DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DETERMINATION OF LANDFILL GAS BY USING METHEMATICAL MODELS

by
Erşan Olcay IŞIN

December, 2012
İZMİR

DETERMINATION OF LANDFILL GAS BY USING METHEMATICAL MODELS

A Thesis Submitted to the Graduate School of Natural and Applied Sciences of Dokuz Eylül University In Partial Fulfillment of the Requirements for the Degree of Master of Since in Environmental Engineering, Applied Environmental Science Program

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M.Sc. THESIS EXAMINATION RESULT FORM

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DETERMINATION OF LANDFILL GAS BY USING METHEMATICAL MODELS

ABSTRACT

In the year of 2012, the landfilling is the most common solid waste disposal method both in the world and in Turkey. Developed and improved waste processing techniques such as composting, gasification, and incineration has started to be used after 1980s, especially in developed countries, but still not widespread. Because landfilling is the simplest and the most economically available method among the others with its low initial investment and operational costs.

In the content of the thesis, as initial steps; the properties of MSW are introduced followed by the presentation of landfilling techniques, reactions occur in the waste body, and leachate production. Then, LFG generation and kinetics are given followed by LFG mathematical modeling. Four different LFG generation models are introduced in this part of the study.

A case study is included to the thesis; the determination of LFG capacity of the Harmandali landfill site in Izmir-Turkey. This landfill has 90 ha of area and has been operated since 1992. The site will be closed by the end of 2014. For this purpose, the composition and characteristics of Izmir MSW is obtained, and used for the calculation of the model variables of k and L_0. The studied LFG models were operated with obtained variables and the results are compared and discussed.

Keywords: LFG, Methane generation, leachate, LFG modeling, methane generation potential, biological degradation of solid waste, dumping of solid wastes.

DEPO GAZININ MATEMATİKSEL MODELLER KULLANILARAK BELİRLENMESİ

ÖZ

2012 yılına gelindiğinde, katı Türkiye'de ve dünya'da atıkların giderimin de kullanılan en yaygın yöntem deponi sahalarında depolanmalarıdır. Gelişmiş ve uygulanan atık işlem teknikleri, kompostlama, gazifikasyon ve yakma olmak üzere 1980'li yıllardan beri gelişmiş ülkelerde kullanılmasına rağmen yaygınlaşamamışlardır. Bu tekniklerin yaygınlaşamama sebebi katı atıkların deponi sahalarında depolamanın basit ve çoğunlukla ilk yatırım maliyetlerinin ve işletme maliyetlerinin az olaması sebebi ile ekonomik olmamasıdır.

Tez kapsamında adım adım evsel kaynaklı katı atıkların özellikleri, depolama teknikleri, deponi sahalarında oluşan reaksiyonların sonucunda katı atık içerisinde oluşan sızıntı suyu ve deponi gazı ve kinetikleri yer almaktadır. Bu tanımlamaların ardından deponi gazı miktarının belirlenmesi için kullanılan matematiksel modeller tanıtılmaktadır ve dört farklı modelleme de deponi gazı miktarı belirlenmesi çalışma kapsamında yer almaktadır.

Örnek uygulama çalışmasında İzmir-Türkiye Harmandalı Katı Atık Depolama Sahası'nın Deponi gazı kapasitesi tespit çalışması yapılmaktadır. 90 ha Alana sahip 1992 yılından beri işletilen depolama sahası 2014 yılının sonun kadar işletileceği ön görülmektedir. Bu kapsamda İzmir İlinin katı atıklarının özelikleri dikkate alınarak model sabitleri olan k ve L_0 hesaplanarak deponi gazı modellemeleri çalıştırılarak sonuçlar karşılaştırılıp tartışılmıştır.

Anahtar sözcükler: Deponi gazı, metan gazı oluşumu, sızıntı suyu, deponi gazı modellemesi, metan gazı oluşum potansiyeli, katı atıkların biyolojik parçalanması, katı atıkların depolanması.

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CHAPTER ONE
INTRODUCTION

In the year of 2012, the landfilling is the most common solid waste disposal method both in the world and in Turkey. Developed and improved waste processing techniques such as composting, gasification, and incineration has started to be used after 1980s, especially in developed countries, but still not widespread. Although, landfilling is the simplest and cost-effective method among the others with its low initial investment and operational costs, it contributes to local air and water pollution generating the leachate and landfill gas, if they are not handled cautiously.

Landfill gas (LFG) is produced as a result of a sequence of physical, chemical, and biological processes occurring within the refuse under anaerobic conditions. LFG contributes to the greenhouse effect because the primary components of landfill gas are methane and carbon dioxide. According to the IPCC, CH_4 produced at SWDS contributes approximately 3 to 4 percent to the annual global anthropogenic greenhouse gas emissions (IPCC, 2001). Therefore, landfill gas recovery has become more common process to reduce CH4 emissions from SWDS.

On the other hand, methane is considered as an alternative energy due to its high heat value. Therefore, there is strong interest in collecting landfill gas and utilizing it as a source of energy. LFG can be used directly either on-site or nearby that is simplest and most cost-effective approach. If a direct use is not practical, the gas can be used to generate electricity by using it to fuel a reciprocating engine or turbine. If the electricity is not required on site, it can be distributed through the local power grid. The gas can also be injected into a gas distribution grid. Compressed gas can be used to power refuse collection trucks that bring refuse to the landfill. Alternatively, there may be a specialized need for gas nearby, such as may be needed by a heated greenhouse. However, these are niche applications which have not been proven cost effective in developing countries (USEPA, 1996).

Waste composition and quantity are the most important factors in assessing the LFG generation potential and gas composition. Other factors which have an effect on the rate of LFG generation include moisture content; nutrient content; bacterial content; pH level; temperature; and the site-specific design and operations plans. The amount of the methane yield from a landfill area is an important decision factor on its beneficial uses. Therefore the methane potential of a landfill area should be predicted before the possible energy investments. The simplest method of estimating the gas yield from a landfill site is rough estimation assuming specific gas production rate (volume of gas/tons of waste/time). Here, assuming that each ton of waste will produce 6 m3 of landfill gas per year, LFG generation can be predicted. On the other hand, the most reliable method for estimating gas quantity is to drill test wells and measure the gas collected from these wells. To be effective, the wells must be placed in representative locations within the site and the numbers should be sufficient to predict landfill gas quantity considering the landfill size and waste homogeneity. Although test wells provide real data on the site's gas production rate at a particular time, models of gas production predict gas generation during the site filling period and after closure. These, models typically require the period of land filling, the amount of waste in place, and the types of waste in place as the minimum data.

There are numerous mathematical models available to calculate LFG production. The results of models can be used to assess the potential for LFG emissions/migration, and for assessing the feasibility of the LFG management project. LFG models predict the gas generation over time. The total gas yield and rate at which the gases are generated can vary somewhat with the different models. However, the most important input parameter for all models is the quantity of decomposable waste, i.e. organic wastes. The other input parameters can differ depending on the model used. Those parameters are influenced by uncertainties in the available information for the site, and how the management of LFG extraction affects LFG generation by inducing any air infiltration.

In the content of the thesis, as initial steps; the general properties of MSW are introduced. Then, various LFG mathematical models namely LandGEM, Multiphase, Tabasaran-Rettenberg and Scholl-Canyon, used for LFG generation are introduced and model parameters are explained. Following to models explanation, LFG capacity is determined by using those models for the landfill site in Izmir city, as a case study. The landfill site has 90 ha of area and has been operated since 1992. The closure time is declared as the end of 2014. In order to determine the energy potential of the site, composition and characteristics of Izmir MSW is used to calculation of the model variables of k and L_0. Then the models are run, whit obtained variables and the results are compared and discussed.

Thus, the LFG and CH_4 capacity of the landfill site is presented and it is seen that LFG production will continue until the end of 2050. The energy content of the methane is also calculated and availability of an energy investment is discussed in this framework.

CHAPTER TWO
LITERATURE REVIEW

2.1 Municipal Solid Wastes

Solid wastes contain all the wastes arising from anthropogenic activities which are normally solid, and are discarded as useless or unwanted. Municipal solid waste (MSW) mainly consists of:

i. Food wastes, commonly called garbage, originate from food products of animal and vegetable origin, arising beyond preparation, processing, handling, catering, and eating.

ii. Rubbish is combustible and non-combustible rejected materials other than those mentioned above. The combustible portion (trash) consists of paper, cardboard, textiles, plastics, rubber, etc. The non-combustible portion consists of glass, ceramics, metals, etc.

iii. Ashes and cinders originate mainly from coal, firewood, and burnt residues of other combustible materials.

iv. Construction and demolition wastes include wide varieties of materials, mostly non-combustible in nature. Civil works of construction, repair works and demolition of building structures and others that include broken pieces of bricks, stones, plasters, dirt, sand, wooden articles, metal pieces, electrical parts, etc.

v. Water treatment plant wastes are obtained from the water treatment plants in solid or semisolid form, such as resins, organic waste, inorganic waste, etc.

vi. Special wastes are uncommon materials accumulated from unpredictable and infrequent sources, i.e., abandoned vehicles, dead animals, limbs, blood, etc.

from hospitals; and that found from street sweepings (Nag and Vizayakumar, 2005).

2.1.1 Sources of Municipal Solid Wastes

Municipal Solid Wastes can be classified depending on sources. The sources of solid waste include residential-household (domestic), commercial, institutional, and industrial activities.

Households: Residential waste or domestic waste is generated from households. It must be discerned from municipal solid wastes collected by the municipal collection systems. Household wastes consist of paper and cardboard, glass, plastics, organic fractions, hazardous waste and bulky wastes.

Commercial establishments: It includes waste from shops and other service providers (restaurants, etc.) and it is essentially composed of packaging waste and organic waste from markets and restaurants.

Institutions (schools, hospitals and government offices): Institutional wastes include wastes from public and private offices and institutions, i.e. from service sector. Quantity and the composition of the waste may not be well known. Although similar to household waste, some additional fractions of paper, glass and plastics can be included. Medical hazardous waste from hospitals should qualify for consideration, but it will not be considered throughout these guidelines.

Industries: Waste from industrial facilities, including related functions like canteens, administration, etc. are considered as industrial wastes. hazardous waste that has to be collected and treated separately are excluded from industrial wastes.(D. O. F. Waste, Of, & Waste, n.d.)

2.1.2 Composition (Characteristics) of MSW

Composition is the term used to describe the components of the municipal solid waste, that make up a solid waste stream and their relative distribution, usually based on percent by weight. Composition of MSW depends on many factors, like geography, population social and economic factors, climate etc.. Information on the composition of solid wastes is important in evaluating equipment needs, systems, and management programs and plans. If the solid wastes generated at a commercial facility consist of only metal base package martial products, the use of special processing equipment, such as tamper and magnetic separation process, may be appropriate. Separate collection may also be considered if the city or collection agency is involved in a package material recycling program. (Tchobanoglous, 1993)

Determination of the MSW composition is the first step of the MSW management practices. In Table 2.1, typical composition of municipal solid wastes generated at various countries is presented. As can be seen from Table 2.1, organic portion of MSW changes between 25% and 80 that ultimately result with great variations in LFG potential. Distribution of MSW components for Turkey is also given in Table 2-2. The residential and commercial portion makes up about 50 to 75 percent of the total MSW generated in a community. The wide variation in the special wastes category (3 to 12 percent) is due to the fact that in many communities yard wastes are collected separately. The percentage of construction and demolition wastes varies widely depending on the part of the country and the general health of the local, state, and national economy. (Tchobanoglous, 1993)

Table 2.1 MSW compositions of certain countries. (Akinci, 2012)

Country	**Organic**	**Paper and paperboard**	**Textile / Leather, etc.**	**Plastic**	**Metal**	**Glass**	**Inert and Other**	**References**
Turkey (Istanbul	60.8	10.1	3.2	3.1	1.4	0.7	20.7	Orbit (2008)
Italy	31	24	5.5	11	4	8	16.5	Calabro (2009)
Greece	41	23	6	13	4	3	10	Koifodimos and Samaras (2002)
Germany	30	24	4	13	1	10	18	Muhle et al. (2010)
UK	38	18	3	7	8	7	19	Muhle et al. (2010)
USA	25.3	32.7	-	12.1	8.2	5.3	16.4	USEPA (2008)
Japan	26	46	-	9	8	7	12	Shekdar (2009)
China	35.8	3.7	-	2.8	0.3	2	47.5	Shekdar (2009)
India	42	6	4	4	2	2	40	Shekdar (2009)
Nepal	80	7	-	2.5	0.5	3	7	Shekdar (2009)
Indonesia	74	10	2	8	2	2	2	Shekdar (2009)
Singapore	44.4	28.3	-	11.8	4.8	4.1	6.6	Shekdar (2009)
South Korea	25	26	29	7	9	4	-	Shekdar (2009)

Table 2.2 MSW composition of certain cities in Turkey. (Akinci, 2012)

City of Turkey	Region	Organic	Paper and paperboard	Textile , etc.	Plastic	Metal	Glass	Inert and Other	Season	References
İstanbul	Marmara	50.2	13.3	5.6	14.4	1.6	5.8	9.1	Yearly around	Kanat (2010)
İzmir	Aegean	46	12	-	12	3	4	23	Unknown	Metin et al. (2003)
Denizli	Aegean	42	12	3	17.5	1.5	4	20	Unknown	Agdag (2009)
Bursa	Marmara	53.1	18.4	-	11.6	3	3.4	10.5	Unknown	Metin et al. (2003)
Kocaeli	Marmara	38.4	11.5	17.2	14.3	1.5	3.3	22.8	Winter	Yay et al. (2011)
Kocaeli	Marmara	43.8	13.3	19.6	16.1	1.3	3.6	2.3	Summer	Kahraman et al. (2011)
Antalya	Mediterranean	55.9	15.7	4.9	11.3	0.7	8.1	3.4	Winter	Yılmaz et al. (2011)
Antalya	Mediterranean	50.8	17.7	7.1	12	1.5	9.6	0.3	Summer	Yılmaz et al. (2011)
Sakarya	Marmara	48	8	1	11	2	3	27	Winter	Yay et al. (2011)
Eskişehir	Central Anatolia	67	10.1	-	5.6	1.3	2.5	13.5	Unknown	Banar et al. (2009)
Bolu	Blacksea	40	6	-	19	2	15	18	Unknown	Kose et al. (2011)
Erzurum	Eastern Anatolia	48	9	-	11	3	3	26	Unknown	Atabarut and Edgu (2005)
Şanlıurfa	Southeastern Anatolia	80	6	-	3	1	2	8	Yearly around	Yılmaz et al. (2003)

Table 2.2 MSW composition of certain cities in Turkey. (Akinci, 2012) (Continue)

City of Turkey	**Region**	**Organic**	**Paper and paperboard**	**Textile , etc.**	**Plastic**	**Metal**	**Glass**	**Inert and Other**	**Season**	**References**
Gümüşhane	Blacksea	20.3	6.6	0.3	4.6	0.6	3.1	64.5	Winter	Nas and Bayram (2008)
Gümüşhane	Blacksea	40	12.8	1	11	1.7	4.3	29.2	Summer	Nas and Bayram (2008)
Gaziantep	Southeastern Anatolia	49	9	2	12	1	5	22	Unknown	Aydogan et al. (2011)

Numerous factors have an influence on the composition and characteristics of solid waste. These factors can be classified as physical, chemical, and biological properties.

2.1.2.1 Physical Properties of MSW

Specific Weight: Specific weight is defined as the weight of a material per unit volume. Because the specific weight of MSW is often reported as loose, as found in containers, uncompacted/ compacted, and the like, the basis used for the reported values should always be noted. Specific weight data are often needed to assess the total mass and volume of waste that must be managed. (Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

The specific weights of solid wastes change with location, season of the year, and length of time in storage. Municipal solid wastes as delivered in compaction vehicles have been found to vary from 180 to 420 kg/m3; a typical value is 300 kg/m3. (Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

Moisture Content: The moisture in a sample is expressed as a percentage and defined as wet weight basis. The overall moisture content of solid waste as received at a landfill ranges typically from a low of 15 to 20 per cent to a high of 30 to 40 per cent on a wet weight basis. Typical average moisture content is 25 per cent.

Particle Size and Size Distribution: The size and size distribution is important features for recovery of materials, especially for mechanical separation, like trammel screens and magnetic separators. (Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

On the other hand particle size and size distribution characteristics are important to packed bed design for good performance, as break predictable flow rates and adequate surface area of the particulate bed are highly desirable for optimal treatment.

Field Capacity: Field capacity is the moisture content that the waste can "hold" under the influence of gravity. The field capacity is important parameter for the determining the formation of leachate in landfills. "*The field capacity of solid waste is the total amount of moisture that can be retained in a waste sample subject to the downward pull of gravity." (Tchobanoglous,1993)* Water in surplus of the field capacity will be released as leachate. The field capacity change to the degree of applied pressure and corresponds to 75 cm / 250 cm. The field capacity of uncompacted mixed house hold solid wastes is in the range of 50 to 60 percent.

Permeability of Compacted Waste: Hydraulic conductivity is a property of vascular plants, soil or rock that describes the ease with which water can move through pore spaces or fractures. Saturated hydraulic conductivity, describes water movement through saturated media. The hydraulic conductivity of compacted wastes is an important physical property for the movement of liquids and gases in a landfill. (Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

2.1.2.2 Chemical Properties of MSW

Information on the chemical composition of the MSW is important in determining alternative processing and recovery options. Typically, solid wastes can be thought of as a combination of semi moist combustible and noncombustible materials. If solid wastes are to be used as fuel, the four most important properties to be known are:

1. Proximate analysis
2. Fusing point of ash
3. Ultimate analysis (major elements)
4. Energy content

Where the organic fraction of MSW is to be composted or is to be used as feedstock for the production of other biological conversion products.

Elemental Analysis : Elemental analysis contain carbon, hydrogen, oxygen, nitrogen, sulphur, and ash contents as per cent to characterize the chemical composition of waste material. Elemental analysis results are useful information to describe the proper mixture of waste materials to achieve suitable C/N ratios for biological conversion processes. Table 2.3. presents the elemental analysis results of residential municipal solid wastes.

Table 2.3 Typical data on the elemental analysis of the combustible components in residential MSW. (Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

Component	**% weight (dry basis)**					
	Carbon	**Nitrogen**	**Hydrogen**	**Oxygen**	**Sulfur**	**Ash**
Organic						
Food wastes	48.0	2.6	6.4	37.6	0.4	5.0
Paperboard	44.0	0.3	5.9	44.6	0.2	5.0
Paper	43.5	0.3	6.0	44.0	0.2	6.0
Yard wastes	47.8	3.4	6.0	38.0	0.3	4.5
Wood	49.5	0.2	6.0	42.7	0.1	1.5
Textile	55.0	4.6	6.6	31.2	0.15	2.5
Leather	60.0	10.0	8.0	11.6	0.4	10.0
Textile	55.0	4.6	6.6	31.2	0.15	2.5
Rubber	78.0	2.0	10.0			10.0
Inorganic						
Glass	0.5	< 0.1	0.1	0.4		98.9
Metals	4.5	< 0.1	0.6	4.3		90.5
Dirt, ash, etc.	26.3	0.5	3.0	2.0	0.2	68.0

2.1.2.3 Biological Properties of MSW

Since organic components can be converted biologically to gases and relatively inert organic and inorganic solids, organic fraction and biological degradability of MSW is crucial factor.

Organic (Volatile Solids) content is the MSW determined by ignitions at 550 °C. This method often used as a measure of the biodegradability of organic fraction of MSW. But some of the organic elements of MSW are highly volatile but low in biodegradability (e.g., newsprint and certain plant trimmings). In this case, lignin content of the waste can be used as alternative. “BF” is used to estimate the biodegradable fraction, using fallowing equation: (Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

$$BF = 0.83 - 0.028\ LC \tag{2-1}$$

BF = biodegradable fraction expressed on a volatile solids (VS) basis
0.83 = empirical constant
0.028 = empirical constant
LC = lignin content of the VS expressed as a percent of dry weight

Lignin content of MSW elements are shown in Table 2-4. The principal organic waste in MSW is often classified as rapidly or slowly decomposable.

Table 2.4 Data on the biodegradable fraction of selected organic waste components based on lignin content. (Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

Volatile solids (VS), Component percent of total solids (TS)		**Lignin content (LC), percent of VS**	**Biodegradable fraction (BF)**
Food waste	7-15	0.4	0.82
Paper	-	-	-
Newsprint	94.0	21.9	0.22
Office paper	96.4	0.4	0.82
CardBoard	94.0	12.9	0.47
Yard waste	50-90	4.1	0.72

Table 2.5 BF values for each type of Organic MSW. (Machado, Carvalho, Gourc, Vilar, & do Nascimento, 2009)

Food Waste	**Paper**	**Cardboard**	**Wood**	**Garden Waste**	**Textiles**	**Adapted From**
0.58	0.44	0.38	0.61	0.45	0.40	Tchobanoglous et al. (1993) and Bonori et al. (2001)
0.70	0.19 0.56	0.39	0.14	0.70 0.34	-	Barlaz et al. (1997)
-	0.30 0.40	0.44	0.30 0.33	0.20 0.51	0.17 0.25	Harries et al. (2001)
0.64	0.40	0.41	0.17	0.35	0.32	Lobo (2003) adopted

2.2 Landfill of Municipal Solid Wastes

2.2.1 General

Landfills are well engineered plant that mast be designed, located, operated, and monitored to ensure compliance with according to regulations and engineering principles. Solid waste landfills must be designed to protect the environment from hazardous affect from solid and semi-solid contaminant. The landfill sitting plan which prevents the sitting of landfills in environmentally sensitive areas as well as on site environmental monitoring systems groundwater contamination and for landfill gas provides additional safeguards. In addition, many new landfills collect potentially harmful landfill gas emissions and convert the gas into energy in developed country.

Turkey consists of at currently 3129 municipalities. Approximately 25,000 thousand tones solid waste are collected by the year of 2008. There are 37 controlled landfills, 4 composting plants, and 2 incineration plants which are actively operated. (TurkStat, 2009). Therefore, approximately 10,000 thousand tons of municipal solid wastes are collected and dumped in the controlled sites which means 58% of the municipal solid wastes generated in Turkey is not under control (wild dump side).(Akinci et al., 2012). Leachate causes ground and underground water pollution and uncontrolled landfill gases emissions cause air pollution and aesthetic pollution. Because of solid wastes are disposed uncontrolled dumping and open dump side. Under such circumstances Turkey needs to be immediately regional and national waste management plan and provide its sustainability. It should not be forgotten land filling technology is the most economical and environmentally acceptable method of the world, due to these reason landfill is the most important elements of the waste management plan.

2.2.2 Landfilling

Landfills are the dumping sites for the solid wastes. Landfill is designed and operated to minimize environmental impacts and public health. Landfills for the disposal of hazardous wastes are called secure landfills. Wild dumps sides do not identified as a solid waste management unit and must be immediately rehabilitated and covered. Landfilling includes monitoring of the incoming waste stream, placement and compaction of the waste and installation of landfill environmental monitoring and control facilities.

Solid wastes are dumped in a cell (see Figure 2.1) and the covered daily by soil. Native soil or alternative materials (like compost) are applied 15 to 30 cm material that to the working faces of the landfill at the end of the operation period (usually one day).(Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993)) The aim of daily cover are to control the blowing of waste materials, to prevent rats, flies, to control the entry of water into the landfill during operation.

