Environmental and economic performance of plasma gasification in Enhanced Landfill Mining

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Title:

Environmental and economic assessment of ‘open waste dump’ mining in Sri Lanka

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Abstract

Open waste dumps in Sri Lanka generate adverse environmental and socio-economic impacts due to inadequate maintenance. In this study, a concept of ‘open waste dump mining’ is suggested in order to minimise the environmental and socio-economic impacts, together with resource recovery. A model based on life cycle assessment and life cycle costing has been used to assess the environmental and economic feasibility of the suggested open waste dump mining concept. Two scenarios have been defined for a hypothetical case, dependent on the destination of the refuse derived fuel fraction. Scenario 1 comprises direct selling of refuse derived fuel as an alternative fuel to replace coal usage in the cement industry, while scenario 2 consists of thermal treatment of refuse derived fuel with the objective of producing electricity. The study shows that both scenarios are beneficial from an environmental point of view, but not from an economic view point. However, economic profits can be obtained by adjusting waste transport distances and the price of electricity. The environmental analysis further reveals that the higher global warming potential of open waste dumps can be eliminated to a large extent by applying suggested mining and waste valorisation scenarios.

Key words

Open waste dump mining; Enhanced Landfill Mining; Life cycle assessment; Life cycle costing

1.0. Introduction

Increasing population levels, a growing economy, rapid urbanization and changes in consumption patterns have greatly accelerated the solid waste generation rate in developing countries (Troschinetz and Mihelcic 2009, Guerrero et al. 2013, Marshall and Farahbakhsh 2013). In 1999, the average MSW generation per capita in Sri Lanka was 0.89 kg/cap/day, and it has been predicted to reach 1.0 kg/cap/day by 2025 (WorldBank 1999, Vidanaarachchi et al. 2006, Menikpura et al. 2012). In Sri Lanka, MSW contains a fraction rich in organic matter, moderate plastic and paper content, and low metal and glass fractions (Vidanaarachchi et al. 2006, Menikpura et al. 2007, Gunawardana et al. 2009).

Like in many other Asian countries, solid waste collection and disposal has been an issue in Sri Lanka for the past decades, where burning and dumping garbage into collection yards are the most common modes of disposal. After collection and transportation, approximately 85 percent of the total MSW generated is disposed of in 'open dumps', without any pre-treatment, cover or compaction (Visvanathan et al. 2003, Visvanathan et al. 2004). An open dump site is (i) a land disposal site at which solid wastes are disposed of without considering environmental protection, (ii) susceptible to open burning, and (iii) exposed to the elements, disease vectors and scavengers. These dumps are located in environmentally sensitive areas such as wetlands, marshes, beaches and areas adjacent to water bodies or close to residential houses or public institutions (Joseph et al. 2004, Gunawardana et al. 2009).

As the waste separation is not well developed in Sri Lanka, the dump sites contain heterogeneous waste piles. The continuous dumping of waste in open areas eventually resulted in a number of garbage mountains in several municipalities in the country. The ‘Bloemendhal’ dump site, located in Colombo, Sri Lanka’s commercial capital city, is an example: it occupies an area of 6.5 hectares, goes to an average height of 30 meters and contains about 1.5–2.5 million tonnes of garbage (Sathees 2014). For many years Bloemendhal has been an eyesore for nearby residents, including the poorest people of around 350 shanty dwellings (Sathees et al. 2014). The daily average waste collection in Colombo city is about 650 tonnes (APO 2007), and such waste is directly dumped into the Bloemendhal site. In addition to this landmarked dump site, many other small dump sites exist in the same municipal area. However, the quantities of waste dumped in these yards are not yet known. ‘Gohagoda’ is another well-known dump site located three kilometres away from Kandy, one of the culturally valued cities of Sri Lanka. Up to 1960 Gohagoda was used as an isolated area to dump hospital waste, then as a sewage dump site, and finally as the place for dumping all the waste generated by the Kandy municipal council. At present, 100 tonnes of MSW collected in the city are dumped at this site per day (Menikpura 2008).

Open waste dump sites cause a number of environmental and socio-economic impacts due to lack of engineering design and inadequate maintenance (Visvanathan 2003,Joseph 2004). The absence of gas collection and utilization systems in open waste dumps results in a severe contribution to global warming potential, as CO_2 and CH_4 act as greenhouse gases (Joseph 2002, Crowley 2003). The International Solid Waste Association explains that the absence of ground water protection and drainage controls accelerates the ground and surface water pollution as the leachate from the waste dumps which contains dissolved methane, fatty acids, sulphate, nitrate, nitrite, phosphates, calcium, sodium, chloride, magnesium, potassium, and trace metals migrates to the water table and surface water (ISWA 2007). This situation is very serious as it yields a severe pollution in the aquifers and serious eutrophication conditions in surface waters (Han et al. 2014).

Data on environmental, health, and social impact assessments of open waste dump sites in Sri Lanka are very limited and not publicly available. However, a few studies are available that were performed for two landmarked dump sites: the Bloemendhal dump site, in Colombo, and the Gohagoda dump site, in Kandy. The study conducted by Sathees et al. (2014) revealed that the soil of the Bloemendhal dump site is sandy, and therefore the percolation is high through the deep layers; hence, the contamination of ground water can be expected. The leachate and soil within 150 and 400 meter radius from the centre of the waste pile contain high amounts of nitrate, phosphate, organic matter, heavy metals, and coliform bacteria. These values always exceed the standard levels set by the Sri Lanka Standards Institute. The data on this site’s gaseous emission has not been reported yet. The characterisation study of leachate and groundwater of the Gohagoda dump site, performed by Dharmarathne et al. (2013), showed that the levels of pH, sulphate, nitrate, nitrites, and heavy metals (Pb, Zn, Ni, Cr, Co, Fe, Mn, Cu) are above the standards required by the World Health Organization for drinking water. This dump site exists at a distance of about 50 meters from the Gohagoda water intake plant. Furthermore, Menikpura et al. (2008) proved that the predicted leachate emission rate from this dump site is 30304 m^3/year and that it is highly polluted, with 15,000–20,000 mg/l of biological oxygen demand (BOD) value. The same study discovered that the predicted amount of greenhouse gas emission of this site is 2.61 Gg/year.

Dump site rehabilitation would help moderate the environmental and health impacts described in the above paragraphs (APO 2007). Dumpsite closure through applying a cover layer (such as soil) on top of the dump site and transforming dump sites into sanitary landfills are possible rehabilitation options (APO 2007). However the latter option is unrealistic in many cases as the basic requirements of a sanitary landfill (landfill gas and leachate collection facility and protection layers) are missing in the dump sites and this leads to complete excavations, waste removals and subsequent construction of a new landfill sector. On the other hand, landfill mining has been used as an option of exhuming existing or closed dump sites and landfills and sorting the exhumed materials for recycling, processing, or other deposition (Joseph et al. 2002). The objectives of traditional landfill mining could be one or more of the following: redevelopment of landfill sites; conservation of landfill space; reduction in landfill area; elimination of potential contamination source; energy recovery from recovered wastes; and reuse of recovered materials (van der Zee et al. 2004, Ayalon et al. 2006, Jones 2008, Prechthai et al. 2008, Raga and Cossu 2014). Several studies address the environmental and economic potential of landfill mining in material recycling, energy recovery, land reclamation and pollution prevention (Zhou et al. 2014, Frandegard et al. 2015, Winterstetter et al. 2015, Zhou et al. 2015). More details on landfill mining projects in the Asian region can be found in APO (APO 2007). The novel concept of Enhanced Landfill Mining (ELFM) can also be applied to open waste dumps as ELFM includes the combined valorisation of the historic waste streams as both materials and energy (or in other words Waste-to Materials (WtM) and Waste-to Energy (WtE)) and finally regaining the land (Jones et al. 2013). Several studies highlighted the usability of ELFM in re-introducing buried resources in to the material cycle (Jones et al. 2013, Quaghebeur et al. 2013). Besides, Danthurebandara et al. (2015a) and Van Passel et al. (2013) described the feasibility of ELFM from an environmental and economic point of view. Hence, to remove the landmarked open waste dumps from urban areas in a sustainable way, the application of the concept of ELFM as ‘open waste dump mining’ appears to be possible with the objectives of minimising the environmental burden, recovery of buried resources and regaining the land. However, the actual situations of landfills/open dumps vary from site to site, It is obligatory to assess the environmental and economic feasibility of open waste dump mining prior to bring the concept towards its operational stage.

