without subsidies.

The research findings show that the viability of LFM projects is related to the country- and site-specific conditions that affect the capital (CAPEX) and operating expenses (OPEX) of the project and its revenues. Thus, the only safe conclusion is that the profitability of the LFM projects from a private point of view is not guaranteed and each and every case should be examined on its own facts and circumstances. To this end, the paper's objective is twofold. First, it aims at analyzing the viability of LFM operations in Greece, as a potential solution for dealing with the problems of inappropriate waste management practices in the country. Second, and most importantly, it wishes to fill a research gap in the relevant literature, namely the influence of e-waste presence in the excavated waste on the profitability of LFM projects.

For the purposes of this study, a "typical" Greek landfill site is considered forming, in total, four different alternatives as regards the objectives of e-waste recovery and processing and, consequently, the cost and benefits of the LFM operations. The profitability of the alternative plans is examined through the use of the Net Present Value (NPV) and the Internal Rate of Return (IRR). Finally, sensitivity and stochastic analyses are conducted to account for the uncertainty involved in the parameters of the economic model.

2. Methodological approach

2.1 Financial profitability analysis

The financial profitability analysis is carried out using a typical discounted cash flow (DCF) equity valuation approach, which is probably the most widely used technique of investment analysis, in real prices. The DCF method values an investment based on a number of project performance criteria, the most commonly applied of which are the Net Present Value (NPV) and Internal Rate of Return (IRR).

The NPV expresses the present value of a project's cash flows, i.e. inflows and the outflows and is estimated according to the following equation (Eq. 1):

$$NPV = \frac{CF_1}{(1+r)} + \frac{CF_2}{(1+r)^2} + \frac{CF_3}{(1+r)^3} + \cdots + \frac{CF_n+RV}{(1+r)^n} - I_0 = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_0 \quad (1)$$

where: CF_i is the cash flow generated by the LFM operations in the period i

I_0 is the equity investment cost

RV is the potential residual value of the facilities and the equipment required for the LFM works in the last year

r is the discount rate (expressed in real terms when cash flows are expressed at constant prices), which determines the minimum acceptable return percentage that the investment in question must earn in order to be worthwhile.

A positive NPV indicates that the project generates earnings that exceed the anticipated costs (in present value), i.e. the investment is profitable, while a negative NPV indicates that the investment results in net losses and shouldn't be undertaken.

The internal rate of return (IRR) is a related metric used to measure the profitability of an investment and express the rate of growth a project is expected to generate. It is estimated according to the following equation (Eq. 2):

$$0 = \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} - I_0 \quad (2)$$

It can be seen as the highest interest rate which the project can support and still break even. Thus, if the IRR exceeds the discount rate used (i.e. the cost of capital), the investment should be undertaken; if the IRR is less than the discount rate, the investment is not worthwhile.

Further, to tackle with the uncertainty related to the costs and benefits of LFM operations, the financial and socioeconomic indicators were explored using sensitivity and stochastic analyses. The sensitivity analysis provides information about how the target value (e.g. NPV) changes with given variations of an input measure or of several input measures and, thus, enables the identification of the most critical parameters by varying one variable at a time (i.e. ceteris paribus) (Götze, Northcott & Schuster, 2008). Nevertheless, sensitivity analysis is not effective in handling situations at which multiple eventualities occur given that it is performed on a *ceteris paribus* basis. When multiple parameters change simultaneously, a stochastic analysis needs to be carried out (Falconett & Nagasaka, 2010). The stochastic analysis involves assigning a probability distribution to each of the critical variables of the financial model and performing a simulation, known as Monte Carlo analysis. The steps involved in the Monte Carlo simulation are, as follows: (a) specify the uncertain input parameters; (b) select a distribution to describe the value range for each uncertain input parameter; and (c) generate the output variable from randomly selecting input values on the basis of the selected distribution for a large number of iterations. The probabilistic NPV and IRR calculations for all combinations of sampled values are then used to develop probability distribution of the NPV and IRR indices offering more comprehensive information about the risk profile of the project.

2.2 Evaluation scenarios

The evaluation scenarios involve the analysis of a hypothetical landfill, having the typical characteristics (quantity and composition of waste) of a 20-30 years old Greek landfill close to an urban center. More specifically, two scenarios, forming in total four alternative cases, are examined:

Scenario 1 – "Typical" LFM project: Given that LFM projects do not involve, in general, the exploitation of e-waste, potential revenues associated with discarded devices are ignored from the analysis.