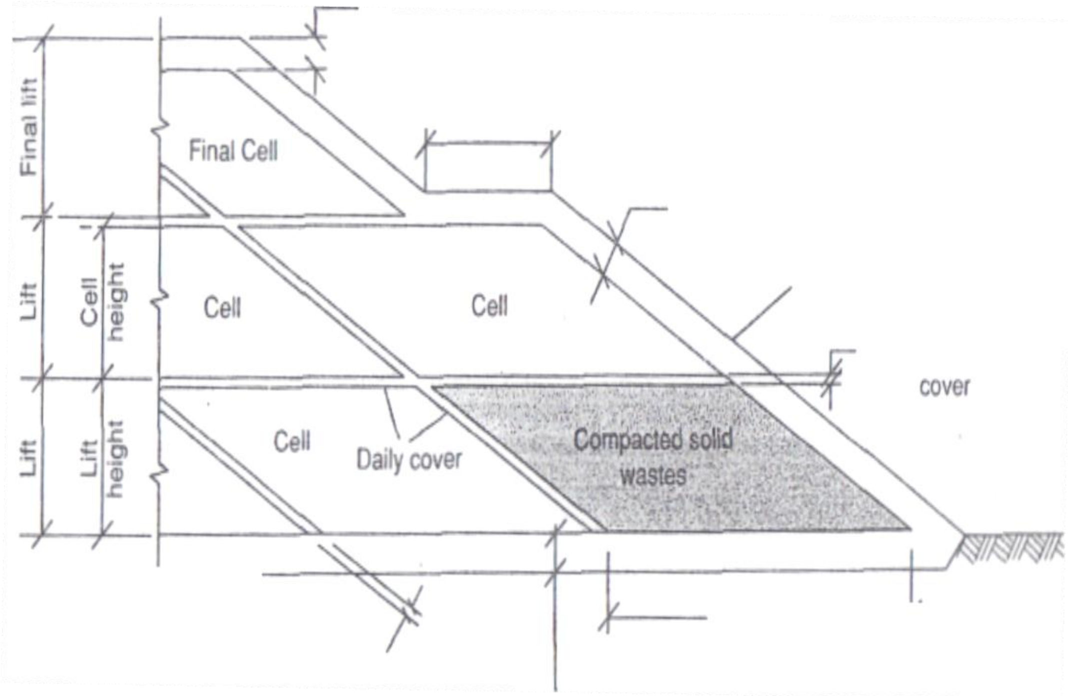


Figure 2.1 Sectional view through a landfill (Tchobanoglou, Theisen, & Vigil, 1993)

A lift is a complete layer of cells over the active area of the landfill (see Fig. 2.1). Typically, landfills are comprised of a series of lifts. Terrace is commonly used where the height 15-20 m of the landfill. Terraces are used to maintain the slope stability of the landfill, for the placement of surface water drainage channels, site road, and for the location of landfill gas recovery piping. The final cover layer is constructed after the all land filling operations are completed. The final cover consisting of multiple layers is protected environmental for the hazardous effect of landfills such as landfill gases, blowing of waste materials, to prevent rats, flies and that is protected against to external factor for landfills (rainfalls, wild animals, etc.).(Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993)) The layers are consisted of soil layer geo-membrane and geotextile layer, clay layer (drainage layer), vegetation for slop protection and are designed to enhance surface drainage, intercept percolating water. (Fig 2.2)

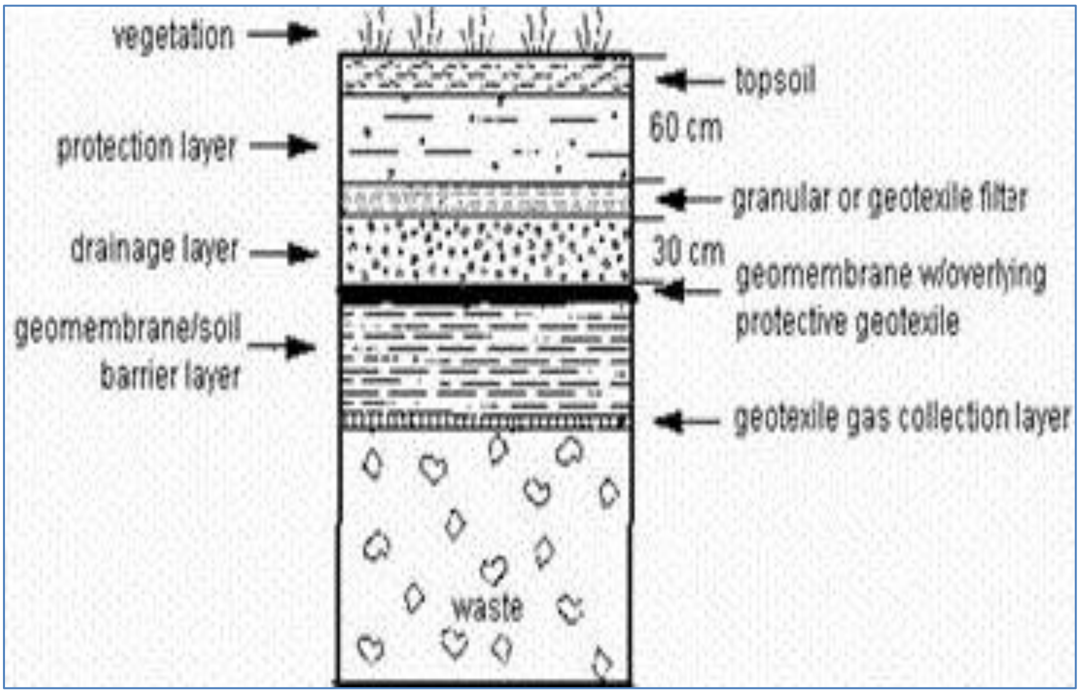


Figure 2.2 Final layer of Landfill.(EUGRIS:portal for soil and water management in Europ http://www.eugris.info/index.asp)

“Landfills may produce leachate that has elevated concentrations of contaminants, such as ammoniacal nitrogen, heavy metals and organic compounds. These could, if not contained and managed, affect both surface and groundwater resources. However, some non-hazardous landfills accept waste with a relatively low pollution potential, so a risk-based approach to all aspects of landfill monitoring should be taken, including the monitoring of leachate, surface water and groundwater.” Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

Landfill produce landfill gas (LFG) as result of biodegradation of organic material and some chemical reactions. The generation rate is influenced by components of waste and geometric form of the waste site, that subsequently effect the bacterial populations found in it, chemical components, thermal attributes, exposure to moisture and gas release. (Young, A.,1992). LFG generally includes around 40 - 60 percent methane and the rest is mainly carbon dioxide. LFG also include different amounts of nitrogen, oxygen, water vapors, hydrogen sulphide, and certain contaminants. Many of varying contaminants are named as "non-methane organic compounds" or NMOCs.

LFG monitoring plans is needed to knowing some specific point, that is to detect undesired conditions, e.g. Excessive extraction in the landfill body or suction in of air to create potentially explosive gas mixtures within the landfill, and to take corrective action as necessary, to identify subsurface migration of landfill gas outside the boundary of the waste mass, to determine the gas formation potential, inform decisions on future utilization or treatment of the landfill gas, optimize the gas flow rate with regard to landfill gas utilization, minimize diffuse emissions of landfill gas, document and assess the functioning and operating condition of the gas collection system.

Landfill liners are such materials (both natural and manufactured), are used to line the bottom area and below-grade sides of a landfill. Liners usually consist of layers of compacted clay and/or geomembrane material designed to prevent migration of landfill leachate and landfill gas. Landfill control point include liners, landfill leachate collection and extraction systems, landfill gas collection and extraction systems, daily and final cover layers.(Tchobanoglous, G., Theisen, H., & Vigil, S.A., (1993))

Environmental monitoring has important role in risk assessment and management strategies during the landfill operation and also be after the landfill closure. Another important issue of the environmental monitoring is before the start of landfilling constriction to determine the baseline conditions.

Important issues of landfill design and operation is landfill layout and design, landfill operations and management plan, the reactions occurring in landfills, the management and treatment of landfill gases, the management and treatment of leachate, setup environmental monitoring program, and landfill closure and post closure care. Each of the elements should be considered in greater detail in landfill operation plan. (Fig 2-3)

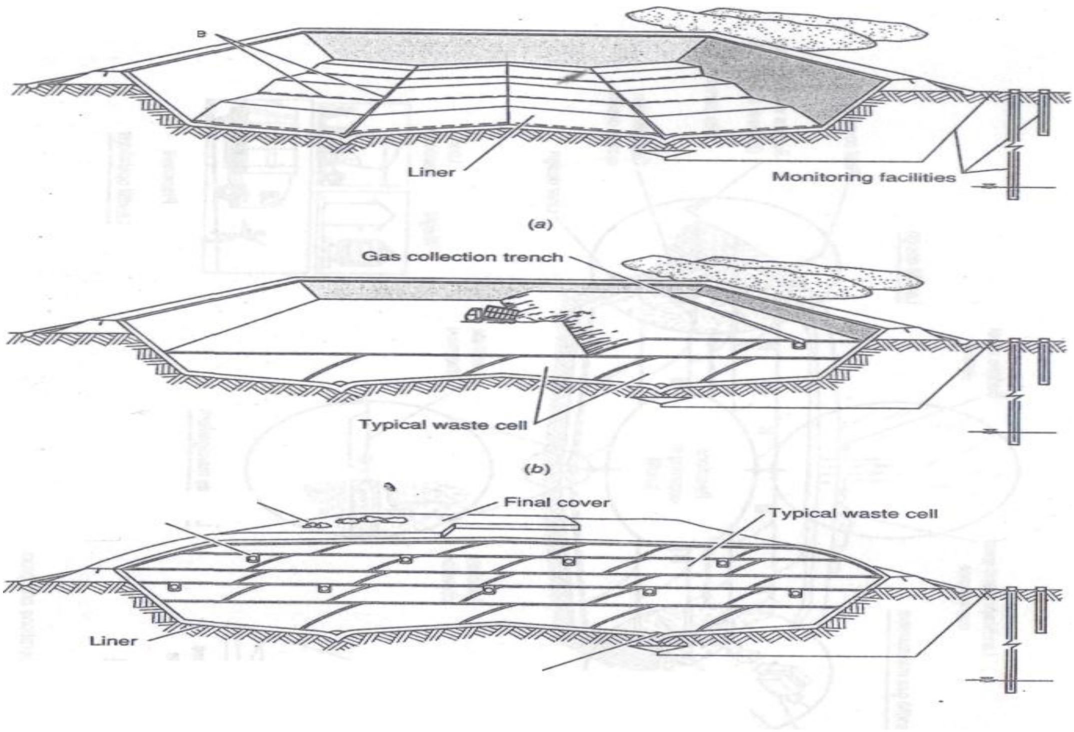


Figure 2.3 Development and completion of a solid waste landfill: (a) excavation and installation of landfill liner, (b) placement of solid waste in landfill, and (c) cutaway through completed landfill.

2.2.3 Reaction in Landfill

Landfill gases and the leachate produced from landfills resulting, biochemical reactions. The biological decomposition process usually proceeds aerobically for some short period immediately after deposition of the waste until the oxygen initially present is depleted. Once the available oxygen has been depleted, and the biological decomposition reactions turn to anaerobic reactions and the organic matter is converted to CO2, CH4, and trace amounts of ammonia and hydrogen sulfide. Many other chemical reactions are biologically mediated as well. Because of the number of interrelated influences, it is difficult to define the conditions that will exist in any landfill or portion of a landfill at any stated time (Tchobanoglous, G., Theisen, H., & Vigil, S.A.,1993)

2.2.4 Properties of LFG

2.2.4.1 Main Components And Their Properties of LFG

Landfill gas is composed of a mixture of different gases, either derived from the decomposition of the waste or gases included in the waste (e.g. aerosol propellants and contents). LFG typically contains 45% to 60% methane and 40% to 60% carbon dioxide percentage of volume. LFG also includes small amounts of nitrogen, oxygen, ammonia, sulphides, hydrogen, carbon monoxide, and non-methane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride. Typical landfill gases, their percent by volume, and their characteristics are listed in Table 2.6

Table 2.6 Typical Landfill Gases and Their Characteristics (Tchobanoglous, Theisen, and Vigil 1993)

Component	Characteristics	Volume in Total LFG [%]
Carbon dioxide	Carbon dioxide is naturally found at small concentrations in the atmosphere (~0.03%). It is colourless, odourless, and slightly acidic.	40–60
Methane	Methane is a naturally occurring gas. It is colourless and odourless. Landfills represent major contributors of methane to the atmosphere.	45–60
Oxygen	Oxygen comprises approximately 21% of the atmosphere. It is odourless, tasteless, and colourless.	0.1–1
Carbon monoxide	Carbon monoxide is an odourless, colourless gas.	0–0.2
Nitrogen	Nitrogen comprises approximately 79% of the atmosphere. It is odourless, tasteless, and colourless.	2–5
Ammonia	Ammonia is a colourless gas with a pungent odour.	0.1–1
Sulphides	Sulphides (e.g., hydrogen sulphide, dimethyl sulphide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulphides can cause unpleasant odours even at very low concentrations.	0–1
Hydrogen	Hydrogen is an odourless, colourless gas.	0–0.2
NMOCs (non-methane organic compounds)	NMOCs are organic compounds (i.e. compounds that contain carbon. Methane is an organic compound but is not considered an NMOC). NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis dichloroethylene, dichloromethane, carbonyl sulphide, ethyl-benzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.	0.01–0.6

2.2.4.2 Dependency Of Landfill Gas Formation

Three processes; bacterial decomposition, volatilization and chemical reactions convert the biodegradable material present in municipal solid waste into landfill gases;

Bacterial decomposition: Landfill gases are mostly generated by bacterial decomposition. Bacteria came from solid waste and environment broke down the organic wastes. Organic wastes including food, garden waste, street sweepings, wood and paper products are decomposed at four phases, and the composition of the landfill gas changes during each phase.

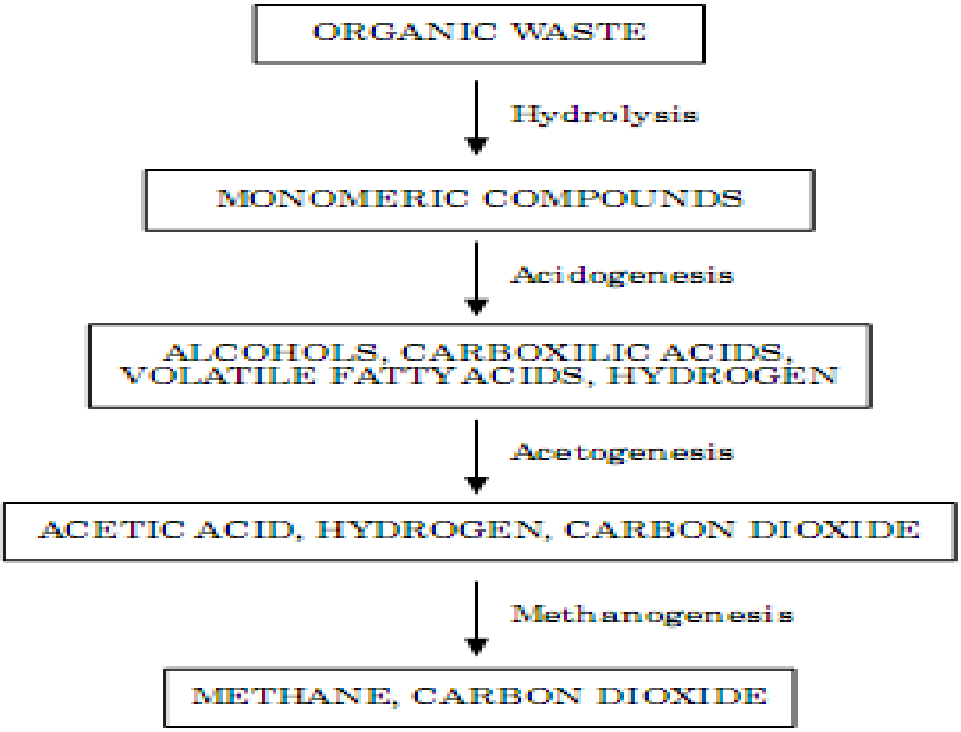


Figure 2.4 Major degradation steps during the anaerobic decomposition phase

Landfills operate over a 20 to 30 year period, during the waste in placing occur different age of wastes in landfill that causes several phases of decomposition at once. An understanding of the time course of landfill gas formation is important to the assessment of monitoring data during operation period. Studies have shown that the stabilization of waste proceeds in five sequential and distinct phases.

The time period of each phase depends on several factors such as the distribution of organic components in the landfill, inputs of nutrients, the moisture content of the waste, the migration of moisture throughout the landfill, waste density and the removal of degradation products such as leachate and gas.

Phase I - Initial Adjustment Phase: Phase I is characterized by rapid breakdown of complex organics in the presence of water and oxygen into simple sugars – often termed hydrolysis. Some components, such as lignin, are only effectively broken down during this phase. This phase is characterized by the depletion of O2 and N2 due to the production of large quantities of CO2. Since only a finite quantity of oxygen is buried within the waste, and there are limitations on air transport into the landfill, aerobic decomposition is responsible for only a small portion of biodegradation within the landfill. It is accompanied by a dramatic drop in redox potential and increase in leachate ionic strength. The large release of energy is also reflected by a rapid rise in landfill temperature.

Phase II - Transition Phase: In the transition phase, the field oxygen capacity is often exceeded, and a transformation from an aerobic to an anaerobic environment occurs, as evidenced by the depletion of oxygen trapped within the landfill media. A trend toward reducing conditions is established in accordance with shifting of electron acceptors from oxygen to nitrates and sulfates, and the displacement of oxygen by carbon dioxide. By the end of this phase, measurable concentrations of COD and volatile organic acids (VOA) can be detected in the leachate.

Phase III - Acid Formation Phase: The continuous hydrolysis of solid waste, followed by the microbial conversion of biodegradable organic matter results in the production of intermediate VOAs, ammonia, hydrogen, and CO2 at high concentrations throughout this phase. Acid phase anaerobic biodegradation processes are carried out by a mixed anaerobic population, composed of strict and facultative anaerobes. Facultative anaerobes aid in the breakdown of materials and reduce the redox potential so that methanogenic bacteria can grow. A decrease in pH values is often observed, and is accompanied by metal species mobilization resulting in a chemically aggressive leachate. The highest concentrations of BOD, COD, and specific conductance occur during the acid formation phase. *"Viable biomass growth associated with the acid formers (acidogenic bacteria), and rapid consumption of substrate and nutrients are the predominant features of this phase."*

Phase IV - Methane Fermentation Phase: During Phase IV, intermediate acids are consumed by methane-forming consortia and converted into methane and carbon dioxide. Reducing conditions corresponding to this phase will influence the solubility of inorganics, resulting in precipitation or dissolution of these constituents. For example, sulfate and nitrate are reduced to sulfides and ammonia, respectively. COD and BOD concentrations decline since much of these materials are converted to gas. A small portion of the original refuse organic content (e.g. lignin-type aromatic compounds) is not degraded to any extent anaerobically and remains in the landfill material. The pH level consequently supports the growth of methanogenic archaic. Heavy metals are removed by compellation and precipitation. Methanogens work relatively slowly but efficiently over many years decomposing any remaining degradable organics.

Phase V - Maturation Phase: Once available organic matter is degraded CO2 and CH4 production ceases and air diffuses back into the landfill. Since available substrates become limiting the biological activity shifts to relative dormancy. However, the slow degradation of resistant organic fractions may continue with the production of humic-like substances. In a landfill, like a bioreactor, enhanced physical, chemical, and biological processes take place to transform and stabilize the readily and moderately decomposable organic waste constituents within few years up to more than thirty years. Solid waste and water are the major inputs, landfill gas and leachate are the principal outputs of that bioreactor.

Volatilization: LFG may be generated by waste material, especially the organic compounds and change phases e.g. from solid to liquid, from liquid to vapor. The process is called volatilization. NMOCs present in LFG could be the result of volatilization of particular chemicals that are present in the site.

Chemical reactions: Certain chemicals present in landfill can create to NMOCs in the LFG by chemical reaction. For example, if chlorine bleach and ammonia come in contact with each other within the landfill, a harmful gas is produced.

2.2.4.3 Factors Affecting Landfill Gas Production

The rate and volume of landfill gas produced at a specific site depend on the characteristics of the waste and a number of environmental factors which are outlined below.

Waste composition: The LFG is produced by the bacteria during decomposition, and mainly affected from quantity of organic waste present in a landfill. Organic waste contains nutrients, such as sodium, potassium, calcium, and magnesium, which help to growing of microorganisms and has an effect on LFG production. Some wastes contain hazardous compounds that harm bacteria and causing less LFG production. High salt concentration in the landfill can inhibited methanogen bacteria. The more chemicals disposed of in the landfill, the more likely NMOCs and other gases will be produced either through volatilization or chemical reactions.

Age of waste: In general, the waste that is buried at a recent time (for waste buried more recent than 10 years) generates more LFG in comparison to more aged waste (more than 10) via decomposition, volatilization and chemical reactions. Gas generation reaches its highest levels commonly after 5 to 7 years. Almost the whole gas quantity is generated in 20 years after waste is buried in the site; however, gas may be generated albeit in smaller volumes. A prediction in a low-methane scenario (the waste is dry), however, estimates that there will be methane generation for 5 years and will efficiently continue gas emission over a 40-year period. Although the generation of gas will most likely continue, the generation rate will decrease in time. "In the same landfill have different portions and might be in different LFG production phases of the decomposition process at the same time, depending on when the waste was originally placed in each area. The proportion of organic material in the waste is an important factor in how long significant gas production lasts." (www.worldbank.com)

Presence of oxygen in the landfill: Only when oxygen is used up will bacteria begin to produce methane. The more oxygen present in a landfill, the longer aerobic bacteria can decompose waste in Phase I. If waste is loosely buried or frequently disturbed, more oxygen is available, so that oxygen-dependent bacteria live longer and produce carbon dioxide and water for longer periods. If the waste is highly compacted, however, methane production will begin earlier as the aerobic bacteria are replaced by methane-producing anaerobic bacteria in Phase III. Barometric highs will tend to introduce atmospheric oxygen into surface soils in shallow portions of an uncapped landfill possibly altering bacterial activity. In this scenario, waste in Phase IV, for example, might briefly revert to Phase I until all the oxygen is used up again.

Moisture content: The presence of water in a landfill increases gas production. Moisture has a positive effect on growth of bacteria and transports nutrients and bacteria to all areas in a landfill. Maximum gas productions are obtained when moisture content rich 40% percentage or higher, based on wet weight of waste. Waste compaction cause increases the density of the waste in landfill decreasing the rate at which water can infiltrate the waste. If the LFG production rate is higher, than heavy rainfall passing through and/or additional water into landfill permeable cover.

Temperature: Bacterial activities tend to increase in higher temperatures and resulted with increased generation rates. Bacterial activity decreases significantly at below 10°C. Especially the generation of gas in slow landfills is influenced greatly to changes in weather. The bacteria are more insulated in terms of changes in temperature in deep landfill sites where soil covers up the waste with a thick dirt level. In an optimized site in terms of operation and closure, the temperature is stable and gas generation is at maximum. The temperature to stabilize the site is between 25°C and 45°C but temperatures up to 70°C may be witnessed because at the end of a bacterial activity, heat is dissipated. Increases in temperature also is a supporting element for volatilization and chemical reactions. As a rule of thumb, NMOC emission is doubled for every 10°C temperature increase.

2.2.4.4 The Migration Of Landfill Gases

The LFG has a tendency to dissipate through the surface once it is generated in the site. LFG "migrate" or move via the pore spaces and soil available on the surface by the pressure of itself as it is produced. Normally air is heavier than gases generated so methane generated may migrate to surface. LFG movement towards the surface is limited by dense waste or landfill cover elements (e.g., by daily or intermediate soil cover and engineered final closure caps). Movement to the surface is unique; the gas migrates to the different parts of the site or other areas that are not in the landfill in order to continue its movement to the surface. Mainly, gases pursue the least resistive layers to reach the surface. Other gases, like carbon dioxide, are heavier than air and will gather in areas just beneath the surface and if it is gathered in manholes or other underground vents may endanger the personnel on the site. Three main influencers for gas migration are described below;

Diffusion (concentration): Diffusion is the gas natural inclination to achieve a uniform concentration at a space, it may be a room or the atmosphere. Gases present in the waste site migrate from places of high concentration to places with low concentration in gas. The concentration of gas is relatively higher compared to the neighboring areas, gases tend to move to spaces that is low in gas concentration.

