1 Intention of this study

1.1 Situation in developing countries

Still today landfilling is often the most commonly practised disposal form of municipal solid waste and takes place mainly in an environmental unfriendly way. This leads to significant environmental pollution. (Hädrich et al. 2009)

In countries like Bangladesh, Nepal or Cambodia the waste management situation is characterised by open waste deposits within the city, numerous open dumps on the outskirts and therewith by insufficient waste infrastructure as well as missing treatment and disposal facilities, see e.g. Alamgir et al. (2005). In Cambodia's capital Phnom Penh, 1.5 million residents dispose most of their municipal solid waste untreated on a dumpsite at the outskirts. Table 1-1 comprises and explains such examples of waste disposal situation in developing countries.

Table 1-1: The waste disposal situation in developing countries

Country	General data	
Nepal (2007)	▪ Disposal of most of municipal solid waste of capital Kathmandu at river bank ▪ Open dumping Bisnumati river, Kathmandu	
Bangladesh (2008)	▪ Disposal of municipal solid waste of city Khulna at outskirts ▪ Open dump → no barriers ▪ 1.5 million inhabitants ▪ Ca. 450 Mg/d Ultimate disposal site Ratjband, Khulna	
Cambodia (2010)	▪ Disposal of municipal solid waste of capital Phnom Penh in a sand/clay dig ▪ Open dump → no barriers ▪ Cut aquifer New landfill, Phnom Penh (Stäudel 2010)	

In contrast to this situation, series of regulations and technical concepts for environmental friendly waste disposal have been developed and implemented in Germany as so-called multibarrier system (DIBt 1995). Subsequent to primary intentions of reutilisation and recycling activities, it comprises the pre-treatment of waste, the more environmentally friendly disposal in sanitary landfills as well as their maintenance. Hence, the waste management is characterised by a complex system, which applies to the landfill too. However, thereby the technical facility landfill with its statutory defined requirements regarding construction and functionality requires accordant material, technique, and monitoring. This demand is reflected in corresponding high technical and financial efforts.

Nevertheless, it has been recognised that available German or European standards are technically and financially hard to realise nation-wide in low and middle-income countries. On the one hand, suitable and necessary material, technique as well does mostly not exist next to right experts. Funds are not available in needed amount on the other hand. For instance in Germany, less than one per cent of the gross domestic product (GDP) are spend for present extensive waste disposal by industry, state and privatised public companies in 2006, as indicated in Figure 1-1. That is ca. 15.1 bn Euro and is equal to almost two-hundred Euro per capita in 2006 (Anonymous 2010a). This amount is adequate to approximately half of the GDP per capita of Bangladesh in 2008/09 or one-third of the GDP of Cambodia in 2008 respectively (Anonymous 2011a; 2011b).

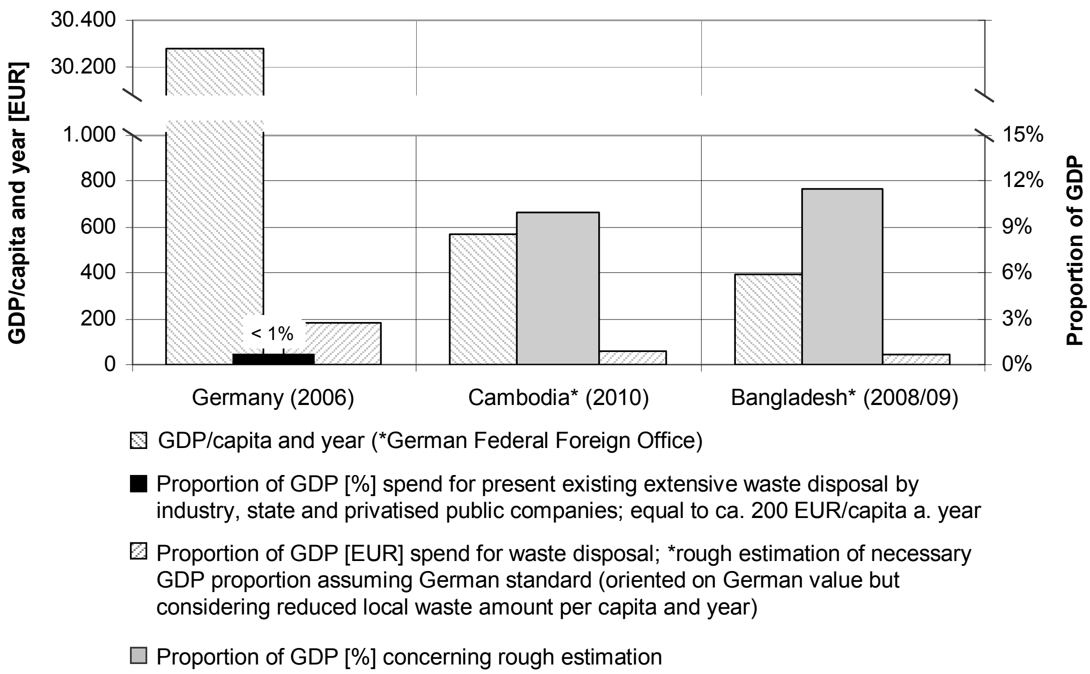

Figure 1-1: Rough estimation of the necessary GDP proportion of waste disposal

Figure 1-1 undertakes the attempt to deepen this context assuming waste disposal according to German standard and waste amounts in the considered countries. However, further factors are unconsidered influencing the GDP, e.g. labour costs. Nevertheless, it is obviously that waste management concepts according to German regulations cannot be implemented currently under these circumstances.

1.2 Existing guides and models

Over the last decades, numerous guides have been created intending to support the landfilling of municipal solid waste especially for low and middle-income countries. Table 1-2 summarises some of these.

Table 1-2: Overview of the existing guides supporting landfilling in low and middle-income countries (by no means complete)

Title	Reference	Additional Info
Guidelines for an appropriate management of domestic sanitary landfill sites	Oeltzschner and Mutz (1994)	GTZ, Germany (Gesellschaft für technische Zusammenarbeit)
Technical Guidelines on Specially Engineered Landfill (D5)	Anonymous (1997)	Technical Working Group of Convention and adopted by the third meeting of the Conference of the Parties to the Basel Convention; Geneva
Observations of Solid Waste Landfills in Developing Countries: Africa, Asia, and Latin America	Johannessen and Boyer (1999)	Urban Development Division Waste Management Anchor Team; The World Bank
Solid Waste Landfills In Middle- and Lower-Income Countries --- A Technical Guide to Planning, Design and Operation	Rushbrook and Pugh (1999)	Technical Paper No. 426; The World Bank
Guidance Note on Leachate Management for Municipal Solid Waste Landfills	Johannessen (1999)	Urban Development Division, Urban Waste Management Thematic Group; Working Paper Series Nr. 5
Guidelines for the Design, Construction and Operation of Manual Sanitary Landfills	Jaramillo (2003)	PanAmerican Center for Sanitary Engineering and Environmental Sciences; Universidad de Antioquia
Solid Waste Management	Diaz et al. (2005)	United nations Environmental Programme
Waste Disposal and Landfill: Control and Protection	Allen and Taylor (2006)	Protecting Groundwater for Health; Section 5; Chapter 24

These documents comprise in different level of detail essential descriptions, technical recommendations, and information to planning, site selection, design, and operation of landfills. They contain references for manual operated landfills for small communities or rural areas to sanitary landfills for urban areas. Information and recommendations are given to nearly each component of a landfill. However, the extent and level of detail varies between the different documents. Table 1-3 shows exemplarily recommendations and information given to the individual design of different barriers.

