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LCA and economic evaluation of landfill leachate and gas technologies

Anders Damgaard[a]*, Simone Manfredi[a1], Hanna Merrild[a2],
Steen Stensøe[b] & Thomas H. Christensen[a]

[a]Department of Environmental Engineering
Technical University of Denmark
Miljoevej, Building 113, DK-2800 Kongens Lyngby
Denmark

[b]COWI
Parallelvej 2, DK-2800 Kongens Lyngby
Denmark

[1] European Commission - Joint Research Centre (JRC), Via Enrico Fermi 2749; Building 27, Office 035; T.P. 270; I-21027 Ispra (VA), Italy
[2] FORCE Technology, Hjortekærsvej 99, 2800 Kgs. Lyngby, Denmark

Abstract

Landfills receiving a mix of waste, including organics, have developed dramatically over the last 3-4 decades; from open dumps to engineered facilities with extensive controls on leachate and gas. The conventional municipal landfill will in most climates produce a highly contaminated leachate and a significant amount of landfill gas. Leachate controls may include bottom liners and leachate collection systems as well as leachate treatment prior to discharge to surface water. Gas controls may include oxidizing top covers, gas collection systems with flares or gas utilization systems for production of electricity and heat.

The importance of leachate and gas control measures in reducing the overall environmental impact from a conventional landfill was assessed by life-cycle-assessment (LCA). The direct cost for the measures were also estimated providing a basis for assessing which measures are the most cost-effective in reducing the impact from a conventional landfill. This was done by modeling landfills ranging from a simple open dump to highly engineered conventional landfills with energy recovery in form of heat or electricity. The modeling was done in the waste LCA model EASEWASTE. The results showed drastic improvements for most impact categories. Global warming went from an impact of 0.1 person equivalent (PE) for the dump to -0.05 PE for the best design. These correspond to a load of 870 kg CO_2-equivalents per tonne of waste landfilled (on a wet weight basis) to a saving of -435 kg CO_2-equivalents per tonne of waste landfilled, respectively. Similar improvements were found for photochemical ozone formation (0.02 PE to 0.002 PE) and stratospheric ozone formation (0.04 PE to 0.001 PE).

For the toxic and spoiled groundwater impact categories the trend is not as clear. The reason for this was that the load to the environment shifted as more technologies were used. For the dump landfill the main impacts were impacts for spoiled groundwater due to lack of leachate collection, 2.3 PE down to 0.4 PE when leachate is collected. However, at the same time, leachate collection causes a slight increase in eco-toxicity and human toxicity via water (0.007E to 0.013PE and 0.002 to 0.003 PE respectively). The reason for this is that even if the leachate is treated, slight amounts of contaminants are released through emissions of treated wastewater to surface waters. The drop in the impact from potentially spoiled groundwater, due to increased collection of leachate, is offset by a rise in increased human and eco-toxicity via water, due to contaminants in the larger amount of treated waste water.

The largest environmental improvement with regard to the direct cost of the landfill was the capping and leachate treatment system. The capping, though very cheap to establish, gave a huge benefit in lowered impacts, the leachate collection system though expensive gave large benefits as well. The other gas measures were found to give further improvements, for a minor increase in cost.

Keywords: EASEWASTE, LCA, landfill, leachate and gas collection

1 Introduction

Landfills have developed dramatically over the last 3-4 decades; from open dumps to engineered facilities with extensive controls on leachate and gas. Albeit many countries have detailed guidelines on how to plan, design and operate landfills, landfills will also in the future on a global scale encompass a wide range of technologies with various potential impacts on the environment. Due to regulations conventional landfills as presented here are being outfaced in a European context as organic waste is being treated with other technologies, but it is still the dominant technology worldwide both in industrialized and developing countries.

The conventional municipal landfill will in most climates produce a highly contaminated leachate and a significant amount of landfill gas. Leachate controls may include bottom liners and leachate collection systems as well as leachate treatment prior to discharge to surface water. Gas controls may include oxidizing top covers, gas collection systems, flares and also gas utilization in terms of electricity and heat production. These technical controls have also increased the direct cost of landfilling, which in some cases may be as high as 150 Euro per tonne (Hogg, 2002).

The purpose of this paper is to asses by life-cycle-assessment (LCA) how important leachate and gas control measures are in reducing the overall environmental impact from a conventional landfill. The direct cost for the measures are also estimated providing a basis for assessing which measures are the most cost-effective in reducing the impact from a conventional landfill. The environmental benefits of introducing new landfill technologies such as the bioreactor, the flushing bioreactor and the semi-aerobic landfill technology are not addressed here but in a paper by Manfredi & Christensen (2009).

2 Life-Cycle-Assessment: Approach and model

LCA provides a consistent framework for assessing potential environmental impacts for a specified system including any related up-stream and down-stream processes. We have chosen to use the EASEWASTE model (Kirkeby et al., 2006) for modeling the environmental impacts from landfilling. The EASEWASTE landfill module is described in detail by Kirkeby et al. (2007).

The functional unit for the study is 1 tonne of wet household waste deposited in a landfill with an average depth of 12.5 m and a compacted density of 800 kg/m^3; all the environmental aspects are accounted for in a time horizon of 100 years after disposal. The depth and density is used to calculate the amount of leachate generation based on the surface associated with this 1 tonne in the overall landfill design. These numbers are used to calculate the amounts of gas and leachate as explained later.

Table 1 presents the impact categories that EASEWASTE uses for aggregating all the quantified emissions to air, soil, surface water and groundwater. Most of the impact categories are based on the EDIP 97 method (Wenzel *et al.*, 1997). Table 1 also presents the normalization references used to convert the individual potential impacts into person equivalents (PE), which is an average value for the yearly contribution to a given impact category by all the activities and consumptions relative to one person. In the article the potential impacts are divided into 3 groups: standard, toxicity related and spoiled groundwater (i.e. groundwater polluted above the drinking water criteria).