Pressure: Gases gathered in landfill sites generate high pressured areas, where the movement of gas is limited by waste or dirt layers and some areas are formed low in pressure where the movement of gas is not limited. These changes in pressure in all landfill site causes the gases to migrate from spaces of high pressure to spaces of low pressure. This movement is called convection. When landfill pressure exceeds the indoor air pressure or atmospheric pressure, the gases migrate to spaces of lower pressure.

Permeability: Gases will migrate through the spaces offering least resistance. Permeability measures the movement of gas or liquids in connected spaces or beneath soil. Dry, sandy soils offer more space therefore permeability is high, (many connected pore spaces), while moist clay show more resistance (fewer connected pore spaces). Gases incline to migrate through highly permeable spaces (e.g., areas of sand or gravel) rather than through lowly permeable spaces (e.g., clay or silt). Landfill covers are generally formed of soils that have low permeability, like clay. Gases present in a covered site will be more inclined to migrate in horizontal movement rather than vertical movement.

Furthermore, LFG migration is based on different elements such as the inclination, speed, and proximity. These elements are detailed below:

Landfill cover type: *"If the landfill cover consists of relatively permeable material, such as gravel or sand, then gas will likely migrate up through the landfill cover. If the landfill cover consists of silts and clays, it is not very permeable; gas will then tend to migrate horizontally underground."* (www.worldbank.com) Gas migrates through the more permeable area. Geo-membrane caps have very low (but still finite) gas permeability, but they are susceptible to puncture damage (usually during construction) and may therefore have very small areas of very high effective permeability. It is for this reason that the vegetation cover of closed and restored landfills and dumpsites should be periodically inspected for vegetative distress as the escaping landfill gas displaces the oxygen in the root zone, leading to vegetative dieback.

Natural and man-made pathways: Trenches, drains, and LFG collection pipelines may act as conduits for gas movement. The natural geology of landfill area often generate underground pathways, for instance fractured rock, and buried stream channels, porous soil, where the gas can migrate.

Wind speed and direction: Landfill gas rich the landfill surface is carried and dispersed by the wind in to the air. Wind speed and direction determine the gas's concentration in the air, which can vary greatly from day to day, even hour by hour.

Temperature: Increases in temperature increases gas particle movement and increase gas diffusion. Warmer conditions accelerate the landfill gas spread in the air. Although the landfill, itself generally maintains a stable temperature, freezing and thawing cycles can cause the soil's surface to crack, causing landfill gas to migrate upward or horizontally.

Groundwater levels: LFG movement is affected by variations in the groundwater layer. If the water layer level is rising into an area, it will force the landfill gas upward. Wet surface soil conditions may prevent landfill gas from venting through the top of an uncapped (or temporarily capped) landfill into the air above. Rain and moisture may also seep into the pore spaces in the landfill and "push out" gases in these spaces.

2.3 LFG Generation

This chapter contain main subject of this thesis, subject is focused of the LFG generation, potential impact of LFG, LFG production and affecting factors, determination of LFG quantity and quality, kinetic and modeling studies, LFG collection, LFG utilization, and best management practices of LFG projects.

2.3.1 Potential Impacts of LFG

When municipal solid waste (MSW) is dumping in a Landfill side, most of the organic material will be degraded different time period (Shorter Longer and moderate), degradation all waste in landfill take a long time from less than one year to 100 years or more. Terms of this process is called bio-degradation. Strongly depending on conditions in the dumping site or landfill where the MSW is disposed, this biodegradation will be anaerobic or aerobic depends on the dumping side operation conditions. Organic waste is degraded two different type of the degradation processes one of the aerobic degradation, that is main products are carbon dioxide (CO_2), water and heat, and other one anaerobic degradation, that is the main products are methane (CH_4) and CO_2. While both methane and carbon dioxide are considered to be greenhouse gases (GHGs), the carbon dioxide present in LFG is generally not considered to be a GHG. Rather, it is considered to be "biogenic" and therefore a natural part of the carbon cycle. The methane present in LFG is considered to be a GHG, however, and thus its collection and combustion results in a net GHG reduction.

The process of collection and combustion of LFG (e.g., in an engine generator, turbine, utility flare, or other combustion device) results in a reduction of the emission of methane, VOCs and HAPs from a landfill. The combustion process, however, does result in the increased emission of criteria air pollutants such as sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter (PM) from landfills.

"The estimated global annual emissions from solid waste disposal sites (SWDS) are in the range of 20 - 40 million tons of CH4, of which the most comes from industrialized countries (Guidance , n.d, ,so-called Annex I countries of the UNFCCC). This contribution is estimated to be approximately 5-20 percent of the global anthropogenic CH4, which is equal to about 1 to 4 percent of the total anthropogenic greenhouse gas (GHG) emissions. The emissions from developing countries and countries with economies-in-transition will increase in the near future

due to increased urban population, increased specific (pro capita) municipal solid waste (MSW) generation due to improved economy and improved MSW management practices. The emissions are estimated to remain stable or decline over the next 10 - 20 years. A recent compilation of reported emissions to the UNFCCC (UNFCC, 2000) indicate emissions of 24 million tons CH4 from Annex I countries in 1990. In the year 1998 these emissions had been reduced to about 20 million tons. The reduction is due to increased recycling and alternative treatments and increasing implementation of landfill gas extraction and recovery systems." (EPA Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC/OECD/IEA)).

2.3.2 LFG Production

Landfill gases (LFGs) most important gas component is CH_4 with other through under the anaerobic conditions organic solid wastes are decomposed by methanogen bacteria. Biological decomposition in the landfill is progressed over a several decades that period is generated LFG and CH_4, usually beginning 1 to 2 years after the waste in placed. LFG is the combination of approximately 50 percent of CH_4 and 50 percent of CO_2 mixed with small quantities of other gases. If the methane is not existed in the LFG, it will escape to the atmosphere or aerobic conditions present. The production of methane process in the landfill depends on several parameters, landfill design, including waste composition, and landfill operating conditions, local climate conditions, etc. The following sections discuss the activity data and emissions factors used to develop baseline emissions. And the following chapters conclude with a discussion of modeling and result of the LFGs.

2.3.3 Determination of LFG

The most reliable method for estimating gas quantity is to drill test wells and measure the gas collected from these wells. To be effective, the wells must be placed in representative locations within the site. Individual tests are performed at each well to measure gas flow and gas quality (Polat, 2007). For measuring LFG emission rate, there is no precise method exist. Few methods used to measure emission rate, some of them are used to quantify the emission rate for small areas, while others used for large surface area (e.g. for the entire landfill). For measuring the emission from small area, some techniques are used, such as chamber method, method of subsurface vertical gradient of the concentration, while for large area measurements, micrometeorological methods, the isotope ratio technique, the trace method and infrared spectroscopy (Biszek et al., 2006).

Direct and indirect measurements techniques can be used for quantify LFG emission rate (Cernuschi and Giugliano, 1996). The direct measurement techniques involve passive sampling methods, and flux chamber methods. The passive sampling methods involve the utilization of sorbent probes in order to trap gaseous that diffuse upwards through the landfill, while flux chamber methods have been utilized to measure emission rate from typical areal sources. The indirect measurement techniques involve measurement of ambient air concentrations of pollutants around the source, these techniques are depend mainly on the accurate measurements of wind speed and direction during the techniques are depend mainly on the accurate measurements of wind speed and direction during the sampling. A comparison between different methods used for measuring CH4 emission rate from landfill sites were reported, however each technique has a unique advantages and disadvantages, and the choice will be depended on economic constraints and measurement objectives (Tregoures et al., 1999).

Rough estimation, assuming that each ton of waste will produce 6 m3 of landfill gas per year is the simplest method for gas estimation. This rough approximation method only requires knowledge of how much waste is in landfill. The waste tonnage should ideally be less than 10 years old. Estimates from this approximation should be bracketed by a range of plus or minus 50%. This rate of production can be sustained for 5 to 15 years, depending on the site (Polat, 2007).

Although test wells provide real data on the site's gas production rate at a particular time, models of gas production predict gas generation during the site filling period and after closure. These, models typically require the period of land filling, the amount of waste in place, and the types of waste in place as the minimum data.

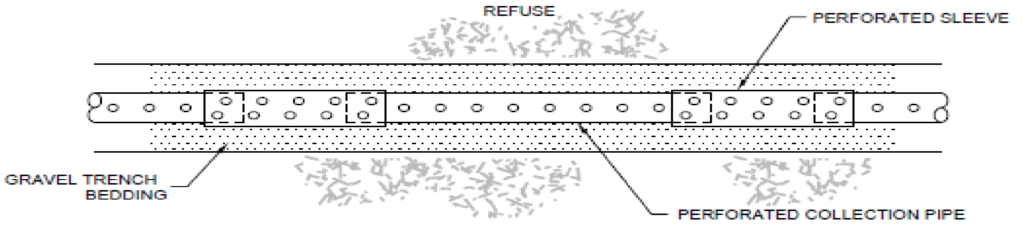
A number of LFG generation models have been developed, e.g. School Canyon Model, Palos Verdes Model, Multiphase Model, LandGEM, Tabasaran / Rettenberger Model, etc. Besides, the IPCC - Guidelines for National Greenhouse Gas Inventories methodologies are introduced to estimate anthropogenic emissions of greenhouse gases. Those models are explained in detail at Chapter 3.

2.3.4 LFG Collection

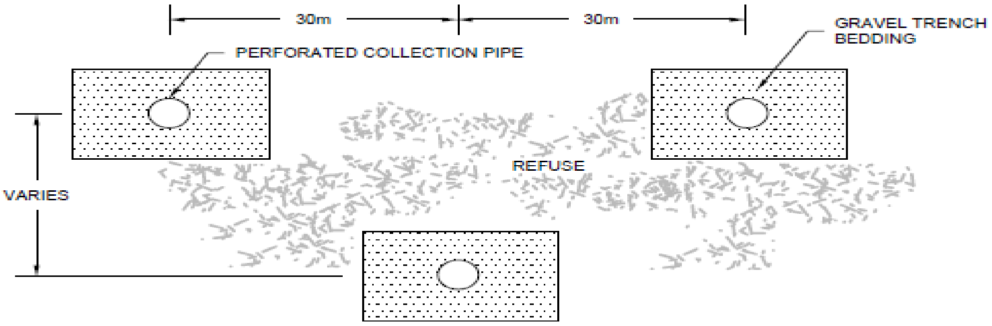
LFG Collection systems are comprehensive reference data and information regarding the proper and correct, techniques and methods to collect and flare LFG. On the other hand, a general insight of the internal and processing of the LFG collection systems is important to comprehend key elements of a LFG management project and risk factors in the management. A common LFG collection system contain following components:

- LFG collection field (wells, trenches)
- Collection piping (laterals, subheaders, headers, etc.)
- Condensate drop-out and disposal system
- Blower system and related appurtenances
- LFG flare.

"LFG management can be successfully achieved through using these components and there is potential, through the development and expansion of the international carbon market, for this type of system to generate substantial revenue through the creation of GHG emission reduction credits. Revenue provided by such a system creates an incentive for better landfill design and management, and a contribution to improve the overall waste management system." (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)



TYPICAL HORIZONTAL COLLECTION TRENCH
PROFILE VIEW



TYPICAL HORIZONTAL COLLECTION TRENCH
CROSS-SECTION

NOT TO SCALE

Figure 2.5 Shows the construction of a typical horizontal LFG extraction trench. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

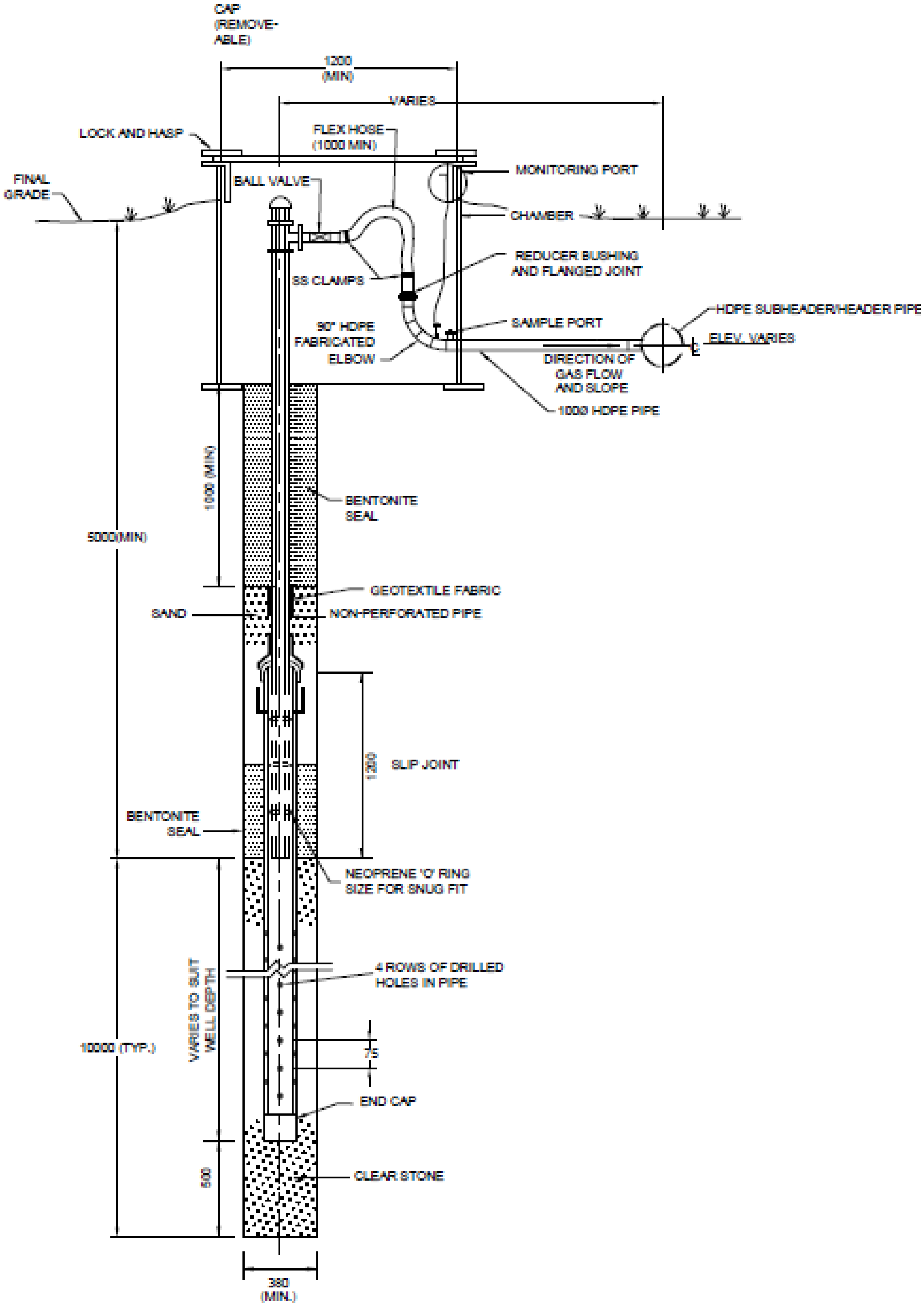


Figure 2.6 Shows the construction of a typical vertical LFG extraction well. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

2.3.4.1 LFG Collection Piping

The purpose of constructing the networks is to link the LFG collection field to the LFG flare or LFGTE plant. Common implementation of an LFG collection is described below:

- Small diameter (minimum 100 mm), short laterals that link the wells/trenches
- Subheaders which connect the laterals
- Headers connecting the subheaders to the extraction plant

Several designs of LFG networks pattern of pipes in order to make sure draining and to reduce the pattern network length within the collection systems. Herringbone and the ring header are commonly used network lay outs throughout the world. The herringbone lay out pattern consist a branching network of sub adders whit a single main header. This type of pipe networking is regarded as the most effective pipe usage method. By applying the piping network system down to the LFG wells, the accumulation of condensate can be minimized in the LFG collection network.

If there is no available land to construct the header system bordering the waste limits, the application of ring header on site may be feasible. Link headers placed off-site may reduce some of the problems faced regarding the implementation piping network into the dumped waste. In order to achieve the isolation of site partially, valves shall be placed on ring headers, also to measure gas volume and quality monitoring port shall be placed. Dual header systems have been implemented to separate the gas rich with methane from the gas that is collected near the surface that is mixed due to air intrusion on certain large and deep landfill sites with a long and active site life. Regarding the pipe network installments, there are challenges in design limitation and requirements, such as application of pipe network inclination, removing condensate moisture, calculation and differentiating settlement stresses and load stresses both dead and alive.

The relative expenditures for the piping systems collecting and transporting the LFG to the facility can vary solely depend on conditions on site and the applicable design schematics. E.g. optimized pipe networks often comes whit a relatively low construction costs.

There are pros and cons for pipe network implementation approaches both surface and underground. An optimized pipe network can cost maximum \$30/meter but underground pipe network whit a larger volume costs up to \$200/meter and may be higher. Factors affected cost of the network can be:

- The nature of the design (e.g., above or below grade)
- The need to remove and relocate any waste
- The need to add fill or grade areas of the cap and perimeter areas
- The extent and number of condensate removal traps
- The cost of petroleum and associated products
- The availability and costs for suitable construction contractors.

Certain aspects of the landfill has direct effects on implementation choices and the related cost. Therefore it is advised that the cost-effects of such as a network project should be evaluated thoroughly. The use of high density polyethylene (HDPE) pipe is a must, since the pipe mentioned is highly durable and withstand high amounts of load generated by the thick layers of waste upon it and comes whit affordable prices. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

2.3.4.2 Blower System and Components.

The blower system consists key elements necessary for generation and application of vacuum effects in order to gather the LFG and send it for end use. A blower system should be in a central location provided with suitable site for expending the network and should be at an appropriate distance to the end user (power grid or end user pipelines). The blower system can be constructed inside a facility or it can be applied externally. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

The blower system includes the components below:

- Valves and controls as required for safe operation (e.g., a flame arrestor)
- Condensate pumping or storage
- LFG flow metering and recording
- Blowers or compressors to meet capacity requirements.

The blower system shall offer the capacity to process 100 percent of the peak rate of foreseen LFG generation and allow the monitoring of migration. For the blower systems that provide LFG to a utilization facility that generating revenue, a system that is backing up the main system for redundancy purposes. Based on the size and age of a waste site, a multi layered method for LFG control facility establishment is usually applicable if minor raise in LFG production is expected. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

The expenses regarding the blower systems factor in different aspects and can be based on the specifics for the whole pipe network. Some of the aspects that has an effect on blower selection:

- LFG flow range proposed to be collected
- Piping system design and head loss criteria
- Available well head vacuum
- Length of the piping system
- Pressure demand for any flare or utilization system being supplied with LFG.

2.3.4.3 LFG flare

The LFG gathered from a landfill shall be disposed of in an environmentally acceptable approach such as a drum flare box and/or utilization system. An LFG flare could be a substitute for the utilization system during times of lengthy downtimes for both planned and unplanned O&M procedures. The need for a redundant flare and equipment is optional based on the reliability of the system in general and the susceptibility to short term LFG losses during extraction and monitoring. LFG flaring in a high temperatures results with transformation of LFG methane components to carbon dioxide and water. In addition to that, as a result of this high temperature combustion elements that are scarcely found in, LFG are destroyed.

Just like many of the other utilization elements expenses of flare systems is a factor in LFG system and the expected flare capacity. There are two mainly used flaring system designs, one is the drum flare box design mentioned before, the other is LFG flare system designs that ignite methane gas without any usage of combustion monitoring platform.

2.3.5 LFG Utilization

All systems that utilize the processing of LFG need a system for collection to optimize the LFG gathering with preventing air to mix in. Gathering and flaring the LFG is a preferred choice in order to reduce the odor and issues related to movement. Added to that, the process of flare in a closed drum set transforms the methane gas to CO2 present in LFG and by this lowering the Green House Gas generation chance. The implementation of this method is in align with foundation attempts to form a market where carbon transaction is possible globally. But LFG flare process does not acquire any sort of power from the LFG.

Three different classifying factors can be used to classify LFG, these are depended on the treatment or level of process before LFG utilizing. They can be seen below:

Low-grade LFG fuel; Utilizing LFG as fuel with a low level generally demands process at a minimum level, only enclosed tanks to seperate condensation added to the system collecting LFG and moist removal components to reduce the moisture in the LFG flow.

Medium-grade LFG fuel; In order to use LFG as medium level fuel, components to process gas are added in order to remove more moisture and finer particles (in addition to contaminating materials). This utilization commonly compress and cool down the LFG and/or processing chemically or process of scrubbing so that mercaptans, sulfur compounds, siloxanes and VOC's that are present at a minimum level in LFG and moisture can be seperated.

High-grade LFG fuel; Utilizing LFG as a high level fuel the separation of CO2 and major consisting gases from methane and the impure components such as mercaptans, sulfur compounds, hydrogen sulfide and VOC's, also a process to remove moisture from the LFG by compressing it. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

2.3.5.1 Features that influence the utilization of LFG

As described on prior pages, there are specific technologies to utilize LFG. The choices that complements the particular site is based upon many different aspects, these are described below:

- LFG potential estimation
- Suitable market availability and proximity
- The market fees of end products
- Factors both Environmental and governmental; and
- The capital and operation expenditures for utilizing systems and related problems and expenditures concerning the process implementation and transportation of goods/end products.

The selection process of an LFGTE project is commonly governed by at which level the LFG will be treated and this is a factor of the financial situation of the certain utilization application.(Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

2.3.5.2 *Features that Influence the Electric Generation Choices*

In the process of generating electricity with the use of LFG, many aspects shall be taken into consideration such as the use of micro module turbines, reciprocation engines, gas turbines, integrated cycle or steam turbines.

The percentage of the energy generation figures of LFG that is being processed to generate power is based on the choice of implementation technology, that value is being expressed as Electrical conversion efficiency. This value can be expressed as net plant "heat rate" (Btu/kWh) or gross system efficiency. This efficiency formula can be expressed as Total power value of LFG / The value of the power value being transmitted to the city mains. The net energy transmitted to the city mains is the total of power generation minus any plant specific loss. This plant specific loss is the combination of power used on compression, pumps, oil pumping mechanisms, fans, transformer and other system specific utilities.

On Table 2.7, the flow ranges that are required to feasibly apply the electric energy generation technologies can be viewed.

Table 2.7 LFG Utilization Technologies and Typical Flow/Power Ranges. (Environment Canada, 1996.)