Table 1-3: Selection of recommendations and information given in the existing guides regarding the landfill design

Barrier	Reference	Recommendations and information
Pre-treatment/ MBT	Oeltzschner and Mutz (1994)	▪ "... advanced methods like composting can be used as an appropriate technology on a landfill." ▪ "... municipal waste collected in many tropical countries contains more than 50% of organic matter which will be perfectly suitable for composting. (...) the volume of the waste will be reduced (...) the quality of the leachate is less harmful (...) there may be almost no biogas (...) the produced material can be used perfectly for the immediate reclamation of the landfill."
Bottom liner	Oeltzschner and Mutz (1994)	▪ "use a two-layer system (each layer about 30 cm thick) of mineral liner (...) local material (...) should be used. (...) if necessary (...) mixed with 2-3% bentonite to further reduce its permeability (...) liner material has to compacted in-situ" ▪ "two liner layers and an effective geology as (...) two artificial mineral liners will be sufficient to prevent the seepage of large amounts of the leachate (...) Nevertheless this system will only work efficiently, when the surface of the liner system has a sufficient incline (...) surface of the liner system is covered by a 30 cm thick layer of coarse material (grain diameter 20-50 mm (...)) forming a drainage carpet"
	Rushbrook and Pugh (1999)	▪ "To serve adequately as a liner, a soil must have a low permeability (less than 1×10^{-7} cm/s)" ▪ "A clay liner usually is constructed as a membrane up to 1 m thick (...) soil liners are constructed of compacted soil installed in a series of layers of specified thickness. (...) thickness of liner layers (...) is on the order of 150 to 200 mm."

Table 1-3: Selection of recommendations and information given in the existing guides regarding the landfill design (continuation)

Barrier	Reference	Recommendations and information
Bottom liner	Diaz et al. (2005)	▪ "To form a bottom liner for the landfill, soil can be used in one layer (i.e., a single-liner system) or in conjunction with layers of other materials (i.e., as one or more layers of a multi-layer, or composite, liner system)" ▪ To adequately serve as a liner, a soil must have a low permeability (preferably less than 1 x 10^{-6} cm/sec)" ▪ A clay liner usually is constructed as a layer 0.3 to 1 m thick. ▪ A soil that is deficient in a required characteristic may be rendered suitable by blending it with another soil or with a soil additive. An example is the addition of bentonite cement (...) hydraulic conductivities on the order of 10^{-8} cm/sec can be achieved" ▪ The constituent material of a flexible membrane liner (FML) is pre-fabricated polymeric sheeting. A flexible liner may be used (...) as a single liner installed directly over the foundation soil; as part of a composite liner placed upon a soil liner, or as a layer of a multi-element leak detection system in a double-lined landfill."
Placement technique	Oeltzschner and Mutz (1994)	▪ "... dumping the waste in layers, not thicker than 2 m and compacting it by means of a bulldozer or compactor. ..." ▪ "... the layers of garbage should get a thin soil coyer at least once a week to reduce problems caused by the flying away of light plastic matter, by bad odours, by insects and birds; ..."
Surface cover/ liner	Rushbrook and Pugh (1999)	▪ "daily cover should be of high permeability, to discourage the later development of perched leachate tables, while intermediate and final cover should be of low permeability, to inhibit the percolation of rainwater into the wastes below (and thus minimize leachate generation). The counter-argument (...) is that, if all water is excluded, the rate of waste degradation may be expected to reduce significantly, thereby extending the period over which landfill gas will be generated (...) and the site becomes environmentally benign."
Emission treatment	Oeltzschner and Mutz (1994)	▪ "The leachate (...) has to be collected (...). A minimum treatment (...) is necessary. As an appropriate method the oxidation-pond-system is recommended" ▪ "lower end of the landfill three ponds should be constructed using at least the same system of mineral liner as used in the landfill, but covered with rocks to prevent erosion (...)." ▪ "The first pond will serve as a settling pond, the 2nd could (if possible) get an artificial aeration (aeration pond), the 3rd one would serve as a final settling pond with only natural aeration." ▪ to collect the biogas (...) gravel, rocks, coarse material (...) should be disposed of (...) one layer on top of the other, forming (...) a sort of a gas collecting "chimney", where the biogas could easily permeate to the surface (...) and put to use, or at least be burned."
	Rushbrook and Pugh (1999)	▪ "the simplest form of treatment could be achieved by either a series of lagoons (...) or flow through wetlands ▪ "There are (..) two types of enhanced leachate treatment (...). The first type (...) are aerobic techniques ranging from simple aeration (..) lagoon to more specialized pre-treatment by flocculation and sedimentation (settling) prior to discharge (...) into aeration lagoon."
	Diaz et al. (2005)	▪ "If (..) leachate is generated, there are several options for managing it: evaporation (natural or forced), recirculation and recycling, discharge to an offsite wastewater treatment facility, and onsite treatment." ▪ "Biological treatment (...). If the ratio is about 0.5, then it may be possible to treat the leachate biologically. (...) if the BOD:COD is less than 0.5:1, a biological system may not be appropriate" ▪ "Aerated lagoons are applicable to landfills that generate relatively small quantities of leachate. (...) aeration and the mixing (...) enhance the degradation of organic substances (...). Retention times on the order of 10 days have produced relatively large reductions in the concentrations of BOD and COD." ▪ Facultative ponds (...) generally are between 1 and 1.5 m deep and are not aerated by artificial means. (...) Facultative ponds typically remove ammonia-nitrogen through nitrification processes." ▪ "Properly designed aerobic lagoons and facultative ponds may be suitable for leachate treatment in a number of developing countries."

The given recommendations and/or data refer to single values, limits (maxima and/or minima) or ranges. The suggestions to design a bottom liner comprise a minimal hydraulic conductivity and a thickness range for example. Insufficient specifications are provided regarding different possible design variants. Possible options for leachate treatment are mentioned including information to the application range for instance. In total, the given information is more or less static and general.