2.1 Standard potential impacts

The standard potential impacts include Global Warming (GW), Photo-chemical Ozone Formation (POF), Ozone Depletion (OD), Acidification (AC) and Nutrient Enrichment (NE). The methodologies utilized for the assessment of these environmental impacts are well-acknowledged, although different units may appear in different models. The degree of certainty of the potential impacts can be considered high. In the case of global warming, emissions of CO_2 of biological origin are considered neutral as discussed in Christensen *et al.* (2009). This means that the CO_2 being emitted from the landfill as well as methane that is oxidized into CO_2 are counted as neutral and not contributing to GW since it originates from organic matter generated by an equivalent uptake of CO_2 during the plant growth. Emissions of CO_2 originating from fossil sources will be counted as contributing to GW, since this release of carbon is not balanced by a recent, equivalent uptake of carbon. The EASEWASTE model also counts the amount of biogenic carbon entering the landfill and left after the time horizon of the study (as default in EASEWASTE set to 100 years). This carbon is considered sequestered in the landfill and will therefore be counted as a saving and thereby decreasing the potential GW impact. The amount of biogenic CO2 released from the landfill is being calculated in the EASEWASTE inventory, it is only in the characterization that it is counted as neutral. It is important to note that the neutrality associated with biogenic CO_2 is only methodologically correct when factoring in carbon sequestration as discussed in Christensen *et al.* (2009). Alternatively the biogenic CO_2 could have been included with an impact, but in this case carbon sequestration should not have been included in order to be methodologically consistent.

2.2 Toxicity-related potential impacts

Toxicity-related potential impacts include Human Toxicity in soil (HTs), water (HTw) and air (HTa) as well as Ecotoxicity in soil (ETs) and in water (ETw). The degree of certainty of the impact potentials calculated for this group is low since the utilized methodology is still being developed and tested. Furthermore the model can calculate the stored toxicity in the landfill. This is an impact that has been introduced in EASEWASTE (adapted from Hansen *et al.* 2004 and Hauschild *et al.* 2008). The model calculates the amount of each toxic substance (heavy metals) that entered the landfill and is left at the end of the time horizon of the study, and ascribes each substance the characterization factor for eco-toxicity to soil and water. In this study it was decided to leave out the graphs for these impacts; this is not to say that these are not important, but because the same amount of toxic substance entered each landfill and it is almost the same amount that is left after the time horizon of the study, the results would be the same for all landfill. Conversely, if the study had included diversion of waste streams from the landfill this would have been extremely important.

2.3 Groundwater impact

Impact on groundwater is usually not addressed in LCA, but is here represented by Spoiled Groundwater Resource (SGWR). The impact is calculated as the volume of groundwater that the input to the groundwater (here leachate) can contaminate up to the drinking water criteria. This impact is adapted after Birgisdóttir *et al*. (2007) where it was used on leaching from bottom ash residues used in road construction. In the present study the WHO (2006) drinking water criteria were used instead of the Danish drinking water criteria used in Birgisdóttir *et al*. (2007). Similarly as for the other impact categories, the calculation is done for each substance and the sum yields the potential impact. The impact is normalized with regards to the amount of contaminated groundwater per person per year in Denmark (2900 m^3/person/year (DMU & DJF, 2003)); the normalization reference is based on the contamination by nitrate and chloride, and must be seen as a rough indicator. In previous studies with EASEWASTE*,* a normalization reference of 140 m^3/person/year was used which was the amount of drinking water consumption per person per year. That should be kept in mind when comparing with previous studies. The Spoiled Groundwater Resource impact potential is relevant only when groundwater is considered a limited resource and utilized.

3 The conventional landfill - modeling and design

3.1 Landfill types

The different landfill designs have been divided into 3 archetypes under which there are a couple of alternatives, giving a total of 7 different scenarios. The 3 archetypes are described briefly and an overview is presented of some of the most important technical differences for each landfill, for more detailed info section 3.3 contains the precise data used for each scenario.

The dump

The dump is considered in terms of an *Open dump* since this represents the theoretical worst case of a landfill with no measures to control leachate or gas. Besides the emissions from leachate and gas, the main environmental load comes from the diesel combusted in the specialized vehicles operating on-site (compactors, dozers, etc). The diesel consumption is estimated to 0.8 L diesel per tonne of waste (as cumulative value throughout 100 years).

Also a *Covered dump* is considered; this is a dump that is supplied with a low quality soil cover and vegetation after filling of the landfill section. This results in a reduced leachate generation since the soil cover can hold some water for evapotranspiration from the wet period to the dry period of the year. The top cover also provides some gas oxidation in particular when the gas generation is modest in the later part of the 100 year period considered. The diesel consumption is here estimated to 0.9 L diesel per tonne of waste for waste compaction, soil moving and for establishing the top cover. It is assumed that the soil for the cover is present at the site.

The simple conventional landfill

The simple conventional landfill has introduced a bottom liner, leachate collection and leachate treatment. The top cover is of higher quality than for the covered dump and therefore it is able to provide a superior oxidation of gas constituents. The gas may migrate through the top cover or be collected and managed by biofilters or by flares. The biofilters are only partially effective while the flare is highly effective in oxidizing the gas. However, the flare produces some secondary air pollutants (NSCA, 2002). The diesel consumption is here set to 2 L diesel per tonne of waste, used for waste compaction, soil moving, establishing the top cover, installing leachate and gas collection systems and for post-closure operations. The collected fraction of leachate is sent to a treatment plant, the pollutants remaining in the treated leachate is assumed discharged to surface water, while the uncollected fraction is assumed to reach the groundwater.

The energy-recovery conventional landfill

The energy-recovery conventional landfill represents the most advanced conventional landfill, where the gas is collected and used for energy production. The design is similar to the simple conventional landfill, but the collected gas is here used for energy production. The produced energy is assumed to substitute 100% for energy production at a coal-fired power plant or a power plant based on natural gas, either in pure power production or as combined heat and power (CHP). The saved emissions from the power plants are credited the landfill gas utilization system. The reason to choose to model both coal and natural gas substitution is that it is found that this can often have a large impact in the life cycle assessment of waste management (Fruergaard *et al*., 2009).

3.2 Basic features

The EASEWASTE model contains a flexible landfill module as described by Kirkeby et al. (2007).. It is assumed that the landfill cell is being filled within 2 years after which it is closed and leachate and gas mitigation systems are installed in relevant scenarios. The annual net infiltration for the vegetated top cover is set to 300 mm.