The purpose of this paper is to assess the feasibility of open waste dump mining in Sri Lanka by considering the insights of the novel ELFM concept. The study includes life cycle assessment (LCA) and life cycle costing (LCC) to identify the environmental and economic drivers of open waste dump mining. Moreover, open waste dump mining scenarios are compared with the existing situation to identify the actual benefits of the concept. The study also encompasses a trade-off analysis to illustrate the association between environmental and economic performances.

2.0. Materials and methods

As the real open dump mining cases do not yet exist in Sri Lanka, a hypothetical case was introduced. The background of the hypothetical case and process flow for open waste dump mining are described in detail in sections 2.1. LCA and LCC methodologies are presented in section 2.2.

2.1. Hypothetical case

Considering the characteristics and situation of Sri Lanka’s major landmarked dump sites: Bloemendhal and Gohagoda, a hypothetical case has been drawn. The basic outline for the hypothetical case is an open waste dump site which contains approximately 1,000,000 tonnes of waste and occupies an urban land of 5 hectares (50,000 m^2) within Colombo's city limits. It is assumed that the waste dump was open for the past 30 years, with a daily waste dumping of 100 tonnes/day. There is currently no waste inflow. Similar to typical waste dumps in Sri Lanka, no gas or leachate collection systems are installed in the considered dump site.

The dump site mining scenario is organized as illustrated in Figure 1, which is moderately similar to the process flow of ELFM described in Danthurebandara et al. (2015). Waste excavation is performed by excavators, bulldozers, cranes, and other suitable equipment. The oversized waste (chairs, tyres, wooden pieces, etc.) identified during the excavation, are disassembled and sorted out manually, and added to the relevant end-product category. After excavation, the waste is directed to a proper separation process. Pre-separation takes place at the dump site right after the excavation to separate the hazardous waste and 'fines'. 'Fines' denotes the material fraction below a certain particle size (<100mm), which has to be removed prior to or during the material separation processes (Spooren et al. 2013).

Advanced separation can be done on site or off-site. As the considered dump sites are situated in highly populated areas, performing advanced processes on site seems difficult. Therefore, in this study it was assumed that the necessary processes after pre-separation are carried out in separate premises outside the city limits. Thus, the pre-separated waste is transported to the required premises. It has to be decided which type of advanced separation technology is going to be used according to the moisture content of the pre-separated waste, composition, and the quantity of the waste, In this study air separation, dense media separation, magnetic separation, and eddy current separation were presumed to be in the advanced separation process. According to the conclusions of previous studies in landfill mining

(Quaghebeur 2013), in this study also, plastic, paper/cardboard, wood, and textile fractions were considered as one refuse derived fuel (RDF) fraction due to their high level of contamination. The major outputs of the advanced separation process include fines, RDF, ferrous metals, non-ferrous metals, stones/aggregates, and glass. Fines and RDF are considered as intermediate products and they can be transformed into valuable materials or energy. In this context, fines are converted into building materials after performing necessary treatments for heavy metal removal while RDF fraction is used as an alternative fuel in the cement industry or is incinerated to generate energy. After excavating and processing the entire dump site, the land can be reclaimed either as land for nature reserve, housing, agriculture, or industry. The products of above processes substitute the virgin material and/or energy production somewhere else or in other words the environmental impact of virgin material/energy production is avoided by the use of recovered materials derived from open waste dump mining.

Considering the destination of produced RDF, two major scenarios have been developed for the analysis.

- Scenario 1 includes the processes of excavation, transportation, separation, fines treatment, and land reclamation. In this scenario, RDF is considered as an end-product of open dump mining and it is sold to the cement industry to be used as an alternative fuel.
- In scenario 2, RDF is treated as an intermediate product and is subjected to incineration in order to produce energy. Scenario 2 comprises the processes of excavation, transportation, separation, fines treatment, thermal treatment of RDF, and land reclamation.

Apart from the scenarios mentioned above, a ‘Do-nothing’ scenario is used as reference scenario. The Do-nothing scenario or reference situation supposes that no mining activities are undertaken; the dump site remains as it is, without any maintenance or environmental protection activity. No collection or treatment takes place for the gases and leachate.

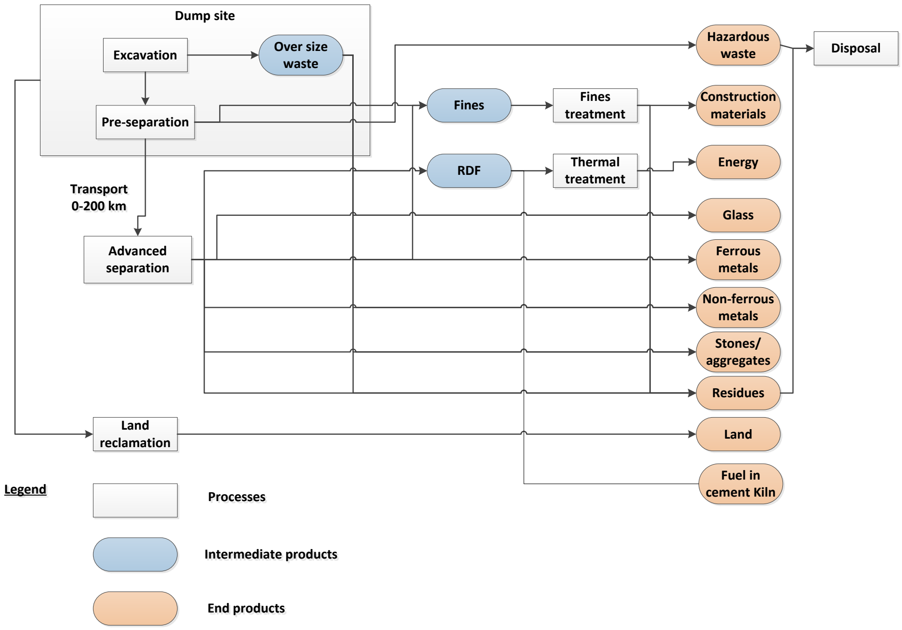

Figure 1: Open waste dump mining scenario

2.2. LCA and LCC methodology

The goal of this LCA study was to evaluate the environmental impacts of the open waste dump mining for resources and land recovery. The methodology is in accordance with the International Standards for LCA (ISO14040 2006, ISO14044 2006). SimaPro 7 was used as the LCA software tool for setting up the LCA model. The LCA model comprises individual building blocks for each activity described in Figure 1 with all possible inputs and outputs and also the relevant substitution of the virgin material/energy production (avoided impact) due to the products (see Figure 2).

Relevant processes were combined to estimate the overall impact of open waste dump mining.

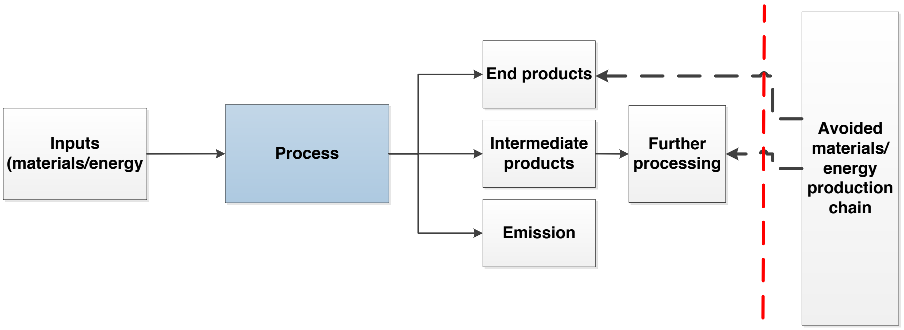

Figure 2: Structure of a building block of LCA model

It was assumed that with the exception of the pre-separation equipment, all other processing plants are situated in a specific ground, which is 150 kilometres away from the studied dump site. The quality of the products of open waste dump mining considered in this study are as follows:

- The metals recovered from separation processes have the quality which enables substituting the corresponding scrap metals.
- Stones and the other construction materials (sand, aggregates, and soil) recovered from separation and fines treatment processes have the quality of gravel that can be used in construction activities.
- When the RDF is used as an alternative fuel in the cement industry, one tonne of RDF replaces the production of 0.6 tonnes of coal. Furthermore, it avoids transportation of the same amount of coal from Indonesia to Sri Lanka. The calculation is based on the average calorific values of RDF and coal (20 MJ/kg vs. 33 MJ/kg (Fisher 2003).