However, the guides are not created to show the effectiveness of the individual barriers and their different construction types subject to regional specific conditions. Moreover, it is not their intention as well. Thus, the consideration of specific conditions in application area is not in focus, its connection with the given recommendations as well.
Additionally, detailed information to necessary technical effort for implementation of barriers or landfill concepts is given sporadically and in minor extent.
On the other side, there are several models, supporting the detailed description of the effectiveness of individual barriers and to predict emissions by numerical solutions and/or simulations. Table 1-4 contains a selection of such models.

Table 1-4: Selection of numerical solution models (by no means complete)

Programme	Application
HELP	"Hydrologic Evaluation of Landfill Performance"; simulation of water balance of a landfill under assumption of saturated and leachate generation
BOWAHALD	Simulation of water balance of unsaturated landfills and heaps as well as their protection systems (cover and bottom liner)
Multimed	Leachate flow/infiltration rate in unsaturated and saturated zones; one-dimensional and steady state and simulates the effect of precipitation, runoff, infiltration, evapotranspiration, barrier layers (which can include flexible membrane liners), and lateral drainage
POLLUTE	"1-1/2-dimensional" solution to the advection-dispersion equation
MIGRATE	Contaminant transport from multiple sources, either at the surface or buried
SIWAPRO DSS	Simulation of transport processes in unsaturated zone
EASEWASTE	Decision support tool (LCA model) considering overall waste management system and treatment technologies [PC-Based LCA model for decision support on waste management systems; ecological (environmental impact and resource consumption) and economical profile (costs and externalities); flexible, transparent, and user-friendly; large database (external and internal processes); covering residential, bulky and garden waste; available in two versions (EASEWASTE2004 and EASEWASTE 2006)]
IPCC 2006	2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 5 Waste: estimation of climate relevant landfill gas emissions

The effectiveness of these models is based on physiochemical properties characterising the landfill barriers or the landfill body itself including area specific frame conditions. The results describe the amount of released emissions, predominantly leachate emissions and therewith the protective potential of a chosen barrier but not of an overall landfill concept.

1.3 Placement and differentiation

The guides and models do not directly answer the questions which protective potential an individual chosen landfill concept has and which technical effort it is demanding with respect to necessary costs of implementation. However, it is not their purpose. A holistic approach is missing considering several barriers of a landfill concept, which enables the user to compare those regarding ecological and economical aspects, to provide additionally the option to choose different barrier construction types as well.

On all these circumstances, the present rating system continues to act as decision support tool. It is graphically displayed in the subsequent Figure 1-2. The present concept should be seen as supplement to existing guides, especially to the technical design of landfills.
It provides information to the individual barriers and different construction types about influence on emission behaviour and necessary technical effort. Thereby, existing knowledge and experience - incorporated in existing models and programmes - are taken into account to estimate and describe the effectiveness of the individual barriers. The estimated results enter the evaluation of the complete

landfill concept. On economical side, the technical effort represents the engineering complexity for implementation. This serves as base for a subsequent economical evaluation. In general, costs for management of municipal waste are shared within a society between producers, consumers, and administration. Thus, socio-economic aspects find consideration as well, this context presumed.

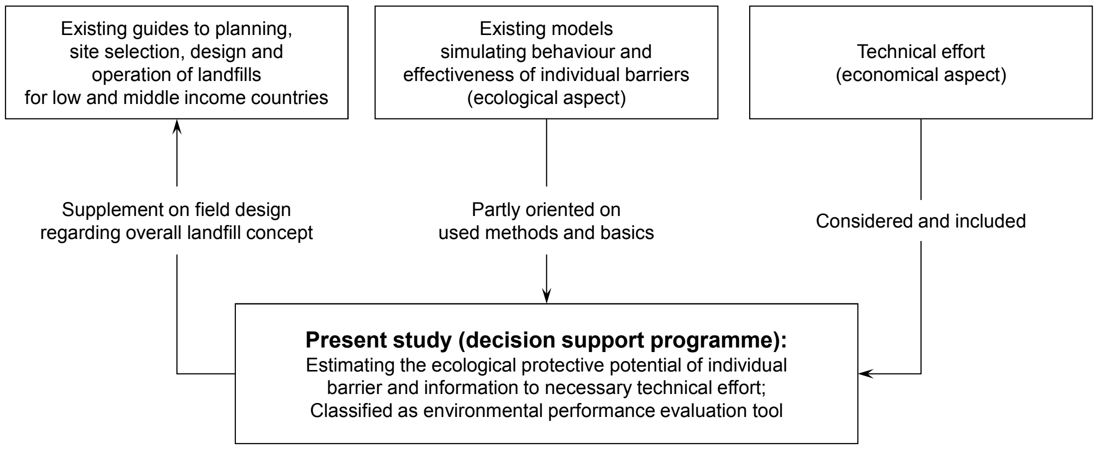

Figure 1-2: Placement of this study in the existing landfill guides

The landfill sets the system boundaries of the rating system comprising its different barriers. Site-specific conditions serve as input data. Thus, it is possible to express the performance of a landfill concept considering region-specific conditions.

The rating system will be on a level to be handled by decision makers and professional within the activity field of landfilling and waste management. Thus, this group will be put in position to decide where available technical and economic resources are used most effectively. In this context, the decision support tool illustrates simultaneously the complex interdependencies within the barriers and between barriers and site-specific conditions.

Chapter 2

Emissions of a landfill

2 Emissions of a landfill

Emissions are defined as negative impacts from a source on its environment, e.g. compartments air and water. According to Voigt (1996) the emissions illustrated in Figure 2-1 can occur at a waste deposit like a dumpsite or sanitary landfill but in different intensity.

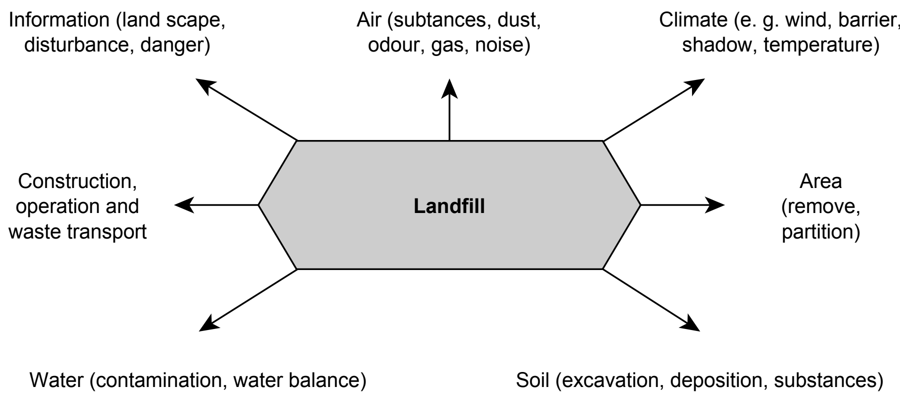

Figure 2-1: Possible emissions of a landfill

Table 2-1 comprises emissions, which influence the protected natural resources air, water and ground and its sphere of influence.

