A case study of landfill gas potential at Kikås landfill

Assessment of environmental impacts and alternatives for mitigation

Master thesis within the Master's Programme Environmental Measurements and Assessments

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Well for passive gas mitigation at Kikås landfill © Jonas Larsson 2014
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Abstract

This thesis evaluates three different theoretical models to estimate landfill gas potential. Specifically, a case study to assess the gas potential at Kikås landfill and alternative mitigation measures has been conducted. Recent years, the waste sector has been increasingly acknowledged as a major contributor to emissions of greenhouse gases. A large part of these emissions are emissions of landfill gas (LFG). LFG consists of approximately 50 % carbon dioxide and 50 % methane. Methane is a strong greenhouse gas, which makes mitigation measures viable. On the behalf of the municipality of Mölndal, a case study was conducted with the aim of evaluating gas potential, environmental impact and options for mitigation if needed. A major threshold for conducting estimations of LFG potential is the major uncertainties related to both model parameters and site specific waste data. These uncertainties were to some extent evaluated by using three different models for estimation of LFG potential: the U.S EPA's waste model LandGEM, IPCC's waste model and the Dutch Afvalzorg's model. The case study indicated a likely remaining gas potential of 2 100 – 3 250 ton methane for year 2015–2035, which is significant with respect to global warming. Nonetheless, uncertainties in estimated gas emissions are large. Therefore an investigation of actual gas flows by conducting test pumping is recommended.

Keywords: Landfill, Landfill gas, waste management, landfill cover, landfill gas emission model

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Two years after this thesis I am still engaged in work at Kikås landfill.

Contents

1 INTRODUCTION

DURING THE LAST DECADES THE WASTE SECTOR has become increasingly acknowledged as an important contributor to environmental impacts. Landfills, i.e. waste disposal sites, are important in this context since they cause emissions of landfill gas (LFG). LFG is formed in landfills during anaerobic degradation of organic matter and consists of roughly 50 % methane (CH_4) and 50 % carbon dioxide (CO_2) (Willumsen, 1990). According to Naturvårdsverket (2012) the total emissions from the waste sector amounted to 2 - 3 % of total greenhouse gas emissions in Sweden in 2011. These emissions are dominated by methane emissions from landfills (almost 80 %). Globally landfill methane represents 3 to 10 of the total CH_4 emissions (De Visscher et al., 2004; Stern et al., 2007; Chanton et al., 2008).

The potential for landfill methane production is approximately proportional to the amount of degradable organic carbon (DOC) deposited at the landfill. By the implementation of the landfill directive (1999/31/EC) in 2002, a major part of the landfills in Sweden were closed. Landfills that have continued to operate receive significantly less biodegradable waste. It has been argued that landfills accepting only waste with low degradable organic carbon content won't yield a significant methane production. Moreover a rapid decline in methane production at old landfills has been expected after they have been closed. However, recent experience from modern landfills, accepting only waste with low DOC-content, indicate that methane production might be significant several decades after the main part of the waste have been deposited.

Kikås landfill is a landfill owned by the municipality of Mölndal. Waste was deposited at the site between 1936 and 2008, although household waste was not accepted after 1972. Since the waste deposited at Kikås is characterized by low carbon content there has been a rather low interest in measures that can mitigate methane emissions. An investigation of gas production and potential for energy recovery from the gas was carried out as recent as in 2001, concluding gas production too low to motivate investment in a system for energy recovery. That investigation mainly focused at economic viability. However, due to increasing interest in environmental issues, the municipality wanted to make a renewed investigation of future LFG production considering also environmental aspects of emissions from the landfill.

The main objective of this thesis is to provide material that can support decision making regarding future need for mitigation of landfill gas emissions at Kikås landfill. Specifically the municipality of Mölndal asked for an estimation of present and future emissions, an evaluation of the environmental impact, possible ways to reduce emissions and if feasible to utilize the gas.

1.1 Problem formulation

When deciding whether investments should be made in order to mitigate emissions from landfills it is a good idea to compare to the zero alternative. That is, what are the consequences if no actions are taken? This requires knowledge of how large gas emissions are. However, present LFG production (and the resulting emissions) is not easy to measure. The future LFG production, i.e. the remaining potential for gas production in the landfill, is even more difficult to quantify. Measurements of present emissions are difficult to perform due to lack of simple and standardized methods. Estimations of the total potential for gas production and thus future emissions are difficult due to lack of site specific data as well as knowledge of previous landfill management. As these difficulties are since long acknowledged several models have been developed in order to facilitate estimation of landfill gas potential. Some have been developed for use in national emission inventories of greenhouse gases, while others have been developed more specifically for landfill owners. Although different in level of detail, most of them build on the same fundamental mathematical model of microbial degradation processes. Figure 1 shows a typical example of this kind of idealized degradation curve.

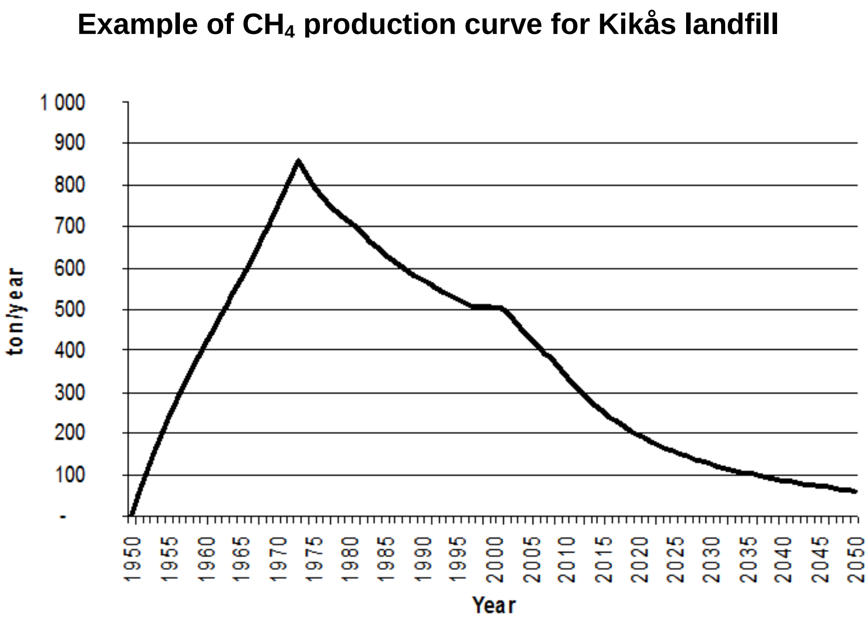

Figure 1 Example of theoretical methane production curve for Kikås landfill

In the case of old landfills there are no legal requirements for mitigation. Consequently there might be few incentives for decision makers to invest in mitigation techniques. Emissions are maybe disregarded due to the fact that the cause of emissions is waste deposited decades ago. However, as the results of this thesis show, there are environmental- and sometimes economic benefits to gain from investments in mitigation. These benefits need to be illustrated in an understandable way.

The use of gas estimation models has been reviewed in several articles (e.g. Scharff and Jacobs (2005); Oonk (2010); Scheutz et al. (2010) and SGI (2011)). Judging from the literature, results of gas estimations tends to vary a lot depending on which model is used. The accuracy of a model is very much dependent on how well model assumptions match the actual landfill. Despite good knowledge of waste composition and amount, estimation of LFG production is connected with large uncertainties. The degradation processes in landfills, which produces landfill gas, is a complex system of reactions dependent on environmental parameters. Many of these parameters are also interdependent (Deublein and Steinhauser, 2008). In order to estimate the outcome of this system major simplifications are necessary in order to establish a useful model. Due to the often highly limited data availability at landfills, it is also necessary to do simplifications of the specific landfill investigated. An important part of estimation of LFG production is to acknowledge these simplifications and assumptions.

1.2 Objectives

The main objectives of this thesis are to:

1. Estimate the environmental impact from Kikås landfill in Mölndal with respect to methane emissions. Assess the use of first order decay (FOD) models for estimation of landfill gas emissions and future potential.
2. Based on estimated emissions suggest how emissions can be reduced.
3. Assess ways to utilize energy in the landfill gas

1.3 Thesis outline

In order to understand the complexity of landfill gas production as well as the difficulties in decision making in this field, this thesis first presents some basic theory on landfill design and degradation processes in landfills. Furthermore, the mathematical interpretation of microbial degradation in landfills is described as well as how this is used in gas estimation models.

The method of the case study is presented in section 4 Method. It describes how data was collected and used in the different models and how the results are assessed in later sections.

Chapter 5 Results simply describes the results from running the models, while chapter 6 explains how the results can be interpreted and used in future decision making.

In the two last chapters the results are discussed with respect to reliability of results and difficulties in decision making regarding future investments in emissions reduction.

2 METHODOLOGY

ALTHOUGH THE MAIN PROBLEM TREATED in this thesis was rather well-defined, the knowledge at the municipality was too limited to suggest a feasible method. Thus, an important first step was to find a useful method for the case study. The initial idea was to combine field measurements with complementary estimations in models of landfill gas production. However, after step 1-4 in Figure 2 were carried out, it was obvious that the scope of the thesis did not allow field measurements comprehensive enough to yield representative results. Due to various reasons field measurements are expensive and not easy to perform. A common method is to use some of the available theoretical models for LFG estimation such as LandGEM and IPCC's waste model. These models offer a rather quick and cheap way to get a general estimation of the gas production in a landfill. Therefore, the scope of this thesis was limited to theoretical estimations and consideration of reliability and feasibility of such estimations.

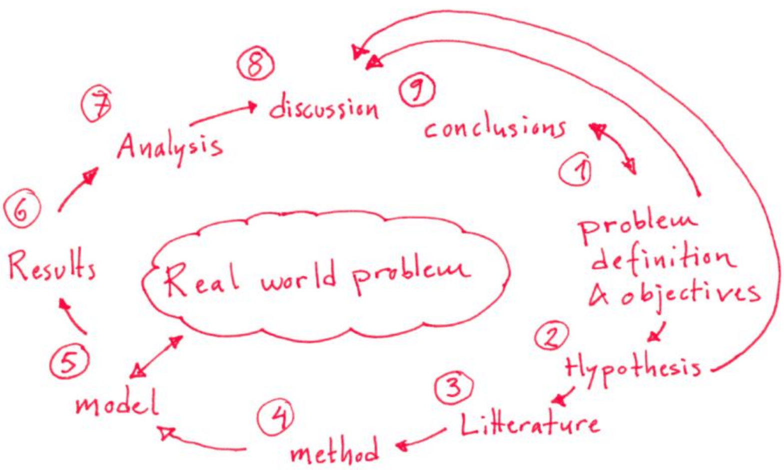

Figure 2 Description of the overall process used in the thesis.

The following steps were carried out in order to estimate the gas potential at Kikås.