- When the RDF is incinerated in order to produce energy, the produced electricity replaces the base load of electricity production in Sri Lanka, which includes 70 percent conventional thermal energy, 23 percent hydro energy, and six percent renewable energy (SLSEA 2012). The produced heat is assumed to be used in the process itself.
- Recovered land is converted into land for a nature reserve.

The input data of this study comprises the data obtained from published sources, calculated data, and estimated data (See Tables 1-3). The data published mainly in the ecoinvent database (version 2.2) was used for the background processes with appropriate modification according to the Sri Lankan standards. In this study we used a reference flow instead of a functional unit as explained in the ILCD handbook (2010). Using a reference flow instead of a functional unit is very common in LCAs of waste treatment (Consonni et al. 2005, Frändegård et al. 2013, Laurent et al. 2014). Hence, the reference flow was defined as a certain mass of landfilled waste. Based on this reference flow, the environmental impact was calculated for valorisation of (i) 1 tonne of waste and (ii) total waste present in the open waste dump. In the second case, the environmental impact of ELFM was compared with that of the Do-nothing scenario. The environmental performance of the Do-nothing scenario was calculated as follows.

The evolution of gas and leachate that can be produced by the hypothetical dump site has been analysed in order to identify the current situation. The gas production curve for the considered dump site was obtained from the LandGEM model (version 3.02) and is presented in Figure 3. LandGEM is an automated estimation tool with a Microsoft Excel interface that can be used to estimate emission rates for total landfill gas, methane, carbon dioxide, non-methane organic compounds, and individual air pollutants from MSW landfills (USEPA 2005). The gas production curve reveals that this dump site is, in 2015, at the peak of gas production; the gas production will then decrease over time and become considerably low after 100 years. In order to decide whether or not the valorisation of waste present in the dump site is environmentally beneficial against the existing situation (Do-nothing scenario), the residual impact of the dump site should be determined. In this study the residual impact starts from year 2015 (Figure 3), as the waste valorisation activities are assumed to have started in 2015. The respective residual environmental impact was calculated for 100 years starting from 2015. CO_2 emission in the Do-nothing scenario was considered as CO_2 neutral because of its biogenic origin. The leachate emission and composition data present in Sathees et al. (2014) were used to determine the emission to water and soil.

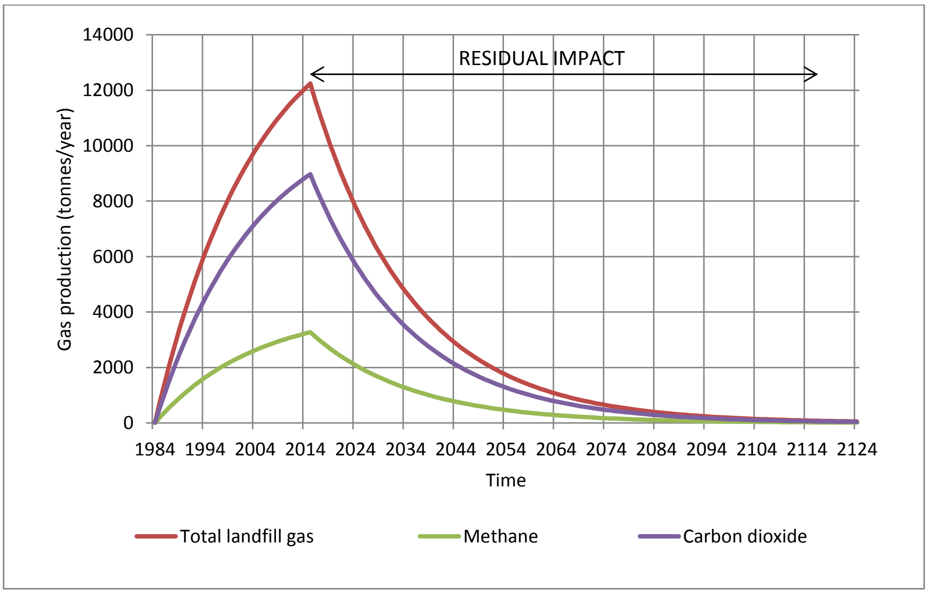

Figure 3: Gas production curve of studied dump site as delivered by LandGEM model (version 3.02)

For the environmental impact assessment of this study, the ReCiPe endpoint method (Hierarchist version, H/A) was selected, as it addresses several impact categories such as (i) climate change on human health; (ii) climate change on ecosystems; (iii) ozone depletion; (iv) terrestrial acidification; (v) freshwater eutrophication; (vi) human toxicity; (vii) photochemical oxidant formation; (viii) particulate matter formation; (ix) terrestrial ecotoxicity; (x) freshwater ecotoxicity; (xi) ionising radiation; (xii) agricultural land occupation; (xiii) urban land occupation; (xiv) natural land transformation; (xv) metal depletion; and (xvi) fossil fuel depletion (Goedkoop et al. 2013).

The goal of the LCC study was to evaluate the economic drivers of open waste dump mining. A cash flow model was set up for the period of 5 years including all costs and revenues associated with the different processes. The waste processing is completed within 5 years and the depreciation rate is assumed to be 5 percent. As a result, all processing plants remain with a residual value after 5 years. These remaining processing plants are considered to be used in future waste separation and processing under developing national solid waste management strategy or in other open waste dump mining cases. Hence, the cash flow was facilitated with a residual value for the processing plants. Net present value (NPV) was used as the major economic indicator in order to determine the major economic drivers of open waste dump mining. The NPV is calculated by subtracting the investment cost from the sum of the discounted cash flow and can be considered as the expected profit of the investment (Brealey et al. 2010). It takes the time value of money and all the relevant cash flow elements over a pre-defined period into account. Equation 1 shows the mathematical representation of NPV.

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{\mathrm{CF}_t}{(1+x)^{t-1}} \qquad (1)$$

Where, CF_t is the cash flow in year t, T is the time horizon and x is the discount rate. The Monte Carlo simulation approach was used to examine the sensitivity of different parameters on NPV, as explained by Van Passel et al. (2013).

Table 1 shows the composition of dumpsite mined waste presented by Menikpura et al., (2008) which was used in this study with necessary modifications. To elaborate our study in detail, the metal fraction is further divided into ferrous and non-ferrous metals with equal percentages. Biodegradables, polyethylene, coconut comb and husk, textile, wood, rubber and leather, and paper fractions are combined into one RDF fraction. The previous landfill mining and open dump mining case studies in Asia and Europe revealed that a considerable amount of fines can be present in the mined waste due to degraded garden and food waste (Joseph et al. 2004, Quaghebeur et al. 2013). Therefore, we assumed that 25 percent of the RDF fraction are degraded into fine particles. Furthermore, we assumed that 50 percent of the fraction of construction demolitions has a particle size less than 10mm. Hence 25 percent of RDF and 50 percent of construction demolitions were considered as fine fraction. The adjusted composition is illustrated in Table 2 with the recovery efficiencies applied for all waste fractions in the separation process. We assumed similar recovery efficiencies for all waste fractions and performed a sensitivity analysis for the efficiencies of most influencing waste fractions. Unrecovered portions of each waste fraction are considered as residues to be disposed of in a sanitary landfill. Energy, materials, and emission data of the incineration plant of Scenario 2 is presented in Table 3. As incineration plants are not yet available in Sri

Lanka, the data of a well-established, large scale incineration plant in Europe (Indaver) were used. It was assumed 50 percent of biogenic fraction in order to calculate the biogenic and fossil CO_2 emission. Energy and materials data for excavation, separation, fines treatment and land reclamation are according to the data presented in Danthurebandara et al. (2015a). Background processes of Eco invent database were used to obtain data for emission due to diesel and electricity consumption in above processes and transportation process. Costs and product selling prices used in the economic analysis are illustrated in Table 4.

