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DTU Environment
Department of Environmental Engineering

PhD Thesis
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The thesis will be available as a pdf-file for downloading from the homepage of the department: www.env.dtu.dk

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Preface

This thesis “Environmental Assessment of Solid Waste Landfilling in a Life Cycle Perspective (LCA model EASEWASTE)” is the result of a 3-year PhD study carried out at the Department of Environmental Engineering of the Technical University of Denmark (DTU) with the supervision of Professor Thomas H. Christensen. Seven journal manuscripts were prepared during the course of the study and are enclosed in this thesis. They are referred to in the thesis by their roman numerals:

I. **Manfredi, S.** & Christensen, T.H. (2009): Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Management* **29**, 32-43

II. Niskanen, A., **Manfredi, S**., Christensen, T.H. & Anderson R. (2009): Environmental assessment of Ämmässuo Landfill (Finland) by means of LCA-modelling (EASEWASTE). *Waste Management & Research*. Accepted for publication

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Kgs. Lyngby – June 2009

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Last, but certainly not least, I would like to express my gratitude to my parents and my whole family for their unconditional love and support.

Simone

Summary

Several alternatives are currently available for the handling of mixed waste; nevertheless, landfilling represents the most common option in many parts of the world. In Europe, policies have been enforced to prioritize recycling and other options but, due to the constantly increasing generation of waste, the amount of waste to landfills is not expected to decrease within the near future.

Landfilling of waste contributes to a variety of environmental impacts and, above all, landfills account for most of the greenhouse gas (GHG) emissions from the waste management sector. These emissions, however, mainly come from old, poorly managed landfills that have little in common with the current up-to-date landfills. In fact, landfills have undergone a substantial technological evolution during the last decades. New technical measures have been extensively implemented to reduce emissions and new technologies have been introduced that optimize the degradation processes and allow for utilization of the collected landfill gas (LFG) for energy generation. The extent to which these improvements influence the environmental performance of landfills was evaluated in this thesis using life cycle assessment (LCA) modelling. This in turn helps evaluating whether LCA modelling is a suitable, flexible and robust tool to support decision-making in the waste management sector. The LCA modelling was approached from the perspective of the unit mass of mixed waste or, individual fraction, being landfilled and all relevant environmental aspects are accounted for in a time horizon of 100 years after disposal. The model EASEWASTE was used to carry out all the LCA calculations. The outcome of the evaluation is given as life cycle impact assessment (LCIA), embracing standard impact categories, toxicity-related impact categories and contamination of groundwater.

Results have shown that the choice of the time horizon is a critical issue in LCA modelling of landfills, as it influences the evaluation at many levels. In particular, the longer the time horizon the higher the need to use data from model predictions and laboratory simulations as inputs (as opposed to data from actual measurements, which typically do not cover more than 30–40 years of the landfill

process). This leads to a high uncertainty regarding the results of the assessment. A short time horizon (e.g. 20 years) is, however, often to be avoided because emissions from landfills typically last for very long periods. An exception to this is found when leachate recirculation is practised, such as in bioreactor landfills. In this case most of the LFG is generated during the period of leachate recirculation, at which point the level of monitoring emissions is the highest. After the recirculation period, gaseous emissions become low and most of the impact potentials estimated are not of great concern; therefore, for gaseous emissions, a short time horizon may be suitable for the assessment of bioreactor landfills. However, several toxic chemicals are found in the waste mass that support leaching for very long periods such as metals and persistent pollutants. The release-rates of these compounds do not noticeably increase when leachate recirculation or other active landfilling technologies are practised. Therefore, very long LCA time horizons (centuries to millennia) should be considered to include in the evaluation a significant portion of the cumulative potential emission from these compounds. Leaching of heavy metals is of particular concern; results from the mass balances made for different landfilling technologies have shown that less than 1% by mass of the amount present in the waste has been released within 100 years after disposal.

Results have shown that amongst the several technical factors and environmental variables influencing the environmental assessment of landfills, the performance offered by bottom liner and top cover and LFG and leachate collection systems is crucial because they control the actual emissions to the environment. In addition, with respect to LFG, high collection efficiencies also give the opportunity to maximize the amount of LFG utilized for energy generation. The latter, from an LCA perspective, leads to notable, potential environmental benefits for global warming (GW) and other impact categories. The magnitude of the savings per unit mass of LFG utilized depends not only on the efficiency of the LFG energy recovery but, also on the energy substituted (electricity and/or heat) by the production of the energy from LFG. Environmental benefits are also credited to landfills when binding of biogenic carbon is accounted for as an avoided emission of carbon dioxide. This accounting approach is, however, not fully acknowledged in the LCA community and is often disregarded in LCA calculations, which tends to underestimate the potential benefits of landfilling compared with other management alternatives. Results have shown that binding of biogenic carbon can lead to very high savings in GW and that the individual fraction in the mixed waste that contributes the most to these savings is “paper” as this fraction has a high content of biogenic carbon but a relatively low degradability.

The EASEWASTE model has proved to be an adequately flexible and robust tool for LCA modelling of landfills. EASEWASTE can handle LCA time horizon of any duration and, in addition to standard and toxicity-related impact categories, other specific issues relevant for landfills can be considered, such as potential groundwater contamination, carbon binding, energy recovery and stored-toxicity. Although several default datasets are available in EASEWASTE, a considerable number of data is still needed for the environmental assessment of landfills, which must be selected and entered by the user. However, data might not be available or fully reliable, thus adding substantially to the uncertainty of the results.

Dansk resumé

Flere alternativer er på nuværende tidspunkt til rådighed for håndteringen af blandet affald; ikke desto mindre repræsenterer deponering den mest almindelig anvendte løsningsmodel i en stor del af verden. I Europa har man vedtaget love, der prioriterer genbrug og genanvendelse samt andre behandlingsmuligheder, men grundet den konstante stigning i genereringen af affald, forventes mængderne af affald, der deponeres, stadig at være væsentlige.

Affaldsdeponering medvirker til en række forskellige miljøpåvirkninger og, frem for alt, er deponeringsanlæg skyld i størstedelen af emissionen af drivhusgasser (GHG) fra affaldssektoren. Disse emissioner kommer imidlertid fra ældre anlæg, der er blevet uhensigtsmæssigt varetaget og næsten intet har til fælles med de nutidige og moderne anlæg. Faktisk har deponeringsanlæg gennemgået en betydelig teknologisk udvikling i løbet af de seneste årtier. Nye tekniske foranstaltninger er i udstrakt grad blevet implementeret for at reducere emissionerne, og nye teknologier, der optimerer nedbrydningsprocesserne og giver mulighed for udnyttelse af den opsamlede losseplads gas (LFG) til energiproduktion, er blevet indført. Omfanget af disse forbedringer påvirker den miljømæssige profil fra deponeringsanlæg, som er evalueret i denne afhandling ved brug af livscyklusvurdering (LCA). LCA modelleringen blev udført med basis i en masseenhed af blandet affald, eller enkeltfraktion, der deponeres, og der er redegjort for alle relevante miljøforhold i en tidshorisont på 100 år efter bortskaffelsestidspunktet. EASEWASTE modellen blev brugt til at udføre alle LCA evalueringer. Resultaterne er givet som en livscykluseffektvurdering (LCIA), der omfatter standard kategorier og toksicitets-relaterede effekter samt forurening af grundvandet.

Resultater har vist, at valget af tidshorisont er en kritisk faktor ved LCA modellering af deponeringsanlæg, da denne har indvirkning på evalueringen på mange niveauer. Især bemærkes at, jo længere tidshorisont, jo højere er behovet for at anvende data fra modellering og laboratorie-simuleringer som input (i modsætning til data fra faktiske målinger, som typisk ikke dækker mere end 30–40 år af processerne i deponiet) og jo større en usikkerhed kan dermed

forekomme i resultaterne af evalueringen. En kort tidshorisont (eksempelvis 20 år) skal imidlertid oftest muligt undgås, da emissioner fra lossepladser typisk forekommer over meget lange perioder. En undtagelse bemærkes dog i tilfælde, hvor recirkulering af perkolat praktiseres, som for eksempel på et bioreaktor-anlæg. I et sådant tilfælde genereres størstedelen af LFG simultant med perkolat recirkuleringen, hvor niveauet af de målte emissioner ligger på det højeste. Efter recirkuleringsperioden falder gas emissionerne til et lavt niveau og størstedelen af de estimerede potentielle effekter giver dermed ikke anledning til bekymring; derfor han en kort tidshorisont kan vise sig velegnet til evaluering af bioreaktor-anlæg. Der er imidlertid flere toksiske kemikalier i affald, som udvaskes i perkolatet over lang tid, eksempelvis metaller og persistente stoffer. Frigivelses-raten for disse stoffer øges ikke mærkbart, når recirkulering af perkolat eller andre aktive deponeringsteknologier praktiseres. Derfor vil det være nødvendigt med meget lange LCA tidshorisonter (århundreder til årtusinder) for at kunne inkludere en signifikant del af den akkumulerede potentielle emission fra disse stoffer i evalueringen. Udvaskning af tungmetaller er særligt bekymrende; resultater fra massebalancer udarbejdet for forskellige deponeringsteknologier har vist at mindre end 1 % (masse) af den mængde, der findes i affaldet, er blevet frigivet efter 100 år.

Resultaterne viser, at blandt flere af de tekniske faktorer og miljømæssige variabler, der påvirker miljøvurdering af deponeringsanlæg, er effektiviteten af bundmembran og toplag og opsamlingsystemer for perkolat og LFG afgørende, da disse styrer de faktiske emissioner til miljøet. Endvidere, hvad angår LFG, giver en høj opsamlingseffektivitet mulighed for at maksimere mængden af LFG, der udnyttes til energiproduktionen. Sidstnævnte fører, fra et LCA perspektiv, til anselige, potentielle miljømæssige fordele med henblik på global opvarmning (GW) samt andre kategorier. Omfanget af de mulige besparelser per masseenhed LFG udnyttet, afhænger ikke kun af effektiviteten af energigenindvindingen fra LFG, men også af de specifikke processer LFG energiproduktionen (elektricitet og/eller varme) erstatter. Miljøfordele krediteres også deponeringsanlæg i tilfælde, hvor der i deponiet sker bindingen af biogent kulstof som en undgået emission af kuldioxid. Denne redegørelsesmetode er imidlertid ikke fuldt ud anerkendt indenfor LCA kredse og ignoreres ofte i LCA beregninger, hvilket har en tendens til at underestimere de potentielle fordele ved deponering retfærdighed sammenlignet med andre håndteringsmuligheder. Resultater har vist, at binding af biogent kulstof kan føre til store besparelser af GW, og at den enkeltfraktion i blandet affald, der bidrager mest til disse besparelser, er ”papir”, da denne fraktion har et højt indhold af biogent kulstof, men har en relativ lav nedbrydelighed.

EASEWASTE modellen har vist sig at være et tilstrækkelig fleksibelt og holdbart værktøj til LCA modellering af deponeringsanlæg. EASEWASTE kan håndtere LCA tidshorisonter af enhver længde og kan udover standard og toksicitetsrelaterede påvirkningskategorier. Desforuden kan en række andre parametre relevant for deponier blive indregnet, såsom potentielt forurenet grundvand, biogen kulstofbinding, energigenvinding og deponeret toksicitet. EASEWASTE indeholder en række standard data sæt, men brugeren skal stadig vælge og indtaste en mængde data der er specifikt for miljøvurderingen for deponiet. Dette kræver imidlertid en betydelig mængde data, hvilket muligvis ikke forefindes eller er fuldt ud pålidelige, og dermed bidrager væsentligt til usikkerheden af resultaterne.

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VIII. Comments on the results of the assessment

These papers are included in the printed version of the thesis but not in the www-version. Copies of the papers can be obtained from the Library at the Department of Environmental Engineering, DTU (library@env.dtu.dk).

1 Introduction and background

1.1 Waste management and life cycle assessment

Waste management systems are expected to provide customised and robust handling of all waste with a minimum of effort for the customer. This should be achieved with the lowest possible load on the environment in terms of contamination of ecosystems (air, water, soil), as well as minimum hazard to human health. As an additional goal, waste management systems should also aim at offering the highest resource recovery from the waste while minimising the resource use in the waste handling. The choice of the best waste handling strategy is still sometimes based on a general principle, the so-called “waste hierarchy”, prioritizing waste minimization and reuse and avoiding landfilling as much as possible. However, the waste hierarchy does not consider the specific waste management context where choices should be made and, as such, cannot support decision in a way that integrates all technical variables and environmental factors involved.

From a life cycle thinking perspective decisions should be based on clear definition of the system boundary, as well as identification and quantification of mass and energy exchanges through the boundary. This has led to the development of life cycle assessment (LCA) models, which are being increasingly used in many different contexts due to their ability to aggregate data into potential environmental impacts and resource consumption, thus addressing issues of real concern. Since the early 1990s, LCA models have been applied to the assessment of waste management systems (Morrisey & Brown, 2004; Björklund at al., 2008) and are nowadays regarded as a major decision support tool, also within this sector. Some of these can model the environmental performance of complete waste management systems (from waste generation to final disposal), as for instance EPIC/CSR (Haight, 1999 & 2004), ISWM DST (Weitz et al., 1999; Solano et al., 2002a & 2002b) IWM2 (Mc. Dougall, 2000), LCA-IWM (Den Boer et al., 2005a, 2005b & 2007), ORWARE (Dalemo et al., 1997; Eriksson et al., 2002), WISARD (jointly developed by the UK EPA and

Ecobilan: www.ecobalance.com/uk_wisard.php), WRATE (Thomas & Mc. Dougall, 2005; Gentil et al., 2005; Coleman, 2006) and EASEWASTE (Kirkeby et al., 2006; Kirkeby et al., 2007). EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies) has been used to perform all the LCA calculations included in the present thesis.

EASEWASTE is a new LCA based model for waste management. The model, developed by the Technical University of Denmark, calculates waste flows, resource consumption and environmental emissions from waste management systems and provides a complete impact assessment in terms of potential global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, eco-toxicity, human-toxicity and spoiled groundwater resources.

Global warming (GW) is today one of the highest priorities on the public agenda and is likely to gain even more importance with the Conference of the Parties (COP 15) in Copenhagen (December 2009) to define the post-Kyoto era beyond 2012. In such a context, reporting of greenhouse gas (GHG) emissions has a crucial importance. With the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Bogner et al., 2007), for the first time, the waste industry was recognized as a separate sector under the subdivision made by the IPCC. In LCA modelling of waste management activities, quantification of GHG emissions is usually approached using the global warming potential (GWP) indices developed by the IPCC, although the accounting of CO_2 of biogenic origin represents an exception and it is an issue of growing relevance. The overall CO_2 emission to air is typically divided into two distinct parts: biogenic CO_2 emission and fossil CO_2 emission. These emissions are generated by degradation of carbon originating from short-life organic matter and from fossil carbon, respectively. In a full life cycle perspective, biogenic CO_2 emission is considered neutral to GW (GWP=0) because it originates from organic matter generated by an equivalent biological uptake of CO_2 during plant growth. Conversely, emission of CO_2 from combustion of fossil carbon constitutes a load to GW (GWP=1) because this release is not counter-balanced by a recent uptake of CO_2. This approach is accepted in most of the recent studies on LCA modelling of carbon-rich waste (for instance: Grant et al., 2001; Smith et al., 2001; Lopez et al., 2003; Dahlbo et al., 2005; Raymer, 2006; Schmidt et al., 2007). However, different accounting principles are used in these studies with regard to the biogenic carbon stored in landfills and soils amended with compost, as well as in the exchanges between the waste industry, the energy industry and forestry (Christensen et al., 2009).

1.2 Landfilling technologies for mixed waste

Amongst the existing waste disposal alternatives, landfilling remains the most common option worldwide for solid waste and is expected to remain so also in the decades to come, although policies are set up in many parts of the world and especially in Europe to increase recycling and reduce landfilling. Landfills have developed dramatically since the 1990s, albeit this development has not yet been implemented in all parts of the world. Landfills range from open dumps to modern engineered facilities with managed operations, including bioreactor, flushing-bioreactor and semi-aerobic landfilling technologies.

The main factors controlling the actual environmental impacts from landfilling are the nature and amount of the waste landfilled, the hydrological setting of the landfill site, the landfill technology adopted, the effectiveness of the technical and environmental protection measures introduced, the daily operations and time. Most of our current understanding of the environmental impacts from landfills originates from observations during the last few decades of impacts from old landfills receiving an unknown mixture of waste from many different sources and with no or very little engineering measures introduced to control emissions and reduce impacts. These observations have promoted the development of engineered landfills adopting extensive technical measures to achieve better control of liquid and gaseous emissions in order to reduce GHG emissions, prevent groundwater pollution, fire hazards, odours and vegetation damage. Technical measures typically include bottom liner, top cover, landfill gas (LFG) and leachate collection and treatment. Quality criteria for the waste to be landfilled have also been introduced (for instance: CEC, 2003).

In addition to the technical measures, a range of active operations have been introduced, including leachate recirculation and waste flushing. This has led to the establishment of new landfilling technologies, such as bioreactor and semi-aerobic technologies, whose actual environmental performance, however, has not yet been methodically evaluated.

1.2.1 Conventional technologies

Conventional landfilling technologies, as typically defined, receive a mix of waste, except hazardous waste, and have a conventional leachate collection system and LFG collection system. Conventional landfills do little to optimize the waste degradation and generation of leachate and LFG, instead they implement technical measures to collect and manage them. Technical measures include bottom liner, leachate collection system and leachate treatment prior to discharge to surface water bodies for leachate emissions, and top soil cover, LFG collection system, flares, and LFG utilization for energy recovery for LFG emissions.