Energy used for operation and maintenance and excavation of the landfill is included for all the landfills and considered to be identical. Emissions associated with these operations as well as upstream production are accounted for as well.

The landfill is considered for a 100 year period. All uses of resources and all emissions during this period are accounted for. It is likely that landfill gas generation is approaching a negligible value within this period. The waste being landfilled is assumed to be municipal solid waste with a wet weight composition of 35% organics (food waste, flowers etc.), 30% paper and cardboard, 10% plastics, 9% glass and 16% of other fractions. The total amount of methane generated during the 100 years is calculated to 77 Nm^3 CH_4 per tonne of wet waste corresponding to approximately 160 Nm^3 landfill gas (LFG) per tonne of wet waste for this waste composition. Contaminated leachate, however, is expected to appear also after 100 year. However, this circumstance is not accounted for in the assessment. If the composition of waste sent to the landfill were to change, this would directly impact the amount of generated methane and thereby the performance of the landfill.

The development in leachate and gas composition and amount over the 100 year period is described by defining typical values for 4 time segments within the 100 year period. The values used in this study are shown in Table 2 and 3.

Table 2 shows the composition of the landfill gas through the 4 defined time periods; average oxidation removal efficiencies relative to each period are also provided. Oxidation implies that the substance is converted to a non-impacting substance. The composition is primarily based on Deipser et al. (1996), Mahieu et al. (2005), NSCA (2002), Rettenberger (2005), Rettenberger and Stegmann (1996), Scheutz et al. (2004), Scheutz and Kjeldsen (2005). Table 3 gives the concentration of modeled compounds in the leachate composition. The composition is assumed to be the same for all the different scenarios, even though there are some variations in infiltration rates. However, it is assumed that the controlling parameters for the leachate formation are comparable in all landfills. Removal efficiencies are here defined as the amount of substance that can be removed in the leachate treatment plant, and therefore does not end up being released into a freshwater source. The composition is mainly based on data from Ehrig (1983), Kjeldsen and Christophersen (2001), Lee and Jones (1993), Reinhart et al. (1998). Removal efficiencies are based on Knox et al. (2003), U.S. EPA (1989 and 1992)

The values in Table 2 and 3 are typical values aggregated from many different sources. These data are the same for all the modeled landfills, and the only difference is the amount of produced leachate and gas multiplied with these generation values.

3.3 Technical measures

The technical measures of the conventional landfill relates primarily to leachate and gas control. Table 4 describes the technical measures applied in each scenario. The performance of these measures, including any functional deterioration over time, is also described by constant parameters within each of 4 time segments. The length of the segments can in EASEWASTE be defined independently for each measure.

Typical or possible measures regarding leachate and gas controls are described below. These are combined to define the various conventional landfills representing different level of environmental protection. The key parameter values are presented in Table 5.

Measures for landfill gas control

- Gas measure 1 (G1): No top cover and no gas collection system are installed. All the generated gas is emitted directly to air. No oxidation of the landfill gas is thus expected to take place. (Open dump)
- Gas measure 2 (G2): A soil top cover is installed after the filling of the cell (2 years) and provides partial oxidation of the various constituents of the gas. The oxidation of methane is assumed to be low during the first 40 years where the flow rate through the top cover is high (an average of 35% is oxidized), and high at the later time segments (around 80% is oxidized) when the flow rate is modest. The oxidation rates used are based on numbers from a review by Chanton *et al.* (2009).(Covered dump)
- Gas measure 3 (G3): A gas collection system is installed after the cell has been filled with waste (2 years). Efficiencies of gas collection systems are widely discussed. Based on a study by Börjesson *et al.* (2009) a rate of 75% LFG collection assuming best available technology performance was decided. This gives an overall gas extraction of 58 m^3 CH_4 per tonne of landfilled wet municipal waste. The collected fraction is treated at the site, either by biological filters (G3A), which on average oxidizes 60% (based on Gebert (2003) and Scheutz (2002)) of the methane without forming any secondary gaseous products except CO_2, or in flares (G3B), which oxidize 98-99.7% of the methane, while some secondary gaseous products are being formed (NOx, CO, dioxin etc.). Data for emissions from flares are based on NSCA (2002) and U.S. EPA. (2000, 2008). The uncollected fraction of the LFG is partly oxidized in the top soil cover, and it is assumed that 80% is oxidized in the period where there is gas collection, resulting in a low flow. The oxidation rates in the last 60 years where there is no gas collection were lowered. This is due to the assumption that fugitive gas releases through leachate and gas collection systems may take place, which would lower the overall oxidation efficiency even though the flow is lower here. (Conventional landfill)
- Gas measure 4 (G4): Similar to Gas Measure 3. The collected fraction of gas is here sent to a facility producing either electricity at an efficiency of 30% (G4E) or heat at an efficiency of 80% (G4H). Data for emissions from boilers and combustion engines are based on NSCA (2002) and U.S. EPA. (2000, 2008). The produced energy is assumed to substitute 100% for energy production at a coal-fired power plant (G4EC and G4HC) or power plant based on natural gas (G4EN and G4HN). The saved emissions from the power plants are credited the landfill gas utilization system. Electricity consumption is assumed generated by the same process as for the avoided electricity. (Conventional energy recovery landfill).

Measures for landfill leachate control

- Leachate measure 1 (L1): No bottom liner and no leachate collection system are installed. The generated leachate migrates directly into the groundwater. (Open and covered dumps)
- Leachate measure 2 (L2): Bottom liner and leachate collection system are installed (done in combination with G2-4 where the landfill is capped which also leads to a lower leachate production). The efficiency of the leachate collection system is high during the first 20 years (95%), assumed to fall to 80% after 20 years where there starts to be some liner failure and clogging, and finally down to 60% in the aftercare period. This is a conservative estimate; the liner might be lasting much longer. The collected fraction of the generated leachate is treated prior to discharge to surface water (marine or fresh). The removal efficiencies of the various leachate constituents are based on a range of values for each constituent(s)*remove s* and has been recalculated to mean values, these give efficiencies ranging from 22% (for phosphate) and up to 97-98% (for BOD and ammonia). Emissions from sludge management are disregarded, and it is acknowledged this can be an issue due to the high amount of contaminants in the sludge. The uncollected fraction of the generated leachate is assumed to reach the groundwater.