Table 2-1: Possible emissions of a landfill and the spheres of influence

Emissions			**Sphere of influence**
Into air	Fire		Local
	Drift/dust		
	Odour/gases		
	Landfill gas		Global
Into water	Leachate	quantity	Local
		quality	
	Avulsion of waste		
Into ground	Soil influenced by leachate*		Local
*Contamination of the soil can happen over the leachate (seeping water), the groundwater (as „long arm“ of the leachate/seeping water) and through depositions from the air (Anonymous 1993a).			

(Anonymous 1993a; Brunner et al. 2001; Hädrich et al. 2007; Kruse 1994; M. Voigt 1996)

The emissions as well as the emission behaviour of compartments air and water are mainly influenced by (Stief 1995 in Heyer and Stegmann 1997; Heyer 2003):

- Amount of deposited waste
- Composition of the waste
- Water balance of the landfill
- Kind of landfill body
- Operation of the landfill
- Running biochemical processes

Landfills and deposits of non-pre-treated municipal solid waste can be seen as a so-called “bioreactor” because of its anaerobic conditions and the running biochemical processes. Especially the microbial processes influence degradation and stabilisation processes of the material. The resulting main emissions are release as leachate via the water path and mainly methane via the gas path. Previous studies have shown that the main emissions arise from the release of carbon and chlorine. These emissions in combination with nitrogen are most relevant for the long-term emission behaviour of a landfill. Considering research results of German municipal solid waste landfills, heavy metals are not considered as problematic regarding the environmental impact of leachate in foreseeable time. (Ehrig et al. 1998; K.-U. Heyer 2003; Krümpelbeck and Ehrig 1999)

2.1 Air emission path

2.1.1 Landfill fires

There are many combustible materials and substances in waste e.g. used tires, plastic, paper, wood, chemicals as well as methane gas, which occurs by anaerobic degradation of biodegradable waste. (Wilhelm 1994)

Methane (CH_4) is a combustible gas with a lower calorific value of ca. 36 MJ/m³ (Görner 2002). It can cause an explosive gaseous mixture in combination with oxygen (O_2) as oxidant. The compositional ranges of mixtures of methane and oxygen are of importance for explosion protection. According to Figure 2-2 shows the explosive range is reached by exceeding 11.6 Vol.-% of oxygen and ranges of methane between ca. 5 Vol.-% (lower explosive limit) and ca. 15 Vol.-% (upper explosive limit) (Rettenberger and Tabasaran 1982). According to Haubrichs (2007) laminar landfill gas emissions lead rarely to methane concentrations above the lower explosive limit of 5 Vol.-%.

Oxygen as oxidant can enter a landfill especial over slopes and can be accumulated in cavities, which can be the results of bad placement (Wilhelm 1994). In case of fire, the stack-effect can intensify the access of air.

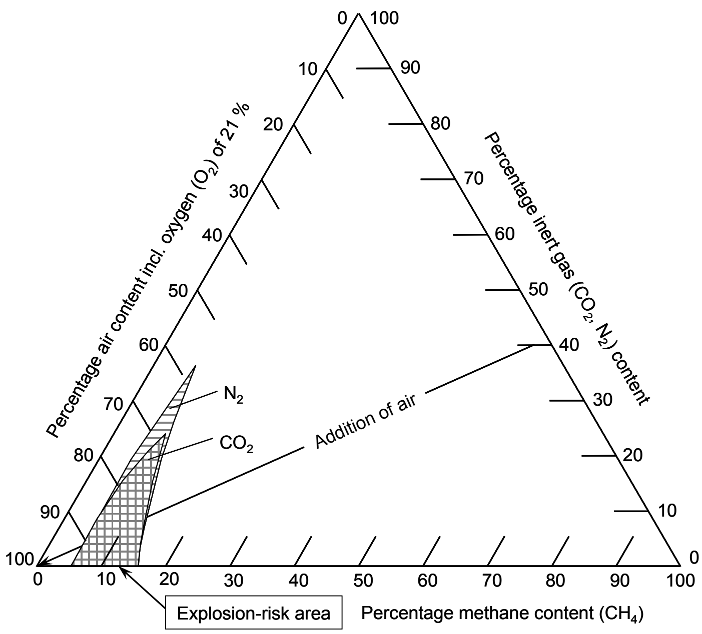

Figure 2-2: Three phase chart showing the explosive range of gaseous mixtures of methane, oxygen, and inert gas

The formation of fire can have different reasons. They can occur naturally (self-ignition) or are man-made. Ignition sources are (Wilhelm 1994):

- Self-ignition by bio-chemical degradation processes of readily degradable, hydrous organic waste
- Self-ignition of chemical substances, which reacted exothermic by water contact
- Burning glass effect of glass waste
- Arson, amongst others to extract metals by so-called scavengers
- Thrown away matches or cigarettes
- Placement of hot waste, e.g. ash or slag
- Overheated or burning vehicles and equipment for landfill operation

The last four points can be avoided rather by a proper landfill operation then technical solutions. Thus, these are not in focus.

Landfill fire can be classified in surface and subsurface smouldering and burnings. Their reasons and possible on-site detection are displayed in Table 2-2. Smouldering is an incomplete combustion at low temperatures around 600°C and insufficient oxygen supply. In contrast, a burning take place by higher temperatures and sufficient oxygen supply which results in better combustion of pollutants. The pollutant concentrations are lower than at a smouldering.

Table 2-2: Classification of landfill fires

Fire type	Surface fires	Subsurface fires
Reason	▪ Combustion by natural manner (self-ignition) ▪ Combustion by ignition source	
Detection	▪ Formation of smoke, burnt odour ▪ Fire, flames	▪ Formation of smoke, burnt odour, vegetation defects, points of sweating ▪ Increased temperature with landfill body and leachate ▪ Increased carbon monoxide (CO) content with landfill body ▪ Increased COD content in leachate ▪ Air supported infrared measuring methods

(Haubrichs 2007; Wilhelm 1994)

The following substances are released by waste burning:

- Carbon monoxide and dioxide
- Nitrogen and sulphur oxides
- Dust containing (heavy) metals
- Toxic substances, e.g. dioxin and furan emissions

The composition of fumes/burning gases depends on the composition of the burnt material and burning condition, e.g. smouldering or burning.