Scenario 2: "Advanced" LFM project: This scenario foresees exploitation of e-waste, based on literature data related to the prospective e-waste volumes and on the beneficiation tests as regards the recovery of valuable materials, which were carried out during the above-mentioned LIFE project (Tsakalakis, Benardos & Sammas, 2016). It involves three different options as regards the recovered WEEE, as follows:

(a) WEEE devices are separated and, then, are sold "as is" without further treatment;
(b) WEEE devices are separated and, are dismantled in order to recover PCBs. In that case PCBs are sold without further processing at a different price compared to that of the rest WEEE quantities; and
(c) WEEE devices are separated and are dismantled in order to recover PCBs. Then, PCBs undergo a specific treatment in order to acquire the desirable size and separate metals and plastic particles. The latter are finally processed using froth flotation to recover valuable metals.

2.3 Technical and financial assumptions

The technical and financial assumptions related to the LFM process derive from information gathered from the first pilot project of LFM in Polygyros landfill, in Greece, in the context of the LIFE RECLAIM "Landfill mining pilot application for recovery of invaluable metals, materials, land and energy" (www.reclaim.gr) project (Damigos et al., 2016a; Tsakalakis et al., 2016).

2.3.1 Technical assumptions

In order to have a representative assessment of a typical Greek LFM case, it is assumed that the landfill under consideration facilitates a city of 200,000 inhabitants, with a design life of 25 years. Taking an average MSW generation per capita per year at 400 kg, this yields a total quantity of 2,000,000 tn.

The data relating to the historical waste composition of Greek MSW have been taken from the Greek National Report from the United Nations Commission on Sustainable Development (UNCSD, 2011). In order to assess the composition of the MSW waste mined, it has been assumed that a recovery rate of 85-90% of the materials is achieved through the LFM activities. The MSW content used under this analysis, along with the expected recovery rate through the mining process is presented in Table 1 These figures are in line with the data presented from the European experience (e.g. Van Vossen and Prent, 2011; Quaghebeur et al., 2013).

Table 1: *Composition of waste and recovery rates*

Typical Greek LF composition	Value	Unit
Ferrous metals (4% @ 90% recov.)	3.60	%
Non-ferrous metals (0.5% @ 85% recov.)	0.43	%
Glass (3.5% @ 85% recov.)	2.97	%
Plastics (4.1% @ 85% recov.)	3.50	%
Gravel, stones (5% @ 90% recov.)	4.50	%
Fines, soil (50% @ 90% recov.)	45.00	%
WEEE (1.5% @ 90% recov.)	1.35	%
Residuals (organics, etc.)	38.75	%

Further, in order to account for variations and uncertainty in composition of the waste content, maximum and minimum concentrations were also estimated, as given below:

- Ferrous metals (baseline, min, max concentration): 4%, 2%, 8%
- Non-ferrous metals (baseline, min, max concentration): 0.5%, 0.3%, 0.9%,
- Glass (baseline, min, max concentration): 3.5%, 2%, 7%

- Plastics (baseline, min, max concentration): 4%, 3.5%, 10%

In general, the percentage of WEEE found in MSW ranges from 0.5 to 2% on a weight basis. Taking into account that from 1990's there was a gradual increase in electrical and electronic goods market and that the WEEE recycling schemes were introduced in Greece in the mid 2000's, a range between 4 and 8 kg of WEEE per inhabitant per year was assumed to be generated and deposited in landfills. For the case of a Greek landfill covering the needs of 200,000 inhabitants for 25 years, this yields amounts from 20,000 to 40,000 tn of disposed WEEE and corresponds to 1% to 2% of WEEE content in the landfill waste, comparable to the values indicated in other EU countries. All in all, the weight content of WEEE in the typical landfill examined is assumed to be 1.5% in the baseline scenario (1% as a minimum and 2% as a maximum content values are also taken so as to include possible variations in content). The portion of IT equipment and small household appliances are approximately 30% of the total WEEE weight (Zoeteman, 2006; Baldé, Wang, Kuehr, & Huisman, 2015). Furthermore, according to Oguchi, Murakami, Sakanakura, Kida, & Kameya (2011), the weight fraction of PCB's ranges between 8% and 13%, in these WEEE categories. Thus, it can be deduced that the PCB's weight deriving from small appliances and IT products is roughly equal to 0.03%. Based on the size reduction and beneficiation tests that were carried out in the RECLAIM project, the estimated recovered quantities of materials from PCBs, on a weight basis, were estimated (Table 2).

The excavation procedure follows the principles of surface (open-pit) mining. More specifically, the mining of the waste is made with conventional surface mining equipment (excavators, backhoe/loaders, front-end loaders or shovels) and the haulage of the material is performed using standard dump trucks. The processing unit involves a trommel, a picking line and hand sorting by workers that collect hard and soft plastic, glass, and non-ferrous (primarily aluminum) metals, and a magnet that separates the ferrous metals. In addition the processing unit recovers soil that is used as landfill covered material. The technical assumptions are briefly summarized in Table 3.