4 The conventional landfill: Cost estimates of technical measures

Landfill costs are highly variable. Hogg (2002) reports that even within Europe the cost may range from 25 to 150 Euro/tonne excluding landfill taxes. This variation is partially due to different levels of technical measures installed at the landfill and partially due to regional differences in the cost of land, wages and earnings from sale of energy from LFG. In reality, the price (i.e. the gate fee) of landfilling may not directly reflect the actual cost, but merely be controlled by the market and availability of alternatives to the actual landfill.

Table 6 presents our estimated typical unit cost for the technical measures described above (based on: Bates and Haworth, 2001; Delaware Solid Waste Authority, 2006; Hogg, 2002; Johannessen, 1999a, 1999b; Purdy and Shedden, 2005). The baseline cost for a dump without any measures to control leachate or gas is set to 40 Euro/tonne, including capital costs and operational costs. This baseline cost is used for all the landfills and in addition the costs for the technical measures are added step by step.

The unit costs are used to evaluate the cost-effectiveness of the different measures in relation to the environmental benefits that are achieved. The hypothesis is that some measures might give a high environmental benefit but at a high cost, while other measures can achieve similar benefits at a much lower cost.

The cost components are combined differently for the seven landfill scenarios. All of the landfills have the same baseline cost which includes land acquisition, construction and landfill operation. Most of the numbers used for the calculations are given in Euro/tonne and can simply be introduced into the “per tonne” calculations. However, the gas collection, leachate collection and treatment, electricity and district heating production were given in other units and therefore have been calculated into Euro/tonne. This has been done with the data from the life cycle assessment inventory, and these amounts are given in the table footnotes. The total costs for the different landfill technologies, can be seen at the bottom of Table 6. Additionally uncertainty in the allocated numbers are presented in Table 6, and this accumulated uncertainty are shown in Figure 3.

5 Results and discussion

5.1 Standard impact categories

Through the use of the LCA model EASEWASTE significant aspects of landfill design have been modeled and associated potential environmental impacts have been estimated. The main results achieved are given in Figures 1, 2 and 3.

Figure 1 gives the normalized impact potentials for the ordinary impact categories. It can be seen that global warming is significant in the dump landfills and in the landfill with the simple soil cover (up to 0.1 PE per tonne wet waste corresponding to 870 kg CO_2-equivalents per tonne wet waste). When a gas collection system is installed, some oxidation of the gas constituent can be provided by biofilters. These do not generate any other new emissions besides carbon dioxide (biogenic). Flares provide a much more efficient reduction of methane emissions, so that the global warming impact is lowered to -0.026 PE per tonne wet waste. The reason for the negative number is due to the fact that carbon sequestration is included in the number for all the landfill (0.05 PE sequestered per tonne wet waste). This sequestration is calculated based on the biogenic carbon content, which is still present in the landfill after the timeframe of the study (100 years). This carbon content in based on the defined waste composition sent to the landfill. The importance of this is illustrated by the "Net value – no sequestration" marks in Figure 1 where the sequestration has been excluded. If the time horizon for the study was further extended the amount of sequestered carbon would drop a little as a certain fraction of the remaining carbon would be released (the last 4% of easily degradable carbon which is not released in the first 100 years where 96% is assumed released), but an amount of the carbon is also expected to be stored in sequestered form in the future. When the collected gas is sent to an energy recovery facility, the global warming savings are further increased, as shown in Figure 1. It can here also be seen that the savings calculated when substituting coal are higher than that with natural gas. This shows that it is important to evaluate what energy source would have been used if the energy had not been recovered from the landfill.

The impact potentials calculated for the other ordinary impact categories are smaller in magnitude than the impact potential estimated for global warming. The impact for photochemical ozone formation is mainly due to emissions of methane and VOC's, which follows the same declining trend as for global warming due to the mitigation measures for these substances. Impact potentials for acidification and nutrient enrichment are very close to zero PE, and the main substances of importance here, is the leaching of phosphate and ammonia to surface water (marine or fresh). Stratospheric ozone depletion is the second largest impact with an impact of up to 0.04 PE per tonne of wet waste. This is due to emissions of CFC11 and CFC12 and their degradation products. Even though a large part of these are oxidized in the landfills as discussed by Scheutz and Kjeldsen (2005), some of the substances left are still emitted as they leave the landfill. In the future, this impact is expected to drop since these substances are banned in new products, but the cooling agent substances that are replacing CFCs are not included, due to lack of data, and it is therefore not known if this impact is still going to be of importance in future environmental assessment of landfills. But in countries where electronic waste must be collected separately this should not be a concern, and this is a good reason to promote separate collection of electronic waste to remove this uncertainty about a potential impact.

5.2 *Toxic impact categories*

Impact potentials on toxicity-related categories are also presented in Figure 1. Leachate controlling measures (bottom-liner and collection) lead to increased toxicity to the water ecosystem (from 0.007 PE to 0.012 PE per tonne waste). This is due to the fact that the leachate is treated at a wastewater plant, and the treated water is discharged into surface waters. There will though still be a minor amount of contaminants left in the treated water (e.g. copper and zinc) that will lead to an increased impact of eco-toxicity in water. The reason this impact is not as high in the not lined systems (L1G1 and L1G2) is that the leachate here will end in the groundwater resource and thereby will not be accredited to the surface water. As it can be seen from Figure 2, it is the unlined systems that cause the largest impact, which shows that the burdens are just shifted when controlling the leachate. The size in PE should not be compared directly since the methodology between the two impacts is quite different, but it gives a good picture of why it is necessary to collect the leachate. It is to be noted that the main contributor to spoiled groundwater resources is ammonia, and the contribution and fate of this substance should be further studied to establish its importance.

Eco-toxicity in soil is having such a small impact that it is not even noticeable on the figure, but has been kept in order to show that it was calculated. The same applies to human toxicity via air. The reason for the very small impact is that it is mainly caused by emissions associated with the combustion from the on-site vehicles; thus, once normalized with the yearly contribution for one person, this impact becomes very small.