Table 1: Average composition of dump site mined waste in Sri Lanka (Menikpura 2008)

Waste fraction	Percentage (%)	Waste fraction	Percentage (%)
Biodegradable	59.69	Paper	0.92
Polyethylene	24.66	Glass	1.28
Coconut comb and husk	4.74	Metal	0.02
Textile	3.66	Stones	1.35
Wood	1.29	Construction demolitions	0.10
Rubber and leather	1.20	Undefined	1.09

Table 2: Adjusted waste composition of dump site mined waste and separation efficiencies of the separation process

Waste fraction	Percentage (%)	Recovery efficiency (%)
RDF	72.12	80
Fines	24.09	80
Ferrous metals	0.01	80
Non-ferrous metals	0.01	80
Glass	1.28	80
Stones	1.35	80
Construction demolitions	0.05	80
Undefined	1.09	

Table 3: Energy, materials and emission data of incineration

Parameter	Value	Source
Calorific value of RDF (MJ/kg RDF)	20	Menikpura et al. (2008)
Start-up energy (kWh/t RDF)	78	Indaver (2012)
Net electrical efficiency (%)	22	BREF (2006, 2010), UCL (2014)
Bottom ash generation (t/t RDF)	0.228 (to be landfilled)	Indaver (2012)
Air pollution control (APC) residues (t/t RDF)	0.043 (to be landfilled)	Indaver (2012)
Auxiliary materials		Indaver (2012)
Activated carbon (kg/t RDF)	0.5	
Urea (kg/t RDF)	3.5	
Limestone (kg/t RDF)	6.7	
Quicklime (kg/t RDF)	4.4	
Emission		Indaver (2012)
Carbon dioxide (kg/t RDF)		
biogenic	839	
fossil	839	
Carbon monoxide (kg/t RDF)	0.09	
Particulates (kg/t RDF)	0.014	
Nitrogen oxides (kg/t RDF)	1.49	
Sulphur dioxide (kg/t RDF)	0.019	
Hydrogen chloride (kg/t RDF)	0.003	
Dioxins (kg/t RDF)	8×10^{-8}	
Mercury (kg/t RDF)	1.6×10^{-6}	
Heavy metals (kg/t RDF)	0.052	

Table 4: Data used in the economic analysis

Parameter	Value	Source
Time length (years)	5	Case study
Depreciation rate (%)	5	Case study
Excavation cost (€/t)	1.60	Industrial reference (United Tractor and Equipment)
Transport cost (€/tkm)	0.13	Rathi (2007)
Investment cost of separation (€/t)	5	Industrial reference (BERNS, ENVIROMECH)
Operational cost of separation (€/t)	7	Industrial reference (BERNS, ENVIROMECH)
Investment cost of incineration (€/t)	60	Ducharme (2010)
Operational cost of incineration (€/t)	40	Ducharme (2010)
Electricity price (€/MWh)	125	PUCSL (2012)
Disposal cost of residues (€/t)	90	Central Environmental Authority
Price of metals (€/t)	800	Commercial reference (Ceylon steel,

		Recycleinme.com)
Price of RDF (€/t)	33	Calculated*
Price of glass (€/t)	6	Commercial reference (Recycleinme.com)
Price of aggregates (€/t)	10	Commercial reference (Recycleinme.com)
Price of land (€/m^2)	25	Central Environmental Authority

* This value was calculated considering the calorific value of RDF and average price and calorific value of coal. Price of coal: 55 €/t (Infomine 2015) , calorific value of coal: 33 MJ/kg (Fisher 2003)

3.0. Results and Discussion

3.1. Environmental performance of open waste dump mining

Top and bottom panels of Figure 4 illustrate the environmental impact of valorisation of one tonne of waste present in the dump site for Scenarios 1 and 2, respectively. Top panel confirms that the separation and the transportation processes dominate most impact categories. The significant benefits of the separation process on several impact categories are due to the avoided burdens caused by different end-products produced during separation. The individual environmental profile of the separation process reveals that the major benefit is due to the replacement of coal production and transportation by using RDF as an alternative fuel in the cement industry. In this study, one tonne of waste present in the dump site is responsible for reducing production and transportation of 0.348 tonnes of coal. Although the recovery of metals, aggregates, and glass also yield environmental benefits, its importance is lower than the benefits due to RDF.

In Scenario 2, thermal treatment of RDF dominates the environmental profile, and separation and transportation become the next important processes. In this scenario, the RDF obtained from the separation process is treated in an incinerator in order to produce energy instead of direct-selling to the cement industry. One tonne of waste present in the landfill contributes to a production of 710 kWh of electricity. In this way, the influence of the separation process in different impact categories is different in the two scenarios.

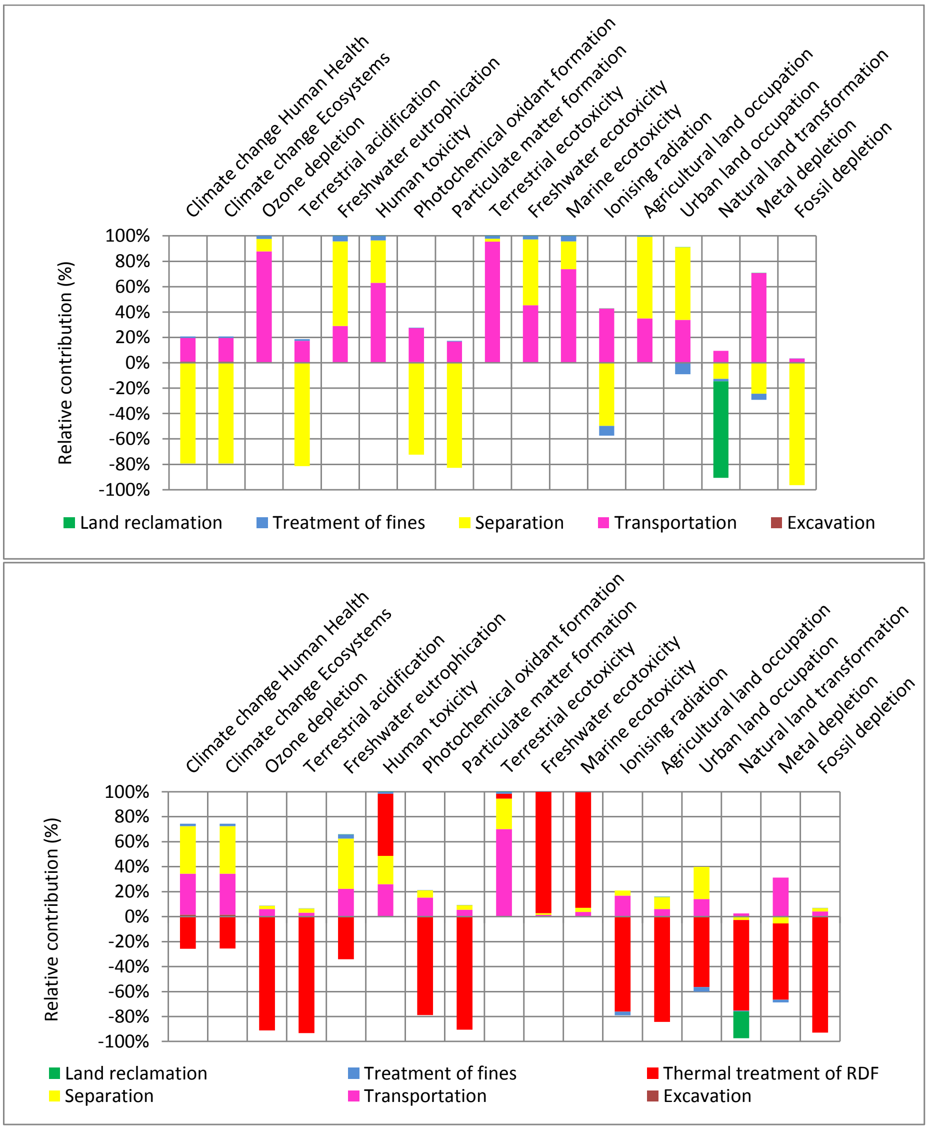

Figure 4: Environmental profiles of scenario 1 (top) and scenario 2 (bottom) (reference flow- 1 tonne of waste in the dump site)

Figure 4 illustrates the contribution of each process in open dump mining relative to the different impact categories. As the total environmental impact in each impact category is set to 100 percent, the figures do not conclude to what extent an impact category has a significant contribution and which scenario performs better. Figure 5 clarifies the overall performance of the scenarios and the mostly influenced impact categories.