The waste is typically compacted to a wet density of 0.7-1.0 tonnes/m^3 and the waste is regularly covered with soil. The cells and sections (group of cells with joint leachate collection system) are filled as the waste is received. The European waste regulation assumes an operational and closure period of 30 years and an aftercare period of at least 30 years (CEC, 1999). This suggests that emission control on landfills should continue for a minimum of 60 years. During the operational life-span LFG and leachate are collected. Collection efficiencies achieved may vary significantly depending on many technical factors and environmental conditions. The collected LFG is either burnt in flares or utilized for energy generation (power only or cogeneration) or a combination of the two options. The collected leachate is typically sent to a leachate treatment plant (LTP) for purification.

The degradation of organic matter is predominantly anaerobic. The initial aerobic phase may last only a few days until the oxygen contained in the air space in the landfilled waste is consumed. The basic microbiological processes in anaerobic landfills are similar to those taking place in anaerobic digesters, except that a landfill cell may have a long acidic phase before methane generation starts. In fact, the conditions in the landfill may be far from optimal because of lack of pre-treatment, heterogeneity of the waste, lack of mixing and sometimes lack of water. The amount of LFG and its main constituents depend on the composition of the waste degraded. Most LFG is generated during the stable methanogenic phase. The overall amount of LFG generated is typically in the range of 100 to 200 Nm^3/tonne depending on the type of waste and time frame considered. The main LFG constituents are methane and carbon dioxide. On average, about 50% to 60% (mass basis) of the biogenic carbon in the waste that undergoes degradation is converted to methane, while carbon dioxide constitutes approximately the remaining part. A variety of trace components is found in LFG, including chlorofluorocarbons (CFCs), volatile organic compounds (VOCs) and hydrocarbons (HCs). Of the trace gases in LFG, vinyl chloride and benzene are often considered the most critical because they are very volatile and highly toxic. Trace gases originate from the waste landfilled and their concentrations depend on the release rate from the waste and the physico-chemical characteristics of the substances (Rettenberger & Stegman, 1996).

Soil top covers are commonly constructed in conventional landfills not only to hide the waste from view but also to provide functions such as control of oxygen and water infiltration, protection of the anaerobic environment and optimization of the microbial processes that oxidize the uncollected LFG. The latter is a key function provided by the cover, as considerable amounts of methane can be converted to biogenic carbon dioxide, therefore reducing fugitive GHG emissions from landfills (for instance: Scheutz et al., 2004; Scheutz & Kjeldsen, 2005). Typically, top covers used in conventional landfills do not have an impermeable liner. This is currently still accepted at a European level as the EU landfill directive 99/31 (CEC, 1999) only recommends, rather than prescribes, surface liners on non-hazardous waste landfills.

Leachate is the drainage collected at the bottom of the landfill. The amount of leachate generated depends on the hydrogeological condition of the landfill. The main variables involved are rainwater precipitation, evapotranspiration, surface run-off and water consumption from waste degradation. Leachate composition varies according to the main phases of the life of the landfill and is usually specified in terms of organic matter content (BOD, COD, TOC, DOC, etc.), nitrogeneous compounds (organic nitrogen and ammonia/ammonium), inorganic macro substances (Ca, Mg, Na, Cl, SO_4^{-3}, etc.), heavy metals (As, Cd, Cr, Cu, Hg, etc.) and trace organic components (aromatic hydrocarbons, phenols, chlorinated solvents, etc.).

1.2.2 Active technologies

Since the early 1990s, new active technologies have been developed to decrease the environmental impacts from landfills by enhancing the waste degradation processes to make it faster and more efficient, improving the control of landfill emissions and utilizing LFG for energy recovery. An additional goal is to decrease the time frame of active landfill operation to 10–15 years. The optimization of the waste degradation process leads to high LFG generation rates early in the life of the landfill (higher than experienced in conventional landfills). This makes it possible to maximize LFG collection and undertake LFG utilization schemes, such as electricity or combined heat and power (CHP) generation. The level of on-site operation needed, however, increases accordingly, as do the emissions generated by these activities.

Bioreactor landfills use recirculation of the collected leachate to the waste mass. This keeps the waste moisture content close to field capacity and provides a continuous supply of moisture and nutrients, resulting in an enhancement of the microbial anaerobic environment. Leachate recirculation also increases the waste density up to 1–1.2 tonne/m^3 (wet) and therefore allows a better utilization of the landfill capacity (Benson et al., 2007). Some bioreactor landfills, called flushing-bioreactor landfills, recirculate considerable amounts of water together with leachate in order to flush-out the soluble waste components in a process known as “waste irrigation” or “waste flushing”. The flushing-rate typically ranges from 1 to 3 m^3 of total liquids (leachate and external water) per tonne of waste landfilled, as cumulative amount recirculated during the time-span of active operation, usually 8–12 years (Hupe et al., 2003; Blakey et al., 1997). Leachate concentrations of ammonia/ammonium (NH_3/NH_4^+) may rise dramatically during waste flushing and thus measures are commonly taken to reduce their concentrations. This is achieved by nitrifying leachate before re-injecting it to the waste mass. The nitrified leachate is rich in nitrates (NO_3^-), which provide further oxidation of waste the components, therefore leading to removal of NH_3 / NH_4^+ through emission of gaseous nitrogen (N_2).

The semi-aerobic landfill technology was developed in Japan (Hanashima, 1999; Matsufuji et al., 2005) and relies on a hybrid anaerobic/aerobic degradation sequence. Initially, the degradation mechanism is anaerobically driven and enhanced by the leachate recirculation operation; the collected LFG is typically used for energy generation. This first step is kept active for 5 to 10 years, at which point the methane (CH_4) generation of the relatively shallow landfill is too low to justify LFG utilization for energy generation. The subsequent aerobic step is initiated by injecting air from the bottom of the landfill. A convective air flow will then proceed autonomously, driven by the temperature gradient between the warm waste (up to 50–70°C) and the colder external environment. This is also known as “chimney effect” (Hanashima, 1999). Compared with anaerobic degradation, aerobic metabolism leads to a faster waste stabilization rate, greater generation of LFG (poor in CH_4 and rich in CO_2 and N_2) and lower leachate production. Anaerobic conditions may naturally re-establish after the natural air flow has ceased, but the waste is, at least in theory, already stabilized and therefore the residual potential for methane generation is typically low.

1.3 Landfill modelling in a life cycle perspective

1.3.1 LCA time horizon, data availability and long-term impacts

The LCA modelling of waste management systems and, in particular, of landfills involves two main issues that are intrinsically connected: data scarceness and choice of time horizon. The latter expresses the duration of the period (years) throughout which the environmental aspects are accounted for in the LCA modelling. In principle, it is important to assume a very long LCA time horizon so that emissions occurring after this time, and consequently not accounted for in the assessment, do not pose significant environmental loads (Camobreco et al., 1999). In fact, due to the considerable duration of the waste degradation processes, emissions from landfills do not occur virtually instantaneously, as is the case for other waste treatment options. Conversely, emissions from landfills remain significant for decades, or centuries for some toxic compounds in the leachate, and therefore landfills pose a considerable, long-lasting threat to the environment (Obersteiner et al., 2007). This becomes of particular concern as landfills have proven to be relatively unstable systems in a long-term perspective due to the gradual deterioration of the barrier systems, which may cause the release of the remaining load of pollutants (Doka & Hischier, 2005).

However, data availability and trustworthiness decrease dramatically for increasing age of the landfill, which essentially limits the possibility of greatly lengthening the LCA time horizon. More precisely, high-quality data from full-scale landfills do not typically cover more than 30 to 40 years of landfill process, at which point leachate and, sometimes LFG concentrations are usually exceeding a tolerable level. Datasets are therefore commonly amended with data from landfill simulations of limited scale, accelerated laboratory tests and models' predictions. The use of this type of data allows the time horizon of the assessment to be broadened but also adds considerably to the uncertainty of the results as various uncertain parameters become relevant when predicting long-term emissions, for example, changes in geochemical weathering and maybe climate conditions (Obersteiner et al., 2007).

Leachate concentrations of some toxic chemicals, and especially of metals and heavy metals, can be far below predicted thresholds of effects in the surrounding environment during the selected LCA time horizon (e.g. 100 years); however, the total amount leaving the landfill in a long-time perspective (centuries to millennia) can be substantial and, in principle, should not be forgotten. Nonetheless, if future emissions from landfills were included in the LCA inventory marked potential environmental impacts would be estimated, whose magnitudes could be by far larger than those caused by emissions occurring within the LCA time horizon. In the LCA community this issue is addressed in considerably different ways. Some account only for emissions occurring within a foreseeable future and disregard the potentially high load of pollutants that may be emitted thereafter (for instance: Nielsen & Hauschild, 1998; Finnveden, 1999). Others account for the entire load of pollutants using models predictions for a very long period (up to several millennia) and often consider a discounting of future impacts (e.g.: Hellweg, 2000; Hellweg et al., 2003). Others consider emission until the time when leachate concentrations of reference compounds reach background concentrations, which adds a lot to the uncertainty of the results because very uncertain predictions of leaching kinetics and redox conditions are needed (e.g.: Birgisdottir, 2007). The issue of accounting for future emissions in LCA modelling has also been approached by introducing a new group of impact categories representing the stored toxicity (stored eco-toxicity and stored human-toxicity). This keeps into account of how much of each toxic substance remains stored in the waste landfilled at the end of a foreseeable LCA time horizon (e.g. 100 years) and assigns each substance the LCA characterization factors for eco-toxicity and human-toxicity. Impact potentials estimated for the stored toxicity categories inherently represents the potential impacts that would be caused if the remaining load of pollutants was released at once after the LCA time horizon (Hansen et al., 2004; Hauschild et al., 2008).

EASEWASTE allows for time horizons of any duration: however, all studies included in this thesis were conducted with a time horizon of 100 years. I believe that beyond this time-span emissions from landfills are hardly foreseeable.

The LCA models EPIC/CSR, LCA-IWM and ORWARE also assume a 100-year time horizon; WISARD assumes 100 years for LFG emissions and 500 years for leachate emissions; WRATE assumes 150 years for LFG and 20,000 years for leachate; ISWM DST allows for 20, 100 or 500 years. Although EASEWASTE can include the stored toxicity categories in the life cycle impact assessment (LCIA), these were here disregarded as consistent data on storage of metals and toxic substances from actual landfills are scarce. In addition, within the LCA community there is currently still considerable disagreement on the way of accounting for long-term impacts from landfills.

1.3.2 Accounting of GHG emissions

Increasing efforts are being made to reduce GHG emissions from landfills. With respect to the EU-15 in 2005, landfills account for about 2/3 of the overall GHG emissions from waste management, mostly due to fugitive methane emissions (Gugele et al., 2007; Skovgaard et al., 2008). Several alternatives exist to reduce emission of methane and other GHGs from landfills, including passive oxidation in soil top covers, combustion in flares and LFG utilization for energy generation (as electricity or cogeneration). The latter, from an LCA perspective, saves emissions to the environment, because emissions are avoided that would have occurred if the same amount of electricity/heat produced from LFG had been produced from fossil resources.

In addition to direct emissions caused by the waste degradation process, other GHG emissions occur that are associated with the landfill but occur outside the landfill site. These emissions are referred to as “indirect emission” and are typically divided into “upstream emissions” and “downstream emissions”. Upstream emissions are related to activities such as the provision of materials and energy used at the site, and the construction of the facilities; downstream emissions are related to activities such as the off-set of energy production substituted by the energy recovered at the site. Indirect emissions associated with waste landfilling typically pose a smaller load on GW than direct emissions but cannot be disregarded in a comprehensive LCA study. Direct methane emission from landfills can be minimized by reducing the amount of organic fractions in the waste landfilled. For instance, the European Landfill Directive 99/31 (CEC, 1999) prescribes a gradual reduction of landfilling of organic waste, aiming at a maximum of 35% organic waste being landfilled by 2014. To date, some EU member states have moved even further and have already banned the landfilling of organic waste (e.g. the Netherlands as of 1996, Denmark as of 1997, and Germany as of 2005). Landfills with less organic matter are therefore becoming increasingly common in Europe but, so far, this type of landfill has received little attention, and data on its environmental performance are scarce.

As previously mentioned, most LCA models for waste management consider biogenic CO_2 emission as neutral with respect to GW. Nevertheless, there is not full agreement on the way to account for the undegraded carbon remaining in the landfill at the end of the LCA time horizon. If emissions of biogenic CO_2 are neutral to GW, then, in principle, biogenic carbon remaining in the landfill should be considered as an avoided CO_2 emission; consequently, a negative contribution to GW (a saving) should be assigned. This in turn implies that fossil carbon remaining in the landfill is to be considered as neutral with respect to GW (Christensen et al., 2009; Gentil et al., 2009). This issue is of crucial importance for the estimation of the GW profiles of landfills where organic waste has been disposed. Despite evidence that significant portions of the carbon in the landfilled waste remain stored for long periods (Barlaz, 1998; US EPA, 2006), actual data on carbon storage in landfills are sparse and uncertain. According to Augenstein (1999), about 9% of the carbon entering the landfill is sequestred; Bogner et al. (1999) suggest a minimum of 20–30%; the LCA model WRATE uses 50% carbon sequestration.

1.3.3 Individual waste fractions

In a context where LCA is becoming a major decision support tool also in waste management, the environmental focus must be extended to several other impact categories in addition to GW. From such a perspective, not only the organic, biodegradable fractions in the mixed household waste are of importance; other fractions should also be considered, such as glass, plastic and metals. Therefore, for any given impact category included in the assessment, it becomes of interest to quantify the relative contribution of each individual fraction to the overall potential impact from landfilling of the mixed waste. Full-scale landfills for individual waste fractions are rare and therefore an in-depth understanding of the behaviour of these fractions under landfilling conditions does not currently exist. Therefore, data are taken from laboratory simulations designed to measure degradation of different materials in a simulated landfill environment (for instance: Barlaz, 1998).

Nonetheless, from the perspective of the individual waste fractions, other management options should be considered, such as incineration, reuse/recycling or composting. It is therefore necessary to develop environmental assessments for the single waste fractions that compare alternative treatment/disposal methods. Several LCA based studies have been published on this topic (for instance: "Environmental benefits of recycling"; WRAP, 2006), but the systems' boundaries and the assumptions made differ considerably, making it difficult or impossible to compare results. Furthermore, in these studies the landfilling option has often not been dealt with in detail and there has been little regard to the substantial improvements that landfills have undergone during the last 20 years, especially in terms of reduced level of emissions to the environment.

1.4 Objectives of the thesis

The major aims of this thesis are to:

- Systematically describe the core features of current landfilling technologies for mixed waste, compare their environmental performance and assess the influence of the active operations on the results of the assessment;
- With respect to the potential impact on global warming, quantify the relative contribution of direct and indirect emissions, with particular focus on the accounting of carbon binding and energy generation from LFG use;

- Establish a consistent framework for the LCA modelling of individual waste fractions. A first sub-goal is to quantify the fractions' contributions to the overall impact potential from landfilling of mixed waste. A second sub-goal is to compare the environmental performance of available management options for individual waste fractions (landfilling, recycling and incineration or composting) in order to find out how a modern landfill compares environmentally with other management options;
- Evaluate the suitability of LCA modelling and, in particular, of the EASEWASTE model, for the environmental assessment of landfilling systems and technologies, with particular focus on the choice of the LCA time horizon and the availability of data.

2 LCA modelling of landfills with EASEWASTE

2.1 Structure of the landfill module and key assumptions

The framework and structure of the EASEWASTE model were defined by Janus Kirkeby during his PhD studies (Kirkeby et al., 2006; Kirkeby et al., 2007) and are still currently used, although the model has undergone a continuous development and, with respect to the landfill module, several technologies have been added. The EASEWASTE landfill module employs process specific material and energy use (mass or energy per tonne of waste landfilled) as well as process specific emissions (mass emitted per tonne of waste landfilled). Process specific emissions are categorized according to the receiving compartment (air, surface/marine/groundwater, soil). Input specific emissions are not employed because emissions to the various environmental compartments depend principally on the way the landfill is designed and operated (conventional, bioreactor, etc.) rather than on the quality of waste landfilled.

Handling of LFG and leachate is structured in sets of independent time periods. For each set, EASEWASTE allows to up to 4 time periods in order to provide high flexibility to the user and, therefore, the possibility of representing the many operational and post-closure phases that a landfill may undergo. The sum of the 4 time periods in years represents the full life-span considered for the landfill and thus is equal to the time horizon of the LCA. The latter has been set to 100 years in all the studies included in this thesis, although EASEWASTE allows for time horizons of any duration. Two key assumptions have been made about LFG and leachate generation. Firstly, the amount of LFG generated in the landfill is directly related to the methane potential in the waste landfilled, while the LFG composition (methane as well as trace gases) is set as typical values within each period, independent of the actual waste composition. Secondly, the amount of leachate generated is set as typical values (mm/year) representing the hydrological conditions (precipitation, evapotranspiration, run-off, etc.) at the site and the composition of leachate (main constituents as well as trace components) is set as typical values within each period, again not directly related to the actual waste composition.