2.1.2 Drifts

Drift comprises blowing litter during tipping, placement and from surface as well as dust-emissions caused by on-site traffic and operation, e.g. placement. (Voigt 1996)

2.1.3 Odour emissions

Two reasons for odour and gas emissions can be indicated. On the one hand, these are emission inhering on substances, which occur mainly by transport and placement. On the other hand, these emissions may be caused by biological degradation processes or internal reactions of substances e.g. odour intensive microelements in landfill gas and leachate. They are rarely in total more than one volume per cent but crucial regarding the effect as odorous substance and harmful gas. Substances like mercaptane, fatty acids, ammonia, amine, sulphurous substances as hydrogen sulphide and ester contribute to odour effects of waste. Especially in the so-called acid phase of a landfill, large amounts of odorous substances can be released. (Krümpelbeck 2000; M. Voigt 1996; B. Weber 1990)

2.1.4 Landfill gas emissions

Landfill gas is the final product of degradation of biodegradable organic waste under anaerobic conditions, which can occur in a landfill body. An optimum biodegradation under anaerobic conditions requires water contents greater than 40%. Biodegradation is inhibited at water contents between 15 and 30%. At even lower water percentages < 15% the biodegradation reactions stop. The optimum temperature range is 30°C to 50 C. At temperatures below 10°C, the methane production comes to a standstill. (Drees 2000)

The amount of gas depends mainly on the biodegradable carbon compounds in the waste. Landfill gas is the main emission source of carbon compounds (Stegmann et al. 2006). Originally, ambient air free and dried landfill gas consists to nearly 99 Vol.-% of the components methane (CH_4) and carbon dioxide (CO_2), whereas the methane proportion is between 50-60 Vol.-% (B. Weber 1990). The remaining components are odorous substances and harmful gases, e.g. sulphur compounds. According to Rettenberger (cited in Krümpelbeck and Ehrig 1999), the ratio of methane to carbon dioxide in the stabile methane phase of a landfill is 1.25. Methane is non-toxic, colour- and odourless with a density lower than atmospheric air. Carbon dioxide is also a colour- and odourless, non-combustible gas but 1.5 times heavier than atmospheric air. (Krümpelbeck and Ehrig 1999; B. Weber 1990)

Possible local and global environmental impacts of the emission of landfill gas are (B. Weber 1990):

- Odour nuisance, see 2.1.3
- Danger of fires and explosions, see 2.1.1
- Gas migration
- Damaging of plants
- Supporting the greenhouse gas effect

In Germany, it is generally agreed that carbon dioxide emissions from biomass usage are not considered to negatively affect the atmosphere, if the biomass results from sustainable cultivation. This means, the harvested biomass has to be replaced by new plants in short-term of maximum 10 years. In that case, the newly crown biomass removes the same amount of carbon dioxide from the atmosphere, which was released by usage of the previous generation. Therefore, the carbon dioxide in landfill gas is classified as climate neutral. (Butz 1997 in Haubrichs 2007)
If there are other gases created by biological degradation of biomass, e.g. methane, the materials cycle is not closed because such gases are not or only in small amounts removed from the atmosphere and converted by plant growing (Seeberg 1994). Then, such gases are considered as greenhouse gases, for instance methane.
On global angle, methane as main component of landfill gas has a global warming potential, which is 25-times higher within a period of 100 years and 72-times higher within a period of 20 years compared to one megagram of carbon dioxide. A global warming potential factor of 21 within the 100 years period is used for reporting under the UNFCCC (Solomon et al. 2007). Thus, the environmentally unfriendly emission of methane is expressed as CO_{2eq} by multiplication of methane in unit mass with previously mentioned factors.

2.1.4.1 Estimation of landfill gas potential

Landfill gas emissions occur already during placement but are not fully collected at this time. Thus, the collection efficiency is below the real gas production and the landfill gas production is not precisely determinable. Therefore, theoretical estimations and laboratory test were performed to estimate the landfill gas potential. (K.-U. Heyer 2003)
However, prognoses of total gas production of a landfill turned out to be difficult, because of the heterogeneity of the deposited waste. This heterogeneity is another reason why gas production prognoses are always an orientation only of the expected gas amount. (Krümpelbeck and Ehrig 1999)
A generally accepted procedure to estimate the total gas production is based on the stoichiometric approach and the principle of the ideal gases. Based on this, 1.868 m³ landfill gas at standard conditions are produced by biochemical conversion of 1 kilogram carbon independent from the created portions of methane and carbon dioxide. Standard gas refers to a temperature of 0°C and a pressure of 1,013 hPa. The factor would be 2.005 at a temperature of 20°C by same pressure.
According to B. Weber (1990), the gas amount or gas potential can be estimated as indicated in subsequent equation Eq. 2-1.

$$G_e = 1.868 \cdot TC \qquad \textbf{Eq. 2-1}$$

G_e - Gas production potential [m³/Mg]
TC - Total carbon in waste [kg/Mg]

Tabasaran compared the gas production in a landfill with that of a digester and established a temperature-dependent term, which considers losses through assimilated carbon. (K.-U. Heyer 2003)
Ehrig (1994 in Krümpelbeck and Ehrig 1999) accounts the term as non-transferable to landfill conditions because in comparison to a digester the microorganism and bacteria in landfill are not removed. Nevertheless, the term delivers the factor 0.7 at the supposed temperature of 30°C (Fellner et al. 2003).
A more important factor could be the biological degradability of the waste. Hoeks (1983 in Kruse 1994) analysed raw material and came to the conclusion that only about 40 Mass % of municipal solid waste contribute to gas production. B. Weber (1990) considered a carbon proportion of 30% of the total carbon, which is not biodegradable, e.g. lignin or plastic. This means 70% are assumed to be biodegradable and are incorporated by a factor f_a with the value 0.7 by B. Weber (1990). According to Ehrig (1994 in Krümpelbeck and Ehrig 1999) 30-40% of the existing carbon is biodegradable. The IPCC

model to determine the national greenhouse gas (GHG) inventories distinguishes three different degradable waste types – readily, moderately, and slowly - and a general decomposable proportion of the degradable organic carbon of 0.5 referring these waste types, however, the possibility is mentioned to used waste type specific one as well (IPCC 2006). Kröger (2006) estimates a factor of 0.5 as too high and claims a factor between 0.2 and 0.4 to be more realistic. In contrast, the model of Marticorena does not at all consider a decomposable proportion for instance (Schachermayer 2007).
B. Weber (1990) considered additionally an optimisation factor f_o which refers to the ratio of real to maximum possible total carbon elimination in the gas. This should consider different milieu conditions within the waste body. A maxima f_o of 1.0 can only be reached under lab conditions, but according to B. Weber (1990) own investigations realistic values under landfill conditions of f_o are in the range of 0.7. The product of both factors f_a and f_o is estimated by B. Weber (1990) to ≤ 0.5. Additionally, in the IPCC model a so-called methane correction factor is incorporated which considers the autonomous methane oxidation of a landfill subject to the operation mode. It ranges from 0.6 for uncategorised up to 1.0 for anaerobic managed solid waste deposits (IPCC 2006). However, Schachermayer (2007) comes to the decision that the value 1.0 should be used on basis of conversation with experts, an evaluation of different models and calculations in frame of the methane emission inventory for Austria.