Figure 5 shows that in both scenarios, impact in fossil depletion is very significant. Next to that, the contributions to particulate matter formation and climate change on human health are also important. The impact on other categories is insignificant. The benefit in fossil depletion is higher when the RDF is used as an alternative to coal fuel in the cement industry (Scenario 1) than when it is thermally treated in order to replace the conventional electricity production in the country (Scenario 2). Contrastingly, the environmental credits in particulate matter formation are higher in Scenario 2. Scenario 1 is beneficial in the climate change impact category, while Scenario 2 is not; the flue-gas emission with high CO_2 concentration in the thermal treatment process is a reason for this difference. However, both scenarios yield a net environmental benefit. Furthermore, Scenario 1 is 30 percent more beneficial than scenario 2.

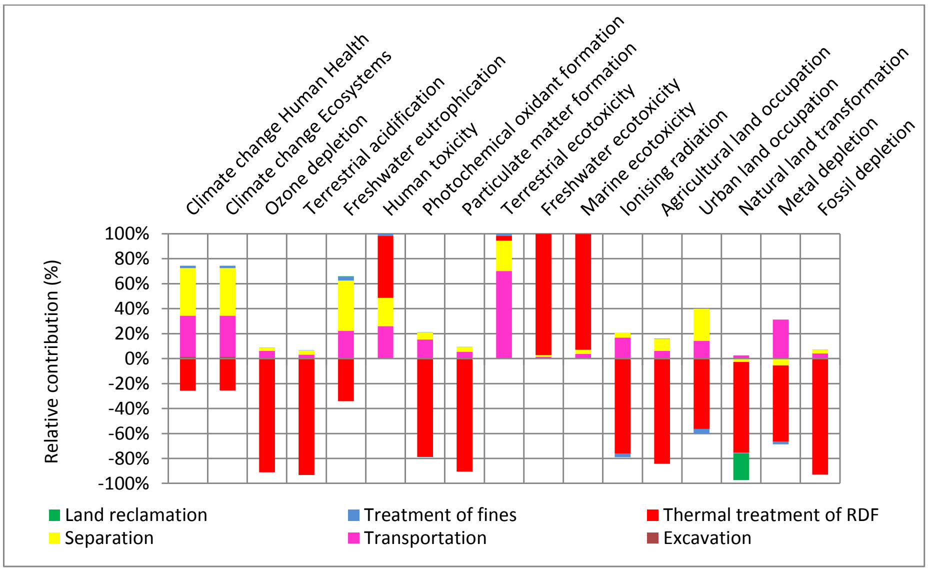

Figure 5: Most significant impact categories of scenario 1 and 2 (reference flow- 1 tonne of waste in the dump site)

We discussed above the environmental impact of the valorisation of one tonne of waste present in the dump site. To bring the open dump mining concept to the operational phase, it is necessary to know whether it is beneficial compared to the Do-nothing scenario or reference situation.

Top panel of Figure 6 shows the environmental impact of the Do-nothing scenario for the total amount of waste. In addition, those impacts were compared with Scenario 1 and Scenario 2. The impact of the two scenarios were calculated for the total amount of waste present in the dump site (valorisation of total waste present in the dump site).

The net environmental impact of the Do-nothing scenario turns out to be very detrimental compared to the waste mining/valorisation scenarios. In the Do-nothing scenario the burdens are mainly found in the impacts of climate change on human health and climate change on ecosystems. These burdens are mainly due to the 66,758 tonnes of total methane emission for 100 years, starting from 2015. This scenario is not responsible for any environmental benefit, as the produced methane is not used in energy production and no materials are recuperated whatsoever.

Another impact assessment was performed by using the method of IPCC 2007 GWP 100a (PRéConsultants 2008); the results are illustrated in bottom panel of Figure 6. The figure reveals that the CO_2 equivalent emission of the Do-nothing scenario can be completely eliminated by Scenario 2. Not only elimination, but also a CO_2 equivalent saving is foreseen for Scenario 1. Additionally, Scenario 2 reduces the

CO_2 equivalent burden of the Do-nothing scenario up to 98 percent. From figures 5 and 6, it can be concluded that a higher fraction of environmental burden taken place due to open waste dumps can be eliminated by applying appropriate mining and valorisation scenarios at the early stages of the waste degradation of a dump site. Over time, a large fraction of methane is freely emitted to the environment and the dump site reaches its maturation/long-term phase (final state of waste stabilisation as explained by Vesilind at al. (2002) and Kjeldsen et al.(2002)). Performing waste mining and valorisation during the maturation phase still allows for environmental benefits through materials and energy recuperation, but is not advantageous in mitigating the emission of CO_2 equivalent, as shown by the case study analysed by Danthurebandara et al. (2015a).

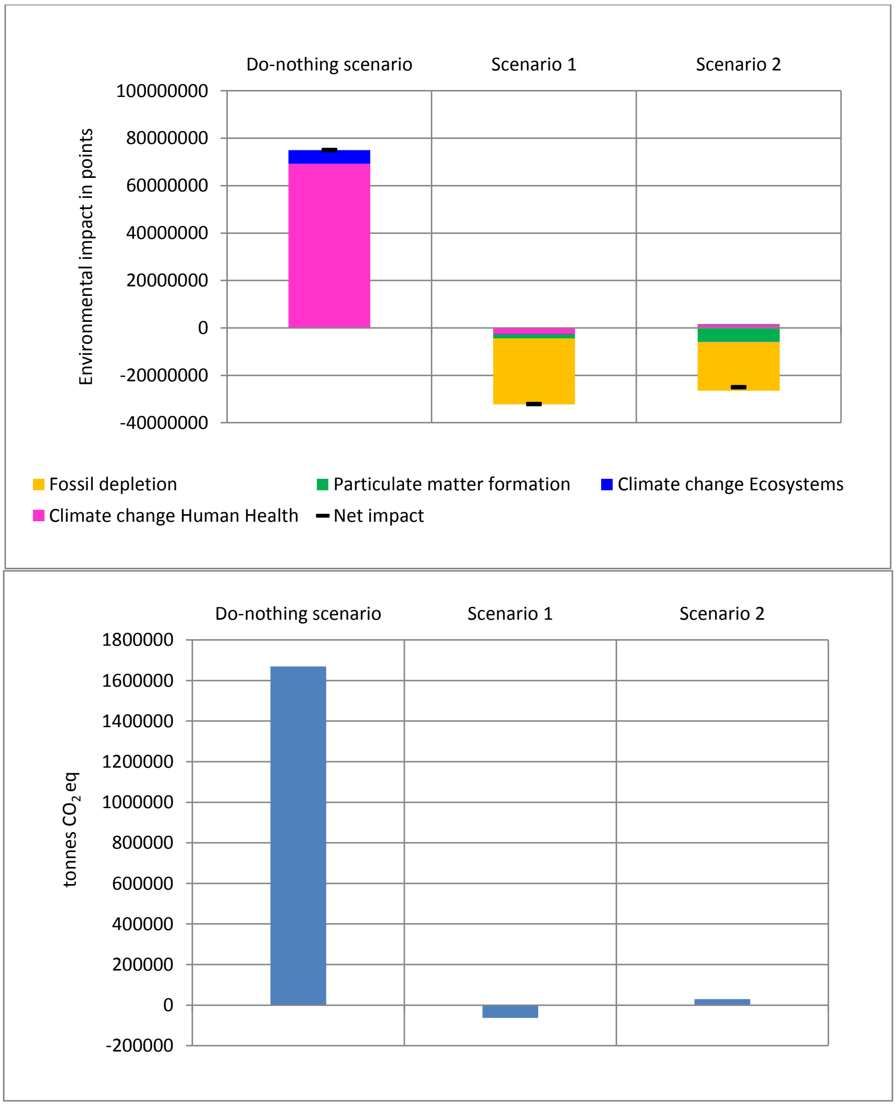

Figure 6: Environmental impact of Do-nothing scenario and waste valorisation scenarios- Single score data (top) and GWP data (bottom)