LFG management is structured in two sets of independent time periods. The first set of time periods addresses LFG generation, composition and oxidation in soil top cover. The second set of time periods addresses LFG collection and treatment. Durations of time periods and selected values for parameters within each time period are independent. A chief parameter influencing LFG generation is the fraction of the total methane potential in waste landfilled that is actually generated within each time period. The choice of this fraction for each period and the length of the periods should reflect the specific way the landfill is operated. For a time period representing for instance the methanogenic stage of degradation, both duration of the time period and LFG generation within the period (in term of fraction of the overall LFG potential) can be set differently for a conventional landfill, a flushing-bioreactor landfill or another landfill type. Likewise, the time period subdivision considered for the LFG collection depends on parameters that are strictly technology-specific, such as duration of the collection stage, way of disposing or treating the collected LFG, and emissions from the considered treatments.

In all studies included it was assumed that a top cover is constructed at the end of the filling phase. The top cover consists of 1 m of soil and does not include an impermeable surface liner. The EU landfill directive (CEC, 1999) recommends, but does not require, surface liners on non-hazardous waste landfills. Assuming there is only a soil cover, which is in compliance with EU regulations, this represents a worst-case scenario allowing leachate generation and migration of LFG through the cover. The efficiency of the LFG oxidation in the top cover is affected by many environmental factors (e.g. temperature, moisture content, redox condition), but the actual rate of LFG migration through the cover (calculated by EASEWASTE for all time periods) has been considered the key factor. The higher this rate the lower the oxidation efficiency for any given substance in the LFG.

As an alternative to LFG treatment in flares, EASEWASTE allows for the LFG utilization in an energy recovery facility. The model includes the options power plant and combined heat and power (CHP) plant. The purpose is to exploit the energy content of the LFG by producing electricity (power plant) or electricity and heat as a co-product (CHP plant). The efficiency of the energy recovery is defined as the fraction of the total energy content in the LFG that is actually recovered to produce electricity and/or heat, and this must be specified by the user. The user must also specify the avoided energy production in order to obtain the credits for saving in resource use and emissions. The energy recovery is the gross energy recovery, since the plant's own use of energy is accounted for in the tables on material and energy input. As for the other LFG management options, the energy recovery facilities provide treatment to the LFG and the removal efficiencies of the LFG constituents must be specified by the user. In addition, for each treatment/utilization option, a specific set of emissions can be entered by the user.

Landfill leachate management is structured in 3 sets of independent time periods. These address leachate generation (in terms of amounts), leachate composition and leachate collection, respectively. The amount of leachate generated in the time periods must be specified by the user and does not depend only on the annual precipitation. Amongst the various technical and environmental factors influencing leachate generation, the user should also consider the effect of the final soil cover in limiting the actual rain-water infiltration to the waste body. An average landfill depth and average waste bulk density must be specified in order to relate the amount of leachate generated to the amount of waste. The composition of the generated leachate, defined by the user, should reflect the evolution of the leaching process. Leachate composition can be specified both in terms of for instance BOD, COD, ammonia, salts, etc, and in terms of heavy metal and organic compounds. Leachate collection efficiencies in time periods should reflect the technical measures adopted in each stage of landfill operation. Uncollected leachate is considered to reach the groundwater as it is or, eventually, somewhat purified because natural attenuation processes have occurred. Cleaning efficiencies of leachate constituents due to natural attenuation are user-defined. Collected leachate is sent to a plant for treatment. Cleaning efficiencies achieved in the leachate treatment plant (LTP) must be specified by the user for all constituents considered in the leachate composition. Treated leachate can be discharged to both surface water and marine water bodies in a proportion that is user defined.

A schematic structure of the landfill module in EASEWASTE and the boundary of the assessment are given in Figure 1. This represents the general landfilling configuration considered in the studies included in the present thesis. In each study, however, changes were made to this structure to make it compatible with to the specific issues and purposes.

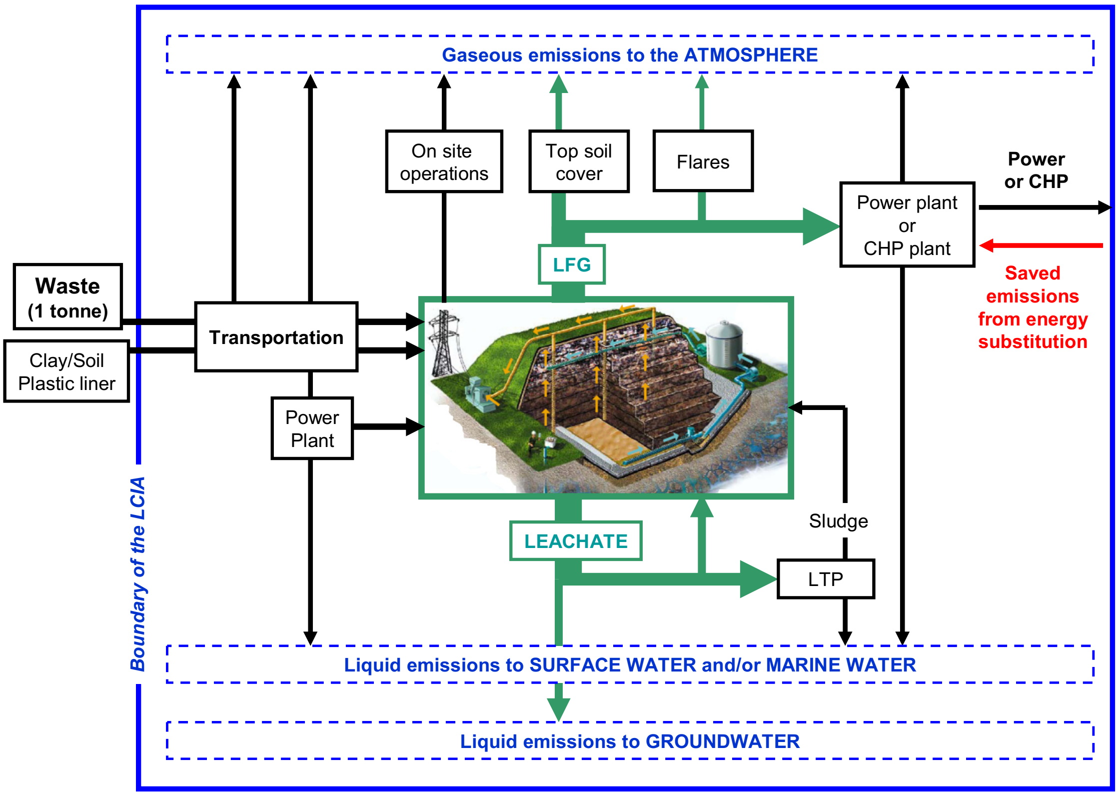

Figure 1 (from [I]): General structure of the landfilling technologies and boundary of the assessment.

2.2 Structure of the LCA modelling

In any LCA study a crucial part is the definition of the "functional unit". The functional unit expresses the primary function (or service) provided by the system being assessed and must be specified in terms of quality, quantity and duration of the function (or service) provided. This also applies to the assessment of waste management systems. With respect to the individual studies included in this thesis, the functional unit has been expressed as "landfilling of one tonne (1000 kg, as wet weight) of mixed waste, or individual waste fraction, for a time horizon of 100 years after disposal". The main processes included are provision of material and energy input, on-site operations (including soil movements) with specialized vehicles and machinery (including emissions from provision and utilization of the diesel fuel needed), LFG collection, LFG treatment/utilization, leachate collection, leachate treatment and electricity consumption at the landfill site and at any facility considered for LFG and leachate treatment/use. Soil excavation and any kind of upstream operation related to the landfill construction were not accounted for. Collection and transportation of waste to the landfill were not included either, because they are not regarded as part of the landfilling system. The assessment includes several potential impact categories (Table 1) covering potential impacts in several environmental compartments (air, surface water bodies and groundwater), and also potential hazards to humans. Impact categories accounting for stored toxicity were not included in the assessment.

The impact categories are divided into three groups: standard (or ordinary) environmental impact categories, toxicity-related environmental impact categories and impact on groundwater resources. Standard impact categories include Global Warming (GW), Photo-chemical Ozone Formation (POF), Stratospheric Ozone Depletion (SOD), Acidification (AC) and Nutrient Enrichment (NE). Toxicity-related impact categories include Eco-toxicity in soil (ETs) and in water chronic (ETwc), Human-Toxicity via soil (HTs), via water (HTw), and via air (HTa). The potential impact on groundwater resources is represented by the single category Spoiled Groundwater Resources (SGR). The latter is calculated based on the amount of groundwater that may be contaminated from an input of leachate by diluting the leachate to the drinking water standard, as described by the guidelines provided by WHO (2006). Standard and toxicity-related impact categories are direct impacts to the environment. Therefore, the estimated impacts, once normalized, can be compared across different categories. However, while the LCA methodology for estimating the impacts for the standard impact categories is acknowledged worldwide, currently there remains considerable uncertainty about the estimation of the impacts for the toxicity-related categories. The SGR impact category stands apart compared with standard and toxicity-related categories. SGR is related to the consumption of a limited resource and from an LCA perspective, impact potentials estimated for this category should not be directly compared with the other impact categories. Furthermore, impacts on SGR have been calculated assuming that the groundwater is used as a drinking water resource, and therefore its contamination may not be an issue if a different utilization were assumed.

Table 1 (from [I]): Standard and toxicity-related impact categories included in the assessment. Reference year: 1990 (Stranddorf et al., 2005, Hansen et al., 2004).

Standard impact categories	**Abbrev.**	**Physical basis**	**EU-15 Normalization reference**	**Unit**
Global Warming	GW	Global	8,700	kg CO_2-eq. /person/yr
Photo-chemical Ozone Formation	POF	Regional	25	kg C_2H_4-eq. /person/yr
Stratospheric Ozone Depletion	SOD	Global	0.103	kg CFC-11-eq./person/yr
Acidification	AC	Regional	74	kg SO_2-eq. /person/yr
Nutrient Enrichment	NE	Regional	119	kg NO_3^--eq. /person/yr
Toxicity-related impact categories	**Abbrev.**	**Physical basis**	**EU-15 Normalization reference**	**Unit**
Eco-Toxicity in soil	ETs	Regional	964,000	m^3 soil /person/yr
Eco-Toxicity in water chronic	ETwc	Regional	352,000	m^3 water /person/yr
Human-Toxicity via soil	HTs	Regional	127	m^3 soil /person/yr
Human-Toxicity via water	HTw	Regional	50,000	m^3 water /person/yr
Human-Toxicity via air	HTa	Regional	60,900,000,000	m^3 air /person/yr
Contamination of groundwater	**Abbrev.**	**Physical basis**	**Normalization reference**	**Unit**
Spoiled Groundwater Resources	SGR	Regional	130*	m^3 groundwater /person/yr
*As average EU-15 groundwater abstraction per person per year				

The results of the LCIAs for the landfill scenarios modelled are expressed as normalized impact potentials in the unit Person Equivalent (PE) per tonne of wet waste landfilled. EU 15 normalization references have been used in the normalization step (Table 1). One PE corresponds to the environmental load caused by one average EU 15 citizen in one year (reference year: 1990) covering all activities in life (mining, agriculture, transport, housing, etc.).

For the carbon accounting, it was assumed that the emission of biogenic carbon as carbon dioxide is neutral with respect to GW. In the calculations this is accounted for by assigning a GWP (as kg CO_2-eq./tonne wet waste) equal to "zero" to emissions of biogenic carbon dioxide. Emissions of non-biogenic carbon (e.g. in plastic and rubber) occurring within the 100-year time horizon are accounted for as contributing to GW (GWP=1), while non-biogenic carbon remaining in the landfill was regarded as neutral with respect to global warming (GWP=0). However, with regards to the biogenic carbon remaining in the landfills at the end of the LCA time horizon (100 years), two different approaches were used because my opinion on the topic has changed since the first assessment was made. Biogenic carbon remaining in the waste landfilled after 100 years was considered neutral to GW ($GWP(C_{BiogenicLeft})=0$) in papers [I], [II], [III] and [IV], while it was considered as a saving in papers [V], [VI] and [VII]. When the last approach was taken, the biogenic carbon remaining in the waste landfilled was assigned a GWP equal to -44/12 (as kg of CO_2 / kg $C_{BiogenicLeft}$).

3 Assessment of landfilling systems and technologies

3.1 LCA comparison of landfilling technologies

An LCA comparison was developed to evaluate the environmental performance of six landfilling scenarios: open dump, conventional landfill with flares, conventional landfill with energy recovery, standard-bioreactor landfill, flushing-bioreactor landfill and semi-aerobic landfill. In addition, mass balances were made for some selected elements in order to quantify how much of these elements remain stored in the landfilled waste at the end of the LCA time horizon [I].

3.1.1 Structure and boundary

The functional unit of the LCA is landfilling of one tonne (1000 kg) of wet household waste in a 10 m deep landfill, considering a time horizon of 100 years after disposal. Based on the composition of the waste landfilled, the cumulative potentials for LFG and methane generation are estimated to 170 and 86 Nm^3 per tonne (wet) of waste, respectively. All the emissions to the environment related to LFG and leachate generation and treatment/use, on-site operations, transportation of soil/clay to the site and electricity needs are accounted for. The LCA was made for 3 different time horizons: 100 years (years 0–100), years 0–15 and years 16–100. Year 15 corresponds to the time when LFG collection/utilization stops in the bioreactor technologies (Table 2). This brings a deeper understanding of the environmental performance offered by the six landfilling technologies.

The open dump landfill does not adopt any technical measures to prevent LFG and leachate emissions and was included in the comparison as a worst-case scenario. All the other landfill scenarios, adopt bottom liner, leachate collection and treatment, soil top cover, LFG collection and treatment in flares (conventional landfill with energy recovery) or utilization for CHP generation (conventional landfill with energy recovery, standard- and flushing-bioreactor landfills and semi-aerobic landfill). The key technical and environmental parameters considered in the modelling are given in Table 2.

Table 2 (from [I]): Technical and environmental parameters for LFG and leachate generation, collection and management in the assessed technologies in four time periods.

Open Dump	**Time Period 1**	**Time Period 2**	**Time Period 3**	**Time Period 4**
LFG generated (% of LFG potential)	2y; 2%	3y; 8%	35y; 70%	60y; 16%
LFG collected	none	none	none	none
Leachate generated (mm/y)	2y; 500mm/y	8y; 500mm/y	30y; 450mm/y	60y; 400mm/y
Leachate collected	none	none	none	none
Conventional Technologies	**Time Period 1**	**Time Period 2**	**Time Period 3**	**Time Period 4**
LFG generated (% of LFG potential)	2y; 2%	3y; 8%	35y; 70%	60y; 16%
LFG collected (% of generated)	2y; none	3y; 90%	35y; 90%	60y; none
LFG management	none	Flare / energy recovery	Flare / energy recovery	none
Leachate generated (mm/y)	2y; 500mm/y	8y; 250mm/y	30y; 200mm/y	60y; 180mm/y
Leachate collected (% of generated)	20y; 95%	20y; 70%	30y; none	30y; none
Bioreactor Technologies	**Time Period 1**	**Time Period 2**	**Time Period 3**	**Time Period 4**
LFG generated (% of LFG potential)	2y; 2%	8y; 72%	5y; 8%	85y; 16%
LFG collected (% of generated)	2y; none	8y; 95%	5y; 90%	85y; none
LFG management	none	energy recovery	energy recovery	none
Leachate generated (mm/y)	2y; 500mm/y	8y; 250mm/y (Recirculation)	30y; 200mm/y	60y; 180mm/y
Leachate collected (% of generated)	20y; 95%	20y; 70%	30y; none	30y; none
Semi-Aerobic Technology	**Time Period 1**	**Time Period 2**	**Time Period 3**	**Time Period 4**
LFG generated (% of LFG potential)	2y; 2%	6y; 50%	7y; 20% (Aerobic)	85y; 10%
LFG collected (% of generated)	2y; none	6y; 95%	7y; none	85y; none
LFG management	none	energy recovery	none	none
Leachate generated (mm/y)	2y; 500mm/y	6y; 250mm/y (Recirculation)	7y; 200mm/y	85y; 180mm/y
Leachate collected (% of generated)	20y; 95%	20y; 70%	30y; none	30y; none

When the collected LFG is used for CHP generation, an overall energy recovery efficiency of 85% was assumed. The electricity produced substitutes 100% for electricity produced at a coal-fired power plant, while the heat produced is used as district heating. Standard- and flushing-bioreactor technologies practise leachate recirculation. It was assumed that external water is added to the leachate in the flushing-bioreactor landfill and the flushing-ratio realized was set to 3 m^3/tonne, as the cumulative amount of liquid injected over 8 years of recirculation. In the scenario made for the flushing-bioreactor landfill, it was assumed that the collected leachate undergoes nitrification to reduce the concentration of ammonia before being recirculated to the waste mass.