Human toxicity via soil is where the largest contribution and also changes are calculated for the toxic impact categories. The main reason for this is that organic compounds (benzene, vinylchloride etc.), which are found to be the main contributing substances to the impact, are oxidized as soon as a retention time is introduced via a cover material. By collecting the gas and flaring or combusting it, the amount of substance being converted is further increased, showing the benefit of recovery over passive oxidation. That these substances have such a high impact is somewhat surprising, as it would have been expected that most of them would quickly degrade when being released to the atmosphere. By comparing the characterization factors with those of EDIP 2003 methodology (Hauschild and Potter, 2005) and USEtox methodology (Rosenbaum *et al.*, 2008) it was found that the impact to soil from these substances is considerably lower in these methodologies. If lowering the impact from these substances the overall impact fell, but the trend for a large importance was the same. This does show that the uncertainty with regards to the toxic methodologies should be kept in mind, and that when the USEtox methodology for metals are finalized it may be better to move to this updated methodology for any future assessment.

For human toxicity via water there can be seen a growing trend as more measures are introduced, the only exception being when there are substitution taking place based on coal. The reason for the impact is mainly due to dioxin formation in the LFG combustion processes, as well as fugitive releases of mercury compounds. The reason for the savings is that coal power itself represents a huge mercury load to the atmosphere, and this offsets the emissions from the LFG leading to a net saving.

5.3 *Economic costs*

In order to link economic costs to environmental performance the net sum of the impacts potentials was plotted as a function of the costs for the landfill setup. The result of this is shown in Figure 3. The net impact potentials are calculated by associating all impacts with a weight of one, meaning all impacts are considered of similar importance. The choice of a uniform weight is taken to be neutral. The reader can compare the individual columns in Figure 1 with the costs in Table 6 to get a view of the disaggregated costs and impacts. Based on Figure 3 it is clear that the open dump is the cheapest but also the worst performing landfill as expected. It can be seen that by covering the dump the impact of the landfill can be drastically lowered for very little additional cost (40 versus 42 Euro). This is due to the drop in leachate formation due to evaporation in the top cover, as well as top cover oxidation of a large amount of the gas constituents. Furthermore, a cover would mean that the landfill is more esthetic, odor problems are minimized, blowing litter will be avoided and less vector intrusion (birds, rodents etc.) will take place. All of these impacts are not measured in a traditional LCA but would still be of relevance in the planning of a landfill. The installation of the leachate collection system is the most costly installation besides the base costs (10 Euro per m^3 leachate), but it can be seen that there is still a large avoided impact from this, which is due to the drop in impact to SGR.

The treatment costs for the non-passive gas treatment systems are not varying very much (57-63 Euro) and are mainly due to differences in cost and income for the combustion systems. The difference from the worst process in this category (L2G2) and the best (G4HC) is an impact of approximately 0.1PE while actually saving 5 Euro, due to the income from the energy paying for the gas collection and combustion equipment. The landfills substituting heat seems to be a better choice than electricity, which is due to the fact that the efficiency of the heat generation is remarkably higher. It has though to be kept in mind that this option is only viable if there is a customer to receive the generated heat. Electricity can on the other hand always be sold to the grid and is therefore an easier default option. In general the energy recovery options are a better option than the non-energy scenarios since the payment for the sold energy offsets the plant costs of the generators, and at the same time the substituted energy means that the environmental impact is considerably lower. This is only true as long as the studied landfill has a high methane production (f.x. from household waste), whereas a low-carbon landfill would most likely not generate enough methane to support energy production. The presented overall uncertainty in Table 6 indicates that there is in reality not any difference between the cost for the more advanced treatment technologies, as the uncertainty is as big as the largest difference between these technologies. There should therefore not be any reason for not going for the optimal treatment technology as long as the energy can be sold.

5.4 Conclusions

Overall, it can be observed that the efficiencies of gas and leachate collection systems are crucial parameters in the assessment, since a poor collection compromises the overall environmental performance. However, when good efficiencies are achieved, other circumstances might affect the assessment. With respect to landfill gas, the considered combustion treatment measures have demonstrated to generate emissions which are of particular concern for the toxicity-related impacts. Furthermore, contaminated leachate is expected to be generated in significant amounts long after the end of the collection period (70 years). As a consequence, a substantial potential impact on spoiled groundwater resource still exists in those landfills collecting leachate.

Since there is a linear correlation per tonne of waste in our calculations, between leachate generation and the amount of leachate substance generated, the uncertainty with regards to the leachate generation per tonne of waste will mean this uncertainty is reflected in the leachate substances and hence the overall impact of the landfill. But of even more importance is the geographical location of the landfill, as the precipitation rates vary considerably from region to region, and a landfill in an arid versus a humid region will mean a difference in orders of magnitude for the potential leachate generation. Similarly, the landfill depth when the final cap is placed will determine the surface area of the landfill, and hence the leachate generation rate. The same is the case for the methane and LFG generation where there is a large variability in generation rates depending on the composition of the landfilled waste. It is therefore important in a study to have a good knowledge of the waste fractions entering the landfill. When for instance doing an integrated waste study with different diversion rates it is crucial to make sure that this is updated whenever the composition changes (if this is not done automatically by the model).

It is therefore very important when doing an LCA study for waste management to make sure that the landfill being modeled is not just an average landfill, but that it actually represents the state of technology present or intended for the system.