Table 2: *Recovered materials from PCBs*

Composition	Value	Units
Mixed non-ferrous metals	12.4	%
Ferrous parts and detritus	10.1	%

Copper parts	2.5	%
Aluminum parts	2.3	%
Pulverized e-waste*	70	%

** The chemical composition of the pulverized e-waste and of the final concentrates have been derived from the beneficiation tests*

Table 3: *LFM process technical assumptions*

Description / Index	**Value**	**Unit**
Hydraulic excavator	1	operating units
Dump trucks	1	operating units
Backhoe Loader	1	operating units
Productivity of processing unit	12	tn/hour
Net working hours	6.5	hours/day
Working days (per year)	250	days/year
Productivity/year	19,500	tn/year
Total waste volume	3,300,000	in situ m^3
Specific weight	0.6	tn/m^3
Work-force requirements	13	persons

Given the size of the landfill, it is assumed that LFM operations will take place for 10 years aiming to: (a) recover recyclable materials and soil, and (b) increase the disposal capacity of the landfill. To this end, avoided or reduced costs of landfill closure and post closure care and monitoring and potential revenues from selling the land, after complete reclamation have not been considered.

2.3.2. Financial assumptions

In a general context, the cash flow analysis of a LFM project should take into account the following factors (e.g. Danthurebandara et al., 2015; Frändegård, Krook & Svensson, 2015; Damigos et al., 2016a):

A. Capital costs

- Pre-activity research and inventory costs, permits, consultancy and design costs
- Site preparation
- Purchase of excavation, hauling, screening and sorting equipment (if purchased)

- Other installation costs (e.g. construction of materials handling facilities, incineration facilities for heat and energy recovery, etc.)

B. Operating costs

- Rental of excavation, hauling, screening and sorting equipment (if rented)
- Labor costs
- Administrative costs
- Fuel / Energy costs
- Maintenance costs
- Water
- Other costs (e.g. training in safety issues, purchase of safety equipment, disposal cost of ash from on-site waste incineration, etc.)

C. Revenues

- Revenues from recyclable and reusable materials (ferrous and non-ferrous metals; glass; plastics; combustible waste; stones and construction waste; waste of electrical and electronic equipment; reclaimed soil used as landfill cover material)
- Value of recovered air-space (in case that landfill continues to operate)
- Value of reclaimed land for development (in case of full site reclamation and re-development of the land for other commercial purposes)
- Avoided costs of post-closure care (in case of full site reclamation)
- Avoided future liability for remediation (mainly in cases of uncontrolled landfills)

In this study, benefits from energy recovery, redevelopment of the landfill area, and reduction in waste management costs (e.g. expenses concerning landfill closure and aftercare), have been excluded from the analysis. This is attributed either to existing conditions in Greece (e.g. RDF energy utilization in Greece is not possible, so far) or the technical assumptions used (e.g. size of the landfills, productivity of processing units, etc.).

The costs and revenues data used in the estimates were mainly extracted by the Polygyros LFM pilot project (Damigos et al., 2016a; Tsakalakis et al., 2016). Additional data, wherever required, were gathered by directly communicating with market experts (Damigos et al., 2016a). Table 4 presents the capital and operating costs. Moreover, Table 5 illustrates the cost for processing WEEE devices under two different treatment scenarios. The first one includes only disassembly of WEEE devices to recover PCBs. The second one considers disassembly of

WEEE devices and further processing of PCB's, so as to recover ferrous, non-ferrous and precious metals. This distinction was necessary because there are considerable differences in the prices of the recyclable materials deriving from the WEEE resources and, thus, useful insights in the most promising processing level could be gained from a financial viewpoint.

Table 4: *Capital and operating costs for LFM operations*

Description	Cost (€)
Site preparation & Development - Greek typical case	60,000
Administrative costs (per year)	15,000
Capital expenditure for excavation, loading and hauling equipment	300,000
Capital expenditure of screening and sorting equipment	800,000
Maintenance cost (per year)	22,000
Personnel cost per year (unskilled workers)	14,000
Personnel cost per year (skilled workers)	30,800
Energy cost (diesel fuel, €/lt)	0.95
Energy cost (electric power, €/kWh)	0.09
Water cost (€/m^3)	0.52

Table 5: *Cost of e-waste processing under different disassembly modes*

Description	Cost (€)
E-waste disassembly to obtain PCBs per device	1
E-waste disassembly to obtain PCBs per ton	100
PCB processing (size reduction and flotation process) per ton	350

The benefits of the LFM activities are associated with the recovered materials and air-space. Table 6 presents the base prices of the recyclables that are used in the financial models related to today's market (end of 2015), along with minimum and maximum estimates. These prices were taken from contacts and direct communication with recyclable marketing enterprises operating in Greece, as well as from data collected from relevant price quoting sites (e.g. letsrecycle.com).