3.1.2 Key results

The LCIAs estimated for the six landfilling scenarios are given in Figure 2–6. Results for the conventional landfill with energy recovery (Figure 2) show that several parts of the system assessed generated emissions that lead to potential impacts, but emissions of LFG and leachate from the landfill (system emissions) constitute the single most important load to all the environmental categories. However, at the same time, LFG utilization for CHP generation gives marked environmental savings to GW and several other impact categories. These savings would have been smaller if an average electricity mix had been considered as substitute process instead of electricity produced from coal. The LCIA comparison of the six landfilling scenarios with respect to the 100-year time horizon is given in Figures 3 and 4. The open dump presents the highest impact potentials in several categories, due to the massive emissions of LFG and leachate. However, due to the absence of emissions from electricity generation and especially from on-site operations the open dump presents lower impact potentials in the toxicity-related categories (except HTs) than those estimated for the other landfilling scenarios, where these emissions occur. The results for SGR are given in Figure 4. The open dump causes by far the highest impact, as it was assumed that all the leachate generated reaches the groundwater. The performance estimated for SGR for the flushing-bioreactor landfill is better than that estimated for the other landfill scenarios. The main reason for this is the removal of ammonia from leachate accomplished through leachate nitrification / on-site denitrification. Results from the mass balances of selected elements show that for all landfilling scenarios less than 1% of the contents of heavy metals such us Cd, Cr, Hg, Pb and Zn is leached within the 100-year time horizon [I].

The results estimated for the time horizons 0–15 years (Figure 5) and 16–100 years (Figure 6) allow for a deeper understanding of the real environmental benefits brought about by the active operations. Leachate recirculation in fact determines higher LFG generation rates but, as a consequence, higher fugitive emissions of LFG are also observed during the first 15 years: this explains the higher impact potentials on HTs and HTa estimated for the bioreactor landfills, compared with the conventional landfill scenarios (Figure 5). However, at the same time, most of the methane potential can be utilized for energy generation within the first 15 years (Table 2), which gives considerable environmental savings especially on GW. After this period emissions are very low and therefore the impact potentials estimated are low too (Figure 6). In contrast, emissions from conventional landfill, and especially open dump, are considerable throughout most of the 100-year time period; consequently, the impact potentials estimated are significant also in the period 16–100 years.

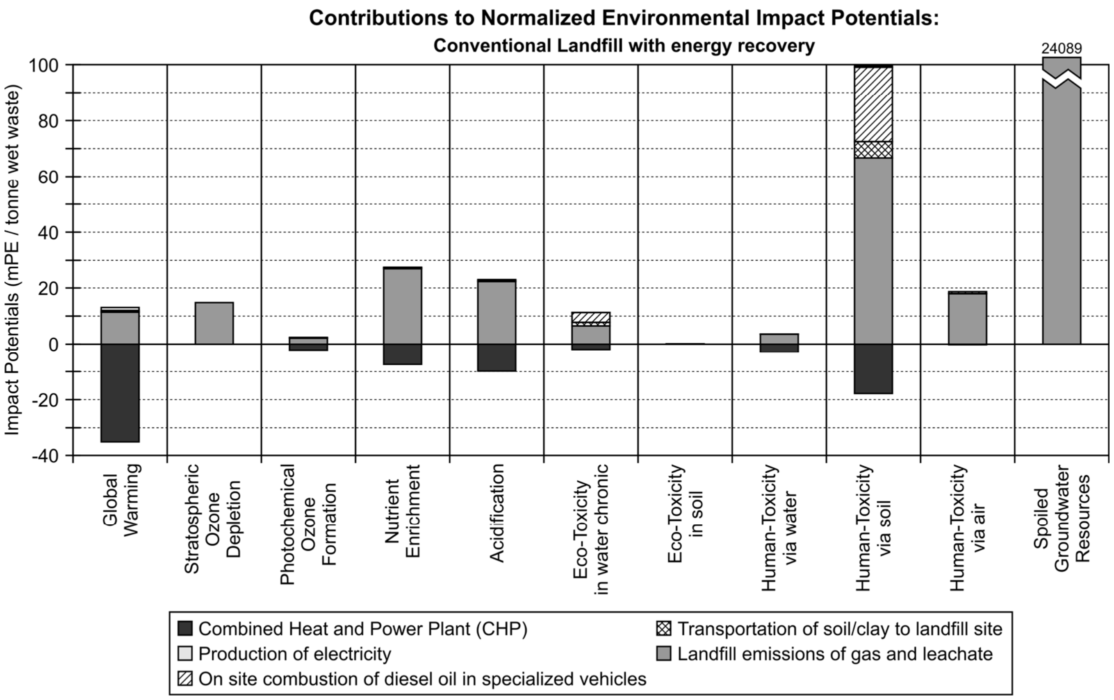

Figure 2 (from [I]): LCIA of the conventional landfill with energy recovery, as normalized impact potentials – standard and toxicity-related environmental impact categories; time horizon 0–100 years.

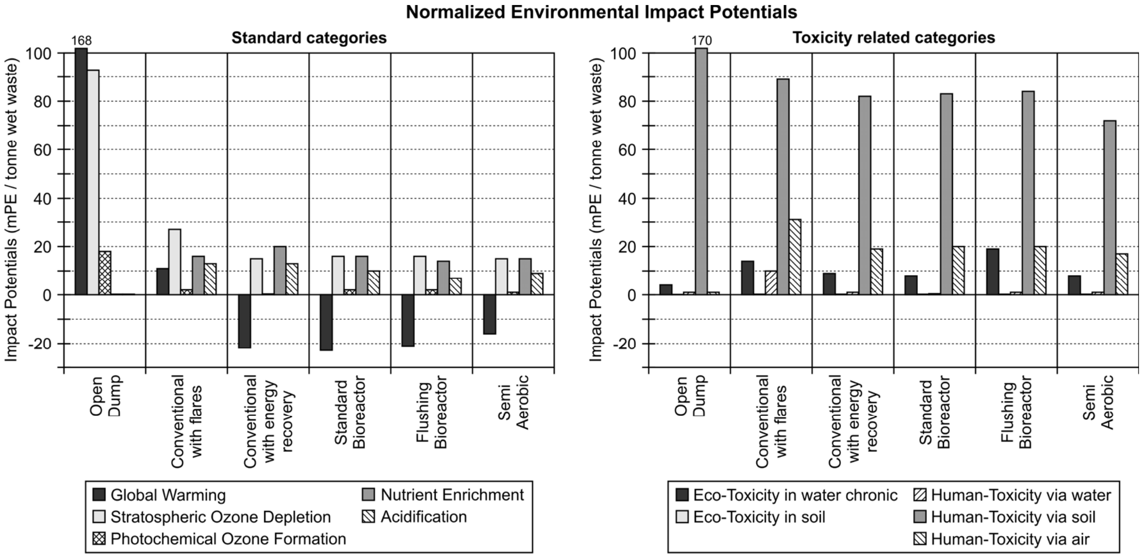

Figure 3 (from [I]): LCIAs of the six landfilling technologies as normalized impact potentials – standard and toxicity-related environmental impact categories; time horizon 0–100 years.

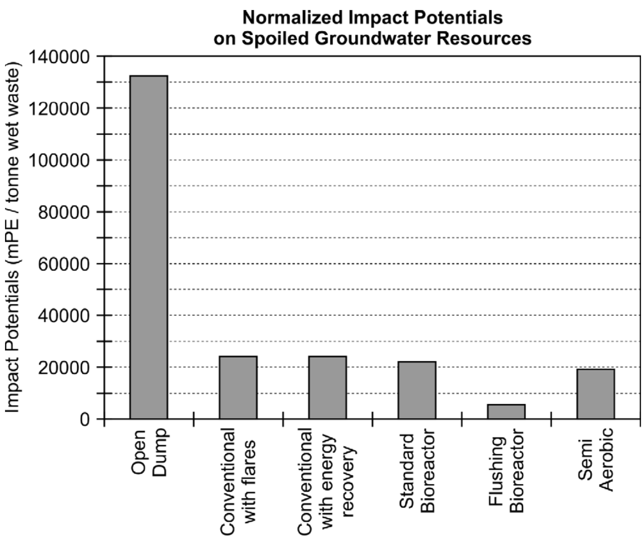

Figure 4 (from [I]): LCIAs of the six landfilling technologies as normalized impact potentials – impact on spoiled groundwater resources; time horizon 0–100 years.

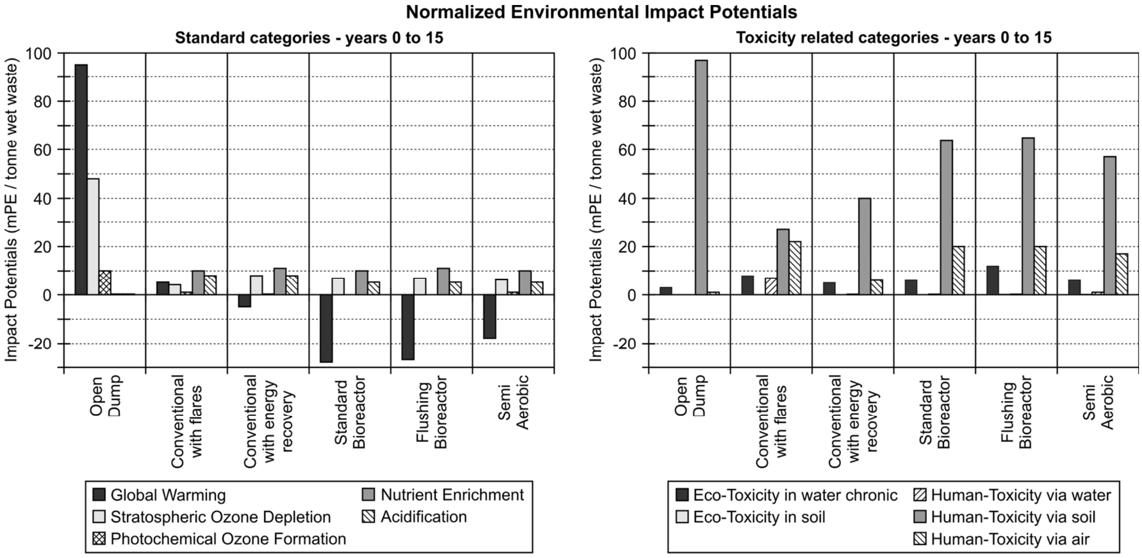

Figure 5 (from [I]): LCIAs of the six landfilling technologies as normalized impact potentials – standard and toxicity-related environmental impact categories; time horizon 0–15 years.

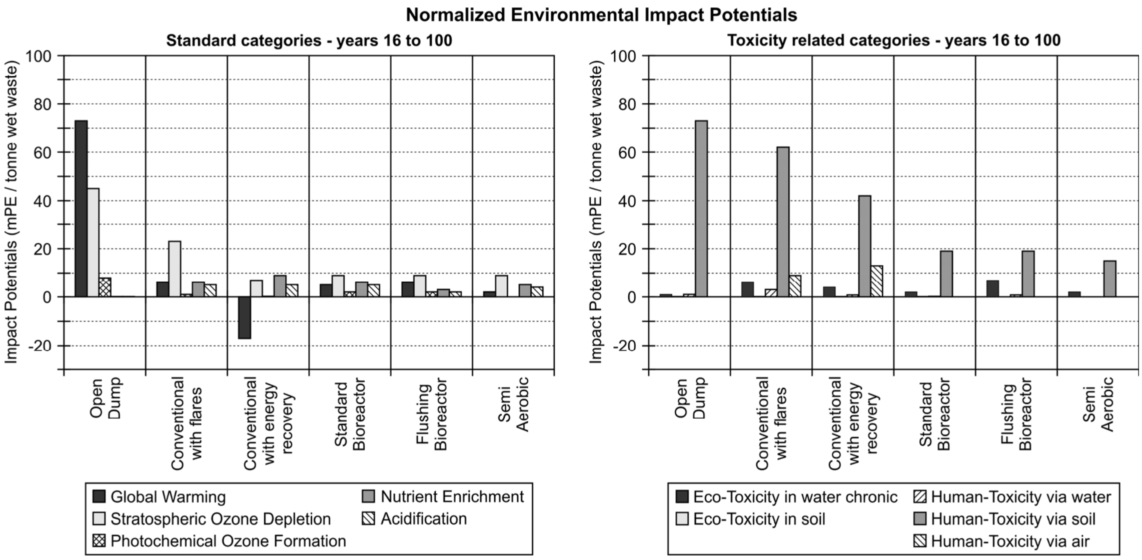

Figure 6 (from [I]): LCIAs of the six landfilling technologies as normalized impact potentials – standard and toxicity-related environmental impact categories; time horizon 16–100 years.

3.2 Role of the individual waste fractions

Based on decades of experience with landfilling of mixed waste, a consistent scientific framework is currently available on the assessment of the environmental performance for this type of landfill. However, little is known about the contribution from the individual waste fractions to the overall impact potentials from landfilling of the mixed waste. In principle, this requires extensive data about LFG and leachate emissions from degradation of the individual waste fractions under landfill conditions. As actual data on the topic are scarce, empirical models are used, which are based on accelerated degradation tests of the individual fractions (for instance: degradation tests carried out by M. Barlaz and reported in US EPA, 2006; Belevi and Baccini, 1989). LFG and leachate quality and quantity estimated using empirical models for individual fractions are often used in LCA studies to compare landfilling of individual fractions with other options, especially recycling, composting and incineration. These studies primarily highlight the environmental benefits offered by recycling and incineration and use landfilling as a worst-case reference scenario. This might, however, be an unfair comparison for many up-to-date landfilling contexts, especially when biodegradable fractions are landfilled. Biodegradable fractions allow for LFG utilization and therefore, in a life cycle thinking perspective, offer environmental savings. In addition, not all LCA studies assign a negative global warming potential to stored biogenic carbon in landfills, which would further improve the global warming profile of the landfill.

3.2.1 Contribution to impact potentials

An LCA was developed to quantify the share of overall potential impact from landfilling of mixed waste caused by the individual fractions in the mixed waste [VI]. The fractions considered were “organics”, “paper”, “plastic”, “metals”, “glass”, “other combustible waste” and “other non-combustible waste” (Table 3). Landfilling of the individual fractions is carried out in a conventional landfill with LFG utilization. The main assumption and technical parameters are given in

Table 4. The collected LFG is assumed to be utilized for electricity generation and the energy recovery efficiency is set to 35%. Emissions and avoided emissions for production of electricity represent an average European electricity mix, based on data from the International reference Life Cycle Data System (ILCD, 2008).

Table 3 (from [VI]): Waste fractions and sub-fractions included in the study, mass distribution in the mixed waste (%), decomposition factors D (%, mass) and methane potential M (Nm^3 CH_4/tonne wet fraction).

Fraction	Waste sub-fractions	% (mass)	D (%)	M
Organics	vegetable waste, animal waste, kitchen tissues	32.3	86.5	117
Paper	magazines, advertisements, books and telephone books, office paper, other clean paper, paper and carton containers, cardboard, milk cartons, dirty paper, dirty cardboard, carton with alu-foil	33.2	40	115
Plastic	soft plastic, hard plastic, plastic bottles, non-recyclable plastic	6.9	1	0
Metals	Al containers, Al trays/foil, metal containers, metal foil, other metal	2.3	50	0
Glass	clear glass, green glass, brown glass, other glass	9.0	50	0
Other combustible waste	yard waste, animals, nappies and tampons, cotton buds, other cotton, wood, textiles, shoes leather, rubber, office articles, cigarette butts, vacuum cleaner bags, other combustible	12.9	27	22
Other non combustible waste	soil, stones and gravel, residuals, ceramics, cat litter, batteries, other non-combustibles	3.4	1	0

Table 4 (from [VI]): Technical parameters relative to waste landfilled, LFG and leachate generation, collection and management.

Parameter	Time Period 1	Time Period 2	Time Period 3	Time Period 4
Waste bulk density	1 tonne/m^3			
Waste LFG potentials	76 Nm^3 CH_4 and 141 Nm^3 LFG / tonne wet waste			
	Duration ; value	Duration ; value	Duration ; value	Duration ; value
Leachate generated	2y: 350 mm/y	5y: 350 mm/y	38y: 200 mm/y	55y: 180 mm/y
Leachate collected (% of generated)	10y ; 95%	35y ; 90%	30y ; 85%	25y ; 80%
LFG generated (m^3/tonne waste/year)	2y ; 0.72	3y ; 1.91	40y ; 2.86	55y ; 0.26
LFG generated (% of LFG potential)	2y ; 1%	3y ; 4%	40y ; 80%	55y ; 10%
LFG collected (% of generated)	2y ; none	5y ; 50%	38y ; 80%	55y ; none
Management of the collected LFG	(no LFG collection)	Electricity generation	Electricity generation	(no LFG collection)

The environmental emissions (LFG and leachate) for the individual fractions were estimated with an empirical model. This model is reported by Doka (2007) and makes use of the results obtained from Belevi & Baccini (1989) and US EPA (2006) about long-term degradation of MSW landfills. As inputs, the model requires the chemical composition of the mixed waste and the degradation factors for the individual fractions (Table 3). The waste chemical composition chosen represents average Danish household waste and it is based on the study from Riber et al. (2009).

Results from the LCIA are given in Figure 7 and Table 5. They show that the impact potentials estimated for the standard categories, and especially for GW, are mostly caused by the fractions “organics” and “paper”. These depend to a large extent on dispersed LFG emissions from the landfill surface. The other waste fractions cause most of the potential impacts estimated for the toxicity-related categories. Nevetheless, the waste fractions that contribute with the highest environmental savings are “paper”, “organics” and “other combustible waste”.