Technology	Preferred Plant Size	Typical Flow Range	Electrical Conversion Efficiency (net to grid without waste heat recovery)
Gas turbines	3 to 18 MW	>4,000 to 20,000 cfm	26-32%
Microturbines	<100 kW	<100 cfm	25-30%
Steam turbines	10 to 50 MW	>6,000 to >25,000 cfm	24-29%
Reciprocating	0.5 to 12 MW	>150 to 5,000 cfm	32-40%
Combined Cycle Systems	>10 MW	38-45%	38-45%

2.3.5.3 Choice Influencers for Direct Fuel End User

The LFG usage for direct fuel implementations is commonly applicable for various project sizes providing there is an end user is within the proximity (<10 km) of the site and the LFG being generated in this site is usable for the mentioned end user. This alternative can be assessed with ease and providing that a buyer is available in the market for the resource. But only a few select landfill sites are generally set up within the proximity of potential users. To assess the availability of the end user the influencers below shall be taken into consideration:

Location of end customer to assess the piping (location, size, scale) needed to convey the resource

- Customer energy necessities both in volume and quality
- Power usage profile of the potential market (daily, monthly, annual)
- Off - gas emission and treatment
- LFG utilization expenditures associated with treatment, pipe network and devices
- O&M expenditures
- Cost of alternative fuels

These influencers shall be investigated thoroughly, which shall be specific to the project, in order to shed light on the technical and financial implementation of the mentioned project. In general, to generate sufficient return of investment for specific LFGTE projects, the customers shall need power in large quantities and must be at a short distance. The customers whose power needs show drastic changes (both high and low) are not feasible since the generation of LFG at a landfill is stable in volume and there is not enough space to store the gas generated. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003

2.3.5.4 LFG Collection Field

An LFG network that is optimized both in design and construction and in optimal operation has the potential to collect 75% of the gas generated on the field. In order to match the fluctuating LFG generation without interfering with the site's ongoing operation, an optimized design and operation of a collection network is a requirement. Adding to the changes in the LFG being generated over the life cycle of the site, the production rate of the landfill gas is influenced by the elements such as climate conditions, changes in settlement plans, efficiency of the system components and coverage network conditions. The site prepared for collecting LFG shall be able to match the fluctuations in production rate. In order to improve and optimize the efficiency of the collection network, the LFG network site shall be monitored and modified accordingly. To achieve LFG gathering without drawing too much from the sites that gas may be exposed to air, necessary adjustments need to be carried out to decrease or increase the gas flow from different parts of the site that gas is being generated. The basic principle that is generally misinterpreted or ignored even by the veterans of the industry is that the operation of a well or trench always depend on the trench or well's gas quality. Operation of a well or trench based on the recovery rate quotas or expected generation rates is often not as productive as expected. (Handbook For The Preparation Of Landfill Gas To Energy Projects World Bank 2003)

Site monitoring that shall be conducted for each collection points shall consist:

- Vacuum
- Differential pressure
- Temperature
- LFG composition (methane and O2 content)
- Valve placement
- Monitoring of each gathering point shall be initiated at vacuum/pressure measurement to counter the interference with the LFG sampling process.

The main monitoring data that shall be collected is the vacuum, LFG composition and valve placement. The points shown below underlines the measurements under optimum operation conditions to maximize the energy saving at gathering points:

- Vacuum maximum 20 inches WC
- Methane 45 to 55 percent by volume
- O_2 less than 2 percent by volume.

2.3.5.5 LFG Gathering Facility

Optimized O&M of the LFG gathering facility which includes condensate drop-out(s), blower(s), flare and related devices improves gathering network effectiveness and increase operating life of the devices. (Handbook for The Preparation of Landfill Gas to Energy Projects World Bank, 2003)

CHAPTER THREE

MATHEMATICAL MODELING of LFG

Since methane is considered as an alternative energy due to its high heat value, estimation of methane emission from MSW landfill is important in terms of not only prevention of climate change but also recovery of energy (Machado, Carvalho, Gourc, Vilar, & do Nascimento, 2009.) Mathematical models are a useful and economical tool for estimating the LFG generation potential at the site. The results of models can be used to assess the potential for LFG emissions/migration, and for assessing the feasibility of the LFG management project. There are numerous models available to calculate LFG production. All of these models can be used to develop an LFG generation curve that predicts the gas generation on time. In this chapter, models that are used in LFG generation calculations are introduced in detail.

3.1 Zero-Order Model

In zero-order model, biogas generated from landfills is remained steady against time. On this basis, waste age and waste type has no effect on gas production. SWANA, IPCC are the examples of zero-order models.

The zero-order model is represented by Equation 3-1 (SWANA 1998).

$$Q = \frac{(ML_0)}{(t_0 - t_f)} \qquad for\ t_0 < t < t_f \tag{3-1}$$

Q: Methane generation rate in volume per time;

M: Waste in place, mass;

L_o: Methane generation potential in volume per mass;

t: Time;

t_o: Lag time

t_f: Time to end point of generation

3.2 U.S. EPA LandGEM Model

The Landfill Gas Emissions Model (LandGEM) is written and improved by EPA. Emission rates of total landfill gas, methane, carbon dioxide, non-methane organic compounds, and individual air pollutants from municipal solid waste landfills are calculated by this program using Microsoft ® Excel interface.

LandGEM is based on a first-order decomposition rate equation and the model needs to be following inputs for estimating the amount of LFG generated in specific time period:

- Design capacity of the landfill
- Amount of waste in place or the annual acceptance rate
- The methane generation rate constant k and methane generation potential L_0 and
- The number of years of waste acceptance

Users of the LandGEM can utilize the own data (i.e. site-specific data) to estimate LFG emissions. If the site-specific data are not available, the model contains two sets of default parameters, CAA defaults and inventory defaults. The CAA defaults are based on federal regulations for MSW landfills laid out by the Clean Air Act (CAA.) This two inventory defaults are based on emission factors in EPA's Compilation of Air Pollutant Emission Factors (AP-42) (LandGEM Version 3.02 User's Guide)

Explanation of the LandGEM Modeling

- ***Spreadsheet Design***

LandGEM Program has nine Microsoft Excel spreadsheets. The name of the worksheets and their functions are described in Table 3.1

Table 3.1 Worksheet title and functions in LandGEM ((LandGem Version 3.02 User's Guide)

Worksheet Titles	**Function**
INTRO	Contains an overview of the model and important notes about using LandGEM
USER INPUTS	Allows users to provide landfill characteristics, determine model parameters, select up to four gases or pollutants (total landfill gas, methane, carbon dioxide, NMOCs, and 46 air pollutants), and enter waste acceptance rates
POLLUTANTS	Allows users to edit air pollutant concentrations and molecular weights for existing pollutants and add up to 10 new pollutants
INPUT REVIEW	Allows users to review and print model inputs
METHANE	Calculates methane emission estimates using the first-order decomposition rate equation
RESULTS	Shows tabular emission estimates for up to four gases/ pollutants (selected in the USER INPUTS worksheet) in megagrams per year, cubic meters per year, and user's choice of a third unit of measure (average cubic feet per minute, cubic feet per year, or short tons per year)
GRAPHS	Shows graphical emission estimates for up to four gases/ pollutants (selected in the USER INPUTS worksheet) in megagrams per year, cubic meters per year, and user's choice of a third unit of measure (selected in the RESULTS worksheet)
INVENTORY	Displays tabular emission estimates for all gases/pollutants for a single year specified by users
REPORT	Allows users to review and print model inputs and outputs in a summary report

- ***Providing Landfill Characteristics***

Some specific landfill data should be entered on the USER INPUTS worksheet that data are related to the identity and size of the landfill before the beginning of modeling.

- Landfill name or identifier
- Landfill open year
- Landfill closure year
- Option to have model calculate closure year
- Waste design capacity.

- ***First-Order Decomposition Rate Equation***

LandGEM is designed based on the first-order decomposition rate equation which is given below. Program is estimated annual Total LFG emissions over a user specific time period.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} kL_0 \left(\frac{M_i}{10}\right) e^{-kt_i}$$

(3-2)

Q_{CH4} = Annual methane generation in the year of the calculation (m^3/year)

i = 1 Year time increment

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

j = 0.1 year time increment

k = Methane generation rate ($year^{-1}$)

Lo = Methane generation potential (m^3/Mg)

Mi = Mass of waste accepted in the i^{th} year (Mg)

t_{ij} = Age of the jt^{h} section of waste mass Mi accepted in the ith year (decimal years, e.g.,3.2 years)

- ***Determined Model Parameters***

Landfill emissions are released on several model parameters by LandGEM. These are;

- Methane generation rate (k)
- Methane generation potential (Lo)
- NMOC concentration
- Methane content.

(i) Methane Generation Rate (k). Methane generation for the mass of waste in the landfill is determined as the Methane Generation Rate, k. The higher k values results with faster methane generation. The value of k is primarily a function of four factors:

- Moisture content of the waste mass,
- Availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide,
- pH of the waste mass, and
- Temperature of the waste mass.

"Use EPA Method 2E is used to determine site-specific k values for user-specified data. The k value, as it is used in the first-order decomposition rate equation, is in units of 1/year, or year^{-1} the five k values used by LandGEM are shown in Table 3-2. Arid area landfills are located in areas that receive less than 60 cm of rainfall per year. The default k value is the CAA k value for conventional landfills. (LandGem Version 3.02 User's Guide) this is the LandGem Modeling parameter. Determination of the theoretical "k" parameter is explained in following sections.

Table 3.2 LandGEM Standard Values for Methane Generation Rate (k) (LandGem Version 3.02 User's Guide)

Default Type	**Landfill Type**	**K Value (year^{-1})**
CAA	Conventional	0.05 (Default)
CAA	Arid Area	0.02
Inventory	Conventional	0.04
Inventory	Arid Area	0.02
Inventory	Wet (Bioreactor)	0.7

(ii) Methane generation potential (Lo). "The Methane generation potential Lo, depends only on the type and composition of waste placed in the landfill. The higher the cellulose content of the waste results with the higher the value of Lo. The default Lo values used by LandGEM are representative of MSW. The Lo value, as it is used in the first-order decomposition rate equation, is measured in metric units of cubic meters per megagram to be consistent with the CAA. The five Lo values used by

LandGEM are shown in Table 3-3 The default Lo values is the CAA Lo value for conventional landfills." (LandGem Version 3.02 User's Guide)

Table 3.3 LandGEM Standard Values for Methane generation potential (Lo) (LandGem Version 3.02 User's Guide)

Emission Type	**Landfill Type**	**L_o Value (m^3/Ton(Mg))**
CAA	Conventional	**170 (default)**
CAA	Arid Area	**170**
Inventory	Conventional	**100**
Inventory	Arid Area	**100**
Inventory	Wet (Bioreactor)	**96**

(iii) Methane Content: LandGEM assume the landfill gas concentration to be 50 percent methane and 50 percent carbon dioxide, with additional, trace constituents of NMOCs and other air pollutants.

Users of the LandGEM Program may choose other Methane Content according to the User-specified data (User-specified selection). However, using LandGEM is recommended data range for methane concentrations 40 to 60 percent.

*"The production of methane is determined using the first-*order *decomposition rate equation and is not affected by the concentration of methane. However, the concentration of methane affects the calculated production of carbon dioxide. The production of carbon dioxide (Q_{CO2} is calculated from the production of methane (Q_{CH4}) and the methane content percentage (P_{CH4}) using the equation:" (LandGem Version 3.02 User's Guide)*

$$Q_{CO_2} = Q_{CH_4}\{[1/(P_{CH_4}/100] - 1\} \qquad (3\text{-}2)$$

This equation is derived as follows:

$$Q_{Total} = Q_{CH_4} + Q_{CO_2} \qquad (3\text{-}3)$$

$$Q_{CH_4} = Q_{Total}\,(P_{CH_4}/100)$$

(3-4)

$$Q_{CO_2} = Q_{Total} - Q_{CH_4} = [Q_{CH_4}/(P_{CH_4}/100)] - Q_{CH_4}$$

(3-5)

$$Q_{CO_2} = Q_{CH_4}\left\{\left[1/(P_{CH_4}/100\right] - 1\right\}$$

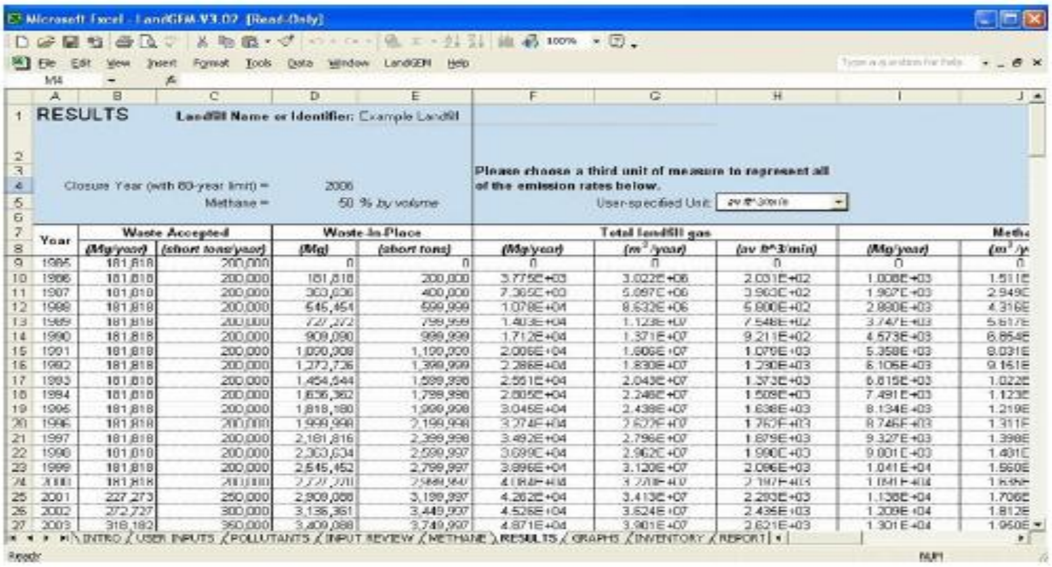
(3-6)

where Q_{total} is the total production of landfill gas.

- ***Results***

LandGEM model is showed the emission estimates in a tabular format in Results Worksheet.

- Data on the RESULTS worksheet include
- Landfill closure year (provided on USER INPUTS worksheet or calculated)
- Methane content from USER INPUTS worksheet
- Years of waste acceptance from open year to closure year of the landfill
- Annual waste acceptance rates used by the model in megagrams per year and short tons per year
- Annual waste-in-place amounts based on acceptance rates used by the model, in megagrams and short tons,
- Annual emission estimates for the four gases/pollutants selected on the USER INPUTS worksheet in megagrams per year, cubic meters per year, and a third measurement unit that you may select from the drop-down menu. The third unit of measure options are average cubic feet per minute, cubic feet per year, and short tons per year. LandGEM uses average cubic feet per minute as the default third unit.



RESULTS **Landfill Name or Identifier:** Example Landfill

Closure Year (with 80-year limit) = 2006
Methane = 50 % by volume

Please choose a third unit of measure to represent all of the emission rates below.
User-specified Unit: av ft^3/min

Year	Waste Accepted		Waste-In-Place		Total landfill gas			Meth	
	(Mg/year)	(short tons/year)	(Mg)	(short tons)	(Mg/year)	(m^3/year)	(av ft^3/min)	(Mg/year)	(m^3/y
1985	181,818	200,000	0	0	0	0	0	0	0
1986	181,818	200,000	181,818	200,000	3.775E+03	3.022E+06	2.031E+02	1.008E+03	1.511E
1987	181,818	200,000	363,636	400,000	7.365E+03	5.897E+06	3.963E+02	1.967E+03	2.949E
1988	181,818	200,000	545,454	599,999	1.078E+04	8.632E+06	5.800E+02	2.880E+03	4.316E
1989	181,818	200,000	727,272	799,999	1.403E+04	1.123E+07	7.548E+02	3.747E+03	5.617E
1990	181,818	200,000	909,090	999,999	1.712E+04	1.371E+07	9.211E+02	4.573E+03	6.854E
1991	181,818	200,000	1,090,908	1,199,999	2.006E+04	1.606E+07	1.079E+03	5.358E+03	8.031E
1992	181,818	200,000	1,272,726	1,399,999	2.286E+04	1.830E+07	1.230E+03	6.106E+03	9.151E
1993	181,818	200,000	1,454,544	1,599,998	2.551E+04	2.043E+07	1.373E+03	6.815E+03	1.022E
1994	181,818	200,000	1,636,362	1,799,998	2.805E+04	2.246E+07	1.509E+03	7.491E+03	1.123E
1995	181,818	200,000	1,818,180	1,999,998	3.045E+04	2.438E+07	1.638E+03	8.134E+03	1.219E
1996	181,818	200,000	1,999,998	2,199,998	3.274E+04	2.622E+07	1.762E+03	8.746E+03	1.311E
1997	181,818	200,000	2,181,816	2,399,998	3.492E+04	2.796E+07	1.879E+03	9.327E+03	1.398E
1998	181,818	200,000	2,363,634	2,599,997	3.699E+04	2.962E+07	1.990E+03	9.881E+03	1.481E
1999	181,818	200,000	2,545,452	2,799,997	3.896E+04	3.120E+07	2.096E+03	1.041E+04	1.560E
2000	181,818	200,000	2,727,270	2,999,997	4.084E+04	3.270E+07	2.197E+03	1.091E+04	1.636E
2001	227,273	250,000	2,909,088	3,199,997	4.262E+04	3.413E+07	2.293E+03	1.138E+04	1.706E
2002	272,727	300,000	3,136,361	3,449,997	4.526E+04	3.624E+07	2.435E+03	1.209E+04	1.812E
2003	318,182	350,000	3,409,088	3,749,997	4.871E+04	3.901E+07	2.621E+03	1.301E+04	1.950E

Figure 3.1 RESULTS Worksheet in LandGEM Model. (LandGem Version 3.02 User's Guide)

- ***Graphical Results***

Graphs Worksheet in the LandGEM model is showed the emission estimates in a graphs format. Every each modeling scenario, LandGEM Shows three graphs on the RESULTS worksheet. The top two graphs are in units of mega grams per year and cubic meters per year, respectively. The third graph represents user selected the units on the RESULTS worksheet, which defaults to average cubic feet or cubic meter per year. All type of LFGs is shown different type of color in the graphs.

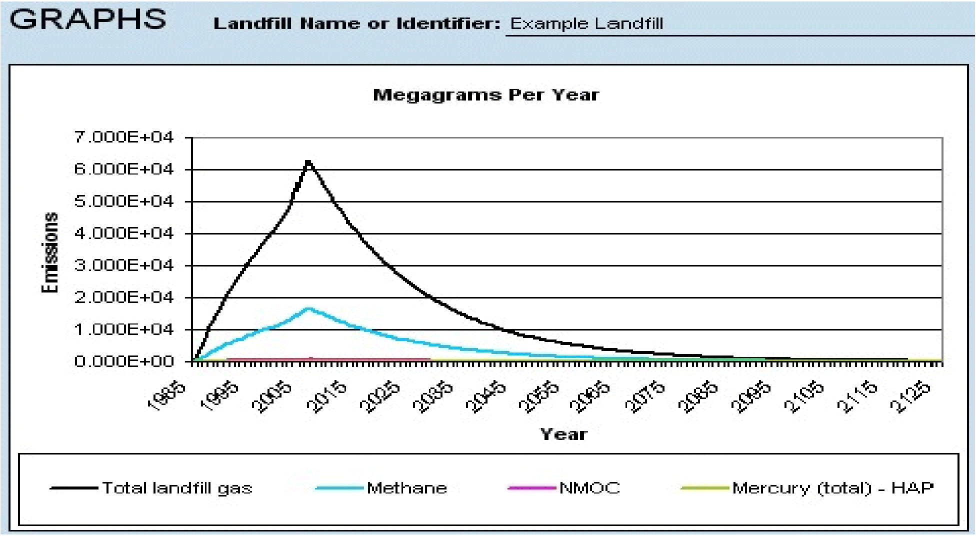


Figure 3.2 Graphs Worksheet in LandGEM Model. (LandGem Version 3.02 User's Guide)

3.3 Tabasaran / Rettenberg Model

Tabasaran / Rettenberg Model fits for landfills whit optimal basic conditions, and optimal water content of 50% in the waste body. Equation (3-7) (Rettenberg, 2004)

$$G_t = 1.868C_{org}(0.014T + 0.28)(1 - 10^{-kt})M_t \qquad (3\text{-}7)$$

Gt: landfill gas formation at a time t

C_{org}: Organic carbon content (kg/ton waste)

T: Temperature (^{0}C)

t: Total length of waste in place (year)

k: first-order rate constant in reciprocal time. (year^{-1})

M_t: waste in place at a time t

3.4 Scholl Canyon Model

"The Scholl Canyon model established by EMCON Associate in 1980 is the most commonly used model for determining methane gas generation. The model does consider neither the first stages nor the second stage of the reaction process. It assumes that the lag phase is negligible, degradation rate follows the first order kinetic and, the methane is assumed to be at the peak at the initial placement. The model does not account for a lag phase, nor does it consider any limiting factors like moisture." (Alex, 2009) The mathematical expression of the degradation process is described as follow:

$$-\frac{dL}{dt} = kL$$

(3-8)

$$\frac{dV}{dt} = kL$$

(3-9)

“Where L is the potential volume of methane production in unit of volume per mass; V is the cumulative methane volume produced prior to time t in unit of volume per mass; and k is the constant rate of decomposition in unit of reciprocal of time.”

$$\mathrm{L} = \mathrm{Lo}\ \mathrm{e}^{-\mathrm{kt}} \tag{3-10}$$

$$\mathrm{V} = \mathrm{Lo}(1 - \mathrm{e}^{-\mathrm{kt}}) \tag{3-11}$$

Lo is shown the ultimate potential of methane volume. It becomes clear that Lo is methane generation potential, the total capacity of the LFG production. The total gas production rate is determined by differentiating equation.

$$\frac{dV}{dt} = -\frac{dL}{dt} = kL = kLoe^{-kt} \tag{3-12}$$

R is the mass of waste in placed during the year t considered, and Q is the total volume of LFG production rate, and write as followed:

$$Q = kRLoe^{-kt} \tag{3-13}$$

$$Q = k_i R_i L_{0i} e^{(-kiti)} \tag{3-14}$$

$$Q_{LFG} = \sum_{i=1}^{n} k_i R_i L_{oi}\, e^{(-k_i t_i)} \tag{3-15}$$

Ri: the amount of waste disposed in year i in unit of (Mg)

K: the gas generation rate constant account for the amount of waste disposed in year i, in unit os (y^{-1})

Loi: the volume of methane remaining to be produced t=0 for the amount of waste i (m^3/Mg)
ti: Stands for the age in year of the waste section placed in the i^{th} year
Q_{LFG}: LFG production in unit of m^3/year.

3.5 Multiphase Model

“M*ultiphase model is developed by the Dutch landfill operator Afvalzorg. The model has been validated for three Afvalzorg landfill sites. Because of its suitability for ‘low organic carbon’ landfills the Netherlands and Denmark, countries that have landfill bans for biodegradable waste, have recommended the model for individual landfill reporting purposes”*

“Landfills in operation have an obligation to register waste activity data including waste mass and European Waste Catalogue-code. Annual waste mass information per waste category is available, allowing for more accurate methane generation estimation. Carbon content is not analyzed for every batch of waste entering the landfill. Annual carbon content might be determined by means of average carbon content for waste categories in the EWC (examples Finland, Netherlands). A multiphase first order degradation model based on IPCC recommended mathematics and default values and including a tool to determine carbon content based on EWC-codes is available.” (Hans Oonk 2011, Practıcal Guıdance Document Landfill Methane Emıssıon Reductıon)

The following steps have to be executed in this model;

- Determine the annual biodegradable organic carbon input into the landfill by means of waste mass and EWC carbon content data.

- Estimate the methane production in kg per year with a model based on IPCC mathematics and climate dependent default values.

- Estimate the potential methane emission by subtracting the methane collected by the gas collection system. The amount of methane collected is determined by means of a gas flow meter. The gas flow is corrected for temperature and pressure at the point of measurement and expressed in kg per year. With respect to future gas recovery estimate the recovery efficiency based on operational period and cover characteristics.

- Estimate the methane emission by subtracting the methane oxidized in the landfill cover. Apply the IPCC default value of 0.1 for areas covered with a material suitable for methane oxidation and the IPCC default value of 0.0 for areas not covered with a material suitable for methane oxidation.