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Figure captions

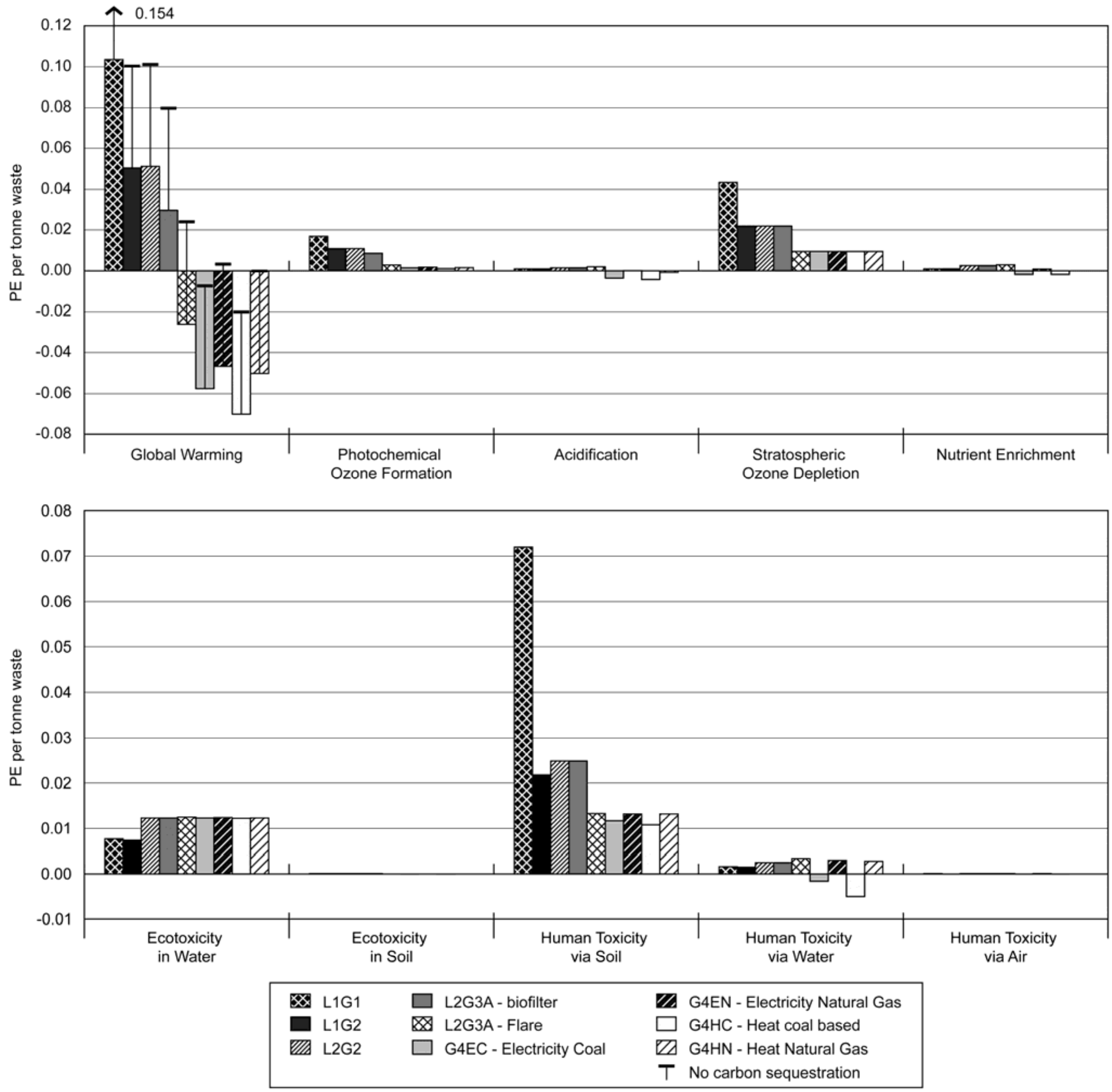

Figure 1 Environmental impacts for the nine landfill scenarios. Values given in person equivalent (PE) per tonne wet waste landfilled.

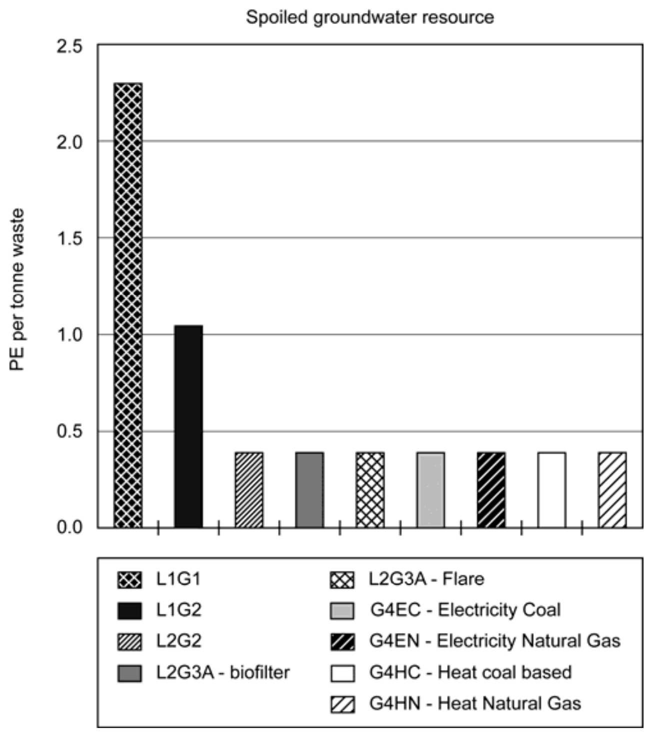

Figure 2 Spoiled groundwater resources for the nine landfills. Values given in person equivalent (PE) per tonne wet waste landfilled.

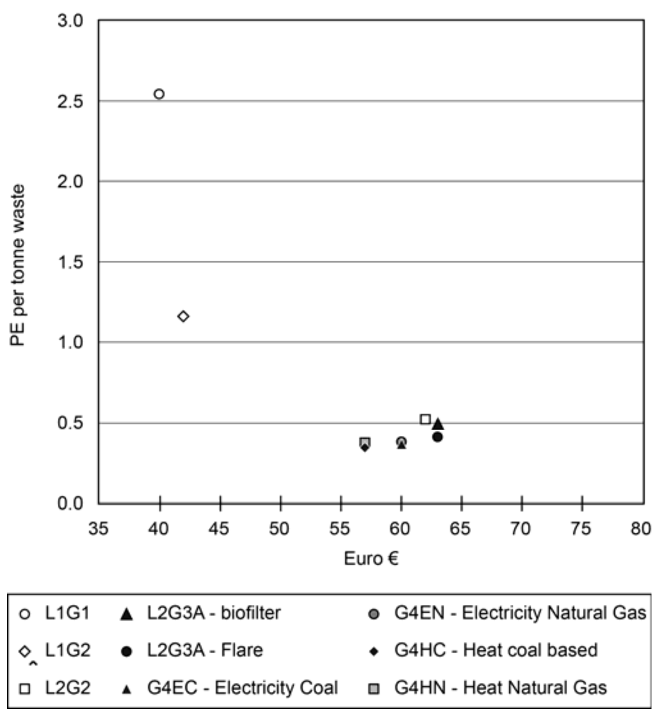

Figure 3 All potential impacts (standard, toxic and SGWR)in PE per tonne waste as a function of the costs of the treatment type in Euro. The error bars show the uncertainty of the individual treatment technologies as presented in Table 6.