According to B. Weber (1990), the realistic potential landfill gas production is described with equation Eq. 2-2.

$$G_e = 1.868 \cdot TC \cdot f_o \cdot f_a \qquad \textbf{Eq. 2-2}$$

G_e - Real gas production potential [m³/Mg]
f_a - Degradation factor; 0.7 [-]
f_o - Optimisation factor considering the ratio of real to maximum possible total carbon elimination in the gas (e.g. different milieu conditions, vulnerable surface); 0.7 under real landfill conditions up to maximal 1.0 under lab conditions

The following three equations Eq. 2-3 to Eq. 2-5 are provided to calculate the methane generation potential in the IPCC model (IPCC 2006). It has to be noticed that the original abbreviation DOC describing the degradable organic carbon is replaced by BOC. This should prevent a mistake with the term Dissolved Organic Carbon in context of this study. It affects as well the abbreviations DOC_f and DOC_i.

$$L_0 = DDOC_m \cdot F \cdot {}^{16}\!/_{12} \qquad \textbf{Eq. 2-3}$$

$$DDOC_m = W \cdot BOC \cdot BOC_f \cdot MCF \qquad \textbf{Eq. 2-4}$$

$$BOC = \sum_i (BOC_i \cdot W_i) \qquad \textbf{Eq. 2-5}$$

L_0 - CH_4 generation potential, [Gg CH_4]
$DDOC_m$ - Mass of decomposable BOC deposited [Gg C]
F - Fraction of CH_4 in generated landfill gas (volume fraction) [%]
$^{16}/_{12}$ - Molecular weight ratio CH_4/C [-]
W - Mass of waste deposited [Gg waste]
BOC - Degradable organic carbon in the year of deposition, fraction [Gg C/Gg waste]
BOC_f - Fraction of BOC that can decompose; recommended default value is 5.0 [-]
MCF - CH_4 correction factor for aerobic degradation in the year of deposition (fraction)
BOC_i - Fraction of degradable organic carbon in waste type i
W_i - Fraction of waste type i by waste category

In IPCC (2006), there are numerous values for degradable organic carbon in different waste types given, which are summarised in Table 2-3.

Table 2-3: Applied default values of the degradable organic carbon of different waste fractions

MSW component	Dry matter content in % of wet weight[1]	BOC content in % of wet waste		BOC content in % of dry waste		Total carbon content in % of dry weight		Fossil carbon fraction in % of total carbon	
	Default	Default	Range	Default	Range[2)]	Default	Range	Default	Range
Paper/ cardboard	90	40	36-45	44	40-50	46	42-50	1	0-5
Textiles[3)]	80	24	20-40	30	25-50	50	25-50	20	0-50
Food waste	40	15	8-20	38	20-50	38	20-50	-	-
Wood	85[4)]	43	39-46	50	46-54	50	46-54	-	-
Garden and Park waste	40	20	18-22	49	45-55	49	45-55	0	0
Nappies	40	24	18-32	60	44-80	70	54-90	10	10
Rubber and leather	84	(39)[5)]	(39)[5)]	(47)[5)]	(47)[5)]	67	67	20	20
Plastic	100	-	-	-		75	67-85	100	95-100
Metal[6)]	100	-	-	-		NA	NA	NA	NA
Glass[6)]	100	-	-	-		AN	NA	NA	NA
Other, inert waste	90	-	-	-		3	0-5	100	50-100

[1)]The moisture content given here applies to the specific waste types before they enter the collection and treatment. In samples taken from collected waste or from e.g., SWDS the moisture content of each waste type will vary by moisture of co-existing waste and weather during handling. [2)]The range refers to the minimum and maximum data reported by Dehoust et al., 2002; Gangdonggu, 1997; Guendehou, 2004; JESC, 2001; Jager and Blok, 1993; Würdinger et al., 1997; and Zeschmar-Lahl, 2002. [3)]40 per cent of textile are assumed to be synthetic (default). Expert judgement by the authors. [4)]This value is for wood products at the end of life. Typical dry matter content of wood at the time of harvest (that is for garden and park waste) is 40 per cent. Expert judgement by the authors. [5)]Natural rubbers would likely not degrade under anaerobic condition at SWDS (Tsuchii et al., 1985; Rose and Steinbüchel, 2005). [6)]Metal and glass contain some carbon of fossil origin. Combustion of significant amounts of glass or metal is not common.

(cited in IPCC 2006)

As addition, Table 2-4 lists results of landfill gas potentials of different references (Krümpelbeck and Ehrig 1999). The potentials where estimated, calculated and practically or experimentally determined. However, the published gas potentials, see for instance Table 2-4, are only comparable and useful with the information of the carbon content at the beginning and at the end of measurements (B. Weber 1990).

Table 2-4: Published landfill gas potentials of municipal solid waste

Reference	Landfill gas potential	Remarks
Tabasaran (1976)*	60-180 m³/Mg	From praxis
Ham et al. (1979)*	60-350 m³/Mg	Predicted a gas rate of 6-35 m³/(Mg·a) over 10 years
Stegmann and Dernbach (1982)*	15-200 m³/Mg DM	Experimentally estimated
B. Weber (1990)	165 m³/Mg FM	Experiments, (volume at standard conditions)
Ehrig (1991)*	128-230 m³/Mg DM	-
Rettenberger and Metzger (1992)*	150-235 m³/Mg DM	-
Stegmann et al. (2006)	120-180 m³/Mg DM	Laboratory experiments with waste from a German landfill for municipal solid waste
*(Krümpelbeck and Ehrig 1999)		

2.1.4.2 Kinetic of the gas production

The generation of landfill gas by biological degradation processes extends over a long period. According to Ehrig (2006), a gas production of 0.1 to 0.3 m³ Gas/Mg is realistic even after 70 to 100 years of degradation. Rettenberger and Metzger (1992 in Krümpelbeck and Ehrig 1999) illustrated the long-term behaviour of the landfill gas composition of old landfills and deposits, see Figure 2-3 starting by phase IV. The authors have divided the long-term behaviour in six phases. Phase one corresponds to phase four - the stabile methane phase - of the model developed by Farquhar and Rovers (1973), see Figure 2-3 up to phase IV. (Krümpelbeck and Ehrig 1999)