3.2. Sensitivity analysis in environmental profiles

From the analysis of the above open waste dump mining scenarios, it was identified that the transportation, separation, and thermal treatment are the most influencing processes to the environment. Likewise, waste transportation distance, RDF recovery in the separation process, and electricity production in the thermal treatment process were recognised as the main factors that dominate the environmental profiles. The amount of produced electricity depends on the calorific value of RDF and the net electrical efficiency of the thermal treatment system. In addition, the recovery efficiency of RDF in the separation process is also a factor to decide net electricity production. Hence, the parameters of transport distance, RDF recovery efficiency, calorific value of RDF, and the net electrical efficiency of the thermal treatment process were subjected to a sensitivity analysis. Table 5 provides a summary of those parameters on which the sensitivity analyses are performed. Figure 7 illustrates the comparative environmental profile of the scenarios with the sensitivity analyses.

Table 5: Overview of the sensitivity analyses

Parameter	Basic value	Best case value	Worst case value
Transport distance from dump site to the separation plant (km)	150	50	250
RDF recovery efficiency in separation process (%)	80	90	70
Calorific value of RDF (MJ/kg)	20	25	15
Net electrical efficiency of thermal treatment system (%)	22	30	20

Transportation of excavated waste from the dump site is necessary when there is no sufficient space to construct further processing plants at the dump site, or when it is essential to process the waste in a specific processing plant, away from the dump site. Reducing the transport distance obviously increases the environmental benefit of the two suggested scenarios. However, this increment is not well pronounced, ranging from five to nine percent only (Figure 7). RDF plays a significant role in both scenarios. When the RDF recovery is higher, the amount of coal replacement is also higher in Scenario 1; this results in a 13 percent increment of environmental benefit when the RDF recovery efficiency increases by 10 percent. Similarly, the higher RDF recovery efficiencies positively affect the electricity production in Scenario 2. As illustrated in Figure 7, a 10 percent increment of RDF recovery efficiency leads to a 15 percent growth in the net environmental impact (benefit) of Scenario 2. As explained earlier, this benefit can further be improved with higher calorific values and higher electrical efficiencies. The calorific value of RDF is mainly dependent on the biodegradables and plastic content. When they are not in larger fractions, then lower calorific values are expected; similarly, when the dump site is in its maturation phase the calorific value of the waste displays lower values due to the waste degradation. Considering these facts, in the sensitivity analysis a 15–25 MJ/kg range was used as the calorific value of RDF (Menikpura et al. 2008). According to Figure 7, the net environmental benefit of Scenario 2 increases by 60 percent for a 25 percent enhancement of calorific value of RDF. Although the average electrical efficiency of a typical incinerator is 22 percent, higher efficiencies such as 30 percent are also reported (Bosmans et al. 2013). Hence, an upper margin of 30 percent was applied for the sensitivity analysis of net electrical efficiency of thermal treatment system. It expands the environmental benefit of Scenario 2 by 92 percent.

Apart from improving the calorific value and electrical efficiency, the thermal treatment technology can also be altered for obtaining higher benefits. Bosmans et al. (2013) concluded that plasma gasification/vitrification is a viable candidate for combined energy and material valorisation in the framework of ELFM. Moreover, Danthurebandara et al. (2014) highlight that the environmental performance of plasma gasification is clearly better than that of incineration. This finding can also be applied in open waste dump mining in order to improve the current environmental benefits. In this context, we replaced incineration technology in scenario 2 with plasma gasification technology with a 27% of electrical efficiency as explained by Danthurebandara et al. (2015a). The other data related to input materials and emissions of plasma gasification process are also according to Danthurebandara et al. (2015a). Using plasma gasification in Scenario 2 improves the overall environmental impact (environmental benefits) by 79%. Furthermore, This technology yields large improvements on GWP which leads to a saving of 147687 tonnes CO_2 emission. Plasma gasification process is more efficient than conventional incineration in converting the energy content of the waste to electricity. Therefore, although both processes give rise to the direct emissions of carbon dioxide from the waste conversion plant, plasma gasification process displaces more conventional electricity generation and is therefore associated with significantly lower lifecycle GWP emissions. In this way, the environmental performance of Scenario 2 is higher than that of Scenario 1 when the plasma gasification process is used in RDF valorisation. This performance can be further improved by using plasmastone, the residues of plasma gasification in production of higher value building materials such as inorganic polymer and blended cement (Danthurebandara et al. 2014, Danthurebandara et al. 2015b).

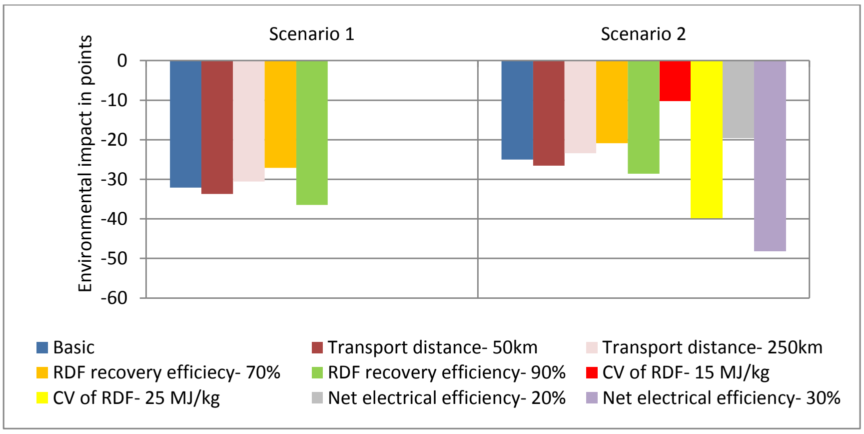

Figure 7: Environmental profile of open waste dump mining scenarios with sensitivity analysis- reference flow: 1 tonne of waste in the dump site (basic scenario comprise 150km transport distance, 80% RDF recovery efficiency, 20 MJ/kg CV of RDF and 22% net electrical efficiency of thermal treatment system)

3.3. Economic performance of waste valorisation

In Figure 8 the economic performances of the two scenarios are plotted against the environmental performances. NPVs and environmental impacts were calculated for the hypothetical case explained in section 2.1. In fact, the positive values of NPV imply economic profits, while the negative values of environmental impact indicate environmental benefits. Hence, Figure 8 shows that none of the scenarios are beneficial in both aspects. Although both scenarios produce environmental benefits, the NPVs are negative within the data used in Table 4. Scenario 2 shows better economic results compared to Scenario 1.

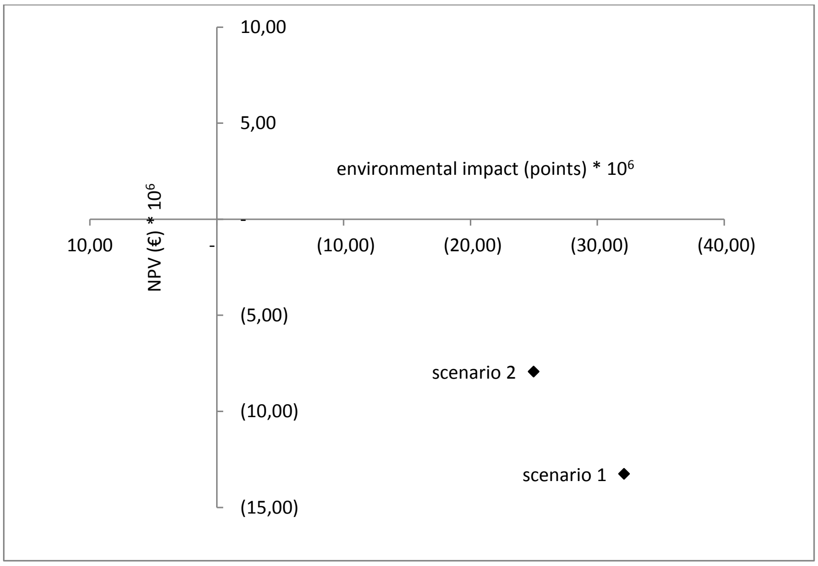

Figure 8: Economic performance against the environmental performance

The contributions of the most influencing parameters to the NPV obtained from Mote Carlo simulations are illustrated in Table 6. An increase in the NPV with an increase of a parameter is specified by a positive value, and the opposite situation is designated by a negative value.