Table 6: *Selling price (€/tn) of recyclables*

	Sell price (€/tn)		
Recyclable type	*Base estimate*	*Min estimate*	*Max estimate*
Ferrous metals	80	60	110
Non-ferrous metals – Aluminum	700	600	1000
Non-ferrous metals – Copper	1000	1000	2500
Non-ferrous metals – Nickel, Lead	750	700	1200
Non-ferrous metals (mixed) *	740	660	1200
Glass	10	10	15
Plastics (mixed)**	200	100	300
WEEE (mixed – no disassembly)	80	70	110
WEEE (PCB's)	400	400	900
Concentrate	700	600	900

* *The analysis is made taking into account a mix of 75% in aluminum, 15% in nickel, lead and 10% in copper.*

** *The mixed plastics include Natural HDPE, Mixed HDPE, clear PET, colored PET, etc.*

In addition to the revenues earned from selling useful materials, benefits derived from increasing the landfill disposal capacity and avoided costs from recovered soil used as landfill covered material are considered. The values used in the financial models derived from real cases, and are given in Table 7.

Finally, it should be noted that under all scenarios the discount rate used is 6%, and the taxation is set to 29%.

Table 7: *Landfill-related benefits from the LFM process*

Description	**Price**	**Units**
Benefit of recovered air-spaces (€/tn)	30	€/tn
Avoidance of landfill cover material	1.34	€/tn

3. Results and Discussion

3.1 Deterministic analysis

As mentioned, four different cases are examined, namely Scenario 1, Scenario2A, Scenario2B and Scenario2C, the main findings of which are summarized hereinafter:

- Scenario 1: The revenues (including avoided costs) are about €624,000 per year. Using a real discount rate of 6%, the NPV of the project is estimated at about €1,600 and the IRR around 6% (i.e. the project repays original investment plus the required rate of return). The total operating cost is approximately €22.3 per tn of waste and the benefits €32 per tn of waste, respectively.
- Scenario 2A: The revenues gained under this scenario (including avoided costs) are about €645,000 per year. Using a real discount rate of 6%, the NPV of the project is estimated at approximately €112,000 € and the IRR is estimated at 8.0%. The total operating cost is approximately €23.1 per tn of waste and the benefits €33.1 per tn of waste, respectively.
- Scenario 2B: The revenues (including avoided costs) are about €644,000 per year. Using a real discount rate of 6%, the NPV of the project is estimated at about €87,000 € and the IRR is estimated at 7.5%. The total operating cost is approximately €23.5 per tn of waste and the benefits €33.2 per tn of waste, respectively.
- Scenario 2C: The revenues (including avoided costs) are about €646,000 per year. Using a real discount rate of 6%, the NPV of the project is estimated at about €92,000 and the IRR is estimated at 7.6%. The total operating cost is approximately €23.5 per tn of waste and the benefits €33.3 per tn of waste, accordingly.

Table 8 presents the breakdown of the benefits for the four sub-scenarios.

Table 8: *Benefits breakdown*

	Benefits (€/tn)			
Category	*Scenario 1*	*Scenario 2A*	*Scenario 2B*	*Scenario 2C*
Ferrous metals	2.88	2.88	2.88	2.88
Non-ferrous metals	3.15	3.15	3.15	3.15
Glass	0.30	0.30	0.30	0.30
Plastics	7.00	7.00	7.00	7.00
WEEE	-	1.08	1.24	1.34
Landfill cover material	0.67	0.67	0.67	0.67
Subtotal 1	***14.0***	***15.1***	***15.2***	***15.3***
Recovered air-space	18.0	18.0	18.0	18.0
Total	**32.0**	**33.1**	**33.2**	**33.3**

3.2 Uncertainty Analysis

The sensitivity analysis focused on the most critical technical and economic parameters related to the uncertainty of the estimates, namely the price of the recyclable materials (ferrous and non-ferrous metals, plastics, WEEE) and the composition of the waste. For conciseness reasons, only the results of the sensitivity analysis of scenarios' NPV to a ±20% change are given in Tables 9 to 12 and in Figures 1 to 4.

Table 9: *NPV sensitivity analysis results (Euros) – Scenario 1*

	-20%	**-10%**	**0%**	**10%**	**20%**
Plastics price	-141,029	-69,699	1,631	72,962	144,292
Plastics concentration	-141,029	-69,699	1,631	72,962	144,292
Non-ferrous metals price	-62,464	-30,416	1,631	33,679	65,727
Non-ferrous metals concentration	-62,464	-30,416	1,631	33,679	65,727
Ferrous metals price	-57,063	-27,716	1,631	30,979	60,326
Ferrous metals concentration	-57,063	-27,716	1,631	30,979	60,326