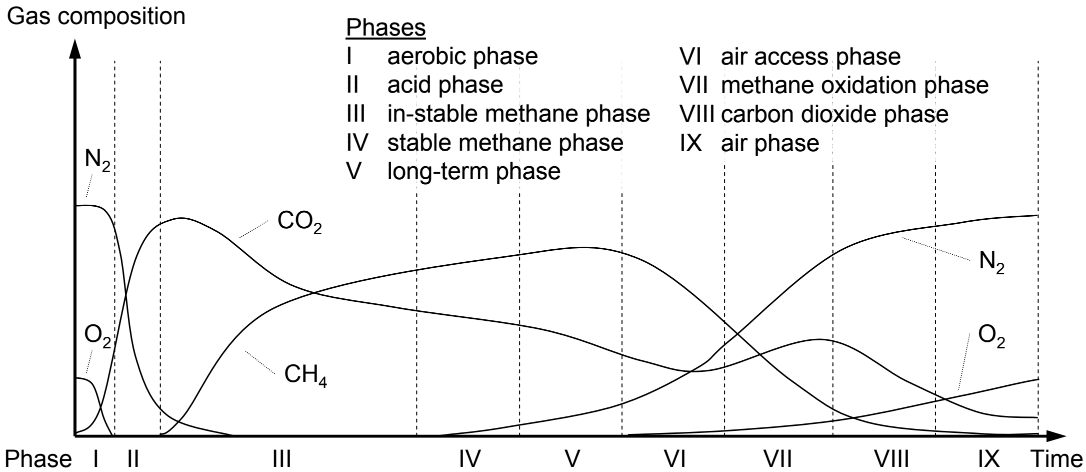

Figure 2-3: Progress of the qualitative composition of the landfill gas
according to Farquhar and Rovers (1973) and Rettenberger and Metzger (1992 in Krümpelbeck and Ehrig 1999)

All gas prognosis models are based on known biological degradation functions, as landfill gas is the main product of the biodegradation processes in landfills. Therefore, the gas production rate corresponds to the degradation rate of the biodegradable organic waste. (Ehrig 1994)
An evaluation of different degradation models (0^{th} to 2^{nd} order) have indicated, that the 1^{st} order model can be accounted as sufficient for practical applications (Krümpelbeck and Ehrig 1999). According to Ehrig (1994), the following approach can be used to estimate the total gas production in dependence of deposit duration.

$$G_{st} = G_e \cdot (1 - e^{-k \cdot t}) \qquad \textbf{Eq. 2-6}$$

G_{st} - Total gas production [m³/Mg]
k - Decay rate ($-\ln(0.5)/t_{1/2}$)
$t_{1/2}$ - Half-life [a]
t - Time since waste deposit [a]

Equation Eq. 2-6 is partly based on the basis 10 instead e, whereas the factor k is 2.303 time greater using same half-life.
By using equation Eq. 2-6 the course of the accumulated gas production can be demonstrated simply knowing the gas potential (G_e) and half-life ($t_{1/2}$). The gas potential defines the final value and the half-life the curvature of the graph. (Ehrig 1994)
The gas production rate at a specific time, which is mostly of main interest, is expressed by the first derivation of equation Eq. 2-6 and illustrated in equation Eq. 2-7 (Ehrig 1994).

$$G_t = G_e \cdot k \cdot e^{-k \cdot t} \qquad \textbf{Eq. 2-7}$$

G_t - Gas production rate at time t [m³/(Mg·a)]

Equation Eq. 2-6 and Eq. 2-7 express the beginning of gas production at time zero. This implied that the gas production starts immediately after deposit. However, in reality biochemical degradation processes pass normally a lag phase with no significant gas production. (Ehrig 1994)
Thus, Ehrig (1994) modified equation Eq. 2-7 as follows:

$$G_t = G_e \cdot k \cdot e^{-k \cdot (t - t_1)} \qquad \textbf{Eq. 2-8}$$

t_1 - Time lag until maximum gas production rate [a]

B. Weber (1990) considers a fixed time lag value of half a year and assumes a lag phase under anaerobic conditions of six months. Additionally, B. Weber (1990) implies a biological degradation near surface of readily degradable carbon under aerobic conditions. That is considered with the factor f_{a0}, and according to B. Weber (1990) with a value of 0.95 for 2 m high tipping line operation and 0.8 for thin layer placement. The respective equations look as follows:

$$G_{st} = 1.868 \cdot TC \cdot f_o \cdot f_a \cdot f_{a0} \cdot (1 - e^{-k \cdot t}) \qquad \textbf{Eq. 2-9}$$

$$G_t = 1.868 \cdot TC \cdot f_o \cdot f_a \cdot f_{a0} \cdot k \cdot e^{-k \cdot t} \qquad \textbf{Eq. 2-10}$$

t - Time since waste deposit considering a lag phase, e.g. half a year [a]
f_{a0} - Considers degradation of readily biodegradable carbon under aerobic conditions (0.8-0.95) [-]

Supplementary and for completion the subsequent three equations describe the calculation of the generated methane emission in the IPCC model (IPCC 2006). The calculation is based on an exponential function, a so-called First Order Decay (FOD) too. In contrast, the results are given in mass.

a) DDOCm accumulated in the SWDS at the end of year T:

$$DDOCma_T = DDOCmd_T + (DDOCma_{T-1} \cdot e^{-k}) \qquad \textbf{Eq. 2-11}$$

b) DDOCm decomposed at the end of year T:

$$DDOCmdecomp_T = DDOCma_{T-1} \cdot (1 - e^{-k}) \qquad \textbf{Eq. 2-12}$$

T	- Inventory year
$DDOCma_T$	- DDOCm accumulated in the SWDS at the end of year T [Gg]
$DDOCma_{T-1}$	- DDOCm accumulated in the SWDS at the end of year (T-1) [Gg]
$DDOCmd_T$	- DDOCm deposited into the SWDS in year T [Gg]
$DDOCmdecomp_T$	- DDOCm decomposed in the SWDS in year T [Gg]
k	- Reaction constant, k = ln(2)/$t_{1/2}$ (y-1)
$t_{1/2}$	- Half-life time [a]

c) Methane (CH_4) generated from decayed DDOCm:

$$CH_4generated_T = DDOCmdecomp_T \cdot F \cdot \tfrac{16}{12} \qquad \textbf{Eq. 2-13}$$

$CH_4generated_T$ - Amount of CH_4 generated from decomposable material [Gg]

Table 2-5 includes published half-lives respectively determined k-values for basis e (modified on Ehrig 1994; IPCC 2006; Krümpelbeck and Ehrig 1999).