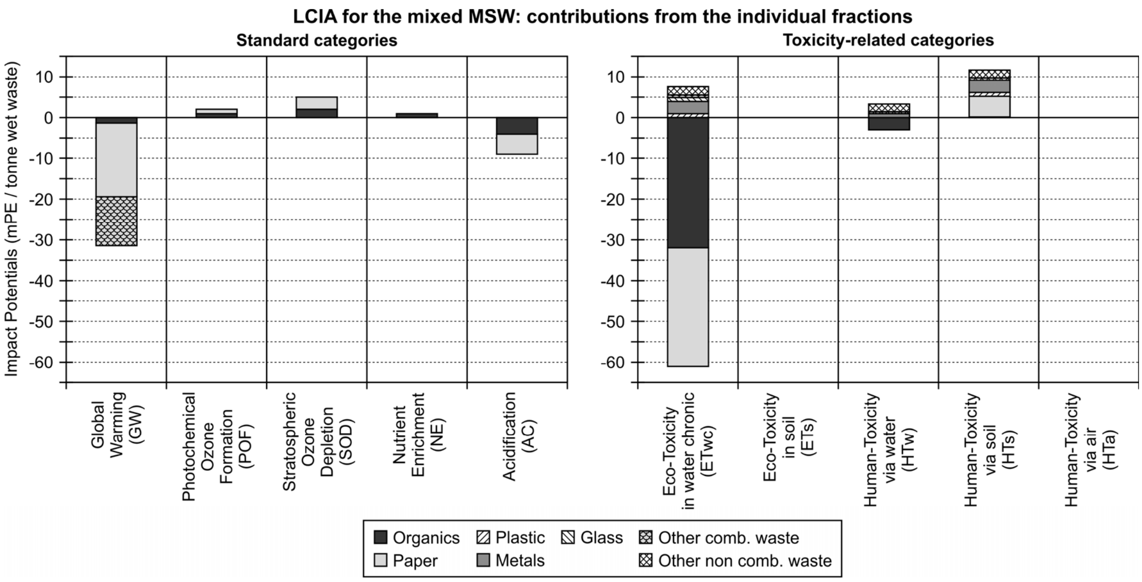

Figure 7 (from [VI]): LCIA for 1 tonne of mixed MSW with focus on the relative contributions from the individual waste fractions.

Table 5 (from [VI]): Contributions of the individual waste fractions to selected impact categories of the LCIA for the mixed MSW (as mPE/tonne): net contributions, positive contributions (environmental loads) and negative contributions (environmental savings).

Category		Organics	Paper	Plastic	Metals	Glass	O.C.W.	O.N.C.W.
GW	net	-1	-18	0	0	0	-12	0
	load	8	9	0	0	0	1	0
	saving	-9	-27	0	0	0	-13	0
POF	net	1	1	0	0	0	0	0
	load	1	1	0	0	0	0	0
	saving	0	0	0	0	0	0	0
SOD	net	2	3	0	0	0	0	0
	load	2	3	0	0	0	0	0
	saving	0	0	0	0	0	0	0
NE	net	1	0	0	0	0	0	0
	load	2	1	0	0	0	0	0
	saving	-1	-1	0	0	0	0	0
ETwc	net	-32	-29	1	3	1	1	2
	load	1.5	3	1	3	1	1	2
	saving	-34	-32	0	0	0	-1	0
HTw	net	-3	0	0	1	0	0.4	2
	load	0	3	0	1	0	0.5	2
	saving	-3	-3	0	0	0	-0.1	0
HTs	net	0	5	1	3	0	1	2
	load	2.5	7	1	3	0	1	2
	saving	-3	-2	0	0	0	-0.1	0

The waste fraction “organics” has high methane potential and high degradability (Table 3) and therefore high amount of LFG is generated from its degradation, which is used for electricity generation. This gives substantial environmental savings to GW, ETwc and other categories (Table 5). The waste fraction “paper” also has a high methane potential but a relatively low degradability (here set to 40%; Table 3). Therefore, the marked contribution to saving on GW estimated for “paper” comes mainly from the biogenic carbon left undegraded within the landfill (accounted for as avoided emission of biogenic CO_2), rather than from the use of the LFG generated by its degradation. With respect to ETwc, overall the mixed waste contributes with a saving of 53 mPE/tonne: direct loads caused by emissions of heavy metals and other toxic chemicals (mostly from “plastic” and “metals”) are smaller than the savings brought about by avoided emissions (mainly heavy metals) from LFG utilization (mostly from “paper” and "organics"). The biggest load to the environment caused by landfilling of the mixed MSW is estimated for HTs (12 mPE/tonne). This mostly comes from leaching of As, Cd and Hg from degradation of "paper", "metals" and "other non-combustible waste".

3.2.2 Alternative management options for individual fractions

The environmental performance of three major management options (landfilling, recycling and incineration or composting) was here evaluated for a number of individual waste fractions: "organics", "recyclable paper", "recyclable plastic", "aluminium" and "glass" [VII]. These fractions represent either the recyclable-part or, for "organics", the compostable-part, of the waste fraction considered in Table 3. This choice was made to include the management option recycling (or composting) for all the waste fractions. Unlike most LCA based studies done on the topic, all the environmental aspects related to the landfilling option are here systematically accounted for, including provision of energy/material, on-site operations, energy recovery, binding of biogenic carbon, etc.

The LCA functional unit is management (landfilling, incineration and recycling or composting) of 1 tonne of wet individual waste fraction and the environmental aspects were assessed for 100 years, starting from the moment when the individual waste fraction is treated (for incineration, recycling and composting) or landfilled. Emissions and avoided emissions for production of electricity represent an average European electricity mix, based on data from the International Reference Life Cycle Data System (ILCD, 2008).

The list of scenarios included in the LCA comparison is given in Table 6. For the fractions "organics" and "recyclable paper" two landfilling scenarios were considered assuming flaring or utilization of the collected LFG, respectively. The energy recovery efficiency of the LFG utilization process was set to 35%. The landfilling scenario assumed for the other fractions considers only leachate management as for these fractions LFG generation is negligible. The incineration scenario is based on the grate furnace incinerator of Copenhagen

(Vestforbænding). Electricity and heat are simultaneously produced and the energy recovery efficiencies were set to 20% and 40% of the lower heating value of each waste fraction, respectively. The produced electricity substitutes 100% for average European energy production (ILCD, 2008), while the heat produced is utilized for district heating. Emissions from bottom ash disposal (in a mineral waste landfill) and for waste water treatment are accounted for, as well as emissions from treatment of waste water used at the incineration plant, while emissions from landfilling of fly ash were not included. Composting of the fraction "organics" is based on a tunnel composting plant located in Treviso (Italy) and described by Boldrin et al. (2009). The compost produced substitutes for use of fertilizer on farm loam soils.

Table 6 (from [VII]): List of the scenarios included in the LCA comparison.

Waste fraction	Scenario name	Technology used (from the EASEWASTE database)
Organics	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (Flares)
	Landfilling	Conventional landfill (Electricity)
	Recycling	Composting and Use on Land
Recyclable paper	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (Flares)
	Landfilling	Conventional landfill (Electricity)
	Recycling	Coreboard, Skjern Papirfabrik, Denmark
Recyclable plastic	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (leachate management only)
	Recycling	Melting of clean PE (LD and HD) plastic to granulated plastic foam (plastic granulation)
Aluminium	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (leachate management only)
	Recycling	Melting and alloying of aluminium scrap
Glass	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (leachate management only)
	Recycling	Cleaning of reusable glass bottles (35%) and melting of glass cullet and casting of new glass products (65%)

Plastic recycling has been modelled assuming that pre-sorted plastic waste (PE) is converted to granulate of PE. This substitutes for similar material produced from fossil resources and the avoided production is set to 90%. For the fraction "recyclable glass", two technologies were considered: cleaning of reusable glass bottles and melting of glass cullet and casting of new glass products. It was assumed that these two technologies accommodate respectively 35% and 65% of the recyclable glass fraction (based on Nejrup & Wesnæs, 2000). Here, results from the LCIA are presented only for the waste fractions “organics”, “recyclable paper” and “metals” (Figures 8, 9 and 10).

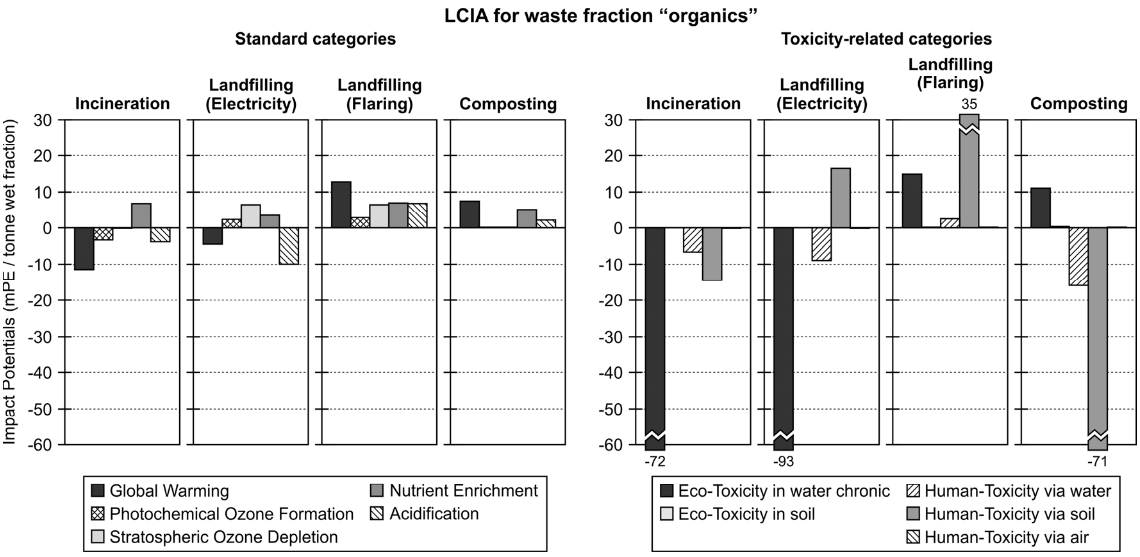

Figure 8 (from [VII]): LCIA for the waste fraction “organics” in four alternative management scenarios – results are given as normalized impact potentials.

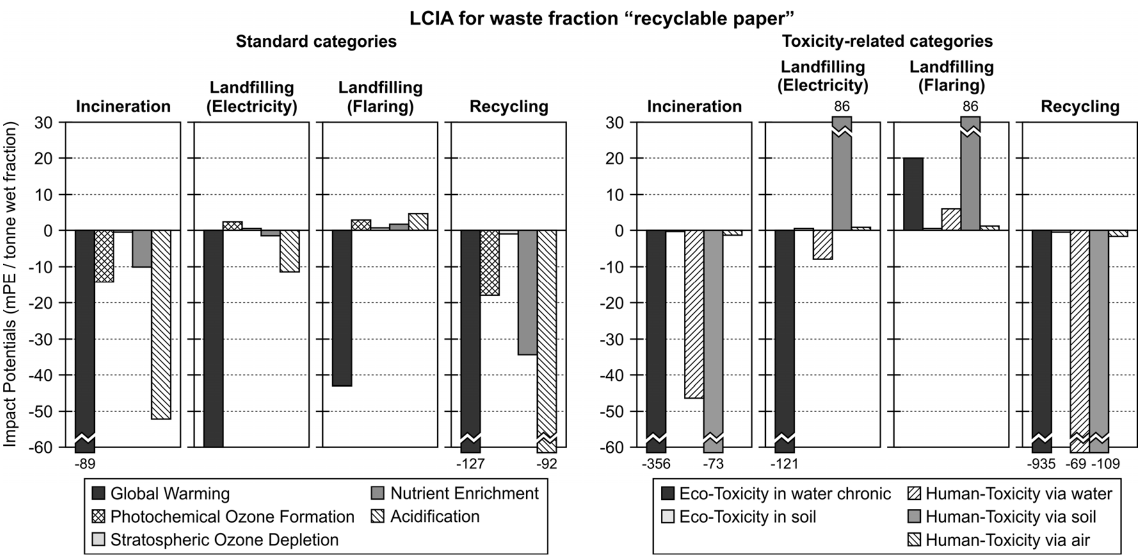

Figure 9 (from [VII]): LCIA for the waste fraction “recyclable paper” in four alternative management scenarios – results are given as normalized impact potentials.

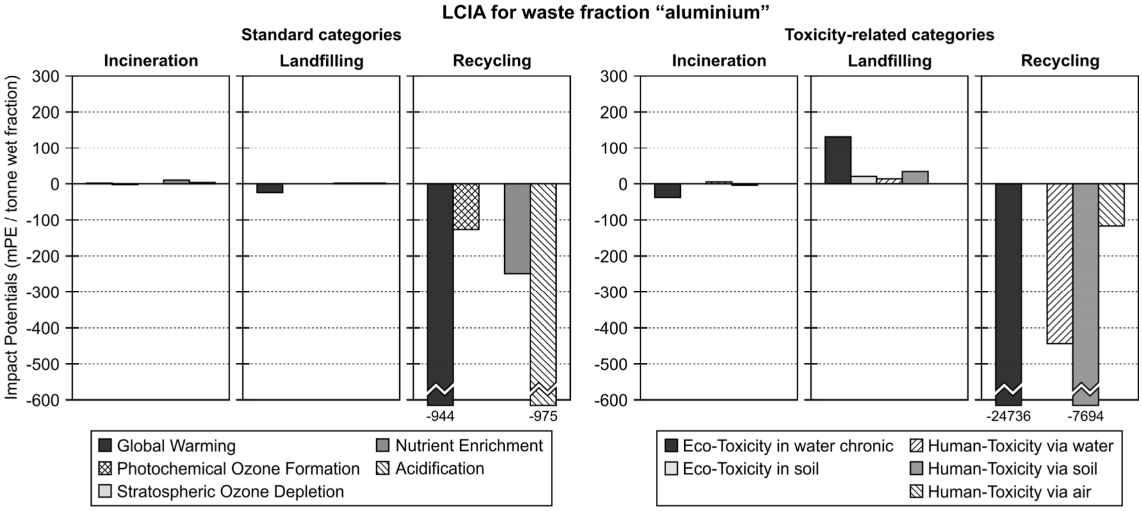

Figure 10 (from [VII]): LCIA for the waste fraction "aluminium" in three alternative management scenarios – results are given as normalized impact potentials.

For the fraction "organics", the best environmental performances are found for the scenarios incineration and landfilling with electricity generation, with considerable environmental savings estimated for GW and especially for ETwc. Composting of "organics" leads to substantial savings on HTs and HTw, as it was assumed that the compost generated substitutes for use of fertilizers. Recycling of "recyclable paper" causes lower impact potentials compared with the other management options, as significant savings were found in GW, NE, AC, ETwc, HTw and HTs. Incineration, however, achieves a comparable performance, while landfilling offers marked benefits on GW only. These savings on GW from paper landfilling are mostly determined by the large amount of biogenic carbon left undegraded in the landfill after the 100-year period and, to a lesser extent, by avoided emission from the LFG utilization process. Paper degradability is relatively low (40%; Table 3); therefore, the amount of LFG available for utilization is also relatively low. Recycling offers the best performance, also for the waste fraction "aluminium". This is particularly evident in the categories GW, AC, HTs and ETwc. However, landfilling of "aluminium" causes significant potential impacts on the toxicity-related categories. The highest impact is estimated for ETwc due to emissions of heavy metals and other toxic chemicals via discharge of treated leachate to surface water.

3.3 Case study: the Ämmässuo landfill (Finland)

LCA modelling of existing, full-scale landfills is a complex and challenging task, as a large number of site-specific data are needed that should cover all the technical and environmental aspects of relevance. Since all these data are not always available, it frequently becomes necessary to fill the gaps with average literature data from similar existing landfills. This should, however, be avoided as much as possible as otherwise results from the LCIA would not be fully representative of the actual landfill under study. In addition, available data from actual landfills are often expressed in a unit that does not fit to the requirement of the LCA model used. For instance, EASEWASTE requires that data relative to material and energy inputs are entered as cumulative amounts realized during the LCA time horizon with respect to the unit mass of waste landfilled (e.g. kWh of electricity used in 100 years per tonne of wet waste). These data, however, are often known with respect to a certain time period (e.g. kWh of electricity used in year 2008) and their conversion to a unit that matches the model requirement might not be straightforward.

Nevertheless, actual data do not typically cover more than 2 to 3 decades of landfill process and therefore they must be supplemented with data from accelerated tests of limited scale and model predictions. In addition, the life-span of active operation could be composite, for instance due to different strategies undertaken for LFG and leachate management at different periods. This creates LCA modelling challenges, as the model used may not provide enough flexibility to accommodate all the changes that the actual site has undergone throughout the selected LCA time horizon.

3.3.1 Assessment of the current situation

The Ämmässuo landfill (Espoo, Finland) was chosen for application of the EASEWASTE model for the environmental assessment of an existing, full-scale household waste landfill [II, III]. The Ämmässuo landfill received waste (mainly household waste) from the Helsinki metropolitan region and, with an area of 52 hectares and about 10 million tonnes of waste landfilled from 1987 to 2007, it is one of the largest landfills in Northern Europe. Leachate collection and treatment started in 1987 and LFG collection started in 1996. Until 2003, all the collected LFG was flared, while from 2004, three quarters of the collected LFG has been utilized for district heat generation. The heat generated substitutes district heat generated from natural gas and coal. Leachate and LFG collection and management are expected to stop in year 2026.