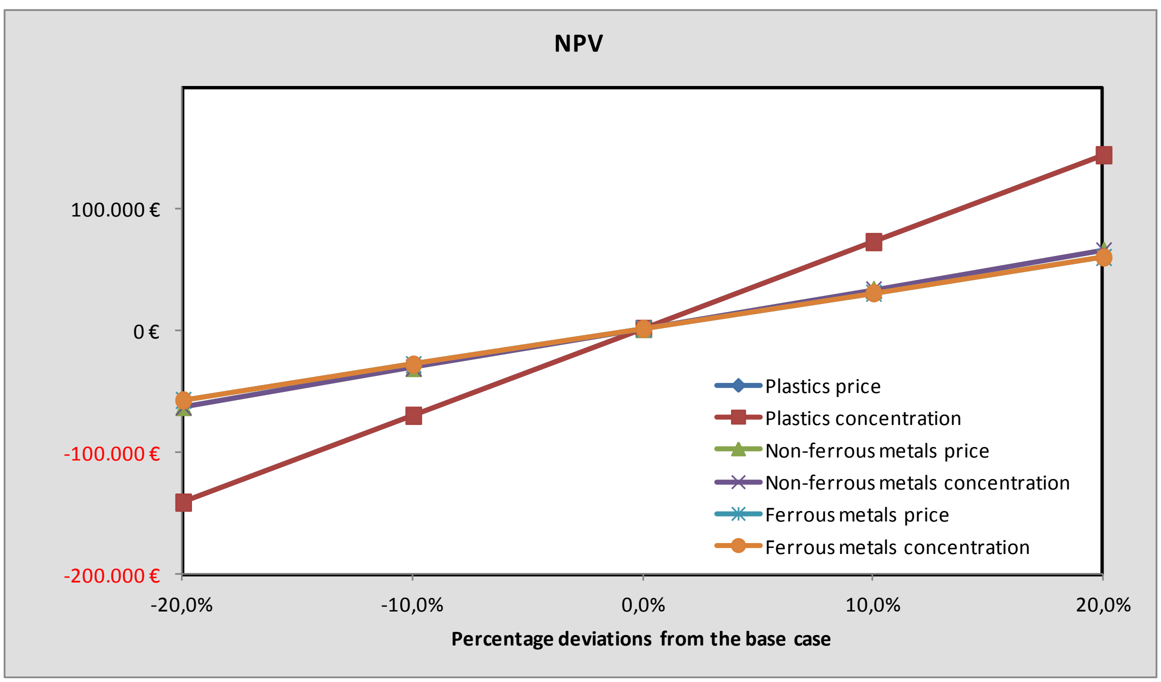

Figure 1: *NPV sensitivity analysis – Scenario 1*

Table 10: *NPV sensitivity analysis results (Euros) – Scenario 2A*

	-20%	-10%	0%	10%	20%
Plastics price	-30,977	40,354	111,684	183,014	254,344
Plastics concentration	-30,977	40,354	111,684	183,014	254,344
Non-ferrous metals price	47,588	79,636	111,684	143,732	175,779
Non-ferrous metals concentration	47,588	79,636	111,684	143,732	175,779
Ferrous metals price	52,989	82,337	111,684	141,031	170,378
Ferrous metals concentration	52,989	82,337	111,684	141,031	170,378
WEEE price	89,673	100,679	111,684	122,689	133,694
WEEE concentration	89,673	100,679	111,684	122,689	133,694