1. Review of available models for estimation of gas potential in landfills
2. Compilation of waste data for the case study (Kikås landfill)
3. Three different models were chosen based on the detail of data
4. Run models and assess results.
5. In order to support decision making at the municipality, the result was assessed with respect to environmental impact from future gas emissions as well as potential for remedial actions

3 THEORY

THIS CHAPTER INTRODUCES some important concepts in the field of landfill management and gas emissions calculations. It first introduces what landfill gas (LFG) is and how it is formed, followed by a brief description of how landfills are designed. Then the basis of degradation processes in landfills is explained which includes the first order decay equation used in most landfill gas models. Finally, the three models used in the case study are described.

3.1 What is landfill gas?

LFG is a colourless gas with the density of LFG 1.25 kg/Nm^3 which means it is lighter than air. LFG often has a rather unpleasant smell; which is due to the hydrogen sulphide content. A typical LFG composition is shown in Table 1. It is composed mainly by methane and carbon dioxide (roughly 50 % each). Methane is a strong greenhouse gas and completely dominates the environmental impact from LFG emissions. It has significant energy content and is also explosive in the concentration range 5 - 15 % in air (Avfall Sverige, 2012a). Depending on the composition (more or less methane) energy content in LFG varies from 4.5 – 5.5 kWh/Nm^3. [1]

Table 1 General landfill gas composition (Avfall Sverige, 2012a)

Component	Part of total gas volume
Methane	40–60 %
Carbon dioxide	30-40 %
Nitrogen	1-10 %
Hydrogen	0-2 %
Oxygen	0-2 %
Hydrogen sulphide	10–1000 ppm

[1] Nm^3 is a standard unit used to describe energy content in 1 m^3 gas at 1.01 bar pressure at 0 °C.

LFG is formed during anaerobic decomposition of organic material. During the early 1990s there was an interest in utilization of the energy in LFG. But since tighter legislation among other reasons put an end to deposition of household waste in Sweden the potential for gas production in Swedish landfills has decreased. Nonetheless LFG has now, as an effect of increased focus on emission of greenhouse gases, gained a renewed interest. In fact, although the profit from collecting and utilizing LFG might be limited, there might still be a significant potential for environmental benefits from emissions reduction. The reason for that is explained by the reaction described below:

$$CH_4 + 2O_2 \rightarrow\ CO_2 + 2H_2O \qquad (1)$$

As the reaction in (1) shows the products of the reaction when burning methane are simply carbon dioxide and water vapour. Carbon dioxide is also greenhouse gas, but has significantly lower global warming potential (GWP) than methane. GWP is a concept used for comparing different emissions (Forster, 2007). The radiative forcing of the actual gas, over a certain time horizon, is related to the radiative forcing of the reference gas as written in equation 2.

$$GWP_i = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_r(t)dt} \qquad (2)$$

Where,

TH = Time horizon

RF_i = Radiative forcing for a gas (e.g. CH_4)

RF_r = Radiative forcing for the reference gas CO_2

The reference for GWP is carbon dioxide, which is defined as having GWP 1. Given a time horizon of 100 years, methane has a GWP of 25 (Forster, 2007). That is, 1 ton methane corresponds to 25 ton carbon dioxide in terms of global warming potential. Hence, avoiding methane emissions from landfills is highly beneficial from a global warming perspective.

3.2 Landfill gas formation process

The degradation of the organic content in landfilled waste is a complex system of reactions. Formation of methane in landfills is the result of degradation during anaerobic conditions. The model in Figure 3 shows methane formation as suggested by Veeken et al (2000). The phases might consist of many parallel reactions, but are dominated by a main process of decomposition carried out by a certain group of microorganisms. Contributing to the complexity of the system is the fact that organisms present in the landfill are partly syntrophic, meaning that some compounds are degraded only during interaction between two or more species of microorganisms (Deublein and Steinhauser, 2008). Any model describing such complex system involves a large number of simplifications, which has to be considered when carrying out gas estimations.

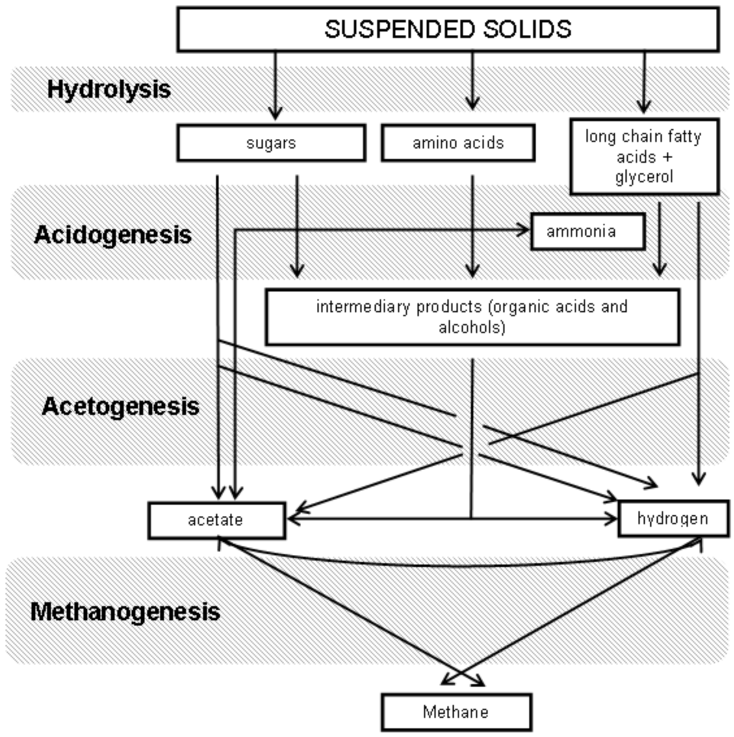

Figure 3 Illustration of methane formation in landfills after Veeken et al. (2000)

According to Veeken et al. (2000) the four metabolic stages suggested in Figure 3 consists of the following reactions:

1. Hydrolysis: complex solid organic material such as carbon hydrates, proteins and fats (Deublein and Steinhauser, 2008) is solubilised by enzymes excreted by hydrolytic micro-organisms. The hydrolysis takes place immediately after DOC-containing waste is deposited; carbohydrates within a few hours and proteins within a few days.

2. Acidogenesis: less complex soluble organic components, including products of the hydrolysis, are converted into organic acids and alcohols.

3. Acetogenesis: acetic acid, hydrogen and carbon dioxide are produced from products of the acidogenesis by anaerobic bacteria.

4. Methanogenesis: Methane is formed mainly from acetic acid or from hydrogen and carbon dioxide. Some methane may also be formed directly from products of the acidogenesis such as formic acid and methanol.

Figure 4 describes variation in composition of the gas formed during the four phases described above. The first phase is characterized by aerobic conditions, which results in formation of carbon dioxide. The last two phases are completely dominated by carbon dioxide and methane. Note that methane is formed exclusively at anaerobic conditions.

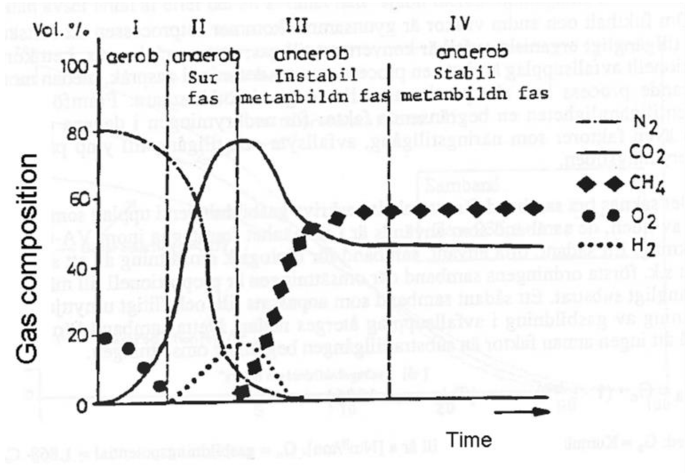

Figure 4 Illustration of phases in degradation process in landfills (Lagerkvist, 1986)

3.3 Landfill cap design

When landfills are closed for waste deposition they are sealed in a way that prevents waste from affecting the environment and risks such as gas explosions to occur. In order to give the reader a basic understanding of the function of these so called landfill cap systems a general description of such systems, with focus on the actual system at Kikås, is presented below. The primary objectives when designing a landfill cap system are to:

1. Minimize leachate: A fundamental function of the cap is to limit leachate production, which is accomplished by limiting the infiltration of rainwater (Bendz et al., 1999). Leachate from landfills may migrate to the groundwater or recipient, which might lead to severe contamination.

2. Prevent air intrusion and control migration of landfill gas: The cap is designed as an impermeable layer. This prevents air intrusion and uncontrolled gas migration (Bendz et al., 1999). However, in order to avoid potential risk of gas explosion, gas migration pathways should be assured.

3. Create an aesthetic landscape and allow vegetation on the site: As a part of the closure of landfills effort is made to restore the landscape.

3.4 Mitigation options: ways to reduce emissions

In addition to the function of the cap, the environmental aspect of LGF emissions should be considered. Depending on how large gas production is and how much gas is expected to be produced in the future some kind of emission reduction is often developed along with the landfill cap. The main concern is to reduce the methane part of the emissions. This can be achieved by either collection and combustion of the gas (reduces CH_4 to CO_2 and H_2O) or by methane oxidation. In gas extraction systems gas is migrated from the landfill either by existing pressure difference in landfill and the atmosphere (i.e. passive systems) or by creating a pressure difference with pumps (i.e. active systems). In some cases gas is collected at landfills and simply flared, which reduces environmental impact since CH_4 is reduced to CO_2 and H_2O. However, if gas production is high, it might be profitable to recover the energy from the gas, e.g. heat production in gas boilers. Where gas production is low microbial oxidation of methane in bio-filters can be a sufficient treatment of landfill methane emissions (Streese and Stegmann, 2003). These filters contain methanotrophic bacteria which oxidize CH_4 into CO_2 (Avfall Sverige, 2012b). According to a study by Broen-Pedersen et al. (2012) this may reduce methane emissions by as much as 79 - 93 %.

Recently there has also been an interest in upgrading landfill gas to vehicle gas. Due to high investment cost this is probably not realistic for old landfills (U.S. EPA, 2009).

3.5 Kikås landfill cap system

The landfill cap system at Kikås is shown in Figure 5. Gas is collected in a gas drainage layer and vented directly to the atmosphere by the natural difference in pressure and gas concentration in landfill and atmosphere (Cheremisinoff, 2003). The drainage layer allows the gas to migrate to the wells, where pressure is lower. Vertical gas wells allow gas migration directly to the atmosphere. The investigations that preceded the closure of Kikås landfill resulted in this system which reduces risks for gas accidents but does not reduce environmental impact with respect to methane emissions.