"In the quest of achieving highly reliable model, the heterogeneity of the organic matter was taken into account to improve. This model distinguishes three fractions of organic matter that degrade at different rates: rapidly degradable, moderately degradable, and slowly degradable (Sharff, H. and J. Jacobs (2006)). For each category of waste, the rate constant and the amount of organic matter are predefined. This will obviously increase the difficulty of parameters identification but the model will gain in accuracy." (T.Ranta, (2009) Sustainable Waste-to-Energy *Production)*

$$\alpha_t = \zeta cA[C_{01}k_{11}\exp(-k_{11}t) + C_{02}k_{12}\exp(-k_{12}t) + (C_{03}k_{13}\exp(-k_{13}t)]$$

(3-16)

In a compact form equation (3-8) becomes:

$$\alpha_t = \varsigma \sum_{i=1}^{3} \mathrm{cAC_{o,i}k_{1,i}}\, \mathrm{e}^{-\mathrm{k_{1,i}t}}$$

(3-17)

"Most commonly C constant is 1,87 symbolize the transformation factor (m^3 LFG.KgC^{-1} degraded), Where αt is the LFG formation at a certain time in unit of

volume per time (m3 LFG year^{-1}), is called the dissimilation factor 0.58 is without unit, A is the amount of waste deposited in unit of mass (Mg), C0 is the corresponding quantity of organic carbon in waste which time of deposition (KgC.Mg^{-1}) The waste fraction is Showed by with its connected degradation rate constant k_1,i, C is the conversion factor in unit of [m^3 LFG.KgOM^{-1}degraded], and the degradation rate constant in unit of [1/y]. The parameters to be identified in the multiphase model are respectively the rate constant (k1,i) for different category of waste, the dissimilation factor (ζ) and the quantity of organic carbon (C0,i) for each category. As compare to the previous model, a predefined table providing a thorough composition of specific values for organic carbon according to each category of waste." (T.Ranta, (2009) Sustainable Waste-to-Energy Production)

Table 3.4 Organic matter content used in the Afvalzorg multiphase model (T.Ranta, (2009) Sustainable Waste-to-Energy Production)

Waste Category	**Minimum organic matter content [KgOM.Mg^{-1}]**				**Maximum organic matter content [KgOM.Mg^{-1}]**			
	Rap	**Mod**	**Slow**	**Total***	**Rap**	**Mod**	**Slow**	**Total***
Contaminated soil	0	2	6	40	0	3	8	42
C&D	0	6	12	44	0	8	16	46
Shredder waste	0	6	18	60	0	11	25	70
Street cleansing water	9	18	27	90	12	22	40	100
Sewage sludge & compost	8	38	45	150	11	45	48	160
Coarse household waste	13	39	104	260	19	49	108	270
Commercial waste	13	52	104	260	19	54	108	270
Household waste	60	75	45	300	70	90	48	320

Source: Adapted from Sharff, H. and J. Jacobs (2006) Applying guidance for methane emission estimation for landfills, Waste management, Volume 26, pp. 417-429

*"*Only rapidly, moderately and slowly degradable organic matters have been taken into consideration. The total organic matters content is higher than the sum of these*

categories due to the presence of organic matters that are not considered biodegradable under anaerobic conditions; examples are lignin and plastic.”

3.6 Palos Verdes Model

The Palos Verdes Model uses first-order kinetics with the following assumptions:

- Two-phase generation
- Gas generation rate increases exponentially in the first phase
- Gas generation rate decreases exponentially in the second phase
- Equal volume of gas is generated in the first and second phase
- The peak rate occurs at the transition between the increasing first and decreasing second phases
- The organic fraction is composed of readily biodegradable, moderately decomposable organics, and refractory organics
- The ultimate yield for each organic fraction is based on the fraction’s corresponding fraction of the MSW times the ultimate yield of the waste

The ultimate yield of the organic fraction can be represented by Equation (3-18).

$$L_{0j} = \frac{P_j}{100} L_0 \tag{3-18}$$

L_{0j}: Methane generation potential of the organic component j

P_j: Component j’s percentage of total organic fraction; and

L_0: Methane generation potential of the whole waste

$$\frac{dV}{dt} = k_1 V$$

for $0 < t \leq t_{1/2}$ (1st phase) (3-19)

$$\frac{dV}{dt} = -k_2 G$$

for $t > t_{1/2}$ (2nd phase) (3-20)

V: Volume of gas produced prior to time t

G: Volume of gas remaining to be produced after time t

k_1, k_2: First and second phase gas production rate constants in reciprocal time

Integrating the first phase equation gives

$$V = V_0 e^{k_1 t}$$

(3-21)

V_0: Initial gas volume produced

The first phase equation becomes applicable when gas production reaches 1 percent of the ultimate yield (i.e., $V_0 = G_0$ equation, knowing that at $t_{1/2}$, the limit for G is G_0 and at time t, the limit is G.

$$G = \frac{G_0}{2} e^{-k_2(t-t_{1/2})}$$

(3-22)

Since $V = G_0 - G$, then

$$V = G_0 \left[1 - \frac{1}{2}\, e^{-k_2(t-t_{1/2})}\right]$$

(3-23)

"Drawbacks of the model are that the methane yield of the individual waste categories is not considered and that the assumption that half the gas is produced in each phase may not be accurate."

3.7 Modified First-Order Model

“This model assumes that methane generation is initially low and then rises to a maximum before declining exponentially.” The equation of this model is represented by Equation 3-24 (Van Zanten and Scheepers 1995).

$$Q = ML_0 \frac{k+s}{s}\left[1 - e^{-s(t-t_0)}\right]ke^{-k(t-t_0)} \tag{3-24}$$

k: First-order rate constant in reciprocal time.

Lo: Methane generation potential (m^3/Mg)

M: Mass of waste accepted in the year (Mg)

t: Total time of waste in place (year)

s: first-order rise phase rate constant in reciprocal time.

3.8 The Default and First Order Decay (FOD) IPCC Methodologies

The IPCC Guidelines for national Greenhouse Gas Inventories are developed, and an upgraded to carry out as accurately as possible national inventories of emissions of CH4. The IPCC default method is a simple mass balance calculation which estimates the amount of CH emitted from the SWDS assuming that all CH4 is released the same year the waste is disposed of. The other method outlined in the IPCC Guidelines is the so-called First Order Decay (FOD) method. The FOD method takes the time factors of the degradation process into account, and produces annual emission estimates that reflect this process, which can take years, even decades. The estimates on annual emissions produced by the two methods are therefore not comparable. The FOD method produces better estimates on annual emissions, whereas the IPCC default method has merits e.g. in studies comparing the potential to reduce the CH4 emissions by alternative waste treatment methods.

3.8.1 The IPCC default method

The default method is based on the main equation 1 (equation 3-25). Methodology is based on the theoretical gas yield (a mass balance equation) and *does not reflect the time variation in SW disposal and the degradation process as it assumes that all potential methane is released the year the SW is disposed. Method will produce fairly good estimates of the yearly emissions. Increasing amounts of waste disposed will lead to an overestimation, and decreasing amounts correspondingly to underestimation, of yearly emissions."* (Guidance, n.d. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories)

$$\begin{aligned}&\text{Methane emissions}(\mathrm{Gg/yr})\\&\qquad=((\mathrm{MSWt})(\mathrm{MSWf})(\mathrm{MCF})(\mathrm{DOC})(\mathrm{DOCf})\mathrm{F}\,16/12-\mathrm{R})(1-\mathrm{OX})\end{aligned} \tag{3-25}$$

MSW_T: total MSW generated (Gg/yr)

MSW_F: fraction of MSW disposed to solid waste disposal sites

MCF: methane correction factor (fraction)

R: recovered CH4 (Gg/yr)

F: Fraction of CH_4 in landfill gas (IPCC default is 0.5)

16/12: conversion of C to CH4

DOC: degradable organic carbon (fraction) (kg C/ kg SW)

DOC_F: fraction DOC dissimilated

OX: oxidation factor (fraction – IPCC default is 0)

IPCC Default Method estimate all the methane emissions are released during the waste disposed year. The method calculations need input of a limited set of parameters. Default values for modeling are provided IPCC Guidelines and country-specific quantities and data are not available in this modeling.

The IPCC Guidelines introduce various specific default values and recommendations, (particularly for use in countries with lack of SW statistics):

MSW_F: *"A selection of national specific MSW disposal figures (in kg/capita/day) are provided*" (to be used instead of MSWT)

MCF: *"Three default values ranging from 1.0 to 0.4 are included, depending on the site management and with 0.6 as general default value"*

DOC: *"A selection of national values for DOC in MSW is provided, although a more limited selection than for MSWT and MSWF. In addition, an equation is provided together with default values related to MSW fractions composition to estimate country specific figures based on national MSW"*

DOC_F: Tabasaran's (1981) theoretical equation $DOC_F = 0.014T + 0.28$, where T = temperature is used to determine the value. The IPCC default value is 0.77 as suggested by Bingemer and Crutzen (1987).

F: 0.5 is the IPCC default value.

OX: 0 is the IPCC default value.

3.8.2 IPCC First Order Decay (FOD) Model

IPCC First Order Decay (FOD) Model is presented through three equations. The first equation is applicable for one or a selection of specific landfills: (equation 3-26)

$$Q = LoR(e^{-kc} - e^{-kt}) \tag{3-26}$$

Q: methane gasses flow rate (generated) in current year (m3/yr)

Lo: methane generation potential (m3/Mg of refuse)

R: average annual waste acceptance rate during active life (Mg/yr)

k: methane generation rate constant (yr^{-1})

c: time since SWDS closure (yr)

t: time since SWDS opened (yr)

The following equation for methane generation in year T from all solid waste landfilled in one specific year x (R_x) may be used:

$$Q_{t,x} = kR_xL_0e^{-k(T-x)} \tag{3-27}$$

$Q_{t,x}$: the amount of methane generated in year T by the waste Rx (Mg)

x: the year of waste input

Rx: the amount of waste disposed in year x (Mg)

T: current year

“In order to estimate all emissions in the year T from waste disposed of in previous years, equation (3-28) can be solved for all values of Rx and the results summed using the following equation:”

$$Q_t = \sum Q_{t,x} \tag{3-28}$$

x = initial year to T

Q_T: total emissions in year T from waste disposed of in previous years (including year T)

Default values for variable factors like k and L_0 have not specific recommendations just a very wide range of values: Lo <100 - >200 Nm^3/Mg; k = 0.005 – 0,4. is provided in literatures. Furthermore, no reduction due to recovery of gas or oxidation factor is introduced. (Guidance, n.d. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories)

3.8.3 Nationally Adjusted FOD model

“Several countries have made adjustments to the presented FOD-model by including supplementary information of the factors Lo and k, and are in the process of using these in their national inventories. A model implemented in Norway in 1998 (Bartness, et al, no date) is proposed as follows:”

$$Q_{t,x} = kMSW_{t(x)}MSW_{f(x)}\, MCF_{(x)}L_{0(x)}\, e^{-k(T-x)}F \tag{3-29}$$

$Q_{T,x}$: the amount of methane generated in the current year from waste disposed in the year x

T: the current year (year of the emission estimate) (Gg/yr)

x: the historical year of the disposal of the relevant national MSW quantities

$L_{o(X)}$: DOC x DOC_F for the year x (Gg CH4/Gg waste)

k: ln (2)/t½. (1/yr)

t $_{½}$: half-life period for the degradation process (yr)

MSWT(x), MSWF(x) and MCF(x) and F are the same factors as in the default method (equation 1), but estimated for the year x.

“This is for the year x and when doing the same calculation for each year back in time from T until a point of time when the majority of the MSW is degraded in year T; total emissions in year T will be the result (equations 2-7 applies). From this total

figure (QT), LFG extracted and flared and/or recovered in year T (RT) must be subtracted together with the oxidation effect to obtain the total net emission in the year T (QNet,T):"

$$Q_{net,T} = (Q_t - R_T)(1 - OX) \tag{3-30}$$

In addition to the necessary input to the IPCC default model, this model will require information on:

- historical MSWT(x), MSWF (x), MCF(x) values or assumptions of the rates of changes over time,

- historical DOC or assumptions of the rates of changes over time,

- a choice of half-life period for bio-degradation in the country.

3.9 Brief Explanation of the Mathematic Model Factors Parameters

Methane correction factor (MCF): MCF is related the side condition of landfill operation and physical condition of landfill and listed below.

- Sufficient depth (minimum 10 m, preferably more);
- High compaction with suitable equipment;
- Properly designed and well-operated leachate and storm water systems;
- Proper site management with no scavenging at the operational area;
- Control of incoming waste types and quantities and environmental monitoring schemes established;
- Frequent surface covering;
- Prevention of landfill fires, litter and scavenging animals, and
- Gas control and extraction/recovery. Open dumps are more favorable for aerobic degradation and are characterized by conditions like:
- Shallow sites (<5 m) (favourable for aerobic degradation);

- Poor and light operational equipment, for instance bulldozers (being in widespread use) have in general a low area pressure, resulting in limited compaction effect (favourable for aerobic degradation);
- No or limited coverage (favourable for aerobic degradation);
- Scavenging by people and animals;
- Aerobic degradation conditions in substantial or all parts of the sites,and
- Frequent fires, often used deliberately and systematically mainly to reduce volumes and to “get rid of ” the SW.

Most sites will have conditions between these two extremes. The default values present the following for each site conditions factor:

- Managed sites MCF = 1.0;
- Unmanaged, deep sites (≥ 5m) MCF = 0.8;
- Unmanaged, shallow sites (<5m) MCF = 0.4, and
- Unspecified SWDS – default value: MCF = 0.6

The reduction implied by the MCF is normally caused by two conditions:

- SWDS conditions allowing aerobic degradation resulting in other emissions than CH4. This may be caused by loose compacting, shallow site or lack of cover material, normally a combination of all these,
- Fires in the landfill instantly reduce the organic matter with very limited emissions of CH4.

(Guidance, n.d. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories CH4 Emissions from Solid Waste Disposal)

Content (fraction) of Degradable Organic Equation (DOC): DOC is provided from the following equation:

$$DOC = 0.4(A) + \ 0.17(B) + 0.15(C) + 0.30(D) \tag{3-31}$$

Table 3.5 Default DOC values for major waste streams

	Waste Stream	**Percent DOC (by weight) in wet SW**
A	Paper and textiles (% portion in SW)	40
B	Garden and park waste, and other (non-food) organic putrescibles (% portion in SW)	17
C	Food waste (% portion in SW)	15
D	Wood and straw waste [a] (% portion in SW)	30
[a] excluding lignin C Source: IPCC Guidelines		

(Guidance, n.d. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories CH4 Emissions from Solid Waste Disposal)

This offers a solid foundation for predicting a DOC value for the particular country. But some components should be discussed:

- The total of A+B+C+D shouldn't be 1.0 (100 %), as other components like metals, plastics, rock/dust etc. are also in the stated MSW generation figures presented on the guidelines;

- In most of the countries, the figures for composition are not related to mixed MSW but to, for example, household waste and non-household waste. An addition calculation of weighted DOC for mixed MSW should be carried out, and

- Questions may be raised if some plastics should be included. Plastics are usually considered non-degradable in SWDS. Some, especially new types of plastics may behave differently, for instance polyethylene (PE) plastics have a high content of organic carbon and may bio-degrade, though over a very long period. As plastics are of fossil origin (oil), the CO2 emissions produced should in theory also be accounted for, although their importance in the national inventories is probably negligible. In some countries, plastics have been included to some extent in the estimated DOC value.

(Guidance, n.d. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories CH4 Emissions from Solid Waste Disposal)

Fraction of DOC dissimilated (DOC_F): "*This factor is based on a theoretical model where the variation depends on the temperature in the anaerobic zone of the landfill:* $DOC_F = 0.014 \times T + 0.28$ *where T is the temperature. This factor may vary from 0.42 for 10oC to 0.98 for* 50^oC*. In fact, in many deep landfills (>20 m) temperatures of more than* 50^oC *have been registered in gas streams from highly productive (thus clearly anaerobic) gas wells."*

"This theoretical factor is currently under review. An IPCC workshop in Washington in 1995 recommended the use of 0.5 as a new default factor on the basis of several experimental studies. It is, however, unclear to what extent the temperature in the strictly anaerobic zone influences the fraction of the total DOC being converted to CH_4 *during the degradation process. The temperature clearly influences the speed of the process, which in the FOD model is mainly reflected in the choice of half-life period for the degradation* ($t^{½}$ *)." (Guidance, n.d. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* CH_4 *Emissions from Solid Waste Disposal)*

Fraction of CH_4 in landfill gas (F): *"Dependency Of Landfill Gas Formation in the additionally various sources operate with a* CH_4 *content in LFG between 50 and 60 percent, and the default value in the IPCC Guidelines are 50 percent.*

Experiences from a number of pumping tests are indicating that composition of undisturbed LFG very often is in the order 55 percent CH_4 *and 45 percent* CO_2*. The adjustment of the default value to e.g., 55 percent* CH_4*.(IPCC Guidelines)"*

Oxidation factor (OX): *"The default value for this is 0, although an increasing focus is being put on this factor. At the IPCC workshop in Washington in 1995 and at an international seminar in Chicago in 1997 there was an agreement of using 10 percent as a standard value, which later on has been subsequently implemented in several national inventories. More recent studies on oxidation have not changed the basis for this value substantially, and it is proposed to introduce this as a default value in the IPCC Guidelines. (IPCC Guidelines)"*

Methane Generation Potential (Lo): A range between less than 100 m^3/Mg SW and more than 200 m^3/Mg SW is presented in the IPCC Guidelines. This parameter determination is explained next chapter. This method is Lo corresponds to MCF x DOC x DOCF x F x 16/12 in the default method.

Methane Generation Rate Constant (K): K is depending on site conditions and waste composition, K describes the rate of the degradation process. K values between 0.005 and 0.4 are given for k in the IPCC Guidelines. This parameter determination is explained next chapter.

3.10 Properties of The Bio Degradation and LFG Production

"As an important parameter for estimation of methane generation from landfills, we measured the most important factors include the waste composition and the presence of readily degradable organic components, the age of the residue, the moisture content, the pH and temperature. The pH and the temperature are relevant for the existence and action of bacteria and they influence the type of bacteria that predominate and the rate of gas generation. (McBean et al., 1995) According to Mehta et al. (2002) and Barlaz et al. (1990), the moisture content is a parameter that

controls methane generation, since it stimulates microbial activity by providing better contact between soluble and insoluble substrates and microorganisms."

Several MSW compositions will decompose at several time periods. Food waste and some part of green waste (grass) have readily degradable components. slowly degradable part includes newsprint, textiles, wood, coated paper, and other materials and Portion of paper waste and green waste are contained moderately decomposable components., Glass, plastic, rubble, concrete and other inert materials are normally considered non-biodegradable.

Municipal solid wastes composition comprises inorganic and organic materials. *"The organic part that typically contains 40–50% cellulose, 10–15% lignin, 12% hemicellulose and 4% protein in dry weight is the part that can be converted into methane through physical–chemical and biological phenomena (Barlaz et al., 1989). This conversion is explained and well-documented in literature (Rovers (1973), Pohland (1975), Tchobanoglous et al. (1993) and Barlaz et al. (1997). In Turkey there is lack of data on composition of MSW, and very limited study on LFG utilization.*

"In anaerobic conditions the degradation rates of the cellulose and lignin vary considerably; while the cellulose content clearly decreases during the waste degradation process, the lignin content increases notably because the lignin is highly recalcitrant and stable under anaerobic conditions (Bookter and Ham, 1982). (Machado et al., 2009). According to Barlaz et al. (1989), in a laboratory- scale simulation only around 70–75% of the initial cellulose and hemicellulose was converted into gas."

3.10.1 Determination of Methane Generation Potential (Lo)

"The biodegradable portion (BF) of the waste or the value of BF concerning a specific waste component can be obtained through tests that quantify the biochemical methane potential (BMP). (Lobo, 2003). The BF value can be calculated using the

ratio between the BMP value and the values predicted by stoichiometric equations (here called Cm), which assumes a complete conversion of organic matter to gaseous products. (Machado et al., 2009) The Cm values vary according to the component of the MSW, but they are normally between 400 and 500 L CH4/dry-kg. According to Barlaz et al. (1990), values of Cm of 414.8 and 424.2 L CH4/dry-kg can be considered for cellulose and hemicellulose, respectively. Tchobanoglous et al. (1993) present biogas generation potential from 750 to 900 L biogas/dry-kg. As the biogas methane fraction usually varies from 0.5 to 0.6, reproduced from Lobo (2003), presents the BF values for different components of waste suggested by several authors. if the biodegradable frac- tion of the waste as a whole, BFW, and the value of Cm are known, the waste methane generation potential, Lo, can be easily calculated. can be used to calculate BFW. The fraction (dry basis) of each component in the waste composition, FR, is multiplied by its BF value, and the value of BFW is calculated by adding the components considered. The waste average value of Cm can be calculated."(Machado et al., 2009)

Table 3.6 BF values for each type of Organic MSW.(Machado et al., 2009)

Food Waste	**Paper**	**Cardboard**	**Wood**	**Garden Waste**	**Textiles**	**Adapted From**
-	0.30 0.40	0.44	0.30 0.33	0.20 0.51	0.17 0.25	Harries et al. (2001)
0.70	0.19 0.56	0.39	0.14	0.70 0.34	-	Barlaz et al. (1997)
0.64	0.40	0.41	0.17	0.35	0.32	Lobo (2003) adopted
0.58	0.44	0.38	0.61	0.45	0.40	Tchobanoglous et al. (1993) and Bonori et al. (2001)

Table 3.7 Water consumption and methane generation (Cm) in MWS (Machado et al., 2009)

MSW organic component	**H_2O consumption (H_2O kg/dry- kg)**	**Cm (m^3 CH4/dry- Mg)**
Food wastes	0.26	505.01
Paper	0.20	418.51
Cardboard	0.16	438.70
Wood	0.24	484.94
Garden waste	0.28	481.72
Textiles	0.41	573.87
Leather	0.64	759.58

$$BF_w = \sum_{i=1}^{n} BF_i . FR_i \tag{3-32}$$

$$C_m = \frac{\sum_{i=1}^{n} BF_i . FR_i . C_{mi}}{BF_w} \tag{3-33}$$

$$L_0 = \frac{BF_w . C_m}{1 + w} \tag{3-34}$$

BF: Biodegradable fraction

BF_W: Biodegradable fraction of the waste as a whole

BMP: Biochemical methane potential

C_m: MSW organic matter methane generation potential

FR: Component fraction in the waste composition, dry basis

W: Water content (dry basis)

IPCC (2006) uses another simplified model. the methane generation potential is estimated through a mass balance approach this method explain in chapter 2.3.3.

“DDOCm is the part of the organic carbon that will degrade under the anaerobic conditions. DDOCm equals the product of the fraction of degradable organic carbon in the waste the fraction of the degradable organic carbon that decomposes under anaerobic conditions (DOCf), and the portion of the waste that will decompose under aerobic condi- tions (prior to the conditions becoming anaerobic) in the landfill, which is interpreted with the methane correction factor (MCF).”(Machado et al., 2009)

$$DDOC_m = DOC.DOC_f.MCF \tag{3-35}$$

$$DDOC_m = MCF.\sum_{i=1}^{n} DOC_i\,.FR_i.DOC_{fi} \tag{3-36}$$

$DDOC_m$:	Decomposable organic carbon
MFC:	Methane correction factor
DOC:	Degradeble organic carbon
FR:	Component fraction in the waste composition, dry basis
DOC_f:	Fraction of DOC that decomposes under anaerobic conditions

Table 3.8 Dry matter content and DOC in suggested by IPCC (2006)

MSW component	**Dry matter content in % of wet weight**	**DOC content in % of dry waste**		**DOC content in % of wet waste**	
	Default	Default	Range	Default	Range
Food wastes	40	38	20-50	15	8-20
Paper/cardboard	90	44	40-50	40	36-45
Wood	85	50	46-54	43	39-46
Garden waste	40	49	45-55	20	18-22
Textiles	80	30	25-50	24	20-40
Rubber and leather	84	47	47	39	39
Nappies	40	60	44-80	24	18-32
Plastics	100	-	-	-	-
Glass	100	-	-	-	-
Metal	100	-	-	-	-
Other, inert waste	90	-	-	-	-

Table 3.9 Values of MCF suggested by IPCC (2006)

Type of Site	MCF default values
Managed – anaerobic	1.0
Managed – semi-aerobic	0.5
Unmanaged – deep (>5m waste) and /or high water table	0.8
Unmanaged – shallow (<5m waste)	0.4
Uncategorized landfill	0.6

Comparing the two methods BF and DOC_f have a closely similar and that DOC and BMP are closely related.