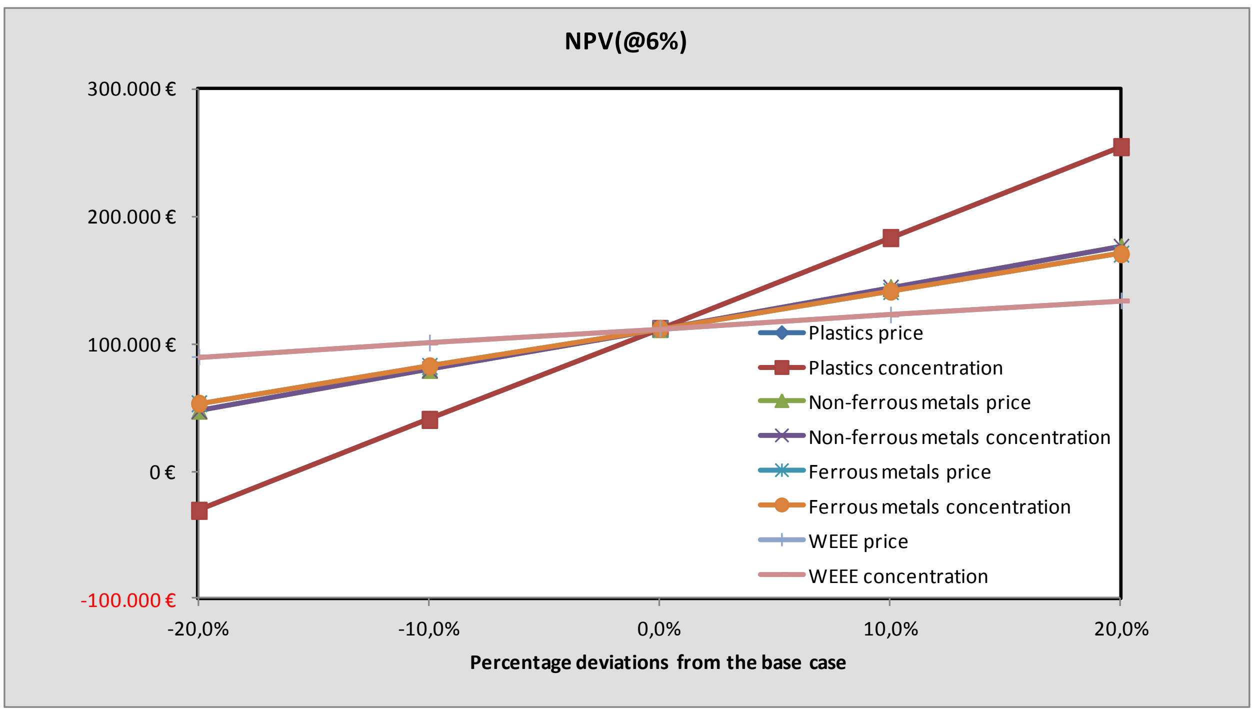

Figure 2: *NPV sensitivity analysis – Scenario 2A*

Table 11: *NPV sensitivity analysis results (Euros) – Scenario 2B*

	-20%	-10%	0%	10%	20%
Plastics price	-55,739	15,592	86,922	158,252	229,583
Plastics concentration	-55,739	15,592	86,922	158,252	229,583
Non-ferrous metals price	22,827	54,874	86,922	118,970	151,017
Non-ferrous metals concentration	22,827	54,874	86,922	118,970	151,017
Ferrous metals price	28,227	57,575	86,922	116,269	145,617
Ferrous metals concentration	28,227	57,575	86,922	116,269	145,617
WEEE price (bulk)	61,610	74,266	86,922	99,578	112,234
WEEE price (PCBs)	64,912	75,917	86,922	97,927	108,933