Table 2-5: Published half-lives and k-values of anaerobic degradation

<table>
<tr><th>Reference</th><th colspan="2">Remarks</th><th>Half-lives</th><th colspan="4">k-value regarding basis e</th></tr>
<tr><td>Tabasaran (1976)</td><td colspan="2">-</td><td>10</td><td colspan="4">0.07</td></tr>
<tr><td>Rettenberger (1978)</td><td colspan="2">-</td><td>2.4</td><td colspan="4">0.288</td></tr>
<tr><td>Stauffer in Stegmann (1978/79)</td><td colspan="2">Readily degradable
Moderately degradable</td><td>1.5
25</td><td colspan="4">n/a</td></tr>
<tr><td>Moolenar (1981)</td><td colspan="2">Readily degradable
Moderately degradable
Slowly degradable</td><td>1-5
5-25
20-100</td><td colspan="4">n/a</td></tr>
<tr><td>Rovers (1977) in Hoeks (1983)</td><td colspan="2">-</td><td>19</td><td colspan="4">0.0365</td></tr>
<tr><td>Hoeks (1983)</td><td colspan="2">Readily degradable
Moderately degradable
Slowly degradable</td><td>1
5
15</td><td colspan="4">0.693
0.139
0.046</td></tr>
<tr><td>Tabasaran, Rettenberger (1987)</td><td colspan="2">General estimations/measurements at landfills</td><td>12-6
8.6-7.5</td><td colspan="4">n/a</td></tr>
<tr><td>Weber (1990)</td><td colspan="2">-</td><td>10-6</td><td colspan="4">0.07-0.12</td></tr>
<tr><td>Ehrig (1991)</td><td colspan="2">-</td><td>5</td><td colspan="4">0.139</td></tr>
<tr><td rowspan="7">IPCC (2006)

NB:
MAT - mean annual temperature,
MAP - Mean annual precipitation,
PET - potential evapotranspiration.
MAP/PET is the ratio between the mean annual precipitation and the potential evapotranspiration.</td><td colspan="2" rowspan="2">Waste type</td><td rowspan="6">---</td><td colspan="2">Boreal and Temperate (MAT≤20°C)</td><td colspan="2">Tropical (MAT>20°C)</td></tr>
<tr><td>Dry (MAP/PET <1)</td><td>Wet (MAP/PET >1)</td><td>Dry (MAP < 1000 mm)</td><td>Wet (MAP > 1000 mm)</td></tr>
<tr><td rowspan="2">Slowly degrading</td><td>Pulp, paper, cardboard (other than sludge), textiles</td><td>0.04</td><td>0.06</td><td>0.045</td><td>0.07</td></tr>
<tr><td>Wood, wood products and straw</td><td>0.02</td><td>0.03</td><td>0.025</td><td>0.035</td></tr>
<tr><td>Moderately degrading</td><td>Other (non-food) organic putrescible garden and park waste</td><td>0.05</td><td>0.10</td><td>0.065</td><td>0.17</td></tr>
<tr><td>Rapidly degrading</td><td>Food, food waste, sewage sludge, beverages and tobacco</td><td>0.06</td><td>0.185</td><td>0.085</td><td>0.40</td></tr>
</table>

modified amongst others according to Ehrig (1994); IPCC (2006); Krümpelbeck and Ehrig (1999)

Ehrig (1994) could not well identify differences of half-lives between the different waste fractions. That does not mean that vegetable and wood are degraded with same rate. However, it expresses, that in short period degradable parts of that fraction are degraded with nearly the same rate. According to Heyer (2003) half-lives determined in laboratory test cannot be directly converted to landfill relations, because they are estimated under ideal conditions. In reality, the half-lives are longer.

Baumeler et al. (1998 in Bogon 2005) divided the biodegradable carbon into three categories, rapidly, heavily and very heavily degradable, considering half-lives of 2, 7 and 2.600 years. This approach is applied in the IPCC model as well (IPCC 2006).

Ehrig (1994) and Bogon (2005) suggested to estimate the gas production with help of several combinations of varying input parameters to get an impression of possible variations and to minimise uncertainties. Their approach equals a sensitivity analyses and should illustrate uncertainties of the prognoses.

According to Bogon (2005), the calculated methane gas production is 2 to 4 times higher than measured or observed. Fellner et al. (2003) mentioned a mid-factor of 2 according to an evaluation of measured data across Europe.

This is mainly caused by overestimated amounts of biodegradable carbon assuming that in the period of 20 to 100 years this biodegradable carbon is decomposed completely and that a biodegradation takes part at all places of the waste body and dry areas do not exists (Fellner et al. 2003).

2.1.4.3 Estimation of avoided landfill gas emissions

Environmentally unfriendly parts of landfill gas are determined as difference between real produced and collected landfill gas amounts. However, it has to be noticed that the real produced landfill gas amounts are based indeed on a theoretical estimate. In contrast, the collected landfill gas is derived from the utilised respectively treatment amount. Therefore, the degree of coverage is a factor, which is based on a mix of real and theoretical gas amounts. Thus, it depends on all factors influencing the gas production rate, like substrate characteristic or milieu conditions respectively (Stachowitz 2004).

B. Weber (1990) considers this with the factor f_s, which describes the system characteristic degree of coverage as ratio of collected landfill gas under operation conditions to estimated produced landfill gas amount. Thus, Eq. 2-9 and Eq. 2-10 are extended as follows:

$$G_{a,st} = 1.868 \cdot TC \cdot f_o \cdot f_a \cdot f_{a0} \cdot f_s \cdot (1 - e^{-k \cdot t})$$ **Eq. 2-14**

$$G_{a,t} = 1.868 \cdot TC \cdot f_o \cdot f_a \cdot f_{a0} \cdot f_s \cdot k \cdot e^{-k \cdot t}$$ **Eq. 2-15**

$G_{a,st}$ - System and temporary collected gas production; [m³/Mg]
$G_{a,t}$ - System and temporary collected gas production at time t; [m³/(Mg·a)]
f_s - Degree of coverage; ratio of collected landfill gas under operation conditions to real produced landfill gas amount [-]

Within the IPCC model (IPCC 2006) the avoidance of landfill gas is considered by the recovery factor R_T and the oxidation factor OX_T. The equation looks as follows:

$$CH_4 Emissions = \left[\sum_x CH_4 generated_{x,T} - R_T \right] \cdot (1 - OX_T)$$ **Eq. 2-16**

CH_4 Emissions	- CH_4 emitted in year T [Gg]
T	- Inventory year
x	- Waste category or type/material
R_T	- Recovered CH_4 in year T [Gg]
OX_T	- Oxidation factor in year T, (fraction)

According to IPCC (2006), the recovered methane has to be subtracted from the generated methane. Only the non-recovered methane fraction will be subject to oxidation in the cover layer of the landfill.

Additional information about several different models to calculated methane emissions from landfills are explained, analysed and compared by Bogon (2005) and Schachermayer (2007).

2.2 Water emission path

Leachate loads are used to characterise the emissions over the water path. They are a precise means to estimate emissions in relation to size and waste amount of the waste deposit. Leachate loads results of the multiplication of leachate amount per unit area and time with the leachate concentration in relation to its mass. In contrast to concentration loads per unit time, different waste deposits can be compared despite external water access. However, that balance cannot be used by leachate recirculation. (Krümpelbeck and Ehrig 1999)