"DOC_f is an estimate of the fraction of carbon that is ultimately degraded and released from landfill, and reflects the fact that some degradable organic carbon does not degrade, or degrades very slowly under anaerobic conditions. DOC_f is usually assumed as 0.5 (on the assumption that the landfill environment is anaerobic and the DOC values include lignin). DOC_f value (as BF) is dependent on many factors such as temperature, moisture, pH, composition of waste, etc."

The methane generation potential (rate), Lo (m^3 CH_4/Mg of MSW), may be calculated using equation 3-37

$$L_0 = \frac{DDOC_m . F_{CH_4} . \frac{16}{12}}{\rho_{CH_4 .}(1+w)}$$

(3-37)

L_0: Methane generation potential

$DDOC_m$: Decomposable organic carbon

F_{CH4}: CH_4 volume concentration in the gas (Field values of FCH4 are around 0.55)

16/12: molecular weight ratio (See Blow equation 3- 23)

q_{CH4}: methane density (which may be adopted as 0.717 kg/m3 for practical purposes)

w: wastewater content, dry basis

$$C_aH_bO_cN_d + \frac{[4a - b - 2c + 3d].H_2O}{4} \rightarrow \frac{[4a + b - 2c - 3d].CH_4}{8} + \frac{[4a - b + 2c + 3d].CO_2}{8} + d.NH_3$$

(3-38)

Stocinometric equation of anaerobic decomposition of organic material

The values of Lo are according to USEPA (1998) between 6.2 and 270m^3 CH_4/Mg of MSW. Developing countries often present higher values of Lo.

3.10.2 Determination of Methane Generation Rate Constant (k)

The fraction of refuse which decays in a given year and produces methane gases is shown k values. Easiest way to determine methane quantity of the LFG, to estimating a single k values for the whole landfills this method alternative approach of determination k constant of the landfill. Laboratory studies have shown that fast-decaying organic material (like food waste) decays at 5 times the rate of medium decay rate materials, (like paper), and 20 times the rate of slowly decay rate materials (like textiles). (Ehrig, Hans-Jürgen, 1996) landfill moisture content important affects of decay rates. *"The relative rates of decay are expected to remain constant, despite varying landfill moisture. precipitation value, if a single overall k value is known for the entire landfill and can be used to calibrate the three k values."* (Drive, 2005)

"SCS has developed a set of default k values for U.S. landfills that vary with average annual precipitation. The k values are based on a database of over 150 landfills with active gas collection systems and recovery data to calibrate the LFG models."

The value of k is a function of the following factors:

- refuse moisture content,

- availability of nutrients for methane-generating bacteria,
- pH,
- Temperature.

The k values obtained from data collected from U.S. landfills range from 0.003 to 0.21 per year (EPA, 1991a).

Table 3.10 Relationship whit methane generation rate constant (k) and annual precipitations.(Muller, 2003)

Annual Precipitations (mm/year)	**k (Per Year)**
0-249	0.040
250-499	0.050
500-999	0.065
At least 1000	0.080

Gas generation is assumed to peak, with a delay time of 4 to 12 months immediately after disposal of the waste and is reduced by 50% after the period of one half-time. In a first order decay model, degradability of waste is mathematically expressed as k, the rate constant of biodegradability. k is linked to halflife of biodegradation (t½) as follows: (Drive, 2005)

$$k = \ln(2)\,/t_{1/2} \tag{3-39}$$

So a k of 0,1 y-1 implies a half-life of 7 years. Values for k, as recommended by IPCC for different climate zones are given in Table 3, under ‘bulk waste’. Some descriptions of landfill gas generation take this approach one step further and use separate half-times for slow, moderate and rapid degradable waste, as indicated in Table 3- . The latter type of models are often referred to as multi-phase models. Multiphase models suggest to give more accuracy than simple first order decay models. However there is no mechanistic reason, nor empirical proof that their outcome is more reliable. According to IPCC both approaches have to be considered equivalent, especially when quality of information on amounts and composition of waste landfilled is limited.(Gronert, 2011)

Table 3.11 Degradability (K values In Y^{-1}) of waste in various climates, according to IPCC. (Gronert, 2011)

phase	**Materials**	**Dry boreal and temperate**	**Wet boreal and temperate**	**Dry tropical**	**Wet tropical**
	bulk waste	0.05 (0.04-0.06)	0.09 (0.08-0.1)	0.065(0.05-0.08)	0.17(0.15-0.2)
rapid	Food and sewage	0.06 (0.05-0.08)	0.185 (0.1-0.2)	0.085 (0.07-0.1)	0.4 (0.17-0.7)
moderate	other (non-food) putrescibles. garden and park waste	0.05 (0.04-0.06)	0.1 (0.06-0.1)	0.065 (0.05-0.08)	0.17 (0.15-0.2)
slow	paper, textiles	0.04 (0.03-0.05)	0.06(0.05-0.07)	0.045 (0.04-0.06)	0.07 (0.06-0.085)
	wood and straw	0.02 (0.01-0.03)	0.03(0.02-0.04)	0.025 (0.02-0.04)	0.035 (0.03-0.05)

- Dry boreal and temperate' means that annual precipitation is lower than potential evapotranspiration. 'Wet boreal and temperate' means that annual precipitation is higher than potential evapotranspiration;
- Dry tropical' means less than 1,000 mm annual precipitation. 'Wet tropical' means more than 1,000 mm annual precipitation;
- Boreal and temperate means that the mean annual temperature is below 20 ^{o}C; Tropical means the mean annual temperature is in excess of 20 ^{o}C

CHAPTER FOUR
CASE STUDY

The main objective of this research was to predict expected methane generation in solid waste landfills to evaluate its potential for energy production. In order to determine the gas generation, various models are utilized and the results are compared with each other. For the implementation of models the landfill site in İzmir Metropolitan City was chosen as the study area. Input data on waste characteristics and site conditions were gathered as first. Then, the models were applied to estimate the gas generation. The calculated values by applying selected models were compared; and energy potential of landfill gas was calculated based on estimated landfill gas generation.

4.1 Solid Waste Characteristics of the City of Izmir

SW contains compostable organic matter (fruit and vegetable peels, food waste), recyclables (paper, plastic, glass, metals, etc.), and certain cases toxic substances (like used batteries, accumulators, etc.), and demolition wastes. Changes in the average composition of municipal solid waste for 1982-2008 have been shown in Table 4.1. Figures given in Table 4.1, shows that SW components like paper, plastic, glass, metals are having the slightly increasing trend. Increasing trend suggest that the establishment of the formal recovery and recycle facilities will be economically a viable option. Compostable matter is having the decreasing trend from 56% to 47.33% between the years of 2005 and 2008.

It is important to note that municipal solid waste has a high proportion of biodegradable wastes (paper and organics). These wastes break down under biological action in landfills to produce greenhouse gases, and thus are the primary target of LFG generation and utilization.

Table 4.1 Waste Composition of Izmir Metropolitan City (G.Akinci, ORBIT 2008 & İzmir Metropolitan Municipality)

(%w)	**İzmir 1982**	**İzmir 1989**	**İzmir 1996**	**İzmir 2005**
Vegetable and Putrescible	45.6	38.0	57.05	56
Paper and Cardboard	7.4	8.5	13.29	4.7
Leather and Textile	2.4	5.3	4.86	1.5
Plastics	4.4	2.7	13.45	12
Stones and Debris	6.5	6.1	10.03	-
Glass	2.0	3.2	10.3	3
Metals	3.3	10.5	10.3	8
Others	26.9	25.7	1.76	14.8

* Others wastes are included leather and textile and stones and debris waste types.

SW data obtained for the years of 2008 and 2009 through winter-summer periods are presented in Table 4.2.

Table 4.2 Properties of İzmir MSW (E.O.Işın, UKAY 2011)

Solid waste components	**2008 Winter-Summer Average %**	**2009 Winter-Summer Average %**	**Average % Waste Component**
Food waste	48,79	40,05	44,42
Paper	8,61	6,32	7,46
Cardboard	3,63	2,74	3,18
Voluminous Cardboard	0,74	2,04	1,39
Plastic	8,31	7,16	7,73
Glass	5,37	5,00	5,18
Metal	1,65	0,32	0,98
Voluminous Metal waste	0,12	0,09	0,11
Electric and electronic waste	0,06	0,14	0,10
Hazardous waste	0,30	0,56	0,43
Yard waste	1,12	4,69	2,91
Other incombustibles	1,71	11,21	6,46

Table 4.2 Properties of İzmir MSW (E.O.Işın, UKAY 2011) (Continue)

Other combustibles	8,04	12,24	10,14
Other voluminous combustibles waste	0,12	0,97	0,54
Other voluminous incombustibles waste	0,00	0,00	0,00
Other	0,25	0,74	0,50
Ash	11,18	5,80	8,49

Table 4.3 SW Quantities of Turkey and Metropolitan City of Izmir (TUİK, 2010)

Provide Service of MSW															
Population			**Number of the survey application in municipality**	**Total Number of the municipality**	**Population of Municipality**	**Total Population ratio to survey population (%)**	**Municipality capita ratio total capita (%)**	**Collected MSW**							
								Total		**Summer**			**Winter**		
Cities	**Total**	**Municipality**						**MSW (Ton/Year)**	**Per. Capita Generation (Kg/Ca.Day)**	**Summer (Ton/Summer)**	**Per Day (Ton/Day)**	**Per. Capita Generation (Kg/Ca.Day)**	**Winter (Ton/Winter)**	**Per Day (Ton/Day)**	**Per. Capita Generation (Kg/Ca.Day)**
TÜRKİYE	**73,722,988**	**61,571,332**	**2,950**	**2,879**	**60,946,131**	**83**	**99**	**25,276,698**	**1.14**	**14,430,540**	**70,352**	**1.15**	**10,846,158**	**66,906**	**1,10**
İzmir	3,948,848	3,670,764	54	54	3,662,026	93	100	1,685,659	1.26	1,145,597	4,695	1.28	540,062	4,463	1,22

4.2 Solid Waste Landfill Site

Solid wastes generated in Izmir Metropolitan City have been disposed of in Harmandalı landfill site. Harmandalı landfill is located at 38.32-38.33 longitude and 27.05-27.10 North latitude and 2.5 km east of the district. Landfill site, which is 25 km away from the centrum, can be accessed via İzmir-Karşıyaka-Menemen highway 12km.

Fig 4.1 Harmandalı New Lot Constraction

The landfill area has an impervious geological structure for underground water transmission. Geological studies show that the transmission coefficient is 10^{-7}m/sec and layered with clay and silt.

Harmandalı Landfill has been in operation since 1992 and consists of 9.000.000 m^2 area. Its capacity was planned to sustain the needs of İzmir 10-15 years at minimum. The capacity of the landfill is 3000 t day^{-1} of domestic, medical, and industrial wastes and wastewater treatment sludge. Capacity of the landfill site was reached to maximum and thus plant was enlarged by arrangement of new lots and it has been still serving as a unique landfill site in city.

With the 31.01.2011 dated Regulated Solid Waste Storage Area New Storage Lot Construction Bid, lot capacity of the current storage area was increased to 3.214.775

m^3. With 1.000.000 tons of solid waste storage annual figure, current lot of Harmandalı Landfill Area's working life will cease in 2014. (http://www.ihale.gen.tr/yilan.php?foy=00819038).

The methane gas generation models were applied for current lot. Closure time of the lot was taken as 2014.

4.3 Evaluating the Model Inputs

In this chapter, the data that would be used for modeling study is defined. Model invariables used in calculations, i.e. k and L_0, are determined by using the equations given in Chapter 2, including parameters such as temperature, rainfall and biological degradability. Theoretical studies and the series of field measurement results were reviewed to improve the existing studies. Data obtained from various field measurements during the professional career of authors, i.e. 5 different landfill rehabilitation projects and 2 Municipal Solid Waste Landfill construction project were considered. However, since required permissions did not receive to use those data; it was used solely to improve the theoretical results.

5 rehabilitation of old dump side (KATSİS Project) and 2 (KATSİS Project and Harmandalı New Lot Construction) Constriction of landfill Environmental projects have been carried out in Aegean Region. Along these projects I also took part in Harmandalı Regulated Landfill LFG Gas Measurements Project, methane gas potential modeling study in Uşak Regulated Solid Waste Storage Area (LandGEM), and LFG potential measurements carried out by Dokuz Eylül University. Field measurements were done to determine the LFG quantity and composition by the author during these projects.

In accordance with these case studies, conditions adversely affecting the LFG quantity are underlined below:

Regarding to operation and storage, the irregular usage of daily cover, lack of storing with the proper method of trench, the inadequate pipelines for collection of leaking water or lack of mentioned pipelines, problems regarding LFG wells and construction of these wells, uncontrolled storage in rehabilitation sites and uncontrolled fire incidents in storage sites are common problems in landfill sites.

Regarding to collecting and transportation system, collection system and characteristics of waste buried at landfill are other elements affecting the LFG quantity and composition.

When regulations and implementations are viewed, the first regulation is the Regulation for Solid Waste Control in 1991. In many occasions in the aspects of collection, transportation and disposal of solid waste, the regulations are inefficient and could not be implemented. Compost facilities, recycling facilities, storage sites are constructed but insufficient in number and could not be operated efficiently. Collection system is still being carried out as mixed collection even today. Even though many settlements and regions were chosen for dual collection pilot program, it is not a common practice. When developing countries were viewed the situation isn’t quite different.

The data that will be used for modeling shall be evaluated in two groups, acquisition and collection. A sensible categorization approach shall be as 1st group of data is the data acquired in field measurements, 2nd group data is the data that shall be gathered in lab environment.

4.3.1 First Group Data

First group data is gathered during field studies by measuring. At this point, the important aspect is the analyzing of the data. The data derived from different sites and different measurement point need to be merged with the characteristics of the waste.

The required measurements are carried out regarding the composition of LFG and as a result an average value of 40% methane gas concentration was attained. A detailed study was conducted in order to measure the LFG capacity in old un-rehabilitated storage sites. In addition to the measurements, in most wells LFG flow rate value was measured below the limits, therefore unqualified data was obtained. Similar problems were also encountered in storage sites in operation.

Another limiting element was the lack of records regarding the quantity and quality (characteristics) of waste in place. In addition, data is partly inconsistent with the model data that was the adverse features of the operating conditions in the site.

In the field measurements, methane, carbon dioxide and oxygen concentrations in LFG as percentage and total LFG flow rate was measured. The waste quantity data were gathered from current records and the waste quantities of daily stored waste. The composition of the incoming waste was determined.

Therefore, the data about the waste quantity and composition was collected through field measurements and previous records.

In general the elements affecting the LFG quantity and composition can be viewed in two groups.

(i) The operating conditions of the storage site
(ii) The collection system and waste generated in households.

The negative conditions were reflected to the modeling as best as possible. In general, most models were not designed to include these negative aspects. But in calculation, some considerations were made for Lo and k in order to reflect these negative elements.

4.3.2 Second Group Data

In landfill constructions and rehabilitation projects, excessive work was done on the field. The data considered as the 2nd group of data was attained by literature, studies specified the biological and chemical properties of the municipal solid waste gathered in the Region, and laboratory analyses.

In Turkey, the studies conducted in order to determine the properties of solid waste are scarce and in irregular periods. For this reason, there is no sufficient data regarding municipal solid wastes. Therefore, results of the studies achieved at foreign countries (i.e. literature) were taken into consideration having similar waste composition and climate attributes.

When the model was run with the data collected through field measurements and reviewing the literature, the applicable results were taken from the study conducted in İzmir Harmandalı Landfill site. The most important reason for this was the detailed data regarding the waste quantity and composition, regular storage compared to other rehabilitation sites and the application of daily cover. In the further pages of this chapter the calculation of L_0 and k values and the running of the model are presented.

4.4 Model Inputs

4.4.1 L_O Methane Generation Potential Data

Lo, Methane Generation Potential is calculated by two methods, i.e. Default Model (USA EPA 1998) and the IPCC Method. Detailed explanation is included Chapter 3 3.10.1. In order to determine the Lo, methane generation potential of the organic matter was calculated by using these methods. Afterwards, Lo was determined using following equation and presented at Table 4.4.

- *Default Model (USA EPA (1998))*

$$C_m = \frac{\sum_{i=1}^{n} BF_i . FR_i . C_{mi}}{BF_w}$$

$$L_0 = \frac{BF_w . C_m}{1 + w}$$

Table 4.4 Methane generation potentials various components of SW

Organic Compounds in SW	**FR***	West Fraction	FRi	BFi	BFi x FRi	**Cmi****	BFi*FRi*Cmi	CM	w (orbit 2006)	Lo***
Food waste	0,74	0,4442	0,33	0,72	0,24	315	74,5510	293,09	0,53	57,22
Office paper	0,80	0,0746	0,06	0,44	0,03	223	5,8558			
Cardboard	0,84	0,05	0,04	0,38	0,01	235	3,4280			
Yard waste	0,72	0,03	0,02	0,65	0,01	127	1,7296			
Textiles	0,59	0,03	0,02	0,40	0,01	262	1,9786			
				∑BFW	0,30		∑87,54			

*Dry matter content in % of wet weight

** organic matter methane generation potential (m3 CH4 / dry Mg)

*** (m3 CH4/Mg of SW)

- *IPCC (2006) Method*

$$DDOC_m = MCF . \sum_{i=1}^{n} DOC_i . FR_i . DOC_{fi}$$

$$L_0 = \frac{0{,}05.0{,}554.\frac{16}{12}(\frac{1000Kg}{MG})}{0{,}72(1 + 0{,}53)} = 32{,}49$$

Table 4.6 Calculation table of DOCF

IPCC (2006)								
Organic compound of Solid Waste	Percent DOC (by weight) in wet SW	West Fraction	DOC*	FR_i	$**DOC_F$	Total	MCF	$DDOC_M$
Food waste	0,15	0,4442	0,07	0,74	0,84	0,04	0,60	0,05
Office paper	0,40	0,0746	0,03	0,80	0,84	0,02		
Cardboard	0,40	0,05	0,02	0,84	0,84	0,01		
Yard waste	0,20	0,03	0,01	0,72	0,84	0,00		
Textiles	0,24	0,03	0,01	0,59	0,84	0,00		

* IPCC (2006) 0,08

$**DOC_F = 0.014 \times T + 0.28$ (Default 0.5) t= 40 ^{0}C

Table 4.7 Calculation table of Lo

F_{CH4}	16/12	$\rho CH4$ (kg/m^3)	(1+w)		L_0 (m^3 CH_4/Mg of MSW)
0,55	1,33	0,72	1,53	0,033	32,549

The results regarding to calculated Lo value obtained from Default model and IPCC are summarized in following table.

Table 4.4 Methane Generation Potential (Lo) Data

Method	**Organic Waste**	**Waste fraction (%)**	**BF***	**Cmi****	**Fri**	**Lo (m^3 CH_4/Mg)**
Default Model (USA EPA (1998))	Food waste	44,42	0,72	315	0,33	57,22
	Office paper	7,76	0,44	223	0,06	
	Cardboard	0,50	0,38	235	0,04	
	Yard waste	0,30	0,65	127	0,02	
	Textiles	0,30	0,40	262	0,02	
	Organic Waste	**Waste fraction (%)**	**DOCF*****	**MCF**	**Fr**	**Lo (m^3 CH_4/Mg)**
IPCC (2006)	Food waste	44,42	0,84	0,60	0,74	32,55
	Office paper	7,76	0,84	0,60	0,80	
	Cardboard	4,57	0,84	0,60	0,84	
	Yard waste	2,91	0,84	0,60	0,72	
	Textiles	3,32	0,84	0,60	0,59	

* BF: BF values are used from literature given in Chapter Two (Machado, Carvalho, Gourc, Vilar, & do Nascimento, 2009)

** Cmi: Methane generation (Cm) and water consumption are used from literature given in Chapter Three (Machado et al., 2009)

***DOC_F: $DOC_F = 0.014T + 0.28$ (Chapter Two)

Table 4.5 Summary of the data (Lo)

Method	**Cm_i**	**MFC**	**$DDOC_m$**	**Lo (m^3 CH_4/Mg)**
USA EPA (1998)	68,76	-	-	57,22
IPCC (2006)	-	0,60	4,26	32,55

In order to compare the results, various data obtained from gas generation model applications are presented in Table 4.6.

Table 4.6 Results of the numerous empirical landfill gas generation model applications (Amini, Reinhart, & Mackie, 2012)

Study	**Models**	**Landfill characteristics**	**k (yr^{-1})**	**L0 (m^3 g^{-1})**	**Error[a]**	**References**
Validating LFG generation models based on 35 Canadian landfill	Zero-order German EPER TNO Belgium Scholl Canyon LandGEM version 2.01	35 Canadian landfills	0.023 – 0.056	90-128	(-81%) - (+589%)	Thompson et al. (2009)
The CDM landfill gas projects by the World Bank	IPCC First-order Rettenberger First-order E-PLUS US EPA LandGEM Dutch Multiphase Scholl Canyon	Six landfills in South America and Europe	0.014–0.28	68–102	(-3%) - (+1109%)	Willumsen and Terraza (2007)

Table 4.6 Results of the numerous empirical landfill gas generation model applications (Amini, Reinhart, & Mackie, 2012) (Countinue)

Comparison of landfill methane emission models: A case study	US EPA LandGEM French ADEME UK GasSim IPCC Tier 2	Four French landfill	0.04–0.50	44–170	(-65%) – (+140 %)	Ogor and Guerbois (2005)
Landfill gas energy recovery: economic and environmental evaluation for a case study	Scholl Canyon	Casa Rota Landfill, Tuscan, Italy	0.07–0.36	13–30	+5%	Corti et al. (2007)
a The error comparing model estimations to actual data, with negative indicating model estimation is lower than actual.						

4.4.2 *k Methane Generation Rate Constant Data*

In Table 4.7, data regarding to methane generation rate constant (k values) which are used in theoretical calculations are given. As a results of those data, k values can be taken as 0,175 for rapid degradation; 0,1 as moderate degradation and 0,056 for slow degradation conditions.

Table 4.7 k Methane generation rate constant data (Amini et al., 2012)

k Value	**Type of waste**	**West Fraction**	**Type**	**Default**	**Range**	**User spc.**	**Ln(2)/(t*1/2)**
Wet boreal and temperate climate	Food waste	44,42	Rapidly degrading	0,185	0,1-0,2	**0.175**	0,175
	Office paper	7,56	Slowly degrading	0,060	0,05-0,07	**0.060**	0,060
	CardBoard	4.57	Slowly degrading	0,060	0,05-0,07	**0.055**	0,055
	Yard waste	2.91	Moderately degrading	0,100	0,06-0,1	**0.100**	0,100

Table 4.7 k Methane generation rate constant data (Amini et al., 2012)

Wet boreal and temperate climate	Texttiles	3,32	Slowly degrading	0,060	0,05-0,07	**0,050**	0,050
Rapidly degrading		**0,175**					
Moderately degrading		**0,100**					
Slowly degrading		**0,056**					

4.4.3 Quantity of MSW in İzmir Region

The annual municipal solid waste generations presented in Table 4.8 together with the population projections. According to the data, waste quantities to be disposed of in the year of 2014 are expected to reach 1,326,914 ton.

Table 4.8 Quantity of MSW in İzmir Region (TUİK, 2007-2010)

Year	**Capita**	**MSW (Ton/Year)**
2007	3,175,133	760,268
2008	3,450,537	815,018*
2009	3,525,202	1,057,274
2010	3,606,326	1,299,530*
2011	3,623,540	1,306,253
2012	3,641,000**	1,313,263**
2013	3,658,000**	1,320,089**
2014	3,675,000**	1,326,914**

* TUİK data

** Population projection and Annual waste production projection

4.4.4 Percentage of Methane Gas Concentration

LFG composition was measured in the field by using Geotech GA 200 and Geotech Innova LS equipments. In the calculations, LFG concentrations are taken as 50% for methane, and 40% for carbon dioxide.