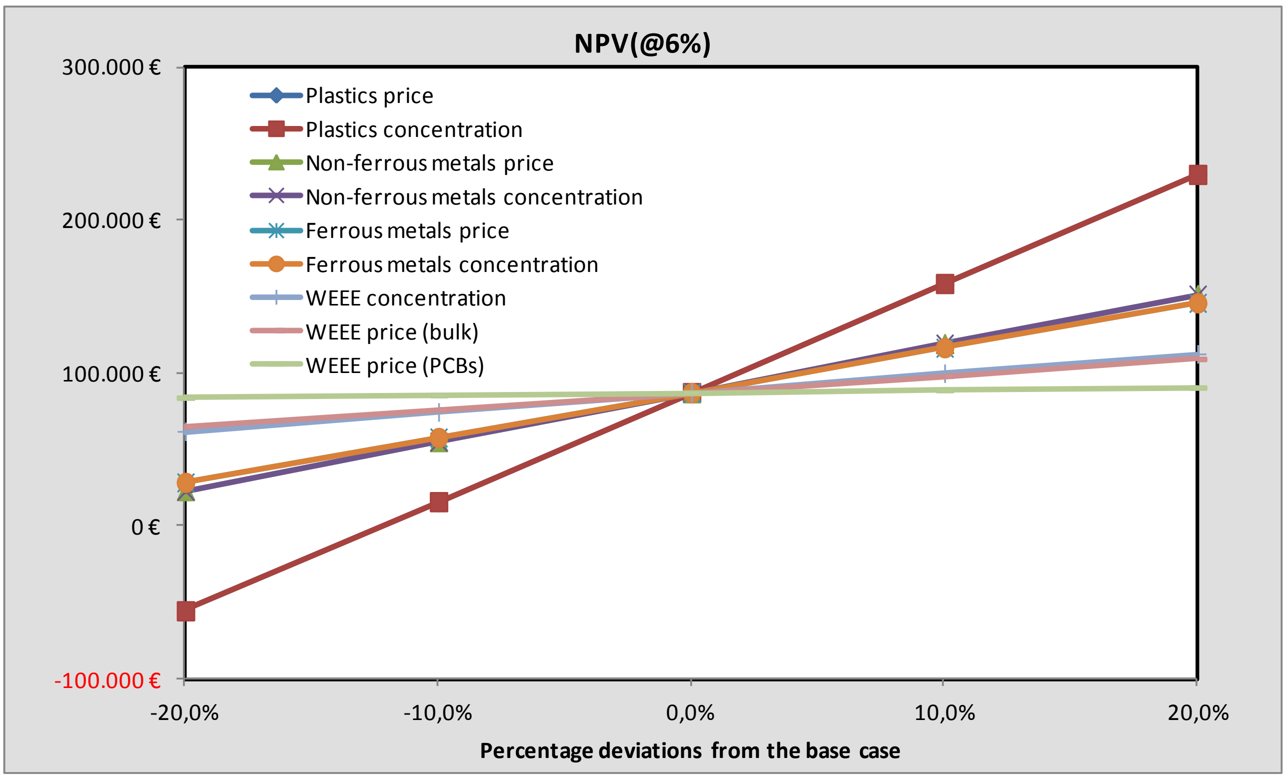

Figure 3: *NPV sensitivity analysis – Scenario 2B*

Table 12: *NPV sensitivity analysis results (Euros) – Scenario 2C*

	-20%	-10%	0%	10%	20%
Plastics price	-50,373	20,957	92,287	163,617	234,948
Plastics concentration	-50,373	20,957	92,287	163,617	234,948
Non-ferrous metals price	28,192	60,239	92,287	124,335	156,382
Non-ferrous metals concentration	28,192	60,239	92,287	124,335	156,382
Ferrous metals price	33,592	62,940	92,287	121,634	150,982
Ferrous metals concentration	33,592	62,940	92,287	121,634	150,982
WEEE price (bulk)	65,077	78,682	92,287	105,892	119,498
WEEE price (concentrate)	70,277	81,282	92,287	103,292	114,298

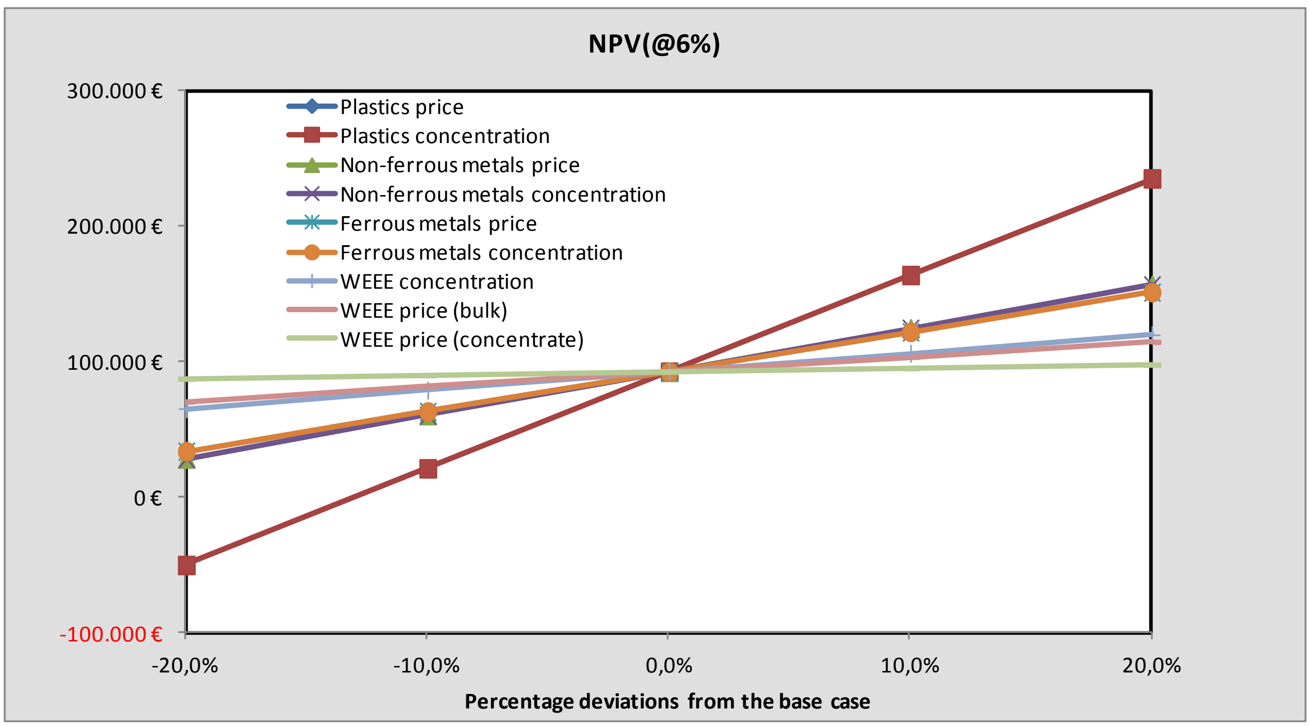

Figure 4: *NPV sensitivity analysis – Scenario 2C*

According to the sensitivity analysis, the price and concentration of plastics are the most significant factors influencing the NPV and IRR indicators of the project, in all scenarios, followed by the non-ferrous metal price and concentration. The Scenario 1 remains financially unattractive even assuming a 5% decrease in the price or concentrations of recyclable materials. The Scenarios 2A, 2B and 2C are deemed acceptable from a financial point of view (i.e. NPV>0 and IRR>discount factor) in case where either the prices or concentrations of recyclables decrease ceteris paribus by 10%.