In Scenario 1, transport costs contribute 54.9 percent to the NPV. The next highest contribution is given by transport distance. In this study we used 150 km of average transport distance, as the waste has to be transported to a specific ground with enough space, beyond the city limits, for further processing. As the hypothetical dump site is assumed to be in Colombo, the distance from Colombo to a specific ground where the processing plants can be installed is estimated. In the sensitivity analysis 250 km of maximum distance was used, assuming that the northern part of the country can also provide a suitable ground for waste processing due to comparatively less population than the other areas. Reductions in transport costs obviously yield higher NPVs according to Table 6. The variation of NPV with the different transport costs for three different transport distances is demonstrated in Figure 9. A decrease of transport costs by 10 percent leads to an increment in NPV by 12 percent, 11 percent, and 10 percent for the transport distances of 50 km, 150 km, and 250 km, respectively. This figure leads to the conclusion that avoiding waste transportation by implementing all processing plants on the dump site or nearby is a prerequisite to obtaining the economic benefits of open waste dump mining for this scenario.

Table 6: Monte Carlo sensitivity analysis

Parameter	Minimum value	Maximum value	Contribution to variance of NPV (%)
Scenario 1			
Transport cost (€/tkm)	0.09	0.23	54.9 (-)
Transport distance (km)	50	250	31.5 (-)
RDF selling price (€/t)	25	42	12.1 (+)
RDF recovery efficiency (%)	70	90	1.5 (+)
Scenario 2			
Calorific value of RDF (MJ/kg)	15	25	31.3 (+)
Electrical efficiency of thermal treatment system (%)	20	30	23.1 (+)
Electricity price (€/Mwh)	100	150	19.6 (+)
Transport distance (km)	50	250	13.6 (-)
Transport cost (€/tkm)	0.09	0.23	6.2 (-)

RDF recovery efficiency (%)	70	90	2.4 (+)
Investment cost of thermal treatment system (€/t RDF)	55	65	2.1 (-)

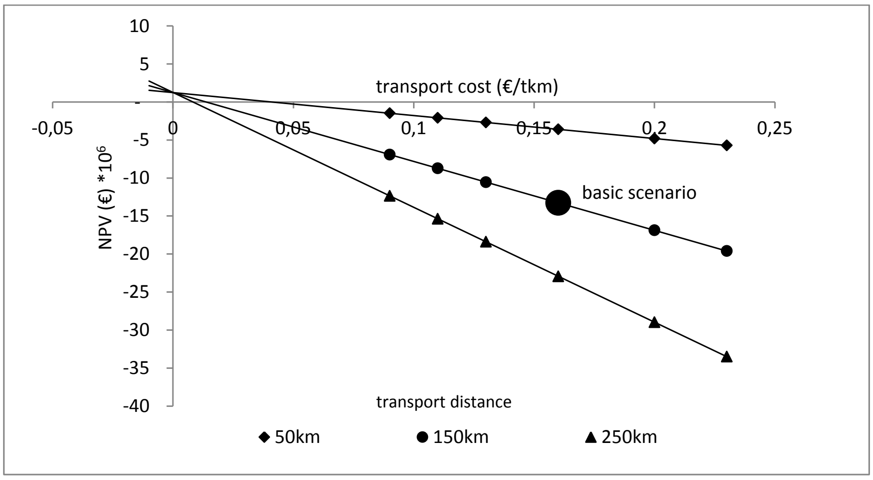

Figure 9: The impact of variations in transport cost and distance on NPV in scenario 1

In addition to transport costs and transport distance, the selling price of RDF is another imperative parameter that gives 12.1 percent positive contribution to the NPV. In this study, the selling price of RDF was calculated as 33 €/t by considering the ratio of the calorific values of RDF and coal (20/33) and the average market price of coal (55 €/t). Depending on the composition of the MSW in Sri Lanka, the minimum and maximum values of calorific value of RDF were decided as 15 and 25 MJ/kg. Based on these values, the minimum and maximum values for selling prices of RDF were calculated as 25 and 42 €/t. It is worthwhile to investigate how the selling price of RDF can alter with varying transport costs and distance, as Figure 9 confirms that obtaining higher NPVs seems to be less possible by changing only the parameters related to transport. Figure 10 shows the variation of NPV with the different transport costs and distances for three different selling prices of RDF.

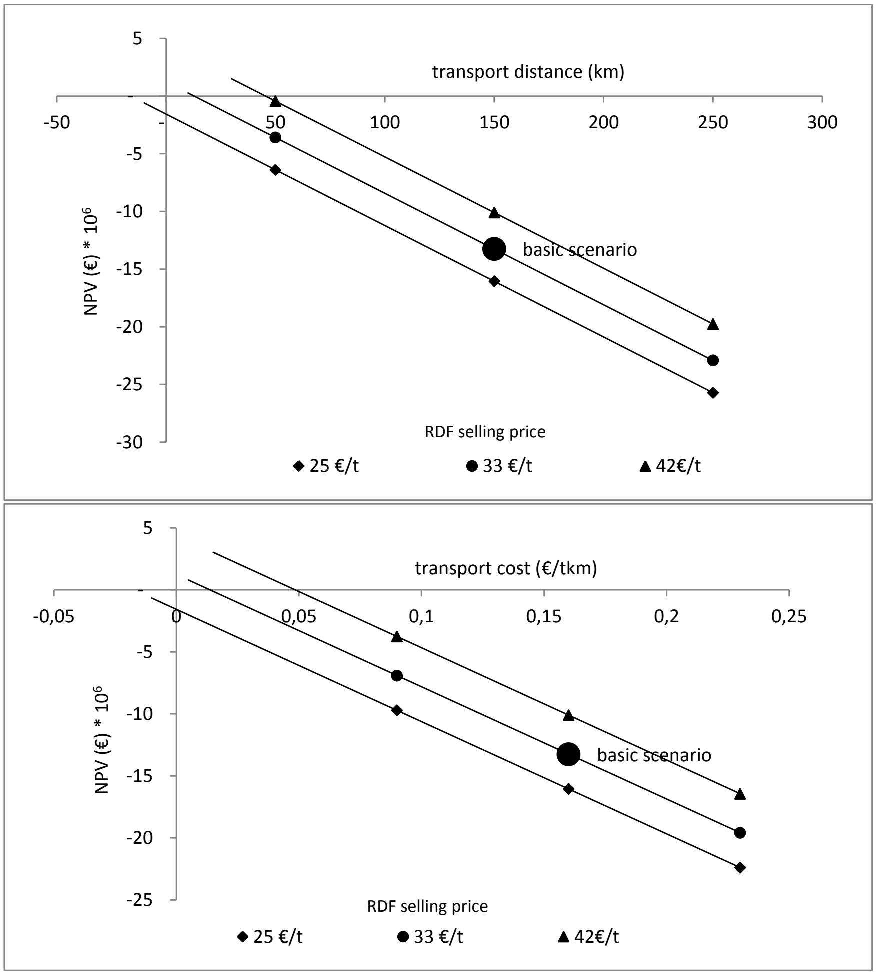

Figure 10: The impact of variations in transport distance (top) and transport cost (bottom) on NPV for different selling prices of RDF in scenario 1

Figure 10 shows that higher selling prices of RDF obviously lead to a gain in higher NPVs for varying transport distances and transport costs. However, increasing the selling price fully depends on the calorific value of RDF. Hence, for this study, the selling price cannot exceed the upper margin of 42 €/t. For that selling price, the maximum transport distance and transport costs should be approximately 50 km and 0.05 €/t km in order to make the NPV at least zero instead of having a negative value. Once more, Figure 10 further confirms the necessity of avoiding transport in this scenario.