Results from the LCIA [II] show that contamination of groundwater due to leachate emission may be a critical issue. It was estimated that each tonne of waste landfilled poses a potential contamination (up to the drinking water standard: WHO, 2006) of the volume of groundwater that approximately 58 Finns use in one year. This threat may however be overestimated because natural attenuation processes (for instance oxidation of ammonia to nitrates) may occur in the subsurface, which were disregarded in the calculation. Potential impacts are estimated in categories other than SGR, and the highest are found in SOD, GW, HTs and ETwc (approximately 23, 16, 13 and 10 mPE/tonne wet waste, respectively). These are mostly caused by fugitive releases of unoxidized CH_4, CFCs and benzene from the landfill surface, emissions of VOCs, PAHs, NO_x, heavy metals and products of incomplete combustion from LFG treatment and from the vehicles operating on-site. Emissions from LFG treatment and on-site operations constitute a marked source of potential impacts at the Ämmässuo landfill. Vehicles operating on-site were assumed to comply with the EU2 emissions limits for diesel combustion, which accounts for the high emissions. A cause of the fugitive LFG release from the landfill surface is the unfinished construction of the soil cover. In 2006, the final cover was constructed on top of only 35% of the entire landfill area; its completion is expected by 2010.

3.3.2 Assessment of alternative LFG management options

As an additional application of EASEWASTE for the Ämmässuo landfill, the current management option for the collected LFG (75% flares and 25%

utilization for heat generation) was compared with three alternatives: “Flaring”, “Heat Generation” and “Combined Heat and Power Generation” [III]. In the last scenario the electricity produced is assumed to substitute for the average Finnish electricity mix (nuclear: 26%; condensing and cogeneration powers: 18% each; hydro-power: 13%; and others: 25%). The assessment considers all the waste landfilled from 1987 to 2007 (10 million tonnes) and focuses on the environmental aspects related to the LFG management as of today (2008) and 100 years into the future. All emissions that are not related to the LFG management are disregarded as they do not vary across the considered management options and consequently do not affect the results of the LCIA (for instance, emissions from on-site operations and from leachate generation/treatment are disregarded).

Table 7 gives details of the scenarios compared, Figures 11 and 12 show the results of the LCIA and Table 8 gives the sensitivity analysis of 3 selected parameters. In all scenarios compared, the highest impact potentials are estimated for GW and SOD. These are caused largely by fugitive release of unoxidized LFG from the landfill surface. For GW the impacts estimated range from 13 mPE/tonne (“Heat generation” scenario) to 19 mPE/tonne (“LFG flaring” scenario), while for SOD they range from 5 mPE/tonne (“Heat/Electricity generation” scenario) to 7 mPE/tonne (all the other scenarios). Potential impacts on the toxicity-related categories are smaller than estimated for the standard impact categories (often < 1 mPE/tonne).

Table 7 (from [III]): Percentage of the collected LFG diverted to treatment/utilization alternatives in the three LFG management options.

LFG Management Options	**Flares**	**Energy utilization**	
Current LFG management	25%	75%	Heat generation only
LFG Flaring	100%	-	/
Heat Generation	-	100%	Heat generation only
Combined Heat and Power Generation	-	100%	Combined heat and power generation

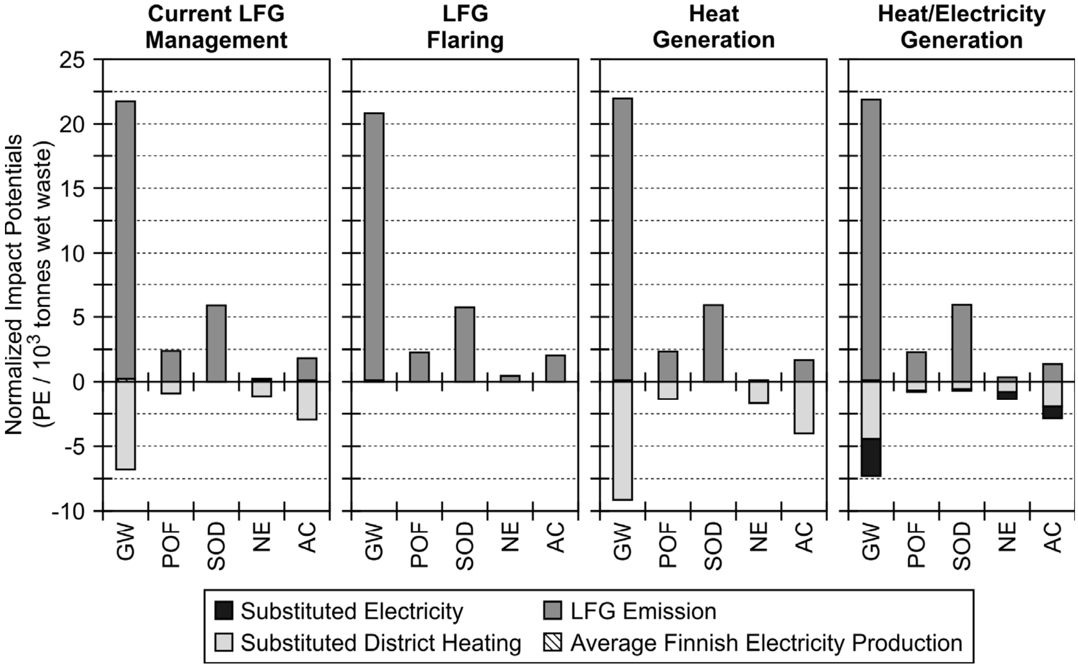

Figure 11 (from [III]): Life cycle impact assessment (LCIA) of 4 LFG management options for the Ämmässuo landfill – contribution of selected processes to normalized impact potentials on the standard categories.

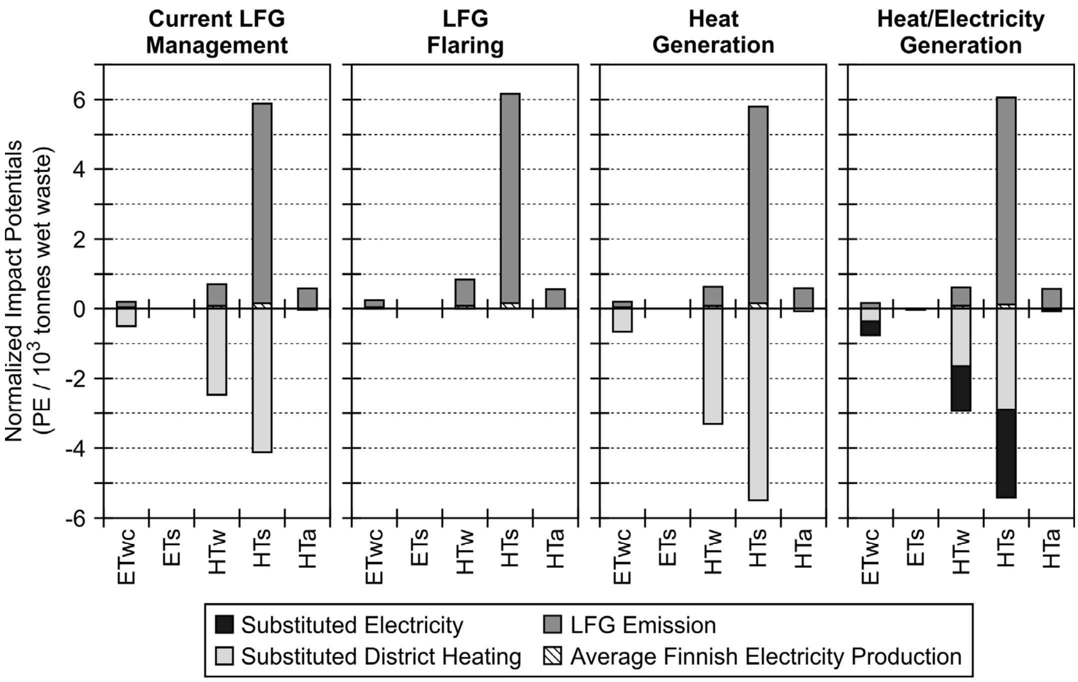

Figure 12 (from [III]): Life cycle impact assessment (LCIA) of 4 LFG management options for the Ämmässuo landfill – contribution of selected processes to normalized impact potentials on the toxicity-related categories.

Table 8 (from [III]): Sensitivity analysis for selected parameters (methane potential, LFG collection efficiency and methane oxidation in top cover) for the impact categories GW, SOD and HTs.

		GW	SOD	HTs
Current LFG management		PE / 10^7 tonne ww		
		148,782	58,985	17,811
CH_4 potential (m^3 CH_4 / tonne ww)	73 +/- 20%	+/- 18.6%	+/- 20.0%	+/- 19.8%
LFG collection efficiency (%)	75 +/- 20%	+/- 56.7%	+/- 36.1%	+/- 41.0%
CH_4 oxidation in top soil cover (% in 2 time periods)	30/70 +/- 20%	+/- 13.3%	+/- 0%	+/- 0%
		GW	**SOD**	**HTs**
LFG management Flaring		PE / 10^7 tonne ww		
		208,913	57,681	61,707
CH_4 potential (m^3 CH_4 / tonne ww)	73 +/- 20%	+/- 18.9%	+/- 20.0%	+/- 19.8%
LFG collection efficiency (%)	75 +/- 20%	+/- 41.3%	+/- 20.7%	+/- 20.6%
CH_4 oxidation in top soil cover (% in 2 time periods)	30/70 +/- 20%	+/- 10.6%	+/- 0%	+/- 0%
		GW	**SOD**	**HTs**
Heat Generation		PE / 10^7 tonne ww		
		128,738	59,420	3,179
CH_4 potential (m^3 CH_4 / tonne ww)	73 +/- 20%	+/- 18.5%	+/- 20.0%	+/- 19.8%
LFG collection efficiency (%)	75 +/- 20%	+/- 63.4%	+/- 19.9%	+/- 28.9%
CH_4 oxidation in top soil cover (% in 2 time periods)	30/70 +/- 20%	+/- 14.5%	+/- 0%	+/- 0%
		GW	**SOD**	**HTs**
Heat/Electricity Generation		PE / 10^7 tonne ww		
		147,197	53,200	7,026
CH_4 potential (m^3 CH_4 / tonne ww)	73 +/- 20%	+/- 16.7%	+/- 20.0%	+/- 19.8%
LFG collection efficiency (%)	75 +/- 20%	+/- 158%	+/- 20.2%	+/- 26.1%
CH_4 oxidation in top soil cover (% in 2 time periods)	30/70 +/- 20%	+/- 28.5%	+/- 0%	+/- 0%

Overall, the worst environmental performance is found for the "LFG Flaring" option. LFG flaring does not lead to energy recovery and therefore environmental savings does not occur. At the same time, LFG flaring does lead to the emission of substances (such as CO, dioxins and other products of incomplete combustion) that create environmental loads and have an impact on both standard and toxicity-related categories. Conversely, the best performance is found for the "Heat Generation" options. This is largely because the highest energy recovery efficiency of the LFG utilized was assumed for this option.

3.4 Assessment of low-organic waste landfills

In the last 10–15 years, the amount of organic waste fractions disposed of in European landfills has been progressively reduced and some member states have already completely prohibited landfilling of organic waste. This process follows the goal set by the Landfill Directive 99/31 (CEC, 1999) of a maximum of 35% organic waste being landfilled by 2014. As a consequence, landfills with a lower content of organic matter will become increasingly common in Europe in the years to come opposed to landfills that received remarkable quantities of organic waste. Consistent data on emissions to the environment from low-organic waste landfills are currently scarce, making it difficult to assess their environmental performance with LCA models.

An LCIA was developed to evaluate the performance of typical low-organic waste landfill scenarios and to compare it with that of household waste landfill scenarios. From an LCA viewpoint, such a comparison could not be done, as the qualities of the waste input are different. However, the goal was not the evaluation of the overall impacts from reducing the amount of organic waste going to landfill including all the upstream technologies. Instead, the perspective taken is that of the unit mass (1 tonne) of waste being landfilled and all the connected environmental aspects are taken into account for a time horizon of 100 years after disposal. Biogenic carbon stored at the end of the time horizon was not accounted for as an avoided CO_2 emission (this is the reason for the different results found here for GW compared with a similar landfilling scenario of low-organic waste landfill presented in [V]). Input data covering the first 15–20 years of the 100-year time horizon are mostly based on data from the Nauerna landfill (Assendelft, the Netherlands), one of the best monitored low-organic waste landfills in Europe, receiving mainly contaminated soils, soil treatment residues and dredging sludge.

The reference scenario created is called “low-organic-energy” and assumes that all the collected LFG is used for heat and electricity generation in a CHP plant. The generated electricity is assumed to substitute for electricity generated at a coal-fired power plant. The electricity utilized at the landfill site is assumed to be generated from the average Danish power mix (54% coal, 21% natural gas, 13% wind, 13% others). Results are given in Figure 13 and show that LFG and leachate emissions and emissions from landfill operations cause most of the potential impacts estimated. Furthermore, it should be noted that despite the low methane potential assumed for the low-organic waste (13 Nm^3/tonne wet waste), LFG utilization still gives a considerable reduction of the impact potential found for GW.

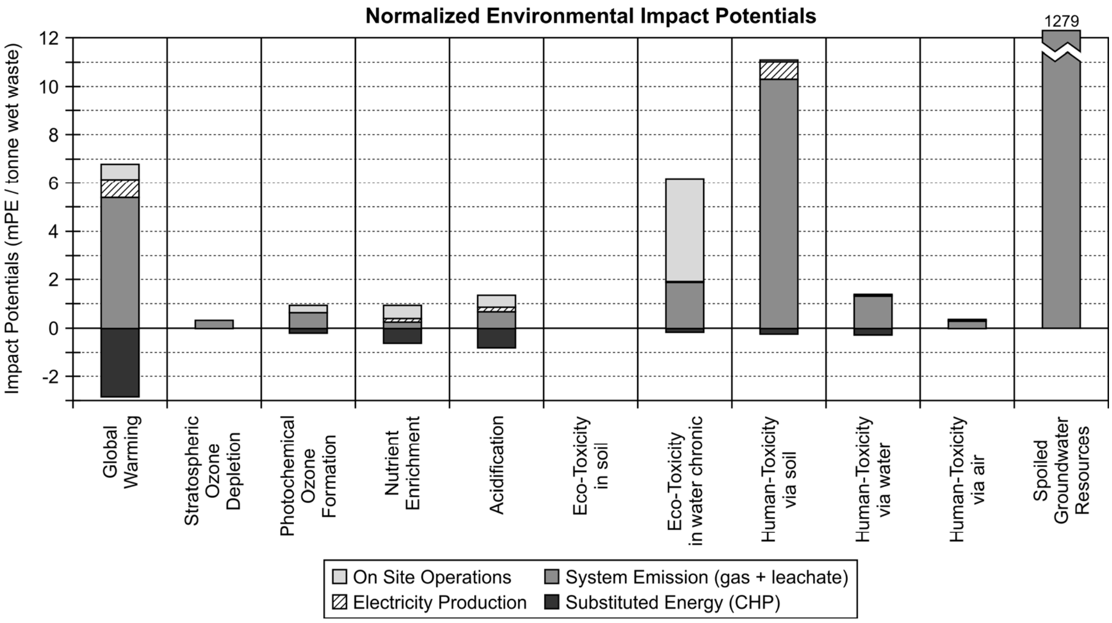

Figure 13 (from [IV]): Individual contributions to the LCIA of the "low-organic-energy" landfill scenario – standard impact categories, toxicity-related impact categories and impact on groundwater resources.

Another scenario was considered for landfilling of low-organic waste, called "low-organic-flare". This assumes that all the collected LFG is flared instead of being utilized for energy generation. In addition, two equivalent scenarios were created for household waste, namely "household-energy" and "household-flare". These differ from the low-organic waste scenarios in several input parameters, such as waste methane potential, LFG and leachate composition, LFG collection efficiency, amounts of electricity and diesel inputs for on-site operations (Tables 9 and 10).

Table 9 (from [IV]): Technical measures for LFG and leachate generation, collection and management utilized in the LCA modelling of the low-organic waste landfill scenarios.

Parameter	Time Period 1	Time Period 2	Time Period 3	Time Period 4
Waste CH_4 potential	13 Nm^3/tonne			
Waste bulk density	1.2 tonne/m^3			
Parameter	Duration;value	Duration;value	Duration;value	Duration;value
Leachate generated	2y: 450 mm/y	8y: 450 mm/y	35y: 300 mm/y	55y: 300 mm/y
Leachate collected (% of generated)	10y ; 95%	35y ; 90%	30y ; 80%	25y ; 80%
Leachate entering groundwater (% of generated)	10y ; 5%	35y ; 10%	30y ; 20%	25y ; 20%
LFG generated (m^3/tonne waste/year)	2y ; 1.77	8y ; 1.12	35y ; 0.33	55y ; 0.06
LFG collected (% of generated)	2y ; 0%	8y ; 50%	35y ; 70%	55y ; none
Management of LFG collected	Microbial oxidation	Flare or CHP and microbial oxidation	Flare or CHP and microbial oxidation	Microbial oxidation

Table 10 (from [IV]): Technical measures for LFG and leachate generation, collection and management utilized in the LCA modelling of the household waste landfill scenarios.