The parameters involved in the stochastic analysis were identical to those used in the sensitivity analysis. Due to the absence of data about the true distribution of the critical parameters, the triangular distribution was adopted, because it emphasizes the most likely value and theoretically provides a better estimate of the probabilities of reaching other values. Furthermore, the triangular distribution can model a variety of different conditions, since there is no requirement that the distribution be symmetrical about the mean. The assumptions used are described in Sections 2.3.1 and 2.3.2.

The results of the simulation values are presented in the following Tables 13 and 14. Again, for conciseness reasons, only the results of NPV indicator are illustrated.

Table 13: *Monte Carlo Simulation Statistics*

Variable	**NPV (€)**			
	Scenario 1	*Scenario 2A*	*Scenario 2B*	*Scenario 2C*
Mean	557,631	653,553	649,373	656,298
Median	504,147	610,347	607,908	610,044
St. deviation	379,300	363,655	378,945	368,116
Minimum	-292,104	-156,626	-280,536	-287,843
Maximum	2,011,160	1,919,700	2,110,220	2,130,012
Mean Std. Error	11,995	11,500	11,983	11,641

Table 14: *Monte Carlo Simulation Percentiles*

Percentage	**NPV (€)**			
	Scenario 1	*Scenario 2A*	*Scenario 2B*	*Scenario 2C*
100%	-292,104	-156,626	-280,536	-287,843
90%	105,029	225,203	195,048	213,835
80%	229,977	341,022	314,476	347,274
70%	323,893	438,664	421,223	440,111

60%	412,389	536,017	526,897	534,535
50%	503,965	609,788	607,732	609,163
40%	616,657	698,084	697,706	709,831
30%	733,089	813,542	808,375	817,511
20%	878,059	954,254	950,927	958,701
10%	1,056,114	1,159,644	1,177,444	1,133,645
0%	2,011,160	1,919,700	2,110,220	2,130,012

According to the simulations, the expected NPV of Scenario 1 is €557,000. The minimum expected value is about €-292,000 and the maximum value is €2,011,000, which means that the probability of rejecting the project from a financial viewpoint is around 10%. The expected NPV of Scenario 2A is around €650,000. The minimum expected value is about €-157,000 and the maximum value is €1,920,000. The probability of having a positive NPV value and thus accepting the project is estimated at 95%. Similar results are reported for Scenarios 2B and 2C.

It is obvious that the project yields positive NPV values under all the scenarios generated by the probabilistic modeling process and thus it is acceptable. Furthermore, according to the sensitivity charts, the value of the project are affected to a great extend by the concentration and the price of the plastics. The concentration and the price of ferrous and non-ferrous metals do not play a significantly role on the overall figures. Although WEEE recycling, would positively contribute to world's finite-resource savings by recovering significant amount of materials, eliminating also greenhouse gas emissions and fossil energy consumption, as compared to the virgin production of equivalent of materials (Menikpura, Hotta, Santo & Jain, 2016), the effect of WEEE concentration and price (bulk, PCBs or concentrate) in the case of LFM activities is practically insignificant to the overall results.

4. Conclusions

This paper presents the first effort to study the economic viability of a LFM project, in Greece, considering the existence of e-waste in the excavated materials. Based on the results of the financial analyses it becomes evident that the operation is most likely profitable, even if financed only by equity. As regards expected revenues from recyclable materials, hard plastic materials seem to have a dominant role. Nevertheless, there is an improvement on the financial indices when WEEE is involved in the estimates. More explicitly, the separation of WEEE adds to the financial benefits of the project, but the dismantling of IT equipment in order to retrieve and sell separately PCBs or the froth flotation processing of PCBs pulverized material in order to reject plastics and recover Cu and precious metals (Pd, Au and Ag), do not significantly impact the profitability of the project. This is attributed to the small quantities of IT equipment that are reasonably anticipated to be found. Moreover, it seems that the overall revenues are significantly affected by the recovered air-space. The results are confirmed by the uncertainty analysis, which shows that the price and concentration of plastics are the most significant factors, in all scenarios, followed by the non-ferrous metal price and concentration.

Nevertheless, the findings of this study should be seen with all its limitations. For instance, the analysis was based on a typical Greek landfill that facilitates a city of 200,000 inhabitants considering an average (national) composition of the waste excavated. It is evident that both the quantity and composition of the waste will be significantly different in major city or in rural area disposal sites. This is consistent with the international experience which shows that the financial success of LFM projects is site-specific and is not assured in all cases. Therefore, it should be clear that further studies in the field are warranted to definitely answer the question.

All in all, under examined assumptions, it seems that LFM projects are more attractive when they are in proximity to higher populations, e.g. the recovered land is more scarce and, thus, more expensive near urban areas, and the recovered-air space in the landfill is more valuable. Further, there are strong indications that LFM operations with low processing effort are likely to be more attractive from a financial viewpoint than processes with high processing effort, e.g. WEEE utilization ‘as is’ vs. IT equipment dismantling in order to retrieve and further process PCBs.

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