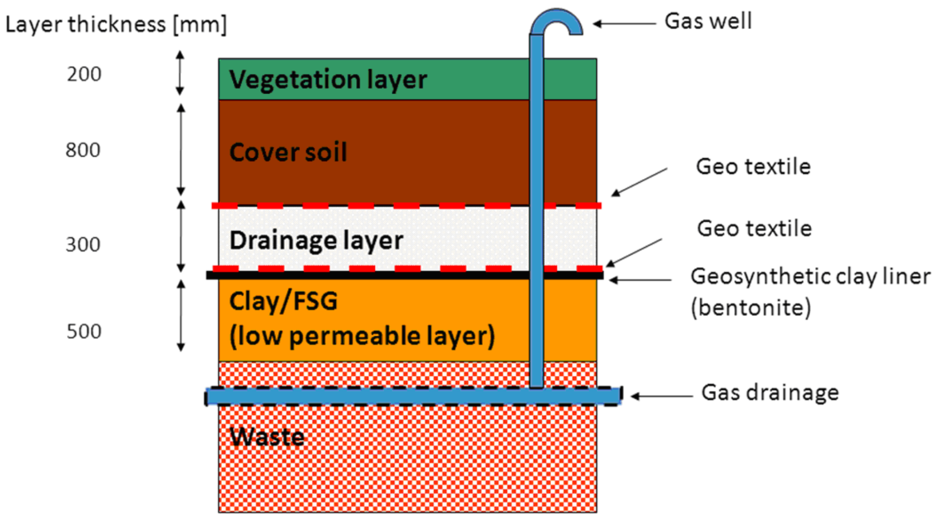

Figure 5 Illustration of landfill cap at Kikås

3.6 Modelling landfill gas potential

Degradation processes in landfills and the resulting gas production is complex and not easy to predict. There are a large number of uncertain parameters and factors affecting the rate of decay, the total amount organic material available for decomposition etc. This chapter presents the basic theory used in landfill gas estimation models.

If the term *recovery* represents the amount of gas collected, the landfill gas emissions from a landfill can be described as in equation 3:

$$emissions = generation - recovery - oxidation \qquad (3)$$

A part of the methane that is formed in the landfill is oxidized to carbon dioxide in the upper parts of the landfill (Avfall Sverige, 2012c). Modelling of the magnitude of the oxidation process in landfills has not received as much attention as modelling of gas formation. In most cases 10 % of the total methane flux through the top layer is assumed to be oxidized (Oonk, 2010).

The environmental impact from LFG emissions is dominated by the methane content, which typically is around 50 %. As describes, the degradation process in landfills is a process consisting of several steps. However, as Oonk (2010) points out, the process is complex. Organic material is not a homogeneous material, but includes a wide range of different molecules with varying biodegradability. Some molecules are easily degraded, such as simple sugars and fats, while others are resistant to anaerobic biodegradation (e.g. lignin, cellulose). Basically the methane generation in a landfill depends on:

1. The amount of waste deposited
2. Amount of degradable organic carbon (DOC) in the deposited waste.
3. How much of the DOC which actually contribute to landfill gas production (DOC_f)

A simple way to theoretically describe the methane generation at a landfill is shown in equation 4 (First order decay equation as written in IPCC's waste model).

$$Q = L_0 \times \mathrm{R} \times (e^{-kc} \times e^{-kt}) \qquad (4)$$

Where,

Q = methane generated in current year (m^3/yr)

L_0 = methane generation potential (m^3/Mg of waste)

R = average annual waste acceptance rate during active life of landfill (Mg/yr)

k = methane generation rate constant (yr-1)

c = time since the landfill closed

t = time since the landfill opened

A first order decay process as in equation (4 is characterized by a fixed half-life for the degradation process. For instance, an assumed half-life of 7 years suggests that methane generation after 7 years is 50% of the initial generation. The generation after 14 years would then be 25 % etc. IPCC (1996) states that results from investigations and measurements in the United States, New Zeeland, the United Kingdom, Argentina and the Netherlands indicate half-life in the range of 3 to 35 years. The half-life is represented by the k-value in equation 4. Slow decay rates (k=0.02, half-life 35 year) are valid for slowly degradable waste such as wood and or paper and dry site conditions. Rapid decay rates (k=0.2 or approximately 3 years half-life) holds for high moisture conditions with rapidly degradable waste such as food waste.

Oonk (2010) points out that this kind of representation does not consider that the waste decomposes continuously rather than discretely which is suggested by equation (4. The result is an underestimated methane generation which is shown in Figure 6. The area below the curve describes methane generation assuming a continuous decline. The area of the blocks represents the case of discrete decline. The difference between the two areas corresponds to the model error.

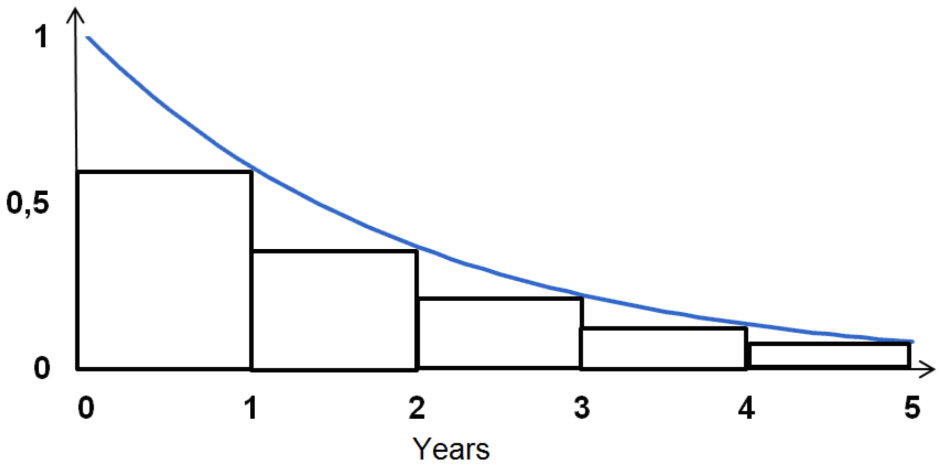

Figure 6 Estimation error in first order model

This error can be handled in different ways. LandGEM for instance minimizes the error by calculating generation each 1/10 of the calculation year (Alexander et al., 2005).

An alternative was suggested by IPCC where the actual generation curve is realized by integration. If conditions are constant, the rate of CH_4 is assumed to depend solely on remaining carbon (IPCC, 1996). Another simplification in the model presented so far is that the total landfilled waste is considered homogeneous. In reality, waste deposited at municipal landfills is often highly diverse. Some fractions are degraded slowly while others are degraded almost immediately after deposition. A solution of this issue is to introduce several phases, which is the idea of multi-phase models.

Often three fractions are distinguished: slow, moderate and fast degrading waste. Calculations are made with specific half-time for each fraction. Single-phase models imply that different types of waste degrade dependent of each other. That is, the decay of slowly degrading waste such as wood products is enhanced by the presence of fast degrading waste such as food waste. Multi-phase models suggest that each fraction in the landfill degrades independently of other slower or faster degrading fractions present. Oonk (2010) argues that actual production probably lies somewhere in between these two models.

3.7 Gas estimation models used in case study

Models developed for estimation of LFG potential typically consist of an excel spread sheet which calculates annual methane production based on waste amounts entered by the user. Two common models for estimation of landfill gas potential are IPCC's waste model and LandGEM (Landfill Gas Emissions Model) developed by the American EPA. Together with a model developed by the Dutch organisation Afvalzorg's these three models represent three different approaches for modelling of LFG potential:

1. Single-phase estimation based on a total amount of waste (LandGEM).
2. Single-phase estimation using different waste categories
3. Multi-phase estimation using different rate of decay for different waste categories

Waste data compiled for Kikås was modified to fit each model and each model was used with its recommended parameters. Characteristics and model parameters of each model are presented in the following three paragraphs. All three models use the principle of first order decay described in Equation 2.

3.7.1 IPCC waste model

The IPCC waste model was developed mainly as a tool for performing estimations of emissions from landfills in national emission inventories. Depending on the level of detail of waste data available the estimations can be made either as a multi-phase model or as a single-phase model. The former estimates methane formation based on waste composition data. That is, amounts of each type of degradable material are entered. In the single-phase model waste quantities are entered as bulk waste (IPCC, 1996). Although intended as a tool for emissions inventories, IPCC's model has also been used at individual landfills in Sweden. In Table 2 all parameters used in IPCC's waste model are listed. The column named *value* lists the value used on each parameter running the model on Kikås landfill.

Table 2 Model parameters with suggested values in IPCC's waste model

Model parameter	Function	Value
Amount degradable organic carbon, DOC	Amount degradable organic carbon	0.19
Amount DOC contributing to methane production DOCf	DOC contributing to methane production	0.5
Characterization of landfill management, MCF	Reflects landfill management	1
Methane content in landfill gas, F	Fraction of CH_4 in total LFG	0.5
Methane oxidized to CO_2, OX	How much CH_4 is oxidized to CO_2	0
Methane generation rate, k	Half-life, time before 50 % of total CH_4 potential is realised	0.08

Organic carbon DOC

DOC is a fundamental parameter since the methane production is proportional to the DOC content in the waste. The DOC amount has to be estimated with respect to the waste composition at the specific site. In this thesis DOC = 0.19 was used as representative to the municipal waste mix (MSW). All waste amounts were scaled by a factor x/0.19 (x representing the actual DOC content) and thus recalculated to the corresponding amount MSW.

Fraction of degradable organic carbon which decomposes under anaerobic conditions (DOC_f)

DOC_f is introduced in the model in order to account for the fact that not all organic carbon degrade and contribute to methane production. The value on DOC_f depends on environmental conditions such as pH, moisture, temperature and composition of waste. The default value suggested by IPCC for anaerobic landfills with lignin deposited is 0.5. That is, in the end approximately 50 % of all DOC contributes to methane generation (IPCC, 1996).

Correction factor

The methane correction factor reflects the management of the landfill. In general unmanaged landfills generate less methane from a given amount of waste compared to managed landfills. In unmanaged landfills, waste is degraded aerobically in the top layer to a larger extent, which results in reduced CH_4.

Fraction of CH4 in generated landfill gas (F)

Landfill gas formed during anaerobic degradation of organic material contains approximately 50 % methane (IPCC, 1996).

Oxidation factor (OX)

Some methane is oxidized to carbon dioxide in the soil or in the material covering the waste. This is handled in the model by an oxidation factor. Oxidation may vary from almost negligible to over 90 % of initially formed methane. However, IPCC's default value is 0. It is recommended that only managed covered landfills with oxidizing material and with supporting data for oxidation available use an oxidation factor higher than 0.1 (IPCC, 1996).