Parameter	Time Period 1	Time Period 2	Time Period 3	Time Period 4
Waste CH_4 potential	85 Nm^3/tonne			
Waste bulk density	1 tonne/m^3			
Parameter	Duration;value	Duration;value	Duration;value	Duration;value
Leachate generated	2y: 450 mm/y	8y: 450 mm/y	35y: 300 mm/y	55y: 300 mm/y
Leachate collected (% of generated)	10y ; 95%	35y ; 90%	30y ; 80%	25y ; 80%
Leachate entering groundwater (% of generated)	10y ; 5%	35y ; 10%	30y ; 20%	25y ; 20%
LFG generated (m^3/tonne waste/year)	2y ; 1.83	3y ; 4.88	40y ; 3.20	55y ; 0.67
LFG collected (% of generated)	2y ; 0%	8y ; 80%	35y ; 80%	55y ; none
Management of LFG collected	Microbial oxidation	Flare or CHP and microbial oxidation	Flare or CHP and microbial oxidation	Microbial oxidation

The results of the LCIA comparison are given in Figure 14 (standard impact categories) and Figure 15 (toxicity-related impact categories) and overall show that the low-organic waste scenarios achieve a better environmental performance. This is especially true when comparing the scenarios that assume the collected LFG is simply flared. An exception was, however, found for the category GW; here the best performance is realized by the scenario made for household waste landfill with energy recovery, where a net saving of 8 mPE/tonne is estimated. However, the small methane potential of low-organic waste (here set to 13 Nm^3/tonne wet waste) is not able to counterbalance the low GHG emissions from this type of landfills. The net potential impact is, nevertheless, small: approximately 5 mPE/tonne.

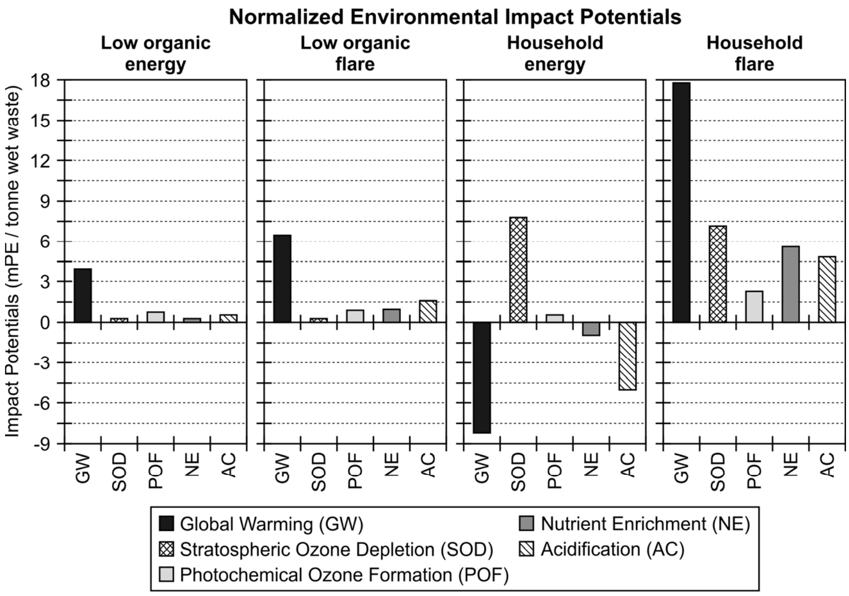

Figure 14 (from [IV]): Comparison of the LCIAs of four landfill scenarios for the standard environmental impact categories.

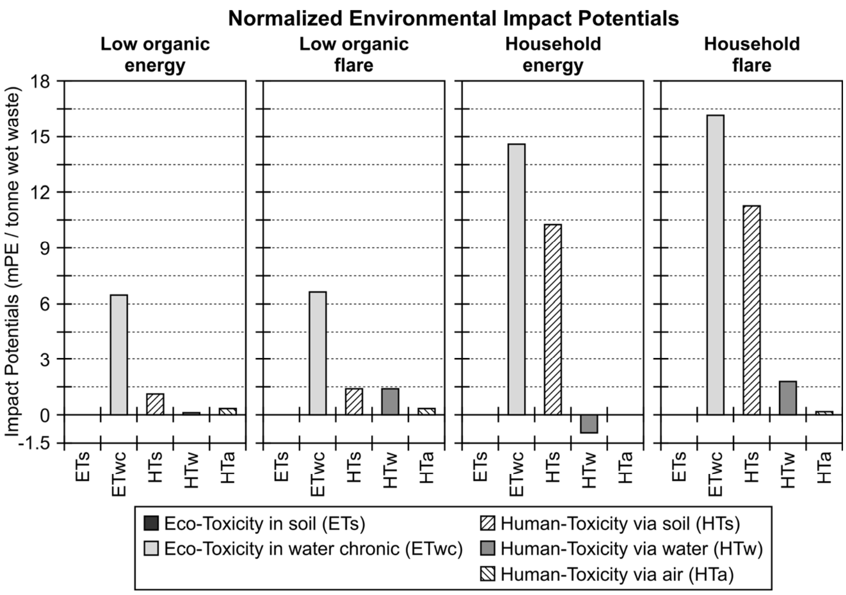

Figure 15 (from [IV]): Comparison of the LCIAs of four landfill scenarios for the toxicity-related environmental impact categories.

3.5 Accounting of GHG emissions from landfills

Emissions of GHGs should be reported annually for each nation, as established by the Kyoto protocol. For landfills, the GHG accounting is done by adding the contributions from individual landfills on a national scale, as recommended by the IPCC in "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (Eggleston et al., 2006). Therefore, on a national scale, the annual cumulative GHG emission from landfills consists of individual contributions from different landfills of different age and, for the individual landfill, from waste of different age and different level of degradation. Moreover, much of the waste that currently contributes to GHG emissions from landfills originates from a time when data on waste amounts and composition were very elementary. Thus this approach towards national GHG accounting merely provides a universal single number that does not allow identification of the key sources of GHG emissions within the landfills considered. This in turn makes it difficult to plan actions to effectively reduce emissions. For this purpose, it is important to categorize GHG emissions from landfills based on the part of the landfill system where these actually occur and to quantify their relative contributions to the overall GHG emission.

3.5.1 Purposes and approach

Landfilling was here approached with focus on GW to provide insight about the individual contributions to GHG emissions from landfills and to provide ranges for the contributions from the technology viewpoint [V]. This accounts for all relevant environmental aspects, including the energy recovery by LFG utilization and sequestering of biogenic carbon in the landfill body (Figure 16). The perspective taken is that of one tonne of waste being landfilled and all emissions expected for a 100-year period are accumulated into a time-integrated value. The GHG accounting is done as suggested by Gentil et al. (2009), distinguishing between direct and indirect contributions and between fossil and biogenic CO_2. Here, biogenic CO_2 is considered neutral with respect to GW when emitted, while biogenic carbon remaining in the landfill is considered a saving. The landfilling technologies included in the study and the key parameters of the waste types included are given in Table 11.

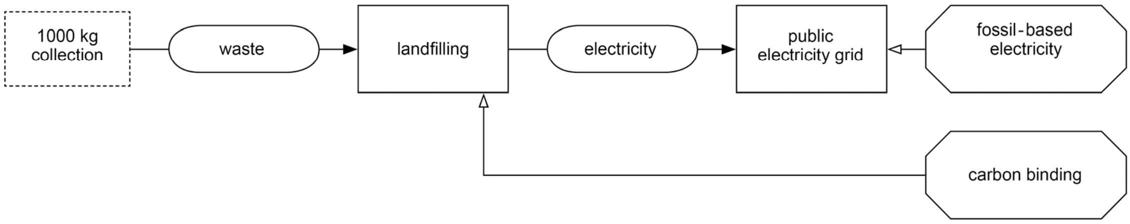

Figure 16 (from [V]): Illustration of the landfilling systems considered in the study.

Table 11 (from [V]): Initial biogenic carbon content of the waste landfilled (bio-C, as kg C/tonne wet waste), methane potential (M, as Nm^3/CH_4 tonne wet waste) dissimilation factors of biogenic carbon for LFG and leachate (D_{LFG} and $D_{Leachate}$, as mass %) and biogenic carbon remaining after 100 years (C_{Left}, as % of bio-C) ([I]; US EPA, 2006; Barlaz, 1998).

Landfilling scenarios	bio-C	M	D_{LFG}	$D_{Leachate}$	bio-C_{Left}
Open dump (mixed waste)	75-105	39-54	50%	4%	46%
Conventional landfill with flares (mixed waste)	75-105	39-54	50%	2%	48%
Engineered landfill with extensive LFG utilization (mixed waste)	75-105	39-54	50%	2%	48%
Engineered landfill for low-organic waste	30-40	10-14	33%	2%	65%
Engineered landfill for mixed paper	320-380	99-117	30%	2%	68%
Engineered landfill for kitchen organics	100-120	82-99	80%	2%	18%
Engineered landfill for glass, metals and plastics	0	0	0%	0%	0

Some of the key parameters (content of biogenic carbon, methane potentials, LFG collection efficiency, energy recovery efficiency, etc) are given as typical values within a range. Waste degradation is approached by assuming that the amount of biogenic carbon in the landfilled waste progressively decreases during the 100-year period due to emissions of LFG and leachate. These are accounted for by means of two dissimilation coefficients, D_{LFG} and $D_{Leachate}$ (Table 11), representing the cumulative fractions of biogenic carbon in the landfilled waste input that is degraded and thus leaves the landfill via emissions of LFG and leachate, respectively. Different types of waste were considered for different landfilling technologies: open dump and conventional landfill receive an input of mixed waste; engineered landfills receive either mixed waste or low-organic waste (contaminated soils, sludge, compost, commercial waste and other waste types with a low content of organic matter) or individual waste fractions (Table 11).

For the GHGs accounting, emissions are categorized to two groups: direct emissions and indirect emissions. Direct emissions represent emissions (environmental loads) or avoided emissions (environmental savings) related to LFG generation and treatment/use (CH_4 releases from top cover, LFG flaring and LFG utilization) and all the activities at the landfill site: combustion of the diesel fuel used on-site in dozers, compactors and other landfill vehicles. Indirect emissions are emissions or avoided emissions occurring outside the landfill but still related to the landfill. These are divided into "upstream emissions" (provision of diesel for construction of the site and on-site operation; provision of electricity, plastic liner materials, gravel and crushed rock for construction of the drainage system) and "downstream emissions" (avoided emissions from LFG utilization for energy generation).

3.5.2 Key results

An extract of the results is given in Table 12 (engineered landfill with extensive LFG utilization) and Table 13 (summary of all landfilling scenarios). Results are given as global warming factors (GWFs), here defined as overall potential contributions to GW expressed in CO_2-eq. per tonne of wet waste landfilled. It was found that direct GHG emissions (mostly from dispersive methane release) are the major contributor to the overall GWF, especially when waste with a significant content of organic matter is landfilled. LFG utilization for energy generation gives credit to the overall GHG balance. In the GHG accounting it was assumed that the electricity generated from LFG substitutes for the same electricity used as input (provision of electricity). The magnitude of such credits largely depends on how these energy deliverables are used and what they substitute. For instance, for 1 tonne of mixed waste in an engineered landfill for mixed waste, the environmental credit given by LFG utilization was estimated as ranging from 5 kg CO_2-eq. (when an electricity mix mostly based on natural gas is substituted) to 140 kg CO_2-eq. (when an electricity mix mostly based on coal is substituted), which can be compared to a load of 58 to 327 kg CO_2-eq. caused by methane emission in the same landfilling scenario (Table 12). As a consequence of the choice made for the dissimilation factors of biogenic carbon, 48% of the biogenic carbon is left undegraded after the 100-year period (Table 11). This gives further savings to GW, here estimated as ranging from 132 to 185 kg CO_2-eq per tonne of mixed waste (Table 12). Overall, the net GWF estimated for the engineered landfill for mixed waste ranges from a saving of 74 to a load of 26 kg CO_2-eq. per tonne (Table 13). Compared with an unmanaged dumping site (open dump), a saving of approximately 0.7 tonne CO_2-eq. per tonne of waste might be achieved in engineered landfills, which highlights the importance of adopting measures to control emissions and utilize LFG for energy generation.

Table 12 (from [V]): Greenhouse gas account and Global Warming Factors (GWFs) for an engineered landfill with extensive gas utilization (values are expressed per tonne of wet waste (ww) landfilled).

Waste type: mixed waste – Water content: 30%		
Indirect: Upstream	**Direct: Waste Management**	**Indirect: Downstream**
GWF (kg CO_2-eq. tonne^{-1}): **Low electricity: 2 to 6** **High electricity: 12 to 16**	**GWF (kg CO_2-eq. tonne^{-1}):** **-71 to 150**	**GWF (kg CO_2-eq. tonne^{-1}):** **-5 to -140**
CO_2- equivalents (kg tonne^{-1}): • Diesel fuel: 0.6 to 2.0 • Synthetic liner (HDPE): 0.9 to 2.8 • Gravel: 0.1 to 0.2 • Electricity: low=0.8; high=10.8	**CO_2- equivalents (kg tonne^{-1}):** • CO_2 fossil from use of diesel for on-site operations: 3 to 8 • CH_4 emission: 58 to 327 • CO_2 emission: 0 (GWP = 0) • C left: -132 to -185	**CO_2- equivalents (kg tonne^{-1}):** • Saved emission of CO_2 due to electricity generation from LFG utilization: -5 to -140
Accounted (unit tonne^{-1}): • Provision of diesel for soil excavation works: 0.5 to 1 l • Provision of diesel for on-site daily operations 1-3 l • Provision of HDPE for liner material: 0.5 to 1.5 kg • Provision of gravel: 80 to 120 kg • Provision of electricity: 8 to 12 kWh	**Accounted (unit tonne^{-1}):** • CO_2 fossil from use of diesel for on-site operations: 1 to 3 l diesel • Use of electricity: 5 to 8 kWh • CH_4 dispersive: 2 to 12 kg • CH_4 flares: 0.1 to 1.5 kg • CO_2 biogenic dispersive: 18 to 75 kg • CO_2 biogenic flares: 67 to 153 kg • C left: 36 to 50 kg	**Accounted (unit tonne^{-1}):** • Electricity produced from LFG utilization: 50 to 156 kWh

Table 13 (from [V]): Overview of Global Warming Factors (GWFs, as kg CO_2-eq.per tonne wet waste) found for all landfilling scenarios included in the assessment.

Landfilling scenarios		**Indirect: Upstream**	**Direct: Waste management**	**Indirect: downstream**	**Net**
Open dump (mixed waste)	Min	0	561	0	561
	Max	0	786	0	786
Conventional landfill with flares (mixed waste)	Min	2	-71	0	-69
	Max	12	150	0	162
Engineered landfill with extensive gas utilization (mixed waste)	Min	2	-71	-5	-74
	Max	16	150	-140	26
Low organic waste landfill	Min	2	-50	0	-48
	Max	10	-13	0	-3
Engineered landfill for mixed paper	Min	2	-645	-13	-656
	Max	16	-229	-304	-517
Engineered landfill for kitchen organics	Min	2	92	-11	83
	Max	16	527	-256	287
Engineered landfill for glass, metals and plastics	Min	2	3	0	5
	Max	10	8	0	18

4 Discussion and interpretation

Landfilling scenarios were evaluated in the studies in this thesis using the LCA model EASEWASTE. The scenarios ranged from unmanaged dumping sites to engineered landfills adopting active measures to reduce emissions to the environment. Different waste types were considered such as mixed waste and low-organic waste, and, individual waste fractions.

At first, a systematic LCA based modelling was done with the main purpose of providing a quantitative understanding of the environmental benefits offered by the implementation of improved technical measures and new landfilling technologies [I]. It was found that direct emissions of LFG and leachate represent the single most important cause of impacts in many categories (Figure 2); however, these emissions can be drastically reduced by adopting effective control measures such as bottom liner and top cover, leachate treatment and LFG flaring. This leads to a markedly improved environmental performance in the categories GW, SOD and POF, as shown the LCIAs estimated for “open dump” and “conventional landfill with flares”. Here, the key variables are the efficiencies of LFG and leachate capture achieved by the collection systems. However, the increased level of operation needed also leads to emissions from on-site operations, soil works and LFG treatment that increase the potential impacts estimated, especially in some toxicity-related categories (ETwc, HTw and HTa) compared with the “open dump” (Figure 3). As an example, a significant contribution from on-site activities to impact potentials was estimated for the Ämmässuo landfill (Espoo, Finland) [II]. This highlights the fact that planning of on-site activities must be carefully considered at landfills. In particular, current EU emissions limits for public auto-vehicles, should also be compulsory for vehicles operating on landfill sites.

LFG utilization for energy generation determines environmental savings, as from an LCA perspective emissions are actually avoided that would have occurred if the same amount of energy had been produced from fossil resources. Avoided emissions give savings to several impact categories, especially to GW, where a net negative impact potential was estimated in all landfilling technologies practising LFG utilization (Figure 3) [I]. Here, it was assumed that the electricity generated from LFG substitutes for coal-based electricity, which offers the highest environmental savings. This choice is somewhat arbitrary and another electricity mix could have been chosen, resulting in smaller environmental savings. The magnitude of the savings depends strictly on how the energy deliverables are used and what they substitute. Results from GHG accounting made for several landfilling scenarios [V] have shown that for landfilling of mixed waste (defined as in Table 11) savings from LFG utilization can vary significantly. The savings estimated range from 5 kg CO_2-eq./tonne to 140 kg CO_2-eq./tonne. This interval represents all the possible combinations of the parameters involved, ranging from substitution of electricity produced from natural gas and low efficiency of the electricity generation process to substitution of coal-based electricity and high efficiency of the electricity generation process, respectively. For the same landfilling scenario, the contributions to GW from direct methane emissions and carbon storage are estimated to range from 60 to 330 kg CO_2-eq./tonne (as environmental load) and from 130 to 190 kg CO_2-eq./tonne (as environmental saving), respectively [V]. For conventional landfilling of mixed MSW with LFG flaring (but with a higher content of organic fractions compared with the mixed MSW considered in Table 11), the US EPA (2006) reports a load to GW from GHG emissions of 220 kg CO_2-eq./tonne wet waste and a saving of approximately 370 kg CO_2-eq./tonne from binding of biogenic carbon. When the collected LFG is utilized for electricity generation, the US EPA (2006) and Fisher et al. (2006) report a reduction of approximately 110 and 170 kg CO_2-eq./tonne wet waste, respectively. In addition to the different contents of biogenic carbon assumed for the mixed waste, these estimates differ from the results found because different assumptions were made for parameters such as methane potential, methane removal in top cover (through biological oxidation) and flares (through combustion), and LFG energy recovery efficiency.