Tables

Table 1 Potential impact categories included in EASEWASTE (after Kirkeby et al., 2006). Normalization references after Stranddorf et al. (2005).

Potential Impact Category	Acronym	Unit	Physical basis	Normalization reference EU-15
Global Warming, 100 years	GW	kg CO_2-eq. /person/yr	Global	8 700
Photochemical Ozone Formation	POF	kg C_2H_4-eq. /person/yr	Regional	25
Ozone Depletion	OD	kg CFC-11-eq./person/yr	Global	0.103
Acidification	AC	kg SO_2-eq. /person/yr	Regional	74
Nutrient Enrichment	NE	kg NO_3^{-}eq. /person/yr	Regional	119
Human Toxicity, soil	HTs	m^3 soil /person/yr	Regional	157
Human Toxicity, water	HTw	m^3 water /person/yr	Regional	179 000
Human Toxicity, air	HTa	m^3 air /person/yr	Regional	2 090 000 000
Ecotoxicity, soil	ETs	m^3 soil /person/yr	Regional	964 000
Ecotoxicity, water chronic	ETwc	m^3 water /person/yr	Regional	352 000
Spoiled Groundwater Resources	SGWR	m^3 water /person/yr	Local	2 900 [a]

[a] Calculated based on the contamination of Danish groundwater

Table 2 Gas concentrations in the landfill gas and oxidation in the top cover for the conventional landfill. Based on: Deipser et al. (1996), Mahieu *et al.* (2005), NSCA (2002), Rettenberger (2005), Rettenberger and Stegmann (1996), Scheutz *et al.* (2004), Scheutz and Kjeldsen (2005).

	Period 1 (2yr)		Period 2 (3yr)		Period 3 (35yr)		Period 4 (60yr)	
substances	Composition	Ox.* (%)	Composition	Ox. (%)	Composition	Ox. (%)	Composition	Ox. (%)
Methane (CH_4)	25%		40%		60%		5%	
Carbon dioxide (CO_2)	70%		60%		40%		30%	
	(g/nm3 LFG)		(g/nm3 LFG)		(g/nm3 LFG)		(g/nm3 LFG)	
Benzene	0.007	0	0.007	26	0.007	26	0.007	50
Carbon Monoxide	1E-5	0	1E-5	20	1E-5	20	1E-5	40
Carbon tetrachloride	3E-5	0	3E-5	*0*	3E-5	*0*	3E-5	*0*
CFC 11	0.01	0	0.01	90	0.01	90	0.01	90
CFC12	0.02	0	0.02	30	0.02	30	0.02	30
Chlorobenzene	0.002	0	0. 0.002	*0*	0.002	*0*	0.002	*0*
Chloroform	0.005	0	0.005	*0*	0.005	*0*	0.005	*0*
Ethylbenzene	0.05	0	0.05	26	0.05	26	0.05	50
Ethylene dichloride	0.05	0	0.05	0	0. 0.05	0	0.05	0
HCFC 21	0.012	0	0.012	60	0.012	60	0.012	60
HCFC 22	0.013	0	0.013	40	0.013	40	0.013	40
Hydrogen chloride	0.006	0	0.006	0	0.006	0	0.006	0
Hydrogen fluoride	0.002	0	0.002	0	0.002	0	0.002	0
Hydrogen sulphide	7E-5	0	7E-5	20	7E-5	20	7E-5	40
Methylene chloride	0.05	0	0.05	40	0.05	40	0.05	40
Mercury	3.5E-6	0	3.5E-6	0	3.5E-6	0	3.5E-6	0
Tetrachloroethene	0.027	0	0.027	40	0.027	40	0.027	40
Toluene	0.16	0	0.16	60	0.16	60	0.16	60
Trichloroethene	0.016	0	0.016	40	0.016	40	0.016	40
Vinyl chloride	0.01	0	0.01	90	0.01	90	0.01	90
VOCs	0.23	0	0.23	60	0.23	60	0.23	80
Xylenes	0.06	0	0.06	30	0.06	30	0.06	30

*The open dump landfill does not have a top cover, hence no oxidation of gas constituents is assumed to occur. For methane oxidation efficiencies for the different landfills see table 5.

Table 3 Leachate data for the conventional landfill for the four time periods (g/m^3 leachate). Based on Ehrig (1983), Kjeldsen and Christophersen (2001), Lee and Jones (1993), Reinhart et al. (1998). Removal efficiencies are based on Knox *et al.* (2003), U.S. EPA (1989 and 1992)

	Period 1 (2 years)	Period 2 (8 years)	Period 3 (30 years)	Period 4 (60 years)	Removal in WWTP (%)
General					
TSS	60	60	60	60	96
BOD	13000	8000	800	30	97
COD	15000	12000	3000	200	80
NH_3	1000	700	500	400	98
PO_4	14	14	14	14	22
Calcium	1000	1000	1000	1000	85
Chloride	2500	2000	1500	980	85
Magnesium	300	300	300	300	85
Sodium	700	500	400	200	85
Trace Organics					
Benzene	0.0065	0.0065	0.0065	0.0065	99
Chloroform	0.0003	0.0003	0.0003	0.0003	99
Ethylbenzene	0.02	0.02	0.02	0.02	80
Ethylene dichloride	0.05	0.05	0.014	0.014	70
Methylene chloride	0.03	0.015	0.008	0.004	70
Tetrachloroethene	0.01	0.01	0.01	0.01	70
Toluene	0.16	0.16	0.02	0.02	80
Trichloroethene	0.005	0.005	0.007	0.007	70
Vinyl chloride	0.05	0.05	0.04	0.04	70
Xylenes	0.05	0.05	0.05	0.05	60
Metals					
Arsenic	0.03	0.025	0.02	0.02	70
Barium	0.5	0.3	0.2	0.16	85
Cadmium	0.012	0.01	0.008	0.006	85
Chromium	0.07	0.06	0.05	0.04	30
Copper	0.12	0.1	0.1	0.07	50
Lead	0.06	0.04	0.02	0.005	85
Mercury	0.0004	0.0003	0.0002	0.0002	85
Nickel	0.07	0.06	0.05	0.04	20
Selenium	0.01	0.008	0.006	0.006	85
Silver	0.08	0.07	0.03	0.01	85
Zinc	4	2.2	1.5	0.7	70

Table 4 The 7 scenarios with the technical measures (L & G) applied in each scenario.