Half-life (k)

IPCC recommends k=0.08-0.1 for bulk MSW. Calculations for Kikås were made using k=0.08. This means that 50 % of the methane potential has been formed after approximately 8-9 years. Either half-life is selected by calculation of a weighted average for half-time for MSW mix (i.e. single-phase) or by dividing the waste into categories of waste according to the rate of degradation (i.e. multi-phase). In this thesis the single-phase approach was used in the IPCC model, in order to investigate differences to a multi-phase approach which was used in the Afvalzorg model.

3.7.2 Afvalzorg

Afvalzorg's model is based on IPCC’s waste model. However, it is more elaborated than IPCC's model in the sense that it considers the fact that waste decomposes at different rate also within each waste category. For each category the amount organic carbon is specified according to fast, moderate and slow decomposing rate. Table 3 shows the categories available in Afvalzorg.

Table 3 the waste categories available in Afvalzorg with corresponding rates of decomposition

Waste category	Fraction OC in waste categories			
	fast	moderate	slow	inert
Soil and soil decontamination residues	0 %	4 %	14 %	82 %
Construction and demolition waste	0 %	14 %	28 %	58 %
Commercial waste	5 %	30 %	30 %	35 %
Shredder	0 %	10 %	30 %	60 %
Street cleansing waste	10 %	20 %	30 %	40 %
Coarse household waste	5 %	15 %	40 %	40 %
Sludge and composting waste	5 %	25 %	30 %	40 %
Refuse Derived Fuel (RDF)	5 %	15 %	30 %	50 %
Household waste	18 %	33 %	18 %	31 %
Vegetable, fruit and garden waste	25 %	25 %	20 %	30 %
Wood	0 %	5 %	40 %	55 %
Inert	0 %	0 %	0 %	100 %

3.7.3 LandGEM

LandGEM (Landfill gas emission model) was developed by the U.S. Environmental Protection Agency (EPA). It is based on first order decay and is the simplest model to use of the three models presented here. Two approaches are possible: Either default values based on empirical data from U.S. landfills are used as model parameters or site specific values can be used. The U.S. EPA provides a rather thorough users’ guide at their website. Included below are some basic characteristics of the model along with assumptions and parameter choice used in this thesis. Equation 5 shows the first order equation used by LandGEM. Methane generation is calculated for each 1/10th year.

$$Q_{CH_4} = \sum_{i}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10}\right) e^{-kt_{i,j}} \tag{5}$$

Where,

i = 1–year time increment

n = (year of the calculation)–(initial year of waste acceptance)

j = 0.1-year time increment

ti,j =age of the jth section of waste mass accepted in the ith year (decimal years, e.g., 3.2 years)

There are two sets of default parameters in LandGEM: CAA defaults and inventory defaults. Estimates based on inventory defaults yield average emissions while those made with CAA defaults tends to yield conservative emissions (Alexander et al., 2005). Table 4 shows parameters used in gas estimations for Kikås.

Table 4 Default parameters in LandGEM

Model parameter	Value	Unit
Methane generation rate, k	0.04	
Potential methane generation capacity, L_0	100	m3/Mg
Methane content	50	by volume

Generation Capacity, L_0

Generation Capacity describes the amount methane produced per mega gram (metric ton) waste. This parameter corresponds to the use of DOC and DOC_f in the IPCC model. The U.S. EPA recommends a number of different default values depending on the kind of investigation (Alexander, 2005)

Waste composition assumption in LandGEM

Figure 7 shows the approximate MSW composition used in LandGEM.

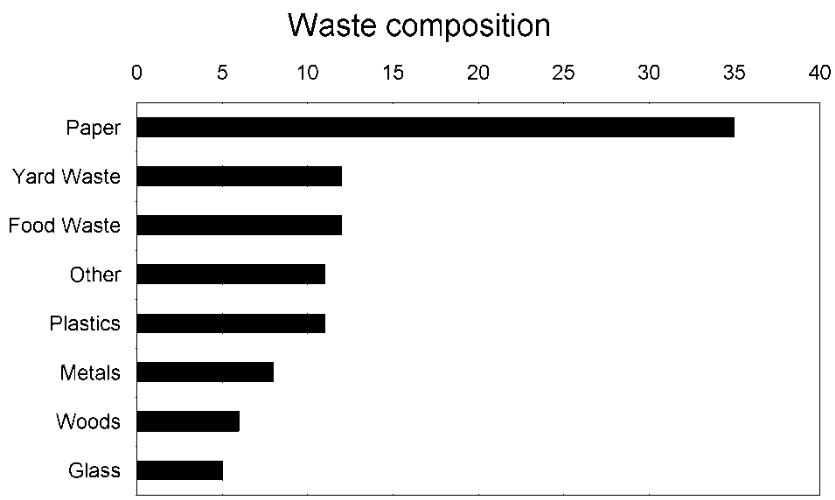

Figure 7 Waste composition assumed in LandGEM estimation (Duffy, 2012)

4 METHOD

THE METHOD USED IN THIS THESIS CONSIST of mainly five steps which are presented in the following sections: Collection of input data to models; adaption of data to each model; running the models (presented in the results chapter); analysis of the results from the models; assessment of environmental impact and mitigation options.

4.1 Collection of input data

The data available on deposited waste at Kikås was very limited with respect to both quantities and composition. Waste quantities from 1990 until 2008 were available in environmental reports. Due to lack of data for most years between 1950 and 1990, these waste quantities was approximated linearly based by inter- and extrapolation of data available for 1964, 1974 and 1980. Information on 1964 waste quantities in Mölndal was available from a regional investigation of waste preceding the construction of the combined heat and power plant in Sävenäs. The investigation presents waste quantities in the participating municipalities in 1964 as well as a prognosis for waste quantities in 1970 and 1980. The waste investigation seems to have been rather thorough, since the prognosis was based on factors such as changes in industrial activity, population and consumption patterns. Figure 8 shows the approximated amounts of industrial waste deposited between 1950 and 1980. The same approximation was made for the other waste categories. The activity before 1950 is very uncertain and it was considered very unlikely that this waste would contribute to gas production today.

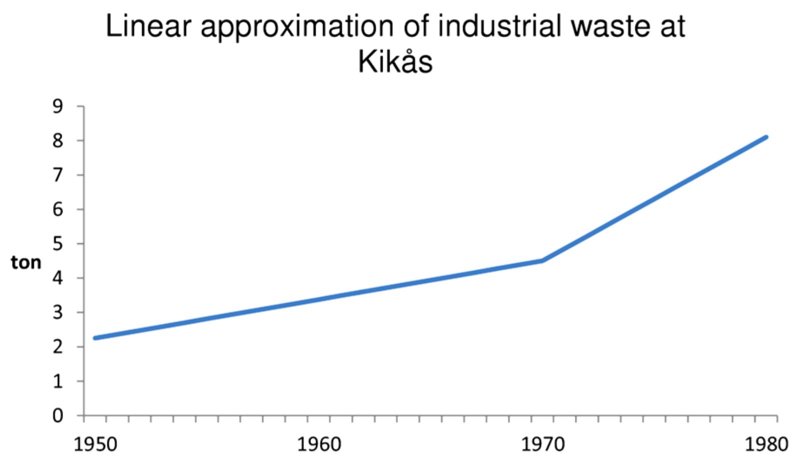

Figure 8 Linear approximation of industrial waste 1950 - 1980. Approximation is based on waste data from 1964, 1970 and 1980.

The data on waste at Kikås was received in three ways:

- Historic data from a waste investigation made in the region of Västra Götaland in 1964 where waste from Kikås is presented from 1950 to 1968, see Table 5.
- Data for 1968 – 1988 is based on a prognosis for 1970 and 1980 that was made in the investigation. Data are interpolated for the years between 1970 and 1980. Data for the years 1980-1989 were interpolated between 1980 and 1989 (Table 6).

Data for 1989 – 2008 was received from environmental reports for Kikås waste facility (Table 7

- Table 7).

Table 5 Waste deposited at Kikås according to waste investigation carried out in 1964 by the region of Västra Götaland. Since 1973 no household waste has been deposited at the site. Data for 1980-1989 was estimated by interpolation based on prognosis for 1970 and 1980 made in the waste investigation.Waste quantitiesin kilo ton.

Year	Total waste (sludge and C&D excluded)	Industrial waste	Construction & demolition waste	Sludge	Household waste
1950	9,43	2,25	9,35	7,50	3,86
1951	9,54	2,36	9,46	7,95	3,97
1952	9,65	2,48	9,57	8,40	4,08
1953	9,76	2,59	9,69	8,86	4,20
1954	9,88	2,70	9,80	9,31	4,31
1955	9,99	2,81	9,91	9,77	4,42
1956	10,10	2,93	10,03	10,22	4,53
1957	10,21	3,04	10,14	10,67	4,65
1958	10,33	3,15	10,25	11,13	4,76
1959	10,44	3,26	10,36	11,58	4,87
1960	10,55	3,38	10,48	12,04	4,98
1961	10,66	3,49	10,59	12,49	5,10
1962	10,78	3,60	10,70	12,94	5,21
1963	10,89	3,71	10,81	13,40	5,32
1964	11,00	3,83	10,93	13,85	5,43
1965	11,72	3,94	11,04	14,31	5,92

Year	Total waste (sludge and C&D excluded)	Industrial waste	Construction & demolition waste	Sludge	Household waste
1966	12,43	4,05	11,15	14,76	6,41
1967	13,15	4,16	11,26	15,21	6,89
1968	13,87	4,28	11,38	15,67	7,38
1969	14,58	4,39	11,49	16,12	7,86
1970	15,30	4,50	11,60	16,58	8,35
1971	17,08	4,86	11,96	15,46	8,87
1972		5,22	12,32	14,35	9,39
1973		5,58	12,68	13,24	
1974		5,94	13,04	12,13	
1975		6,30	13,40	11,02	
1976		6,66	13,76	9,90	
1977		7,02	14,12	8,79	
1978		7,38	14,48	7,68	
1979		7,74	14,84	6,57	
1980		8,1	15,20	5,46	

Table 6 Waste deposited at kikås between 1980 and 1989. Data interpolated between 1980 and 1989 (from 1989 - waste data has been documented). Waste quantitiesin kilo ton.

Year	Total waste (sludge and C&D excluded)	Industrial waste	Construction & demolition waste	Sludge
1980		8,1	15,20	5,46
1981		7,95	15,05	
1982		7,81	14,91	
1983		7,66	14,76	
1984		7,51	14,61	
1985		7,37	14,47	
1986		7,22	14,32	
1987		7,07	14,17	
1988		6,93	14,03	
1989	6,78	13,88		

Table 7 Waste data received from environmental reports for Kikås waste facility (1989-2008). Waste quantitiesin kilo ton.