As example of active technology, leachate recirculation is practised at bioreactor landfills. Within a 100-year LCA time horizon, the recirculation of the collected leachate does not significantly improve the environmental performance, as can be seen by comparing the LCIAs found for conventional landfill with energy recovery and standard-bioreactor landfill (Figure 3) [I]. Leachate recirculation, however, makes waste degradation faster and more efficient, leading to a much higher LFG generation during the time-span when recirculation is practised (here set to 8 years) than otherwise experienced in conventional landfills. This makes it easier and valuable to utilize LFG for energy generation; nevertheless, dispersed LFG emissions might also increase during leachate recirculation if an impermeable surface liner is not used. The actual benefit from leachate recirculation is that most of the gaseous emissions occur within a short period; consequently, the impact potentials estimated after this time are very low (Figure 6). Consequently, for gaseous emissions, bioreactor landfills can be more sustainable than conventional landfills [I].

Measures to reduce ammonia concentration in leachate are usually taken at flushing-bioreactor landfills and were accounted for in the LCA modelling. This reduces about 70% the potential impact on SGR compared with the standard-bioreactor landfill, where these measures are not taken: approximately 7 PE/tonne compared with 22 PE/tonne, assuming the WHO (2006) concentration limit in drinking water as reference concentration [I]. Lower impacts would have been found if a less severe quality standard had been assumed. In addition, groundwater contamination might not be viewed as an issue in a region where the drinking water does not come from the groundwater. Leachate may also undergo natural attenuation processes when moving from the bottom of the landfill towards the groundwater table, lowering the estimated SGR potentials. However, the occurrence of natural attenuation processes should not be regarded as a general circumstance and the effectiveness of these processes is highly site-specific and difficult to predict. Despite this, in the LCA of low-organic waste landfills [IV], an assumption was made that 50% (mass) of the ammonia in the uncollected leachate is converted into nitrates, which inherently assumes that the redox conditions in the subsurface become favourable to oxidation at a certain distance from the landfill. This reduces the load on SGR, as 1 kg of ammonia makes 5,000 m^3 of groundwater unsuitable for drinking water, compared to 20 m^3 of 1 kg of nitrates (based on WHO, 2006).

Landfills for low-organic waste are becoming increasingly common in Europe, but little is known about their environmental performance. Here, low-organic waste is defined as a mixed waste type whose main constituents are contaminated soils, soils-treatment residues and contaminated (dewatered) dredging sludge. The methane potential of low-organic waste was estimated to 10–14 Nm^3/tonne, much lower than that estimated for mixed household waste. Therefore, the potential for disperse emissions of LFG is also lower and this is a major reason for the overall improved environmental performance compared with landfilling of household waste, especially when LFG management relies only on flares (Figures 14 and 15). Conversely, results have shown that the benefit from LFG utilization in low-organic waste landfills is reduced proportionally to the reduced waste methane potential; therefore, LFG utilization might not be economically viable [IV]. However, LFG management at low-organic waste landfills should at least rely on flares and top soil cover; in fact, a methane generation of 10–14 Nm^3/tonne still represents a potential GHG emissions of approximately 180–250 kg CO_2-eq./tonne.

LCA modelling of landfills was also conducted at the level of the individual waste fractions, as opposed to the overall mixed waste. The purpose was to understand how the different fractions contribute to the potential impacts estimated for landfilling of mixed waste [VI] and, in addition, to establish a consistent framework to compare landfilling with other management alternatives [VII]. Although studies have been done on the topic, several are old and do not always reflect the marked improvements that landfills have experienced and often do not account for binding of biogenic carbon as an environmental saving. In addition to the effectiveness of the emissions control measures taken at the landfill, the key variables for LCA modelling of individual fractions are methane potential and degradability of the individual fractions. These variables control not only the potential for LFG generation and emission but, indirectly, also the potential for LFG utilization and the amount of biogenic carbon remaining in the landfill, two factors that lead to environmental savings. Significant savings were estimated on GW and ETwc, which are attributable to landfilling of the fractions "paper", "organics" and "other combustible waste" (Figure 7 and Table 5) [VI]. Results from the comparison of alternative management options (Figures 8–10) have shown that recycling always leads to the highest environmental savings in the GW and the other standard categories. For “paper” and “aluminium”, recycling is by far the best performance also with respect to the toxicity-related categories. However, recycling of “plastic” and “glass” might lead to substantial impacts on the toxicity-related categories, suggesting that emissions from the recycling process should be carefully controlled, as otherwise other management alternatives become competitive. The environmental performance estimated for landfilling (with energy recovery) of “organics” and “paper” is comparable to that offered by incineration of the two fractions. Composting of “organics” also offers considerable environmental benefits [VII].

A crucial part of any LCA study is the choice of the time horizon. Here, a 100-year time horizon was assumed for LCA modelling of landfilling scenarios. This is often considered as a foreseeable time horizon in LCA of landfills. However, within this period only a very small fraction of the toxic substances in the waste are emitted. This is particularly evident for heavy metals as results have shown that for Cd, Cr, Hg, Pb and Zn less than 1% (mass) of the amount present in the landfilled waste has been released after 100 years [I]. Consequently, a marked potential for toxic releases remaining in the landfill exists, which creates the issue of addressing the problem of long-term impacts from landfills in LCA studies.

The choice of the LCA time horizon also influence the type and number of data needed. These are usually a combination of actual data regarding measurable parameters and data from accelerated laboratory simulations and model predictions of emissions over time. In particular, it is difficult to make long-term predictions on the performance offered by the emission control measures implemented, such as LFG and leachate collection efficiencies. These are uncertain yet crucial parameters. For instance, for leachate emissions a critical factor is the sealing performance of the bottom liner, which controls the volume of leachate that infiltrates to the groundwater. Although no liner is ever-lasting, a total failure seems unlikely within a 100-year time horizon. Both approaches on the bottom liner performance (total failure / progressive deterioration) were considered in the studies included in this thesis, leading to very different SGR potentials. In addition to the uncertainty about data and parameter used (parameter uncertainty), consistency and correctness of the landfilling scenarios might also be somewhat doubtful (scenario uncertainty), both at technical and methodological levels. For example, are the scenarios made for current landfilling technologies relevant; have the energy issues been modelled consistently; are the scenarios used comparable from an LCA perspective; are the LCA functional units used in an appropriate and consistent manner? Consequently, results from LCA of landfills are very uncertain due to the intrinsically high complexity of the systems assessed and the many uncertain assumptions made.

5 Conclusion

In a global perspective, landfilling remains the predominant option for solid waste management. Active landfilling technologies and extensive measures have been implemented in the last decades to optimize the degradation process, monitor emissions and reduce impacts to the environment. The extent to which technologies and measures implemented at landfills can actually reduce environmental pressures was thoroughly evaluated in this thesis by means of LCA modelling. This has provided an unprecedented quantitative understanding of waste landfilling in terms of potential global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, eco-toxicity and human-toxicity.

The LCA modelling was conducted with the EASEWASTE model, which has proven to be adequately robust, flexible and user-friendly. The model can handle a broad range of landfilling situations and allows for customized, multiple values of many input parameters reflecting different stages of the LCA time horizon. This is a key feature for LCA modelling of landfills as it allows methodical accounting for the evolution over time of the main processes. The number of data required, however, increases accordingly and creates the challenge of finding consistent data covering the entire time horizon. EASEWASTE offers a number of default datasets for many different processes that could be used to amend the data available; however, results have shown that the choices made for some parameters must be as accurate as possible because these significantly influence the outcome of the assessment. Crucial parameters include waste methane potential, efficiencies of LFG and leachate collection, LFG oxidation efficiency in top cover, performance of the bottom liner and, in the case of LFG utilization, the processes that the energy deliverables substitute.

Results from the LCIA are, nonetheless, relatively uncertain. For landfills both scenario and parameter uncertainty are relevant and become increasingly significant for increasing duration of the LCA time horizon selected because data are needed that come from model predictions and accelerated tests. A short time horizon (e.g. 20 years) would reduce the number of data needed and, in turns, uncertainty on the results would also diminish. In principle, a short time horizon would not be appropriate as emissions from landfills can be significant and exceed tolerable levels for long periods (several decades to several centuries). This is particularly true for compounds such as heavy metals that support leaching far beyond a foreseeable future. However, results have shown that active technologies can be implemented at landfills (such as leachate recirculation in bioreactor landfills) that reduce the time-span when gaseous emissions from organic waste degradation are of concern. For a landfill practising leachate recirculation, it was found that the potential impacts caused by gaseous emissions occurring after the first 15 years of active operation are significantly smaller than estimated for open dump and conventional landfills. This happens because most of the gaseous emissions occur during the time-span when leachate recirculation is undertaken. A major drawback of the implementation of active technologies at landfills is the increased level of operation needed on-site. Data on emissions from on-site activities are scarce, but results have shown that, in a context where fugitive emissions of LFG and leachate are being progressively decreased, emissions from on-site activities may become significant, as estimated for the Ämmässuo landfill (Finland).

Despite the optimization of the waste degradation processes at landfills, there is evidence that at the end of the 100-year time horizon a significant portion of the biogenic carbon from the input waste is left undegraded. However, the accounting methodology for binding of biogenic carbon in LCA modelling is not unanimously recognized and different approaches are found in literature that lead to different estimations of the impact on global warming. Results have shown that when the biogenic carbon remaining in the landfill is accounted for as an avoided emission of CO_2, the savings on global warming may then become significant (up to approximately 200 kg CO_2-eq./tonne wet MSW). This is comparable with the load caused by direct GHG emissions (up to approximately 330 kg CO_2-eq./tonne wet MSW) estimated for the same landfilling scenario. From the perspective of the individual fractions in the mixed waste, “paper” gives the major contribution to savings on global warming from binding of biogenic carbon, as this fraction has a high content of biogenic carbon but has a relatively low degradability.

A major advantage from the increased level of control over gaseous emissions at landfills is the possibility of utilizing LFG for energy generation as, from an LCA perspective, this offers environmental advantages in global warming and other impact categories. Results have shown that the magnitude of the savings can vary dramatically as it is strictly dependent on a number of technical factors (e.g. the amount of LFG utilized per unit mass of waste, the efficiency of the LFG energy recovery) and on the processes that the energy deliverables substitute. The latter is a key factor but, within the LCA community, very little agreement exists on the accounting method. Depending on the values assumed for these factors, it was estimated that electricity generation from LFG use reduces the contribution to global warming with savings ranging from 5 kg CO_2-eq./tonne (substitution of natural gas based electricity) to 140 kg CO_2-eq./tonne (substitution of coal-based electricity) of wet mixed MSW landfilled. Amongst the individual fractions in the mixed waste, the fraction “organics” contributes the most to LFG generation and therefore the major contribution to environmental savings from LFG utilization is to be assigned to this fraction.

The waste hierarchy has been used for decades as reference criteria to support decisions in waste management. The waste hierarchy makes decision-making fast, but not all variables and parameters that influence the environmental performance are covered and integrated holistically, which is the core characteristic of state-of-the-art LCA models. With LCA models, not only the technological improvements experienced at landfills can be systematically considered in the evaluation but landfills can also be credited for environmental savings from LFG energy recovery and carbon binding. Results showed this accounting approach can drastically improve the environmental profiles of landfills, making landfilling a more sustainable option than commonly considered (provided appropriate landfill engineering is in place). This substantiates the fact that a simple hierarchy principle does not necessarily do justice to the alternatives to recycling and is therefore not appropriate for evaluating waste management options involving landfilling.

6 Perspectives

The research done during my PhD and reported in this thesis has identified some areas where technical efforts must be made and further investigations are needed.

With respect to landfill operation and management, technical efforts should be made for:

- Ensuring the highest performance of bottom lining system, LFG and leachate collection systems the highest LFG oxidation performance in top soil covers and an efficient treatment of the collected leachate;
- Improving LFG management and, in particular, maximizing LFG utilization for energy generation at any landfill, including low-organic waste landfills as results have shown that, despite the relatively low amount of LFG generated, low-organic landfills may still constitute a significant source of GHG emissions;
- Reducing emissions from on-site operations, especially emissions from diesel combustion in landfill vehicles.

Future research should be focused on the following aspects:

- Providing, for increasing age of landfills, a better quantification of the amount of biogenic carbon that remains undegraded in the waste. Results have shown that the global warming profile of landfills can improve significantly when binding of biogenic carbon is accounted for as an avoided CO_2 emission. This is of particular relevance for landfills where considerable amounts of organic fractions have been disposed;
- Providing a better qualitative and quantitative understanding of the long-term degradation processes under landfill conditions, especially for persistent pollutants (in particular metals) that support emissions for very long periods of time.

In addition to the issues concerning the LCA time horizon, data availability and trustworthiness, energy use and recovery, several other limitations and challenges arise when applying life cycle modelling to landfills. For instance, it is important to build large consensus within the LCA community on the way of approaching the issues of binding of biogenic carbon and of long-term impacts from landfills. Most LCA models, including EASEWASTE, account for potential future emissions by applying the same potential impacts as if the emissions had occurred today, although external environmental conditions might have changed considerably in the meantime. In addition, although the impact categories included in the evaluation are categorized into “global”, “regional” and “local”, EASEWASTE does not consider the site-specific conditions of the landfilling contexts examined. This may be acceptable when modelling average, hypothetical landfills but, represents a limitation when evaluating actual sites. Future versions of EASEWASTE should progressively integrate more parameters accounting for relevant site-specific aspects. Vulnerability and sensitivity of the ecosystem might, for instance, be considered; in turn, these are influenced by factors such as hydrogeological conditions, typical exposure pathways, etc. Finally, parameters relative to area use, social and environmental costs associated with construction and operation of the landfill could also be included.

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8 Appendices

I. **Manfredi, S.** & Christensen, T.H. (2009): Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Management* **29**, 32-43

II. Niskanen, A., **Manfredi, S**., Christensen, T.H. & Anderson R. (2009): Environmental assessment of Ämmässuo Landfill (Finland) by means of LCA-modelling (EASEWASTE). *Waste Management & Research*. Accepted for publication.

III. **Manfredi, S.**, Niskanen, A. & Christensen, T.H. (2009): Environmental assessment of gas management options at the Old Ämmässuo landfill (Finland) by means of LCA-modeling (EASEWASTE). *Waste Management* **29**, 1588-1594

IV. **Manfredi, S.**, Scharff, H., Jacobs, J. & Christensen, T.H. (2009): Environmental assessment of low-organic waste landfill scenarios by means of life-cycle assessment modeling (EASEWASTE). *Waste Management & Research*. Accepted for publication

V. **Manfredi, S.,** Scharff, H. Tonini D. & Christensen, T.H. (2009): Landfilling of waste: accounting of greenhouse gases and global warming contributions. *Waste management & Research*. Submitted

VI. **Manfredi, S**., Tonini, D. & Christensen, T.H. (2009): Contribution of individual waste fractions to the environmental impacts from landfilling of municipal solid waste. *Waste Management*. Submitted

VII. **Manfredi, S**., Tonini, D. & Christensen, T.H. (2009): Environmental assessment of different management options for individual waste fractions by means of life-cycle modelling. *Resources, Conservation & Recycling.* Submitted

VIII. Comments on the results of the assessment

These papers are included in the printed version of the thesis but not in the www-version. Copies of the papers can be obtained from the Library at the Department of Environmental Engineering, DTU (library@env.dtu.dk).

VIII

Comments on the results of the assessment

In this thesis landfilling scenarios were evaluated using LCA modelling. Despite the variety of landfilling contexts considered, at first glance, some of the scenarios modelled might appear very similar. However, the results from these scenarios varied considerably at times. This depended on various differences made between the scenarios included (assumptions, data, etc.). It is possible that these differences were not always systematically pointed out in the thesis. Any omissions were in order to keep the flow in the reading and to make the writing accessible to a wide audience. The list that follows is an attempt to record some of these differences:

- Different compositions of the waste landfilled, in particular different contents of biogenic carbon. This in turn leads to different methane potentials and also to different amounts of biogenic carbon stored;
- Different ways of accounting for binding of biogenic carbon;
- Different LFG and leachate quantities and qualities;
- Different energy recovery efficiency assumed for LFG utilization;
- Different choices in the energy processes substituted by the energy produced from LFG;
- Different assumptions made for the bottom liner: total failure after 40–50 years, or slow progressive deterioration of the sealing performance.
- Different assumptions made regarding natural attenuation of leachate, especially for ammonia attenuation;
- Different LFG oxidation performance in top cover due to different flows of LFG through the cover;
- Different performance assumed for treatment of LFG in flares, power-plant or CHP-plant, and different specific emissions from LFG treatment.

The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within four themes:
Water Resource Engineering, Urban Water Engineering,
Residual Resource Engineering and Environmental Chemistry & Microbiology.
Each theme hosts two to five research groups.

The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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