Landfill Type	Technical Measure	Description
Dump		
Open Dump	L1 + G1	Open, no treatment
Covered Dump	L1 + G2	Covered with soil to allow for top cover oxidation.
Simple conventional		
Simple	L2 + G2	Leachate is collected and sent to treatment, no gas mitigation besides top cover oxidation
Biofilter	L2 + G3A	Leachate is collected and sent to treatment, gas collection and treatment with biofilter
Flaring	L2 + G3B	Leachate is collected and sent to treatment, gas collection and combustion in flares.
Energy recovery landfill		
Energy recovery for electricity production	L2+G4E	Leachate is collected and sent to treatment. Gas is collected and sent to a combustion engine for electricity production. Substituting electricity based on combustion of coal or natural gas
Energy recovery for heat production.	L2+G4H	Leachate is collected and sent to treatment. Gas is collected and sent to a boiler for heat production. Substituting heat based on combustion of coal or natural gas.

Table 5 Key parameters describing the defined conventional landfill technologies in terms of measures for leachate and gas control. For each cell per period is defined the number of years, and the amount per period or year.

	Time period 1	Time period 2	Time period 3	Time period 4
The dump (L1, G1)				
Gas generated (% of gas potential)	2y: 2%	3y: 8%	35y: 70%	60y: 16%
Gas collected (% of generated)	None	None	None	None
Gas oxidized by top cover (% of uncollected)	None	None	None	None
Leachate generated (mm/y)	2y: 500	8y: 500	40y: 450	50y: 450
Leachate collected (% of generated)	None	None	None	None
Leachate entering groundwater (% of generated)	2y: 100%	8y: 100%	40y: 100%	50y: 100%
The covered dump (L1, G2)				
Gas generated (% of gas potential)	2y: 2%	3y: 8%	35y: 70%	60y: 16%
Gas collected (% of generated)	None	None	None	None
Gas oxidized by top cover (% of uncollected)	2y: 0%	3y: 35%	35y: 35%	60y: 80%
Leachate generated (mm/y)	2y: 500 mm/y	8y. 250 mm/y	30y: 200 mm/y	60y: 180 mm/y
Leachate collected (% of generated)	None	None	None	None
Leachate entering groundwater (% of generated)	2y: 100%	8y: 100%	40y: 100%	50y: 100%
The simple conventional landfill (L2 and, G2, G3A or G3B)				
Gas generated (% of gas potential)	2y: 2%	3y: 8%	35y: 70%	60y: 16%
Gas collected (% of generated)	2y: 0%	3y: 75%	35y: 75%	60y: 0%
Gas management	None	Flared/filter	Flare/filter	None
Gas oxidized by top cover (% of uncollected)	2y: 0%	3y: 80%	35y: 80%	60y: 70%
Leachate generated (mm/y)	2y: 500 mm/y	8y. 250 mm/y	30y: 200 mm/y	60y: 180 mm/y
Leachate collected (% of generated)	20y: 95%	20y: 80%	30y: 60%	30y: 0%
Leachate entering groundwater (% of generated)	20y: 5%	20y: 20%	30y: 40%	30y: 100%
The energy-recovery conventional landfill (L2, G4)				
Gas generated (% of gas potential)	2y: 2%	3y: 8%	35y: 70%	60y: 16%
Gas collected (% of generated)	2y: 0%	3y: 75%	35y: 75%	60y: 0%
Gas management	None	Flared	Elec/CHP	None
Gas oxidized by top cover (% of uncollected)	2y: 0%	3y: 80%	35y: 80%	60y: 80%
Leachate generated (mm/y)	2y: 500 mm/y	8y. 250 mm/y	30y: 200 mm/y	60y: 180 mm/y
Leachate collected (% of generated)	20y: 95%	20y: 80%	30y: 60%	30y: 0%
Leachate entering groundwater (% of generated)	20y: 5%	20y: 20%	30y: 40%	30y: 100%

Table 6: Typical unit costs for technical measures included in the seven landfill configurations.

Configuration	Unit	G1 + L1	G2 + L1	G2 + L2	G3A + L2	G3B + L2	G4EN/G4EC + L2	G4HN/G4HC + L2	Uncertainty
Baseline cost	€/tonne	40	40	40	40	40	40	40	
Simple top cover	€/tonne		2						
Top cover	€/tonne			3	3	3	3	3	±1
Bottom liner	€/tonne			4	4	4	4	4	±1
Leachate collection [a]	€/tonne			2.5	2.5	2.5	2.5	2.5	±0.5
Leachate treatment	€/tonne			11.2	11.2	11.2	11.2	11.2	±2
Gas collection [b]	€/tonne				1	1	1	1	±0.01
Biofilter	€/tonne				0.1				
Flare	€/tonne					0.15			
Electricity plant	€/tonne						2		± 0.5
Heat plant	€/tonne							1.0	± 0.5
Electricity sold	€/tonne						5.2		
District heating sold [c]	€/tonne							6.9	
Total cost	€/tonne	40	42	62	63	63	60	57	
Accumulated uncertainty	€/tonne	0	0	±4.5	±5.6	±5.6	±6.1	±6.1	

[a] 1.12 m^3 leachate per tonne waste.
[b] LFG collection and treatment based on 100 m^3
[c] 56m^3 methane recovered for energy generation