Year	Industrial waste	Construction & demolition waste
1989	6,78	13,88
1990	6,63	13,73
1991	6,49	13,59
1992	6,34	13,44
1993	6,19	13,29
1994	6,05	13,15
1995	5,9	13,00
1996	5,53	9,60
1997	7,80	8,40
1998	8,35	10,70
1999	5,91	20,15

Year	Industrial waste	Construction & demolition waste
2000	7,50	13,89
2001	4,07	6,90
2002	2,60	10,26
2003	1,96	10,44
2004	1,89	11,94
2005	1,58	8,78
2006	1,23	10,70
2007	2,59	6,51
2008	0,74	6,39

4.2 Adaption of data to models

The input of waste differs for all three models used in this thesis. LandGEM calculates methane generation based on total waste deposited, assuming a waste mix similar for all municipal landfills. Calculations made in the IPCC model were also based on one type of waste. However, adjustments were made due to the fact that the waste mix at average municipal landfills is probably not representative for the waste deposited at Kikås. That is, the amount of waste in one category were recalculated using the factor x/0.19, where x is the DOC content in the actual waste category and 0.19 is the DOC content in the waste mix used in the calculations. The difference of the initial total waste and the "adjusted" total waste can be seen by comparing Figure 9 and Figure 11. Figure 10 shows waste as entered in Afvalzorg, thus divided into four applicable categories.

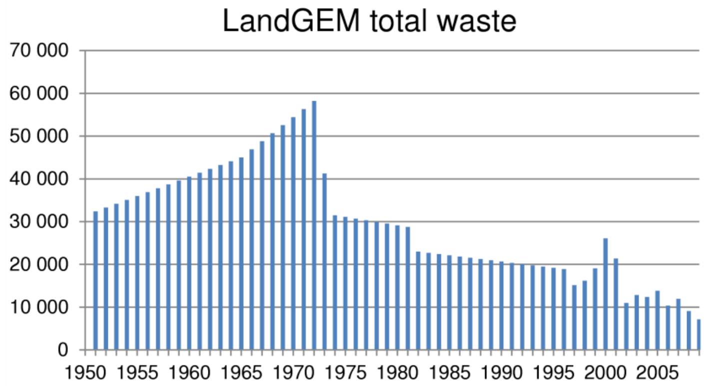

Figure 9 Total waste as entered in LandGEM

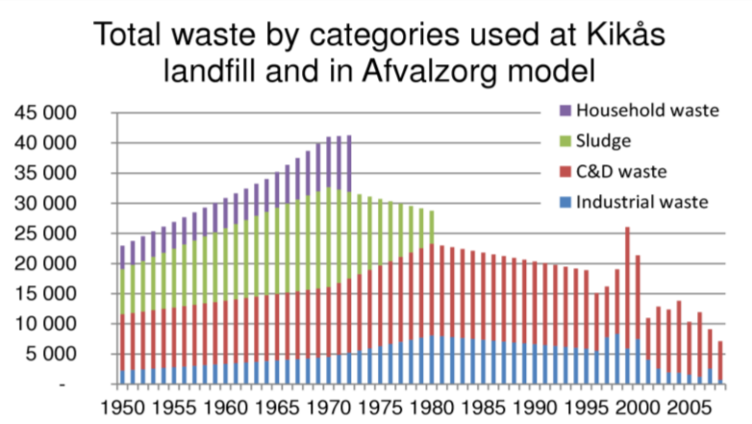

Figure 10 Waste entered into Afvalzorg according to the four different waste types that have been registered separately at Kikås

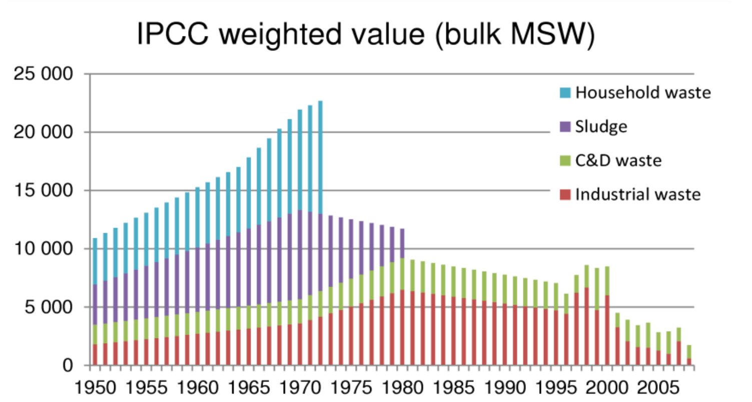

Figure 11 Waste entered in IPCC model. Waste in different categories were converted to corresponding amount bulk MSW by using the relation between DOC content in each category to DOC content in bulk MSW (IPCC uses 0.195 as representative DOC value for bulk municipal waste)

4.3 Running the model

The adapted data was entered in each model. The estimation result from each model is presented in Chapter 5 Results. It begins with estimation results from each model.

4.4 Analysis of results from models

The results from each model then were compared and analysed. The idea was that by comparing results received by different models estimating the uncertainties, and based on this arrive at a conservative but “most likely” estimation.

4.5 Assessment of results

In order to facilitate decision making the municipality of Mölndal wanted an assessment of the environmental impact with respect to LFG emissions from Kikås, as well as suitable options for emissions reduction.

First the environmental impact was illustrated by converting all emissions to equivalent carbon dioxide emissions, by using GWP (global warming potential). GWP for methane was chosen as 25, thus 25 times more effective than carbon dioxide as a greenhouse gas. The magnitude of the equivalent CO_2 emissions then was illustrated by comparison to the corresponding number of cars.

Second, as a way to motivate a mitigation option such as collection of gas and energy recovery, the energy content in the estimated gas was calculated. This energy then was compared to the corresponding number of houses that could be heated by the energy content.

A useful way to appreciate environmental impact is to relate it to something we are used to. By monetization of emissions the value of mitigation becomes very clear. The emissions were monetized in two different ways:

1. By using the same price on carbon dioxide emissions as used for fuel
2. By using the price on carbon dioxide emissions used in trade of emission allowances

5 Results

THIS CHAPTER PRESENTS RESULTS from estimation of methane production according to each model used in this thesis. The results are evaluated in Chapter 6 with respect to environmental impact and possible ways to motivate investments in mitigation.

The results from estimations of methane production for the next 20 year period as well as total production 1950-2050 are shown for each model in Table 8. Afvalzorg's model calculates estimated minimum and maximum production. An average of these estimations was chosen as results. As stated earlier in this report, methane production in landfills is highly dependent on parameters such as amounts of waste deposited and amount of organic material as well as assumptions regarding the rate of decay. This was very evident when results from the three different models were compared. Figure 12 presents the results of methane production for all three models. The models indicate that methane production peaked somewhere between 1974 and 1980. However, the total potential 1950-2050 (see Table 8) indicates a large difference between gas production estimated in LandGEM compared to booth IPCC and Afvalzorg.

Afvalzorg and IPCC

Results from estimation in Afvalzorg's and IPCC's waste models differ mainly with respect to the rate of methane production decline (see Figure 12). Methane production estimated in Afvalzorg's model indicates 168 ton methane produced in 2015 compared to IPCC's 213 ton. However, the production in 2035 according to Afvalzorg is 70 ton, which is twice the amount suggested by IPCC's model (35 ton). The Afvalzorg model emphasizes the differences in waste composition more than IPCC's model. According to Afvalzorg's model total methane production 2015-2035 is 2 306 ton which is slightly more than the 2 103 ton suggested by IPCC's model.

LandGEM

The result from estimation of methane production in LandGEM suggests significantly higher potential than the two other models. According to LandGEM the total methane production from 2015 to 2035 is 15 413 ton, which is 7 times more than calculated in IPCC's model (2 103 ton) and Afvalzorg's model (2 306 ton). The annual production in 2015 was estimated at 1 063 ton in LandGEM and 213 ton and 168 ton in IPCC and Afvalzorg. The corresponding methane production in 2035 is: LandGEM (478 ton) IPCC (35 ton) Afvalzorg (70 ton).

Table 8 Estimated annual and accumulated methane production [ton] the next 20 years. Results from LandGEM, IPCC single phase waste model and Afvalzorg's multiphase model.

Year	LandGEM	IPCC	Afvalzorg (average)
2015	1 063	213	178
2016	1 022	195	168
2017	982	178	160
2018	943	163	152
2019	906	149	144
2020	871	136	137
2021	836	124	131
2022	804	114	125
2023	772	104	119
2024	742	95	114
2025	713	87	109
2026	685	79	105
2027	658	72	100
2028	632	66	96
2029	607	61	92
2030	584	55	89
2031	561	50	85
2032	539	46	82
2033	518	42	79
2034	497	38	76
2035	478	35	73
Total production 2015-2035	15 413	2 103	2 306
Total production 1950-2050	109 331	35 289	26 255