For Scenario 2, calorific value of RDF, net electrical efficiency of thermal treatment system, and price of electricity become the highest positively contributing parameters to the NPV (Table 6). The range of the price of electricity in the sensitivity analysis was decided as follows: according to the announcement of the Public Utilities Commission of Sri Lanka (PUCSL), the list of rates for electricity purchased by the Ceylon Electricity Board (CEB) from Non-Conventional Renewable Energy (NCRE) sources shows that the rate for electricity from MSW is 26.10 LKR/kWh (1€=165LKR) (PUCSL 2012). As this technology is not yet well developed in Sri Lanka, this price was used in this study as the upper margin (150 €/MWh) of the range of electricity price. For the lowest margin, the price of electricity generated by mini hydro plants that are well developed in Sri Lanka (17.15 LKR/kWh, 100 €/MWh) has been used. Thus, the average electricity price used in this study is 125 €/MWh. Figure 11 illustrates the relationship between the net electrical efficiency, calorific value of RDF, and electricity price. The top panel of Figure 11 shows that for a fixed calorific value (20 MJ/kg), a 10 percent change in electrical efficiency yields 17 percent and 38 percent increments in NPV for electricity prices of 100 €/MWh and 125 €/MWh, while NPV doubles for the electricity price's upper margin (150 €/MWh). This Figure suggests that Scenario 2 (RDF valorisation via incineration) is economically feasible even with the moderate electrical efficiencies (21–25 percent) if the electricity purchase price by the CEB is high, as suggested above. According to the bottom panel of Figure 11, for a fixed electrical efficiency (22 percent), 10 percent, 18 percent, and 36 percent gain in NPV can be foreseen for 100-150 €/MWh of price range when the calorific value increases by 10 percent. The figure reveals that positive NPVs can be obtained even for the calorific values of less than 20 MJ/kg when the electricity price is in its upper margin.

Similar to LCA study, plasma gasification was used as an alternative thermal treatment technology in the LCC study as well with the similar costs reported in Danthurebandara et al. (2015a) (50 €/t RDF for investment cost and 67 €/t RDF for operational costs). Use of plasma gasification with 27% electrical efficiency in RDF valorisation shows a positive NPV (7032836 €). This positive NPV can be further increased by using plasmastone in production of higher value building materials (Danthurebandara et al. 2015b).

Apart from the private costs and benefits considered in this study, mining of open dumps obviously generate social costs and benefits. The related monetary value of such social costs and benefits can be estimated using cost- benefit analysis and contingent valuation method as used in recent landfill mining research (Van Passel et al. 2013, Marella and Raga 2014, Zhou et al. 2015).

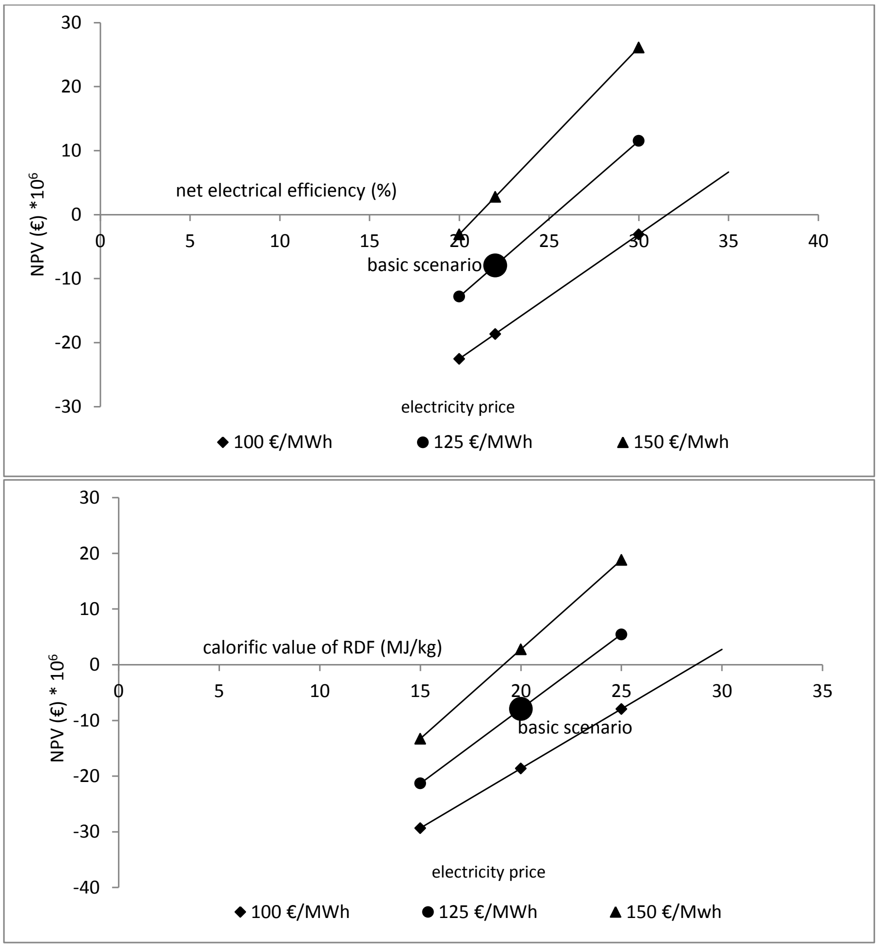

Figure 11: The impact of variations in net electrical efficiency (top) and calorific value of RDF (bottom) on NPV for different electricity prices in scenario 2

4.0. Conclusions

This paper discusses the feasibility of open waste dump mining in Sri Lanka. The study comprises two scenarios based on the destination of RDF: Scenario 1 includes the direct selling of RDF as an alternative fuel to replace coal usage in the cement industry, while Scenario 2 consists of processing RDF in an incineration plant in order to produce electricity. The LCA analysis reveals that both scenarios yield higher environmental benefits compared to the Do-nothing scenario. The environmental burden due to waste transportation is fully compensated by the avoided burden resulting from the replacement of production and transportation of coal in Scenario 1 and electricity generation in Scenario 2. More than 1.6 million tonnes CO_2 equivalent of GWP that occurred in the Do-nothing scenario can be eliminated by the discussed scenarios. The LCA study concludes that starting the waste valorisation during the early stage of waste degradation of a dump site is beneficial in GWP's viewpoint. The sensitivity analysis concludes that the RDF recovery efficiency, the calorific value of RDF, and the electrical efficiency of the thermal treatment system are the most important parameters from an environmental point of view. The LCC analysis shows that none of the scenarios are beneficial economically within the data used for the analysis; nevertheless, Scenario 2 performs better than Scenario 1 in this regard. The analysis further highlights the necessity of avoiding waste transportation in order to obtain economic profits. Moreover, the government may introduce higher subsidies or higher electricity prices in order to encourage entrepreneurs to initiate this type of projects. The study shows that technological changes such as introducing plasma gasification instead of incineration yield higher economic benefits. However, the immaturity of plasma gasification process may create higher levels of uncertainties and technical, legislative and institutional barriers for implementation. Overall, the study concludes open waste dump mining is beneficial from an environmental point of view. To realize open waste dump mining in a cost-effective way, above mentioned technological improvements or governmental support will be needed. The environmental benefits can be used to motivate the development of financial support instruments for open waste dump mining. The study highlights, the ELFM approach with energy and materials recovery through efficient technologies which results in lower net costs is a promising way to minimise the environmental burden of open waste dumps as traditional dump site remediation (including excavation, cleaning up the dump site area and re-landfilling the excavated waste in a different sanitary landfill) is an extremely costly operation. Finally, further research is needed to investigate the possibility of developing the ‘open waste dump mining’ concept as a clean development mechanism (CDM) project.

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