4.5 Model Outputs

4.5.1 EPA LandGEM Model

EPA LANDGEM Model was run the input data, i.e. Lo and k, calculated using the USA EPA (1998) method (RUN 1) and IPCC (2006) method (RUN 2). Lo values were taken as 57.22 and 32.55 for RUN 1 and 2 respectively. Other parameters, i.e. k and methane percentage, were used as 0.142 and 50% for both conditions. The results are presented at Table 4.9 and 4.10 for RUN 1 and RUN 2.

Table 4.9 EPA LandGEM RUN1 Table

RUN 1					
Year	**Waste Accepted**	**Waste-In-Place**	**Total Landfill Gas**	**Methane**	**Carbon Dioxide**
	(Mg/year)	**(Mg)**	**(m^3/year)**	**(m^3/year)**	**(m^3/year)**
2007	478,817	0	0	0	0
2008	513,298	478,817	7,305,422	3,652,711	2.922.169
2009	665,871	992,115	14,169,855	7,084,927	5.667.942
2010	818,444	1,657,986	22,453,423	11,226,711	8.981.369
2011	822,678	2,476,430	31,968,262	15,984,131	12.787.305
2012	827,093	3,299,108	40,288,141	20,144,070	16.115.256
2013	831,392	4,126,202	47,574,005	23,787,003	19.029.602
2014	835,691	4,957,593	53,960,962	26,980,481	21.584.385
2015	0	5,793,284	59,568,008	29,784,004	23.827.203
2016	0	5,793,284	51,682,470	25,841,235	20.672.988
2017	0	5,793,284	44,840,810	22,420,405	17.936.324
2018	0	5,793,284	38,904,840	19,452,420	15.561.936
2019	0	5,793,284	33,754,666	16,877,333	13.501.866
2020	0	5,793,284	29,286,266	14,643,133	11.714.506
2021	0	5,793,284	25,409,387	12,704,693	10.163.755
2022	0	5,793,284	22,045,724	11,022,862	8.818.290
2023	0	5,793,284	19,127,339	9,563,669	7.650.935
2024	0	5,793,284	16,595,286	8,297,643	6.638.114
2025	0	5,793,284	14,398,423	7,199,211	5.759.369
2026	0	5,793,284	12,492,377	6,246,189	4.996.951
2027	0	5,793,284	10,838,652	5,419,326	4.335.461
2028	0	5,793,284	9,403,845	4,701,923	3.761.538
2029	0	5,793,284	8,158,976	4,079,488	3.263.590
2030	0	5,793,284	7,078,901	3,539,450	2.831.560

Table 4.9 EPA LandGEM RUN1 Table (Continue)

2031	0	5,793,284	6,141,805	3,070,902	2.456.722
2032	0	5,793,284	5,328,760	2,664,380	2.131.504
2033	0	5,793,284	4,623,346	2,311,673	1.849.338
2034	0	5,793,284	4,011,313	2,005,657	1.604.525
2035	0	5,793,284	3,480,301	1,740,150	1.392.120
2036	0	5,793,284	3,019,583	1,509,791	1.207.833
2037	0	5,793,284	2,619,854	1,309,927	1.047.942
2038	0	5,793,284	2,273,041	1,136,521	909.216
2039	0	5,793,284	1,972,139	986,069	788.856
2040	0	5,793,284	1,711,070	855,535	684.428
2041	0	5,793,284	1,484,560	742,280	593.824
2042	0	5,793,284	1,288,036	644,018	515.214
2043	0	5,793,284	1,117,528	558,764	447.011
2044	0	5,793,284	969,591	484,795	387.836
2045	0	5,793,284	841,237	420,619	336.495
2046	0	5,793,284	729,875	364,938	291.950
2047	0	5,793,284	633,255	316,628	253.302
2048	0	5,793,284	549,426	274,713	219.770
2049	0	5,793,284	476,694	238,347	190.677
2050	0	5,793,284	413,590	206,795	165.436
	TOTAL		664,577,453	332,288,727	265,996,417

Table 4.10 EPA LandGEM RUN2 Table

RUN 2					
Year	**Waste Accepted**	**Waste-In-Place**	**Total Landfill Gas**	**Methane**	**Carbon Dioxide**
	(Mg/year)	**(Mg)**	**(m^3/year)**	**(m^3/year)**	**(m^3/year)**
2007	478,817	0	0	0	0
2008	513,298	478,817	4,155,741	2,077,870	1.662.296
2009	665,871	992,115	8,060,622	4,030,311	3.224.249
2010	818,444	1,657,986	12,772,788	6,386,394	5.109.115
2011	822,678	2,476,430	18,185,371	9,092,686	7.274.148
2012	827,093	3,299,108	22,918,193	11,459,096	9.167.277
2013	831,392	4,126,202	27,062,808	13,531,404	10.825.123
2014	835,691	4,957,593	30,696,073	15,348,037	12.278.429
2015	0	5,793,284	33,885,681	16,942,841	13.554.272
2016	0	5,793,284	29,399,937	14,699,969	11.759.975

Table 4.10 EPA LandGEM RUN2 Table (Continue)

2017	0	5,793,284	25,508,010	12,754,005	10.203.204
2018	0	5,793,284	22,131,292	11,065,646	8.852.517
2019	0	5,793,284	19,201,579	9,600,790	7.680.632
2020	0	5,793,284	16,659,698	8,329,849	6.663.879
2021	0	5,793,284	14,454,309	7,227,154	5.781.723
2022	0	5,793,284	12,540,865	6,270,433	5.016.346
2023	0	5,793,284	10,880,721	5,440,361	4.352.289
2024	0	5,793,284	9,440,345	4,720,173	3.776.138
2025	0	5,793,284	8,190,644	4,095,322	3.276.258
2026	0	5,793,284	7,106,377	3,553,188	2.842.551
2027	0	5,793,284	6,165,644	3,082,822	2.466.257
2028	0	5,793,284	5,349,444	2,674,722	2.139.777
2029	0	5,793,284	4,641,291	2,320,645	1.856.516
2030	0	5,793,284	4,026,883	2,013,441	1.610.753
2031	0	5,793,284	3,493,809	1,746,904	1.397.524
2032	0	5,793,284	3,031,303	1,515,651	1.212.521
2033	0	5,793,284	2,630,023	1,315,011	1.052.009
2034	0	5,793,284	2,281,864	1,140,932	912.745
2035	0	5,793,284	1,979,793	989,897	791.917
2036	0	5,793,284	1,717,711	858,855	687.084
2037	0	5,793,284	1,490,322	745,161	596.129
2038	0	5,793,284	1,293,035	646,518	517.214
2039	0	5,793,284	1,121,865	560,933	448.746
2040	0	5,793,284	973,354	486,677	389.342
2041	0	5,793,284	844,503	422,251	337.801
2042	0	5,793,284	732,708	366,354	293.083
2043	0	5,793,284	635,713	317,857	254.285
2044	0	5,793,284	551,558	275,779	220.623
2045	0	5,793,284	478,544	239,272	191.418
2046	0	5,793,284	415,195	207,597	166.078
2047	0	5,793,284	360,232	180,116	144.093
2048	0	5,793,284	312,545	156,272	125.018
2049	0	5,793,284	271,171	135,585	108.468
2050	0	5,793,284	235,273	117,637	94.109
	TOTAL		**378,049,565**	**189,024,782**	**151,313,935**

The results obtained for RUN 1, RUN 2 and RUN3 are shown in Table 4.11. RUN 3 was determined by default values of LandGEM model. The highest landfill gas production was obtained for RUN 3 due to higher input parameters. RUN 1 and RUN 2 which were considered local conditions in the calculations, were resulted lower values.

Table 4.11 Summary data of LFG generation (EPA LandGEM model)

	RUN1	**RUN2**	**RUN3***
Lo	57.22	32.55	170
k (year^{-1})	0.142	0.142	0.05
Methane Concentration	50%	50%	50%
TOTAL LFG (m^3/year)	664,577,453	378,049,565	1,693,533,842
TOTAL METHANE (m^3/year)	332,288,727	189,024,782	846,766,921
TOTAL CARBON DIOKSİDE (m^3/year)	265,996,417	151,313,935	677,413,536

4.5.2 Multiphase Model

The results of Multiphase model are presented in Table 4.12. Input data, i.e. Lo and k values, were calculated using EPA (1998) method (RUN 1).

Table 4.12 Multiphase Model RUN1

Year	**Total LFG (m^3/year)**	**Methane (m^3/year)**
2007	0	0
2008	6,313,235	3,156,618
2009	11,162,093	5,581,047
2010	15,942,113	7,971,056
2011	20,384,774	10,192,387
2012	23,290,534	11,645,267
2013	25,031,132	12,515,566
2014	25,896,957	12,948,479
2015	26,116,053	13,058,027
2016	22,590,469	11,295,235
2017	19,588,896	9,794,448
2018	17,029,952	8,514,976
2019	14,845,133	7,422,567
2020	12,976,758	6,488,379
2021	11,376,243	5,688,122
2022	10,002,656	5,001,328
2023	8,821,495	4,410,747
2024	7,803,667	3,901,833
2025	6,924,630	3,462,315
2026	6,163,670	3,081,835
2027	5,503,294	2,751,647
2028	4,928,722	2,464,361
2029	4,427,455	2,213,727
2030	3,988,917	1,994,458
2031	3,604,153	1,802,076
2032	3,265,571	1,632,786

Table 4.12 Multiphase Model RUN1 Table (Continue)

2033	2,966,733	1,483,367
2034	2,702,169	1,351,084
2035	2,467,229	1,233,615
2036	2,257,955	1,128,978
2037	2,070,974	1,035,487
2038	1,903,404	951,702
2039	1,752,785	876,393
2040	1,617,007	808,504
2041	1,494,262	747,131
2042	1,382,995	691,497
2043	1,281,867	640,933
2044	1,189,722	594,861
2045	1,105,560	552,780
2046	1,028,516	514,258
2047	957,834	478,917
2048	892,858	446,429
2049	833,015	416,507
2050	777,800	388,900
Toplam	**346,661,257**	**173,330,629**

Table 4.13 Summary data of LFG generation (Multiphase Model)

Multi-Phase	**RUN1**
C (Kg C/Ton Waste)	100
$k_{\text{Rapidly degrading}}$ (year^{-1})	0.1750
$k_{\text{Moderately degrading}}$ (year^{-1})	0.1000
$k_{\text{Slowly degrading}}$ (year^{-1})	0.0560
TOTAL LFG (m^3/year)	346,661,257
TOTAL METHANE (m^3/year)	173,330,629
TOTAL CARBON DIOKSIDE (m^3/year)	138,664,502

4.5.3 Tabasaran Rettenberger Model

Tabasaran Rettenberger Model was run by input data, i.e. Lo and k values, obtained from EPA (1998) Method (RUN 1). The results are presented in Table 4.14 for the years of 2007 and 2050. Total LFG generation at the end of the 2015 was calculated as 106,683,725,16 m^3.

Table 4.14 Tabasaran Rettenberger Model Results (RUN1)

Year	**Total LFG (m^3/year)**	**Methane (m^3/year)**
2007	0	0
2008	14,214,726	7,107,363
2009	26,644,003	13,322,001
2010	28,393,649	14,196,824
2011	10,219,450	5,109,725
2012	7,615,134	3,807,567
2013	5,695,303	2,847,652
2014	4,314,117	2,157,059
2015	2,673,859	1,336,930
2016	1,928,140	964,070
2017	1,390,396	695,198
2018	1,002,625	501,312
2019	723,000	361,500
2020	521,361	260,680
2021	375,957	187,979
2022	271,106	135,553
2023	195,496	97,748
2024	140,974	70,487
2025	101,657	50,829
2026	73,306	36,653
2027	52,861	26,431
2028	38,119	19,059
2029	27,488	13,744
2030	19,822	9,911
2031	14,293	7,147
2032	10,307	5,154
2033	7,433	3,716
2034	5,360	2,680
2035	3,865	1,932
2036	2,787	1,394
2037	2,010	1,005
2038	1,449	725
2039	1,045	523
2040	754	377
2041	543	272
2042	392	196
2043	283	141
2044	204	102

Table 4.15 Tabasaran Rettenberger Model Results (RUN1) (Continue)

2045	147	73
2046	106	53
2047	76	38
2048	55	28
2049	40	20
2050	29	14
TOTAL	**106,683,725,16**	**53,341,863**

Table 4.16 Summary data of LFG generation **Tabasaran Rettenberger Model**	**RUN1**
C (Kg C/Ton Waste)	100
k (year^{-1})	0.142
TOTAL LFG (m^3/year)	106,683,725,16
TOTAL METHANE (m^3/year)	53,341,863
TOTAL CARBON DIOKSIDE (m^3/year)	42,673,490

4.5.4 Scholl Canyon Model

Scholl Canyon Model was run by input data, i.e. Lo and k values, obtained from EPA (1998) Method (RUN 1) and IPCC (2006) method (RUN 2).. The results are presented in Table 4.17 for the years of 2007 and 2050. Total LFG generation at the end of the 2015 was calculated as 97,235,791 m^3 for RUN1 and 105,536,012 m^3 for RUN2.

Table 4.17 Summary data of LFG generation (Scholl Canyon Model RUN1 and 2)

Year	RUN1		RUN2	
	Total LFG (m^3/year)	**Methane (m^3/year)**	**Total LFG (m^3/year)**	**Methane (m^3/year)**
2007	0	0	0	0
2008	3,375,483	1,687,742	1,920,167	960,084
2009	6,068,183	3,034,091	3,451,928	1,725,964
2010	8,798,481	4,399,240	5,005,078	2,502,539
2011	11,402,053	5,701,026	6,486,138	3,243,069
2012	13,179,038	6,589,519	7,496,988	3,748,494
2013	14,301,044	7,150,522	8,135,250	4,067,625
2014	14,907,966	7,453,983	8,480,501	4,240,251

Table 4.17 Summary data of LFG generation (Scholl Canyon Model RUN1 and 2) (Continue)

2015	15,114,803	7,557,401	8,598,162	4,299,081
2016	13,113,924	6,556,962	7,459,948	3,729,974
2017	11,377,919	5,688,960	6,472,410	3,236,205
2018	9,871,725	4,935,862	5,615,600	2,807,800
2019	8,564,918	4,282,459	4,872,214	2,436,107
2020	7,431,105	3,715,553	4,227,236	2,113,618
2021	6,447,385	3,223,692	3,667,640	1,833,820
2022	5,593,888	2,796,944	3,182,123	1,591,061
2023	4,853,376	2,426,688	2,760,877	1,380,439
2024	4,210,892	2,105,446	2,395,396	1,197,698
2025	3,653,460	1,826,730	2,078,296	1,039,148
2026	3,169,819	1,584,910	1,803,174	901,587
2027	2,750,203	1,375,101	1,564,472	782,236
2028	2,386,134	1,193,067	1,357,369	678,685
2029	2,070,261	1,035,130	1,177,682	588,841
2030	1,796,202	898,101	1,021,782	510,891
2031	1,558,423	779,212	886,520	443,260
2032	1,352,121	676,061	769,164	384,582
2033	1,173,129	586,565	667,343	333,671
2034	1,017,832	508,916	579,001	289,500
2035	883,092	441,546	502,353	251,177
2036	766,190	383,095	435,852	217,926
2037	664,763	332,381	378,155	189,077
2038	576,762	288,381	328,095	164,048
2039	500,411	250,206	284,662	142,331
2040	434,167	217,084	246,979	123,490
2041	376,693	188,346	214,284	107,142
2042	326,827	163,413	185,918	92,959
2043	283,562	141,781	161,306	80,653
2044	246,024	123,012	139,953	69,976
2045	213,456	106,728	121,426	60,713
2046	185,199	92,599	105,352	52,676
2047	160,682	80,341	91,405	45,703
2048	139,411	69,706	79,305	39,653
2049	120,956	60,478	68,807	34,403
2050	104,944	52,472	59,698	29,849
Total	**185,522,906**	**92,761,453**	**105,536,012**	**52,768,006**

Table 4.18 Summary data of LFG generation (Scholl Canyon Model)

	RUN1	**RUN2**
Lo	57.22	32.55
k (year^{-1})	0.142	0.142
Methane Concentration	50%	50%
TOTAL LFG (m^3/year)	185,522,906	105,536,012
TOTAL METHANE (m^3/year)	92,761,453	52,768,006
TOTAL CARBON DIOKSİDE (m^3/year)	74,209,162	42,214,404

CHAPTER FIVE
RESULTS AND DISCUSSION

5.1 Model Outputs (Graps)

Graphical representation of gas generation results obtained EPA LANDGEM Model, Multiphase Model, Tabasaran Rettenberger, and Scholl Canyon Models are shown from Figures 5.1 to 5.7. Peak values were obtained in 2015 for the each model except Tabasaran Rettenberger.

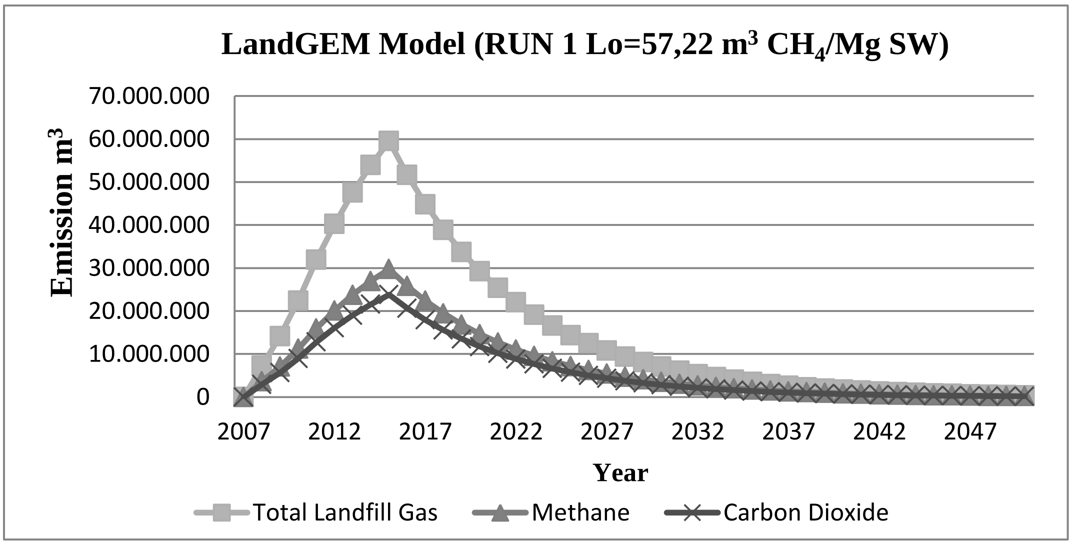


Figure 5.1 Emission Estimations by LandGEM Model (RUN 1 Lo=57,22 m3 CH4/Mg SW) x axial is represented year and y axial is represented Total LFG m3.

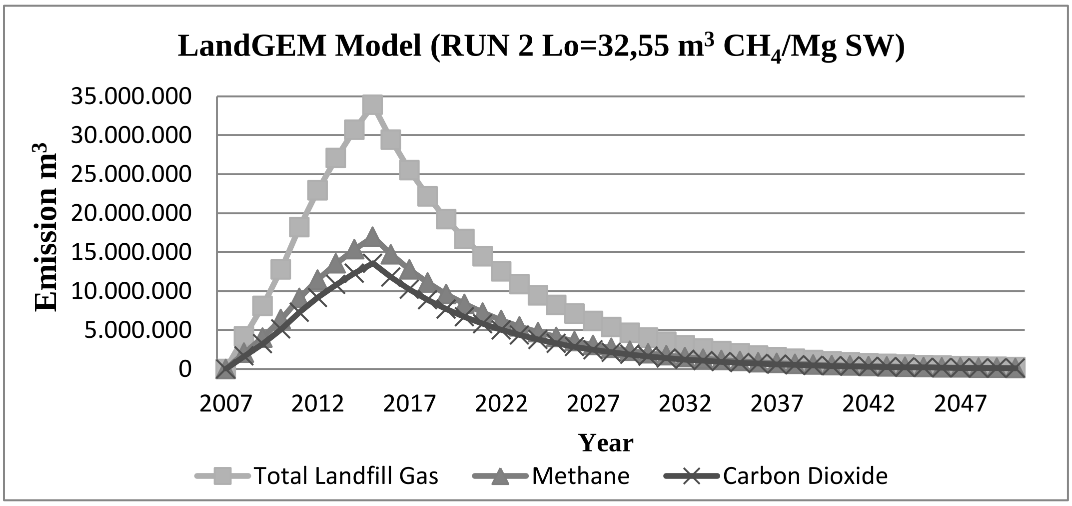


Figure 5.2 Emission Estimations by LandGEM Model (RUN 2 Lo=32,55 m3 CH4/Mg SW) x axial is represented year and y axial is represented Total LFG m3

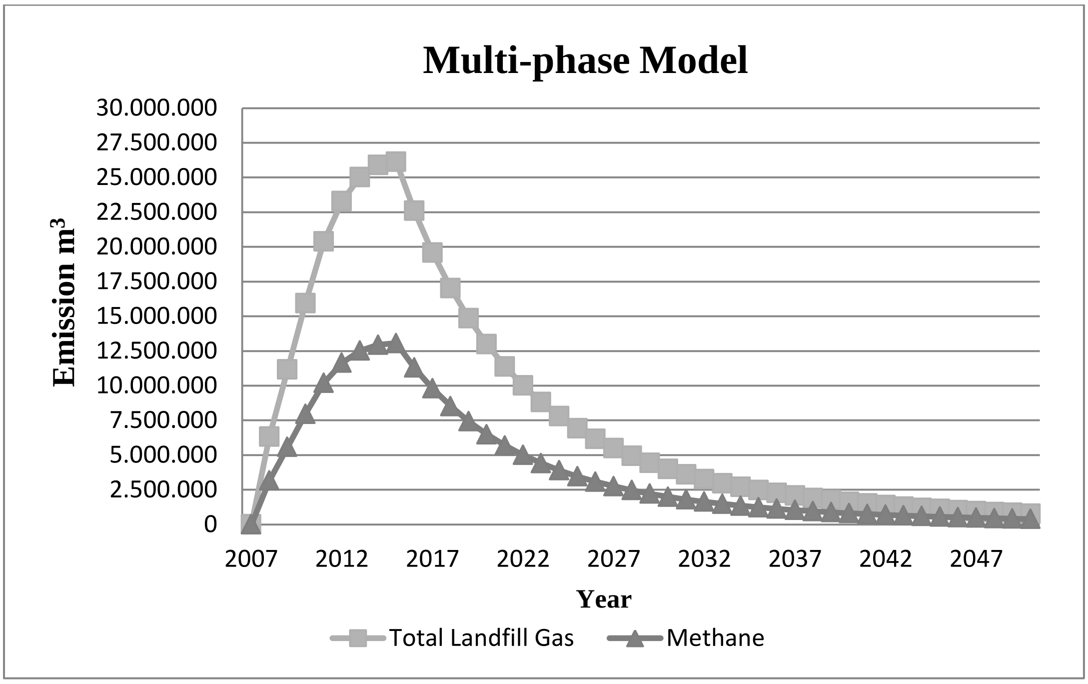


Figure 5.3 Emission Estimations by Multi-Phase Model, x axial is represented year and y axial is represented Total LFG m^3