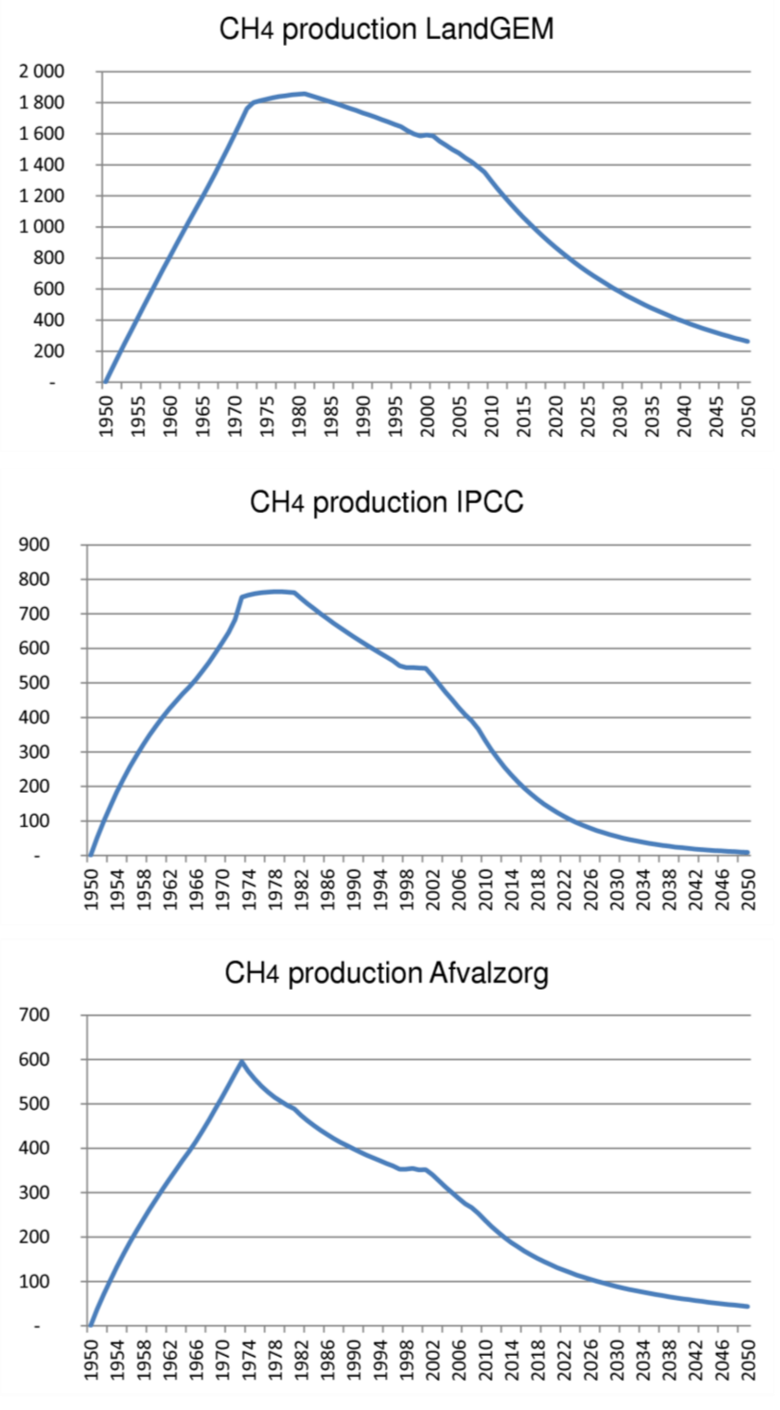

Figure 12 Result of estimations of annual methane production (1950-2050) [ton]. The result was calculated as an average of minimum and maximum estimations from the model

6 ANALYSIS OF RESULTS FROM LFG ESTIMATION

COMPARING THE RESULTS it is clear that the choice of model very much affects the outcome of landfill gas estimation. Two of the models (IPCC and Afvalzorg) yielded results in the same range. The highest estimation (LandGEM) of methane production for 2015-2035 is more than 7 times higher than the lowest estimation (IPCC). The large deviation mainly depends on the fact that different assumptions regarding waste are made in the different models. LandGEM assumes all waste to have the same potential for methane production as well as rate of decay. LandGEM assumes a waste mix representative for landfills accepting all kinds of municipal waste, including household waste. Considering the waste deposited at Kikås, this definitely overestimates available amounts of DOC.

The two other models (Afvalzorg and IPCC) yielded results in the same range. The models estimated total methane production at 35 289 (IPCC) and 26 255 (Afvalzorg) ton for 1950 - 2050. Earlier studies on LFG potential estimation, such as Lemming and Kjeldsen (2006), also indicate that LandGEM overestimates methane potential for landfills with low amounts of organic waste. Lemming and Kjeldsen included experimental measurements of methane productions which pointed towards results by Afvalzorg's model. Based on this and due to the high data uncertainties an average of results from IPCC and Afvalzorg were chosen for the further analysis of environmental impact and possible mitigation options (Table **10**).

6.1 Environmental impact from LFG emissions

The environmental impact from estimated CH_4 emissions was evaluated by calculating equivalent CO_2 emissions. Emissions thereby become easier to appreciate. It also allows for monetization of the emissions, which can be useful as support for decision making.

It should be mentioned that neither gas extraction systems nor oxidation filters yield a 100 % reduction of emissions. Efficiency of gas extraction systems was estimated at between 38 % and 73 % at eight different landfills (Samuelsson et al., 2005). However, a more recent report by Avfall Sverige (2012a) suggests that a well-developed gas collection system should reach extraction efficiency around 80 %. Considering development of technology and the tight final cover of Kikås, calculations of potential energy yield and environmental benefits were based on 80 % gas extraction efficiency, as suggested by Avfall Sverige (n.d.). The potential for CH_4 reduction was calculated at almost 3 000 ton CO_2 equivalents for 2015 which is shown in Table 10.

As a way to illustrate the CO_2 equivalent emissions the corresponding number of cars driven a whole year was calculated. Table 9 shows average driving distance per year according to SCB (2012) and CO_2 emissions per km for a gasoline powered Volvo V50.

***Table 9** Car average driving distance, CO_2 emissions by km and resulting average annual emissions from cars in Sweden (SCB (2012) & Europe's Energy Portal (2012))*

Factor		Unit
Average distance(1)	12 180	km/year
CO_2 per distance(2)	153	g/km
Average CO_2 per year	1 864	Kg

***Table 10** Potential for reduced CH_4 emissions at Kikås landfill, assuming gas extraction efficiency = 80 %. Right column illustrates impacts by showing the number of cars yielding the same emissions (emission calculation based on a Volvo V50).*

Year	CH4	CH_4 (80 %)	CO_2	Potential CO2 reduction by LFG extraction	Corresponding number of cars
2015	196	156	3 910	2 933	1 574
2016	182	145	3 633	2 725	1 462
2017	169	135	3 379	2 535	1 360
2018	157	126	3 146	2 360	1 266
2019	147	117	2 932	2 199	1 180
2020	137	109	2 735	2 051	1 101
2021	128	102	2 553	1 915	1 028
2022	119	95	2 386	1 790	960
2023	112	89	2 232	1 674	898
2024	105	84	2 090	1 568	841
2025	98	78	1 960	1 470	789
2026	92	74	1 839	1 379	740
2027	86	69	1 727	1 295	695
2028	81	65	1 623	1 218	653
2029	76	61	1 528	1 146	615
2030	72	58	1 439	1 079	579
2031	68	54	1 354	1 016	545
2032	64	51	1 278	959	515
2033	60	48	1 208	906	486
2034	57	46	1 142	857	460
2035	54	43	1 081	811	435

Besides developing the existing passive gas venting system to include methane extraction, emissions could be reduced by methane oxidation filters. An oxidation filter use microbial oxidation of methane into carbon dioxide and water. The efficiency of methane oxidation filters depends on several factors, and is also difficult to evaluate. Efficiencies vary from negligible up to 60 % (Gebert and Grongroft, 2006 & Avfall Sverige, n.d.). In a study by Huber-Humer et al. (2008) 90 % efficiency was reached at optimized conditions.

6.2 Energy content: example of utilization

Most landfills extracting LFG recover heat energy from the gas. Total potential for heat generation (2015-2035) was calculated at around 17 GWh using equation 6 and assuming lower heating value (LHV) 13.88 for methane (Elert, 2004).

$$E = m \times LHV_m \qquad (6)$$

where,

E = Energy content [kW]

m = mass [kg]

LHVm = Lower heating value per weight unit [kW/kg]

Table 11 presents an average of IPCC and Afvalzorg CH4 production as well as the potential for energy recovery. Considering that an average detached house in Sweden consumes 13 480 kWh per year for heating, the potential for heat recovery at Kikås would be sufficient to cover demand of 129 houses (year 2015).

Table 11 *Average CH_4 production 2015 - 2035 and the potential for energy recovery (80 % gas system efficiency)*

Year	Average CH_4	GWh	Number of houses
2015	156	1,74	129
2016	145	1,61	120
2017	135	1,50	111
2018	126	1,40	104
2019	117	1,30	97
2020	109	1,21	90
2021	102	1,13	84
2022	95	1,06	79
2023	89	0,99	74
2024	84	0,93	69
2025	78	0,87	65
2026	74	0,82	61
2027	69	0,77	57
2028	65	0,72	53
2029	61	0,68	50
2030	58	0,64	47
2031	54	0,60	45
2032	51	0,57	42
2033	48	0,54	40
2034	46	0,51	38
2035	43	0,48	36

6.3 Monetization of emissions

Landfills as sources of emissions are complicated in the sense that emissions continues long after the activity generating the emission takes place. As an effect mitigation measures may be more difficult to motivate. The illustration of environmental impact by using CO_2 emissions from the corresponding number of cars is one way of showing environmental benefits from mitigation. Another way to motivate mitigation is to calculate cost for emissions. There are different ways of doing this. For instance, Avfall Sverige calculates benefits from investments in oxidization facilities by monetization of prevented emissions of carbon dioxide equivalents. The calculation is based on the assumption that the cost per emitted kg CO_2 is 1 SEK (suggested by Avfall Sverige)[2]. Performing the calculations it is realized that savings from prevention of LFG emissions adds up to a large sum even when emissions are rather small. For instance, using the average of estimated CH_4 in Table 12 , the accumulated emissions during 2015-2035 equals 2 676 ton CH_4 which corresponds to 66 900 ton CO_2. Using the price 1 SEK for emitting 1 kg CO_2 the total cost during 2015-2035 would be 66 900 000 SEK. A more conservative approach would be to assume an emission cost based on the European Union's Emissions Trading System (EU ETS), which is a tool designed to decrease the emissions of industrial greenhouse gases. Within the system a limited number of emission allowances are distributed to companies. Allowances could either be used or sold, but the total number of allowances on the market is limited. The system creates an incentive for industries to reduce their emissions (European Commission, 2012). Judging by price development since initiation of ETS in 2005 the price of emission allowances has varied significantly which is described in Figure 13. In 2006 the price on 1 ton CO2 emission peaked at 32 euro, while in the end of 2011 allowances were sold at 7 euro. However, considering the general trend, a level around 15 euro per ton seems to represent a reasonable stable lowest level over the period.

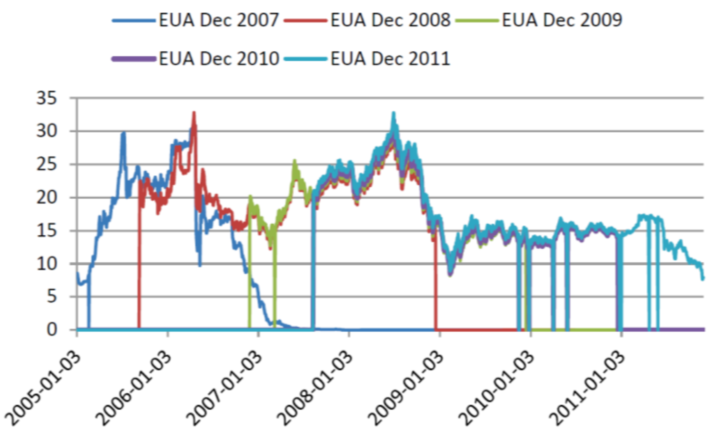

Figure 13 Price of emissions allowances 2005-2011 in euro per ton CO_2 (Energimyndigheten, 2011)

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[2] In Sweden the tax on fuel (e.g. standard vehicle gasoline) is 2.50 SEK per liter (Skatteverket, 2014). The CO_2 equivalent for 1 liter gasoline is 2.71 CO_2. The tax on CO_2 emissions would then be a little less than 1 SEK per kg.

Assuming 15 euro per ton CO_2 emission the total cost for methane emissions at a landfill can be calculated by equation 7.

$$Cost\ of\ emissions = CH_4 Emissions \times GWP \times EA \qquad 7$$

Where,

CH_4 Emission = estimated methane emission

GWP = Global Warming Potential ($1\ CO_2 = 25\ CH_4$)

EA = Emission allowance price

In this way the economic incentive for mitigation measures was appreciated as presented in Table 12, which shows the accumulated emissions as well as annual emissions. The total cost of these emissions are € 1 077 645during 2015-2035, which could be seen as the alternative cost for not doing future investments in mitigation measures.

Table 12 Estimated cost for LFG emissions from Kikås landfill assuming a price based on cost for emission allowances € 15 per kg CO_2

Year	CH_4	CO_2 - equivalent	Cost (Euro)	Accumulated cost (Euro) or alternative cost for not investing in mitigation measures
2015	196	4 888	122 189	199 286
2016	182	3 084	77 097	276 383
2017	169	2 869	71 735	348 118
2018	157	2 672	66 810	414 928
2019	147	2 491	62 283	477 211
2020	137	2 325	58 119	535 330
2021	128	2 171	54 287	589 616
2022	119	2 030	50 757	640 373
2023	112	1 900	47 504	687 877
2024	105	1 780	44 503	732 380
2025	98	1 669	41 733	774 113
2026	92	1 567	39 174	813 288
2027	86	1 472	36 809	850 097
2028	81	1 385	34 621	884 717
2029	76	1 304	32 594	917 312
2030	72	1 229	30 717	948 029
2031	68	1 157	28 928	976 957
2032	64	1 093	27 316	1 004 272
2033	60	1 033	25 818	1 030 090
2034	57	977	24 426	1 054 516
2035	54	925	23 130	1 077 645

6.4 Suggested remedial action

The estimations of future gas production at Kikås indicate considerable future LFG production. There are environmental, and to some extent economic, incentives for developing an active gas extraction system. Collected LFG could for instance be used to generate electricity used at the landfill. The surplus heat can be used to enhance efficiency of leakage treatment. However, the uncertainties in gas estimations might be too large to motivate such investment. My recommendation for the municipality of Mölndal is to:

- Perform complementary investigation of gas potential by gas flow measurements (test pumping) in order to decrease uncertainties.
- Compare results from test pumping and results from gas estimations.
- If test pumping indicates gas potential as estimated the calculation examples in the previous section shows that investment in an active gas collection system can be motivated both with respect to reduced environmental impact and energy utilization.

Based on the result in Table 12 an investment in an active gas collection system could definitely be motivated economically. Assuming a cost around 5 million Swedish crowns[3] the investment would pay off in less than 10 years with respect to reduced emissions.

If the energy would be used for heating the pay-off time would be even less. The energy from a gas extraction system with 80 % efficiency would yield 4.85 GWh the first 3 years according to Table 10. Assuming that 1 kWh cost 1 SEK this means that the energy extraction would correspond to 4.85 million SEK the first 3 years.

If test pumping indicates low gas production a more suitable option can be to create oxidation filters.

[3] According to Mikael Kempi, civil engineer at Atleverket in Örebro, an active gas collection system cost approximately 5 million Swedish crowns (email correspondence 2012-07-18)

7 DISCUSSION

ACCORDING TO A STUDY MADE BY Scharff and Jacobs (2005) differences in results from different models are often very large. The same holds for differences between measured gas extraction and model estimations. The study compares results from applying six different models, on three different landfills. The highest estimates obtained were five to seven times higher than the lowest. Scharff and Jacobs explain deviations by differences in assumptions regarding carbon content in waste, e.g. total organic carbon content, anaerobically decomposable carbon and decomposition rates.

The main consideration when assessing results from LFG estimations is accuracy and reliability of data. It might be argued that often the knowledge of waste quantities and waste composition is too limited to produce reliable results. The results in this specific thesis definitely suffer from limited data. Except from uncertainties regarding landfilled waste, the lack of a gas extraction system at the landfill makes it impossible to estimate the amounts of gas already produced. The kind of estimations carried out in this thesis describe the ideal case where degradation processes starts almost immediately after the waste is landfilled and then continues undisturbed until all degradable matter is degraded. Earlier experience from landfills tells us however that landfills are far from ideal with respect to degradation processes. It would thus be safe to say that the actual remaining degradable matter at Kikås is significantly larger than the results from gas estimation models.

Gas estimation models are useful in the sense that they provide a rough indication of present gas production and remaining potential. It is necessary to assess the indication with respect to the level of knowledge at landfill. Of course, decisions on whether a gas extraction system should be developed need to relate uncertainties to the consequences if the gas is not collected. The highest estimation yielded by LandGEM may not be realistic. Still, the lower estimation also shows significant remaining methane potential.

A problematic aspect of emissions from landfills is who should bear the cost for remediation. There are a large number of closed landfills in Sweden (e.g. Kikås) and the actual deposition of waste yielding methane production might have taken place several decades ago. It might be easier to motivate actions aiming at present sources of pollution. However, as the illustrations of environmental impacts and possible actions for mitigation in this thesis show, it is possible to achieve rather large emissions reductions to a relatively low cost.

Having carried out the work presented in this thesis a conclusion is that the knowledge of environmental impacts from landfills is limited in many municipalities. Thus the incentives for political decisions are generally low. However, there is in fact a potential for remediation of landfills with respect to methane emissions. Since methane is very prominent as a greenhouse gas also minor reductions yield noticeable environmental improvement. Cost for remediation should be compared to costs for the zero alternative. This could be estimated by using CO_2 equivalents and costs based on the emission trading system.

8 CONCLUSIONS

TOTAL METHANE POTENTIAL at Kikås was estimated in three different models. The US EPA's model LandGEM generated results deviating significantly from the two other, with a total potential more than four times higher than the estimation made in Afvalzorg. Most likely, the major difference is due to the fact that LandGEM's estimation is based on a significant overestimation of degradable organic carbon in the deposited waste. The two other models generated more similar results. An important difference between IPCC's model and Afvalzorg is when the emission takes place. Based on literature and experience at landfills in Sweden the result generated by Afvalzorg's multiphase model probably is closer to the reality with a slower rate of decline. According to Afvalzorg the annual methane production exceeds 100 ton until 2026. On average (considering an average of results from IPCC and Afvalzorg) the annual methane production was estimated at between 196 ton (2015) and 52.5 ton (2035). Considering the high GWP of methane this could be considered a significant emission.

Estimation of landfill gas potential is characterized by large uncertainties in data as well as environmental conditions as well as the parameters affecting the degradation process. This was increasingly apparent during the work carried out during this project. After applying three different models for estimation of LFG potential at Kikås landfill some conclusions were made. First of all, booth knowledge of the type and amounts of waste deposited at the actual site has to be considered when choosing model. For instance, LandGEM is not a suitable model for landfills characterized by waste with low carbon content. On the other hand, it was initially chosen due to the fact that it is a simple model with few demands on data. This was considered as an advantage, since the data availability at Kikås was very low. Second, the rate of decay (and thus the decline of LFG production) in models vary a lot. Moreover, experiences from existing landfills indicates that the decline of methane production in old landfills often have been overestimated, thus leading to underestimation of remaining potential. Mathematical models of biological processes such as anaerobic degradation of organic matter in waste, which are used by LFG estimation models, are built on a number of simplifications which do not completely cover the complexity characterizing landfill processes. The diagrams presented in this thesis describe a continuous process where the rate of production depends solely on the amount of degradable carbon left. Yet, it is probably more likely that the process is not continuous but sometimes interrupted and slowed down by changed environmental factors such as for instance oxygen availability and moisture content.

Although estimation of methane potential in LFG estimation models involves several uncertainties mitigation measures should definitely be considered for Kikås. Two different mitigation measures might be further investigated: oxidation filters or development of the existing gas venting system to a gas extraction system. Even though oxidation filters probably would be a less expensive system which is easier to motivate considering the uncertainties in remaining gas potential a gas extraction system might still be worth investigating. Such solution might be interesting if the existing gas venting system can be used and developed. Still, extraction systems have, in addition to initial costs, also a cost of operation which might be hard to motivate with uncertain and decreasing production rates.

A reflection made writing this thesis was that there is a need for communication of experience in the field of cost effective mitigation measures for old landfills where methane is neither collected nor oxidized. The gas potential of a landfill can always be estimated, but uncertainties in the results along with the fact that the emissions are sometimes caused several decades ago makes decision making difficult. Mitigation focused at emission reduction, rather than utilizing the gas, such as oxidation filters, has the potential to be an interesting technique which provides a “good enough” solution. Still, active gas collection systems are far more common in Sweden. While oxidation solutions might be good enough, it is more difficult to assess.

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APPENDIX

1 Waste data

Calculations were made for three different scenarios in order to appreciate how an underestimation or overestimation of deposited waste would affect model results:

1. Scenario 1: 30 % less waste than estimated
2. Scenario 2: 30 % more waste than estimated
3. Scenario 3: Additional scenario which assesses the effect of negligible organic content in waste deposited after 1990. That is, equal to no waste after 1990.

1.1 LandGEM & IPCC

Total waste (kton)

(Sludge and construction and demolition waste excluded)

Year	Low waste scenario (factor 0.7)	High waste scenario (factor 1.3)
1950	6,60	12,25
1951	6,68	12,40
1952	6,76	12,55
1953	6,83	12,69
1954	6,91	12,84
1955	6,99	12,98
1956	7,07	13,13
1957	7,15	13,28
1958	7,23	13,42
1959	7,31	13,57
1960	7,39	13,72
1961	7,46	13,86
1962	7,54	14,01
1963	7,62	14,15
1964	7,70	14,30
1965	8,20	15,23
1966	8,70	16,16
1967	9,21	17,10
1968	9,71	18,03
1969	10,21	18,96
1970	10,71	19,89

Year	Low waste scenario (factor 0.7)	High waste scenario (factor 1.3)
1973	9,00	16,71
1974	8,88	16,50
1975	8,77	16,29
1976	8,66	16,08
1977	8,55	15,87
1978	8,43	15,66
1979	8,32	15,45
1980	8,21	15,24
1981	6,35	11,78
1982	6,24	11,60
1983	6,14	11,41
1984	6,04	11,22
1985	5,94	11,04
1986	5,84	10,85
1987	5,74	10,66
1988	5,64	10,48
1989	5,54	10,29
1990	5,44	10,10
1991	5,34	9,92
1992	5,24	9,73
1993	5,14	9,54
1994	5,04	9,36
1995	4,94	9,17
1996	4,30	7,99
1997	5,42	10,07
1998	6,02	11,18
1999	5,84	10,85
2000	5,94	11,03
2001	3,15	5,85
2002	2,74	5,09
2003	2,41	4,47
2004	2,56	4,75
2005	1,99	3,69
2006	2,03	3,78
2007	2,27	4,21
2008	1,22	2,26