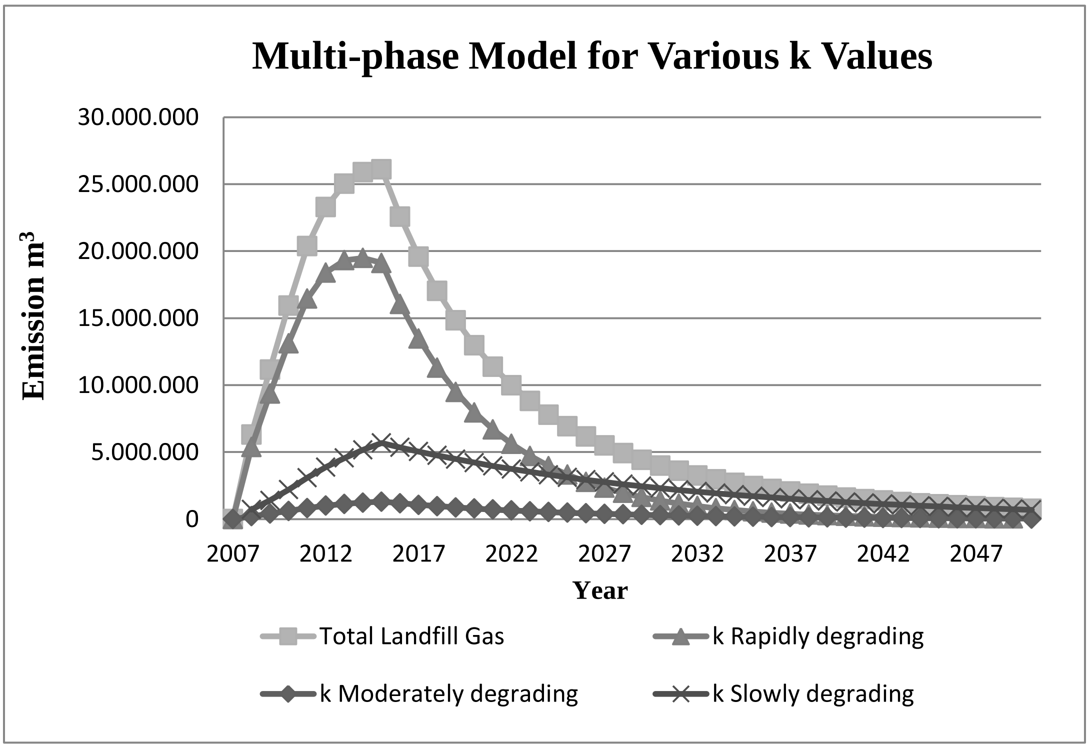


Figure 5.4 Emission Estimations by Multi-phase Model for Various k Values . That is shown total LFG generation and under the LFG generation, slowly degrading, moderately degrading and rapidly degrading organic waste decomposition

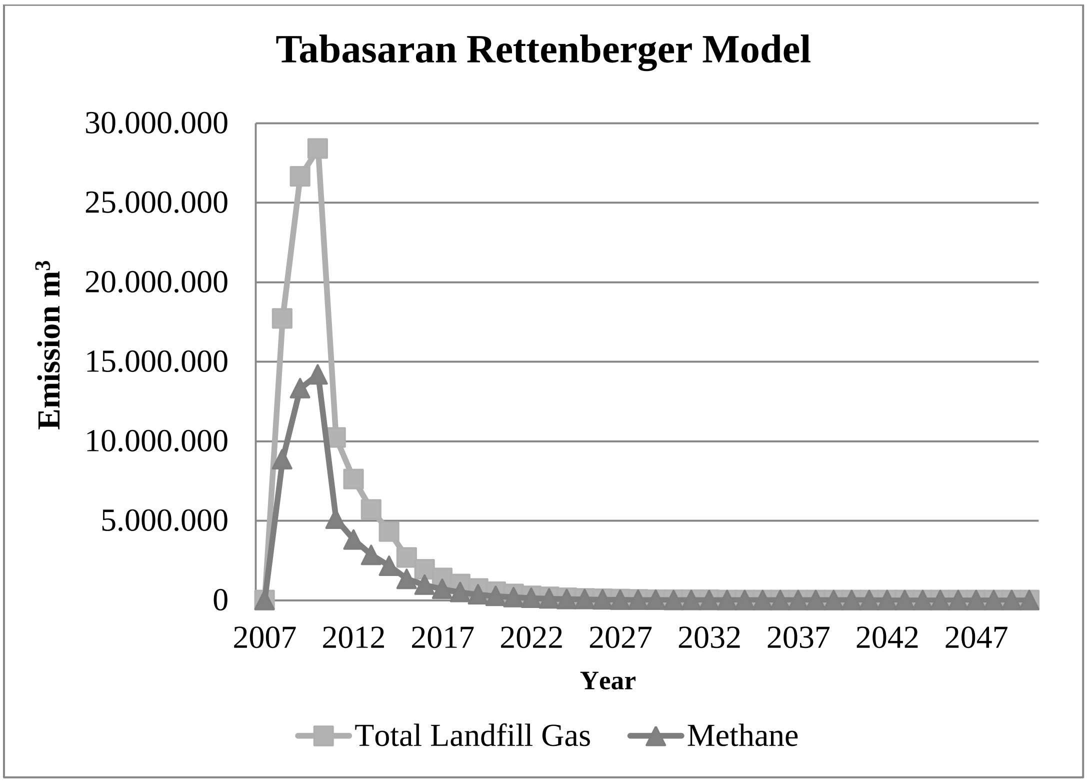


Figure 5.5 Emission Estimations by Tabasaran Rettenberger Model, x axial is represented year and y axial is represented LFG m3

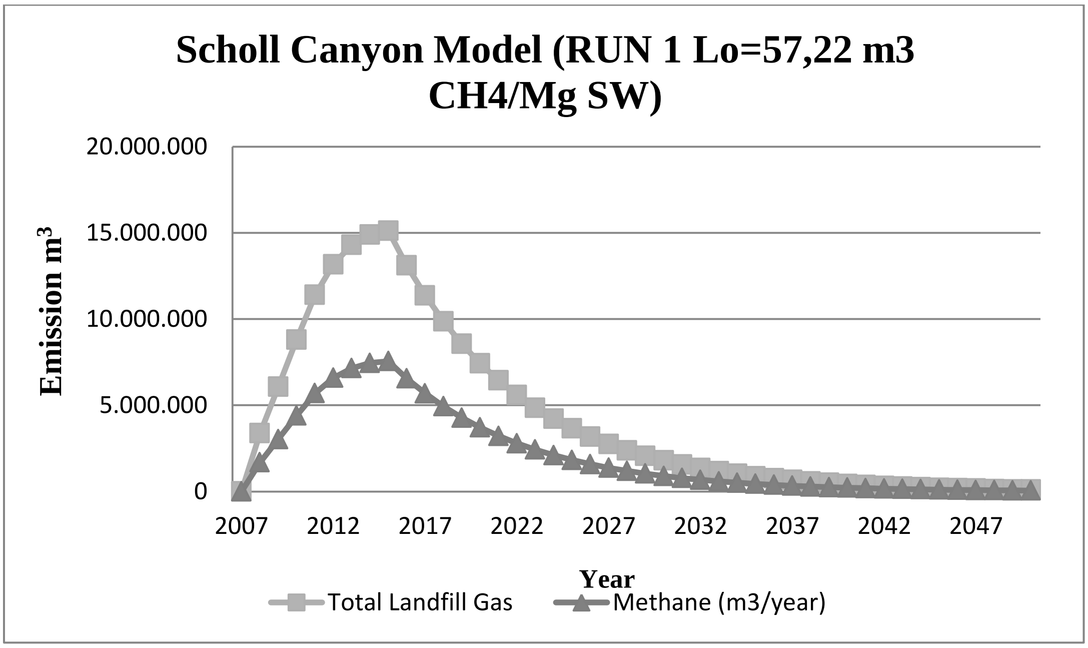


Figure 5.6 Emission Estimations by Scholl Canyon Model (RUN 1 Lo=57,22 m3 CH4/Mg SW)x axial is represented year and y axial is represented LFG m3.

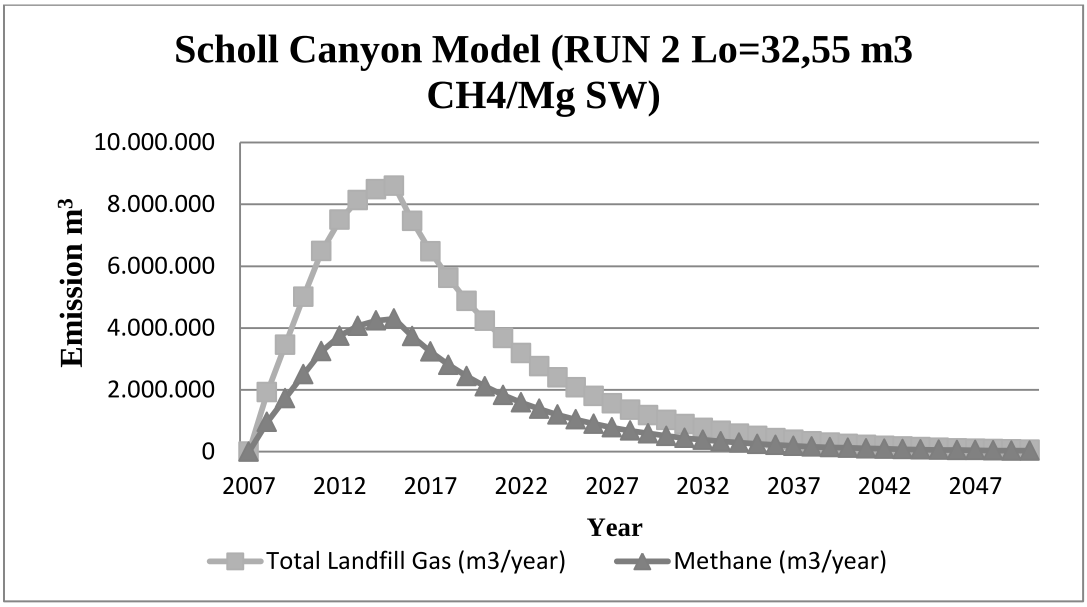


Figure 5.7 Emission Estimations by Scholl Canyon Model (RUN 2 Lo=32,55 m3 CH4/Mg SW) x axial is represented year and y axial is represented Total LFG m3.

5.2 Comparison of the Data (LFG Emissions)

Comparative data including input and out parameters are shown in Table 5.1. The k values were taken as 0,142 for each model excluding Multi-Phase model. Lo values were calculated based on USA EPA (1998) and IPCC (2006) methods and used as 57,22 and 32,55 in the models. C constant was selected from the data for MSWs in İzmir Region in literature. As a results of the modeling studies, the highest gas generation was obtained in LandGEM Models (Run 1 and 2) while lowest generation was Scholl Canyon Model.

Table 5.1 Comparison table of the output data.

Model		**k (year^{-1})**	**Lo (m^3 CH_4 / Mg)**	**C (Kg C / Mg Waste)**	**Total LFG (m^3)**	**Methane (m^3)**
LandGEM	Landgem RUN1	0.142	57.22	-	664,577,453	332,288,727
	Landgem RUN2	0.142	32.55	-	378,049,565	189,024,782
Multi-Phase	Rapidly degrading	0.1750	-	100	346,661,257	173,330,629
	Moderately degrading	0.1000	-	100		
	Slowly degrading	0.0560	-	100		

Table 5.1 Comparison table of the output data. (continue)

Tabasaran Rettenberger	Tabasaran Rettenberger	0.1420	-	100	110,176,022	55,088,011
Scholl Canyon	Scholl Canyon Run1	0.142	29.99	-	97,235,791	48,617,895
	Scholl Canyon Run2	0.142	32.55	-	105,536,012	52,768,006

Actually, model results of LandGEM and Multiphase were close to each other. Even though multi phases model run with different degrading rates, average of the k values was are reviewed for the waste quantities, it is seen that k values used in other models were approximate. C value calculated in accordance with current literature was one of the lowest C values for İzmir. When high C values are accepted and used in models, inconsistent and highly differentiated results were obtained. Lo and C values were shown indirect similarities. Tabasaran Rettenberger model was used in landfill areas where independent collection was executed and operation conditions were offered accordingly, as seen in literature. In modeling, biological degradation is fast in short period. It is estimated that the modeling is especially formed for a regulated storage area where municipal food based waste will be predominant. With this approach, higher k values for the same waste quantity was used, it is estimated that the results will be similar to two models used before.

According to Figure 5.8 When literature and case studies are reviewed, it is seen that low L_0 values are obtained. When L_0 and other input parameters are taken into consideration, the first point to review was that availability of an integrated solid waste management system. The next step was the operational conditions of landfill area. These two fundamental points were included indirectly in the equations. Placement of hazardous and inert waste to the landfill have negative effect on biological degradation, seepage water in landfill and biofilm layers and decrease the methane generation potential. The lack of independent collection will decrease the landfill generation in accordance to the overall solid waste.

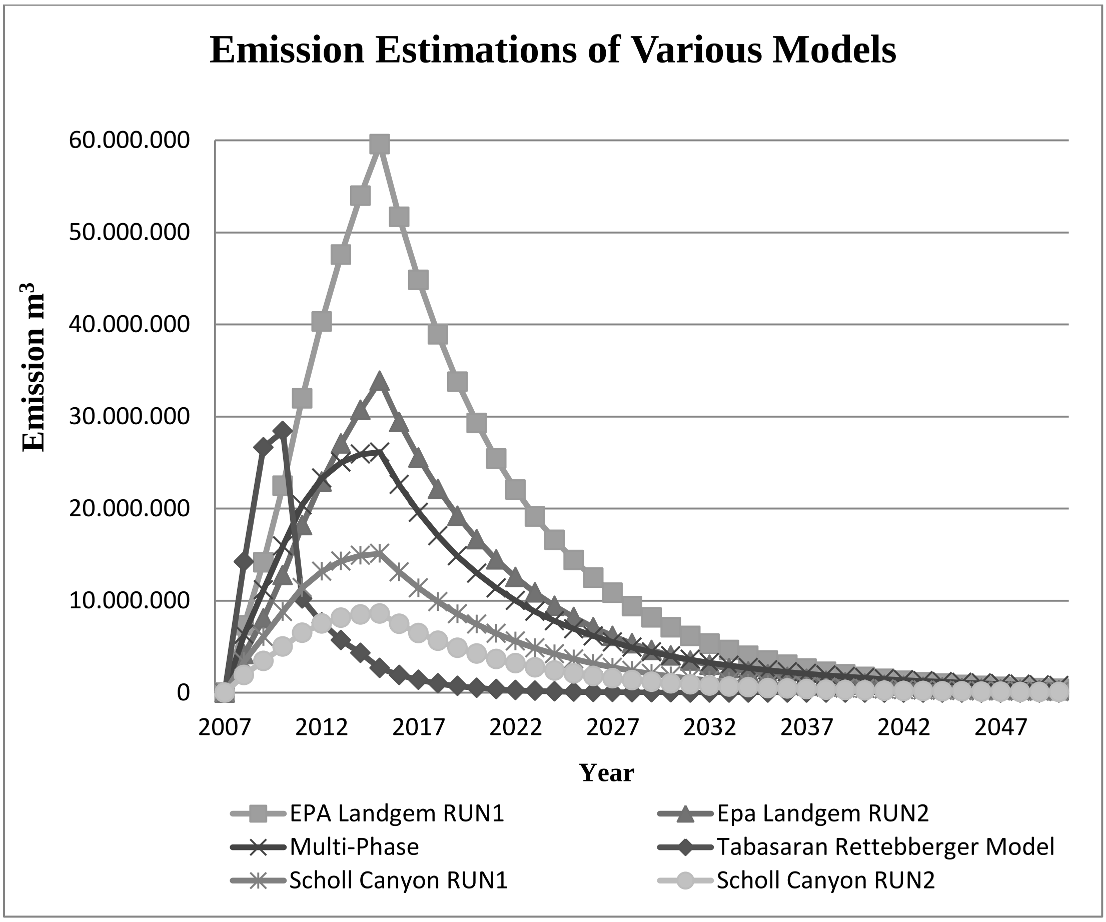


Figure 5.8 Comparative Representation of Emission Estimations of Various Models

5.3 Electricity Potential of LFG

As noted above, various technologies exist for the utilization of LFG. The alternative that is best suited for a specific site is dependent upon a number of factors including:

- projected LFG availability
- presence and location of suitable markets
- market price for end products
- environmental and regulatory factors
- capital and operating costs of utilization system options, including processing and transporting issues/costs.

Scope of these application important issues is economical factors, if the utilization plant is suitable to be application for economical that can be constructed. This decision related whit methane concentration in LFG and flow rate of LFG. The other factor is quantities of waste in place and how long can be operated the dumping side. After that this determination it is need to be evaluated the methane gasses, like this thesis. In This Chapter Part is determined and calculated electrical potential of LFG.

5.3.1 Electrical Generation Selection Factors

"Several factors must be evaluated when considering generating electricity with LFG, whether the technology involves microturbines, reciprocating engines, gas turbines, combined cycle, or steam turbines." (Factors, 1989)

"Electrical conversion efficiency, which is an indication of what portion of the energy value of the LFG can be converted into electrical power, varies with each technology. The efficiency can be described in terms of net plant "heat rate" (Btu/kWh) or gross equipment efficiency. This efficiency is equal to the total energy value in the collected LFG divided by the energy value of the power fed to the grid. The net power fed to the grid is equal to the total output from the generator less any plant parasitic losses. These parasitic losses include energy spent on gas compressors, jacket water pumps, lube oil pumps, radiator fans, generator fans, station transformer, and other station auxiliaries." (Factors, 1989)

"Other important factors that must be considered when deciding on whether or not to utilize the LFG for electrical generation include availability, installation cost, operation and maintenance costs, and emissions, all of which are site specific. Availability is the actual time of power generation divided by the available hours annually. This is mainly a measure of reliability of power generation equipment and the supply of the fuel to the facility. Cost/kW installed describes the cost per installed kW of a given technology. Operation and maintenance costs include all labor and materials used to produce power, and are expressed as $/kWh for equipment operation. Maintenance charges cover major and minor overhauls. The emissions

from exhausts of a LFG flare or a piece of generation equipment must be controlled to within acceptable limits set by governmental agencies. Emissions of concern can include nitrogen oxides, carbon dioxide, carbon monoxide, non-methane hydrocarbons, volatile organic compounds (VOCs), and products of incomplete combustion." (Factors, 1989)

"Table 5-2 presents the typical flow ranges required to make the implementation of the following electrical power generation technologies viable. It also shows the typical power ranges associated with the various LFG technologies and flow rates." (Factors, 1989)

Table 5.2 LFG Utilization Technologies and Typical Flow/Power Ranges (Factors, 1989)

Technology	**Typical Flow Range (cfm)**	**Typical Flow Range* (m^3/h)**	**Preferred Plant Size**	**Electrical Conversion Efficiency (net to grid without waste heat recovery)**
Microturbines	< 100 cfm	< 170 (m^3/h)	< 100 kW	25-30%
Reciprocating engines	>150 to 5,000 cfm	>255 to 8495 (m^3/h)	0.5 to 12 MW	32-40%
Gas turbines	>4,000 to 20,000 cfm	>6796 to 33980 (m^3/h)	3 to 18 MW	26-32%
Steam turbines	>6,000 to >25,000 cfm	>10194 to >42475 (m^3/h)	10 to 50 MW	24-29 %
Combined Cycle Systems	>5,000 to >25,000 cfm	>8495 to >42475 (m^3/h)	>10 MW	38-45 %

* Cmf x 1,699 = 1 (m^3/h)

5.3.2 Calorific value of the LFG

In the lecture, 1 m^3 LFG value is 8500 kcal. Total energy value is determined and calculated equation 5-1.

$$Total\ Energy = MGxMKD \tag{5-1}$$

Total Energy: kW

MG: Annual methane gas production (m^3 methane/ year)

MKD: Methane colorific value

Table 5.3 Total energy value of methane

Year	Landgem RUN1 (kW/year)	Landgem RUN2 (kW/year)	Multi-Phase (kW/year)	Tabasaran Rettenberger (kW/year)	Scholl Canyon RUN1 (kW/year)	Scholl Canyon RUN2 (kW/year)
2.007	0	0	0	0	0	0
2.008	8.624	4.906	7.453	16.781	3.985	2.267
2.009	16.728	9.516	13.177	31.455	7.164	4.075
2.010	26.508	15.079	18.821	33.520	10.387	5.909
2.011	37.740	21.469	24.065	12.065	13.461	7.657
2.012	47.562	27.056	27.496	8.990	15.559	8.851
2.013	56.164	31.949	29.551	6.724	16.883	9.604
2.014	63.704	36.238	30.573	5.093	17.600	10.012
2.015	70.323	40.004	30.831	3.157	17.844	10.151
2.016	61.014	34.708	26.669	2.276	15.482	8.807
2.017	52.937	30.114	23.126	1.641	13.432	7.641
2.018	45.929	26.127	20.105	1.184	11.654	6.630
2.019	39.849	22.669	17.526	854	10.111	5.752
2.020	34.574	19.668	15.320	615	8.773	4.990
2.021	29.997	17.064	13.430	444	7.611	4.330
2.022	26.026	14.805	11.809	320	6.604	3.757
2.023	22.581	12.845	10.414	231	5.730	3.259
2.024	19.592	11.145	9.213	166	4.971	2.828
2.025	16.998	9.670	8.175	120	4.313	2.454
2.026	14.748	8.389	7.277	87	3.742	2.129
2.027	12.796	7.279	6.497	62	3.247	1.847
2.028	11.102	6.315	5.819	45	2.817	1.602
2.029	9.632	5.479	5.227	32	2.444	1.390
2.030	8.357	4.754	4.709	23	2.121	1.206
2.031	7.251	4.125	4.255	17	1.840	1.047
2.032	6.291	3.579	3.855	12	1.596	908
2.033	5.458	3.105	3.502	9	1.385	788
2.034	4.736	2.694	3.190	6	1.202	684
2.035	4.109	2.337	2.913	5	1.043	593
2.036	3.565	2.028	2.666	3	905	515
2.037	3.093	1.759	2.445	2	785	446
2.038	2.683	1.527	2.247	2	681	387

Table 5.3 Total energy value of methane. (Continue)

2.039	2.328	1.324	2.069	1	591	336
2.040	2.020	1.149	1.909	1	513	292
2.041	1.753	997	1.764	1	445	253
2.042	1.521	865	1.633	0	386	219
2.043	1.319	750	1.513	0	335	190
2.044	1.145	651	1.405	0	290	165
2.045	993	565	1.305	0	252	143
2.046	862	490	1.214	0	219	124
2.047	748	425	1.131	0	190	108
2.048	649	369	1.054	0	165	94
2.049	563	320	983	0	143	81
2.050	488	278	918	0	124	70
kW	**785.059**	**446.586**	**409.253**	**125.946**	**219.020**	**124.591**

CHAPTER SIX
CONCLUSION

In the content of the thesis, properties of the SW of Izmir are presented and the LFG potential of Harmandali Landfill site is determined by mathematical models.

The model variables of L_0 and k are determined by using available data in the literature and used in the applied models. For obtaining timely and actual LFG potential, the LFG models were operated with the waste amounts between the years of 2007 and 2050.

The mathematical LGF determination models of EPA, Multiphase, Tabasaran-Rettenberger, and Scholl Canyon were applied in the content of the study. By using the city waste characteristics L_0 was calculated according to USA EPA and IPCC as 30 and 32.55 m^3CH_4/Mg, respectively.

Methane generation rate constant of k is determined between 0.175 and 0.056 y^{-1} for different biodegradable compounds in waste. The weighted average of k values is calculated according to the distribution of different types of biodegradables in the waste and found as 0.142 y^{-1}. These calculated variables used in the models to determine the LFG potential of the area between the years of 2007 and 2050.

It was found that expected CH_4 production from Harmandali landfill site may vary between 189 Mm^3 (maximum with EPA LandGEM model by applying L_0 of 32.55 m^3CH_4/Mg) and 48.6 Mm^3 (minimum with Scholl Canyon model by applying L_0 of 30 m^3CH_4/Mg).

Accordingly, the energy equivalence of that much of methane will be between 446.000 kW and 114.000 kW by the end of 2050.

Since Harmandali landfill site has been operated since 1992 and methane collection and energy production could not be realized until now, this data is important to show the released emissions to the atmosphere and the wasted non-fossil fuel renewable energy.

Therefore, the LFG potentials of future landfill sites need to be predicted by mathematical models and energy investments should be decided and applied in early stages of the landfill in order to use the methane produced from the site beneficially.

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