1.2 Avfalzorg low waste scenario (factor 0.7)

Waste in k ton				
Year	Industrial waste	Construction & demolition waste	Sludge	Household waste
1950	1,58	6,54	5,25	2,70
1951	1,65	6,62	5,56	2,78
1952	1,73	6,70	5,88	2,86
1953	1,81	6,78	6,20	2,94
1954	1,89	6,86	6,52	3,02
1955	1,97	6,94	6,84	3,10
1956	2,05	7,02	7,15	3,17
1957	2,13	7,10	7,47	3,25
1958	2,21	7,18	7,79	3,33
1959	2,28	7,25	8,11	3,41
1960	2,36	7,33	8,42	3,49
1961	2,44	7,41	8,74	3,57
1962	2,52	7,49	9,06	3,65
1963	2,60	7,57	9,38	3,73
1964	2,68	7,65	9,70	3,80
1965	2,76	7,73	10,01	4,14
1966	2,84	7,81	10,33	4,48
1967	2,91	7,88	10,65	4,82
1968	2,99	7,96	10,97	5,16
1969	3,07	8,04	11,28	5,50
1970	3,15	8,12	11,60	5,85
1971	3,40	8,37	10,82	6,21
1972	3,65	8,62	10,05	6,57
1973	3,91	8,88	9,27	
1974	4,16	9,13	8,49	
1975	4,41	9,38	7,71	
1976	4,66	9,63	6,93	
1977	4,91	9,88	6,15	
1978	5,17	10,14	5,38	
1979	5,42	10,39	4,60	
1980	5,67	10,64	3,82	
1981	5,57	10,54		
1982	5,46	10,43		
1983	5,36	10,33		
1984	5,26	10,23		
1985	5,16	10,13		
1986	5,05	10,02		
1987	4,95	9,92		
1988	4,85	9,82		
1989	4,75	9,72		
1990	4,64	9,61		

Waste in k ton				
Year	Industrial waste	Construction & demolition waste	Sludge	Household waste
1993	4,34	9,31		
1994	4,23	9,20		
1995	4,13	9,10		
1996	3,87	6,72		
1997	5,46	5,88		
1998	5,85	7,49		
1999	4,14	14,11		
2000	5,25	9,72		
2001	2,85	4,83		
2002	1,82	7,18		
2003	1,37	7,31		
2004	1,33	8,36		
2005	1,10	6,15		
2006	0,86	7,49		
2007	1,81	4,56		
2008	0,52	4,48		

1.3 Avfalzorg high waste scenario (factor 1.3)

Waste in k ton				
Year	Industrial waste	Construction & demolition waste	Sludge	Household waste
1950	2,93	12,16	9,74	5,02
1951	3,07	12,30	10,33	5,16
1952	3,22	12,45	10,92	5,31
1953	3,36	12,59	11,51	5,46
1954	3,51	12,74	12,10	5,60
1955	3,66	12,89	12,69	5,75
1956	3,80	13,03	13,28	5,89
1957	3,95	13,18	13,87	6,04
1958	4,10	13,33	14,47	6,19
1959	4,24	13,47	15,06	6,33
1960	4,39	13,62	15,65	6,48
1961	4,53	13,76	16,24	6,63
1962	4,68	13,91	16,83	6,77
1963	4,83	14,06	17,42	6,92
1964	4,97	14,20	18,01	7,06
1965	5,12	14,35	18,60	7,70
1966	5,27	14,50	19,19	8,33
1967	5,41	14,64	19,78	8,96
1968	5,56	14,79	20,37	9,59
1969	5,70	14,93	20,96	10,22
1970	5,85	15,08	21,55	10,86
1971	6,32	15,55	20,10	11,53
1972	6,79	16,02	18,66	12,20
1973	7,25	16,48	17,21	-
1974	7,72	16,95	15,77	-
1975	8,19	17,42	14,32	-
1976	8,66	17,89	12,88	-
1977	9,13	18,36	11,43	-
1978	9,59	18,82	9,98	-
1979	10,06	19,29	8,54	-
1980	10,53	19,76	7,09	0,00
1981	10,34	19,57		
1982	10,15	19,38		
1983	9,96	19,19		
1984	9,77	19,00		
1985	9,58	18,81		
1986	9,39	18,62		
1987	9,20	18,43		
1988	9,00	18,23		
1989	8,81	18,04		
1990	8,62	17,85		
1991	8,43	17,66		

Waste in k ton				
Year	Industrial waste	Construction & demolition waste	Sludge	Household waste
1992	8,24	17,47		
1993	8,05	17,28		
1994	7,86	17,09		
1995	7,67	16,90		
1996	7,19	12,48		
1997	10,14	10,92		
1998	10,86	13,91		
1999	7,69	26,20		
2000	9,74	18,05		
2001	5,29	8,97		
2002	3,37	13,34		
2003	2,54	13,58		
2004	2,46	15,52		
2005	2,05	11,41		
2006	1,60	13,92		
2007	3,37	8,46		
2008	0,96	8,31		

2 Results of LFG gas estimation

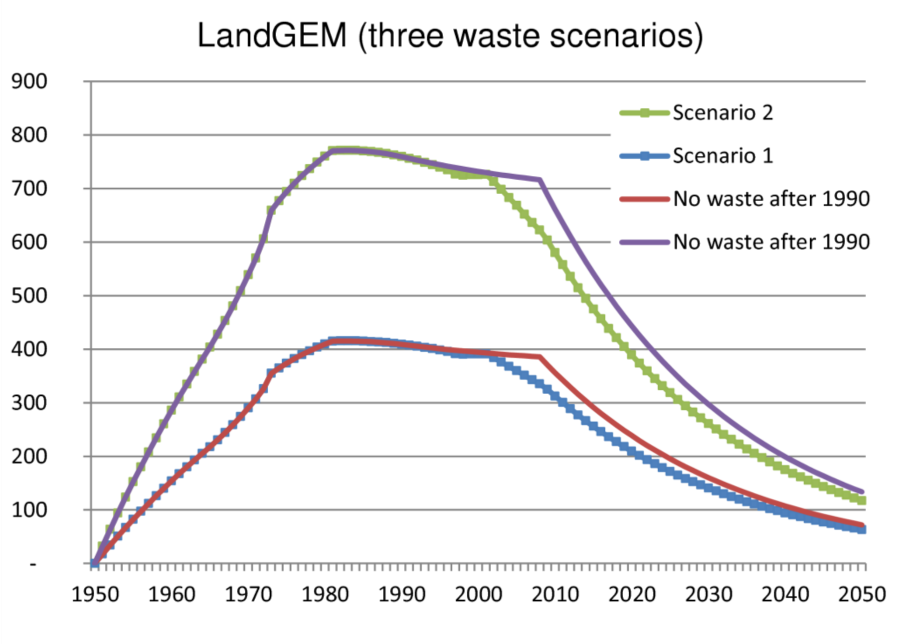

*Figure **14** CH_4 production calculated in LandGEM for three different scenarios*

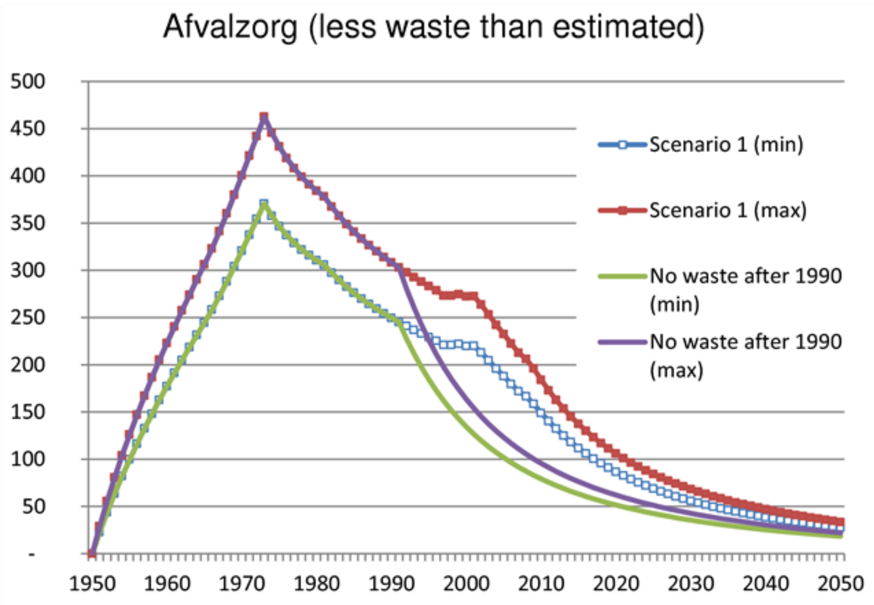

Figure 15 CH_4 production calculated in Afvalzorg for three different scenarios (min-estimation).

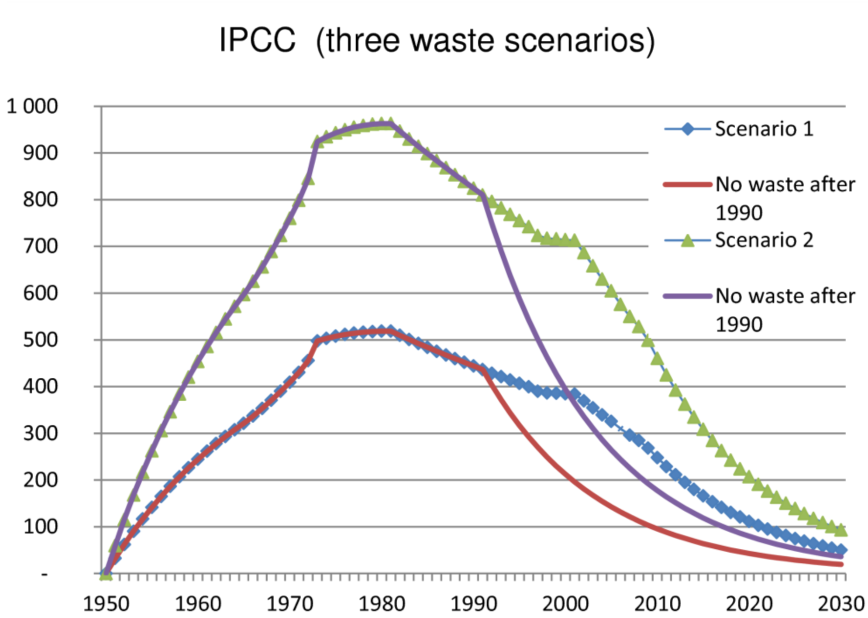

Figure 16 CH_4 production calculated in IPCC for three different scenarios (min-estimation)