Guidance Document for Best Management Practices (BMPs) to reduce GHG emissions from Landfills

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Environment Policy and Governance

Waste Management Options for Greenhouse Gases Emissions Control (WASTE-C-CONTROL)

DELIVERABLE:

Guidance Document for Best Management Practices to Reduce GHG Emissions from Landfills

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1.1 Introduction

Global Warming appears to be the most emerging environmental problem of our days, threatening the lives and the living environment not only of animal species but of humans also. Table 1 following presents the ten countries that are affected most by global warming, all of which are developing countries. The same study mentions that in the list with the twenty most heavily affected countries by global warming are also included developed countries such as Italy, Portugal, Spain and the United States. [1]

Table 1: The 10 countries affected most by Global Warming [1]

The 10 countries affected most by Global Warming		
1. Bangladesh	5. Nicaragua	9. The Philippines
2. Myanmar	6. Haiti	10. China
3. Honduras	7. India	
4. Vietnam	8. Dominican Republic	

Global warming is directly connected with GHG emissions caused by human activities, one of which is Solid Waste Management (SWM). Landfilling is the most common method worldwide to treat waste and it is considered an increasing factor of climate change because of the methane produced from the anaerobic decomposition of waste. Methane, along with Carbon Dioxide, is the basic component of the Landfill Gas (LFG) produced in all sites. However, methane is considered a drastically multiplying factor of climate change, since it has 21 times greater warming potential than carbon dioxide. Globally, landfills are the third largest anthropogenic source of methane, accounting for approximately 11 percent of estimated global methane emissions or nearly 799 Million Metric Tons CO^2 eq. in 2010. [2] Figure 1 presents the countries with the highest methane emissions from the landfill sector in 2010.

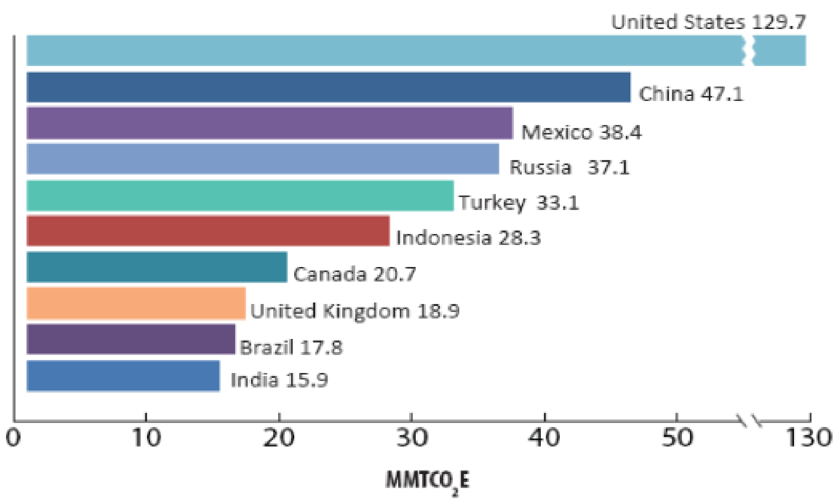


Figure 1: Methane emissions from the landfill sector in selected countries, 2010 [2]

Given the contribution of landfills to global warming, purpose of this report is to focus on the GHG emissions arising from landfills and to present a variety of Best Management Practices (BMP) that can applied on a site, according to its specific characteristics. More specifically, this report aims at providing a 'Guidance Document' for landfill operators and regulators with the recommended technologies and management practices for reducing landfill gas (LFG) emissions (especially methane) through improved landfill design, construction, operation, and closure. In addition, it can be used as a tool to evaluate whether potential landfill changes will lead to reduced LFG emissions.

Among the practices presented, are included best practices for LFG collection systems and technologies, best practices related to design and operation of a landfill, closure and maintenance practices and others. For each BMP is given a short description and is examined its feasibility. Moreover, they are provided specific recommendations to implement each BMP, the relative cost of each one and finally the potential GHG benefit that each one provides.

1.2 Landfill Gas production – Methane as a GHG

1.2.1 Estimating the quantity of methane [35]

A sanitary landfill can be defined as the biochemical reactor of the anaerobic fermentation of organic and other biodegradable fractions included within disposed municipal solid waste (MSW). Landfill control systems are employed to prevent unwanted movement of landfill gas into the atmosphere or the surrounding soil. Recovered landfill gas can be used to produce energy or to be flared under controlled conditions to eliminate the discharge of greenhouse gases to the atmosphere.

Landfill gas is composed of a number of gases, but mainly methane (CH_4) and carbon dioxide (CO_2) at a ratio of about 50:50. The rest gases represent no more than 3-5% of the total landfill gas volume. The principal gases are produced from the decomposition of the organic fraction of MSW. Landfill gases occur in five or less sequential phases:

i. Aerobic phase: in the 1st phase organic biodegradable components undergo microbial decomposition as they are placed in the landfill and soon after under aerobic conditions until entrapped O_2 is consumed. This may last for a few weeks up to several months. The predominant gases synthesized during this stage are carbon dioxide (CO_2) and water vapour (H_2O).

ii. Transition phase: The second phase begins as conditions shift from aerobic to anaerobic as a result of oxygen depletion. The principal gases produced are CO_2 and – to a lesser extent – hydrogen (H_2)

iii. Acid phase: The microbial activity initiated during phase II accelerates with the production of significant amounts of organic acids and lesser amounts of hydrogen gas. This three steps phase includes:

   - The hydrolysis of higher-molecular mass compounds into compounds suitable for use by microorganisms as source of energy and cell carbon.
   - The microbial conversion of the compounds resulting from step a, into lower molecular mass intermediate compounds (CH_3COOH).
   - The last step involves the conversion of the intermediate compounds produced in phase b into carbon dioxide and lesser amounts of hydrogen gas.

iv. Methane fermentation phase: another group of microorganisms convert the acetic acid and hydrogen gas into CH_4 and CO_2. Microorganisms responsible for this conversion are strictly anaerobic and are called methanogenic.

v. Maturation phase: the maturation phase occurs after the readily available biodegradable organic material has been converted to CH_4 and CO_2 in phase IV. The rate of landfill gas generation diminishes significantly since most of the available nutrients have been removed with leachate.

During the anaerobic phases, production of sulfur and carbon compounds in trace concentrations (sulfides and volatile organic acids) is observed.

In literature, several approaches have been published with regards to the chemical equation (kinetics) that best represents landfill gas formation within a landfill. One of the most common approaches is the first order decay (FOD) equation, which is adopted by US EPA and many researchers, especially when field data are limited (i.e. recording of methane production of an existing landfill in order to determine the equation parameters).

Also, the IPCC guidelines adopt the First Order Decay method (FOD) for the calculation of methane emissions from municipal solid waste disposal.

In particular, the IPCC approach indicates that CH_4 emissions from solid waste disposal for a single year can be estimated using Equation 1. Part of the CH_4 generated is oxidised in the cover of the landfill, or can be recovered for energy or flaring. The CH_4 actually emitted from the landfill will hence be smaller than the amount generated.

The IPCC method assumes that the degradable organic component (degradable organic carbon, DOC) in waste decays slowly throughout a few decades, during which CH_4 and CO_2 are formed. If conditions are constant, the rate of CH_4 production depends solely on the amount of carbon remaining in the waste. As a result emissions of CH_4 from waste deposited in a disposal site are highest in the first few years after deposition and then gradually decline as the degradable carbon in the waste is consumed by the bacteria responsible for the decay.

$$CH_4 emissions = \sum_x [CH_4\ generated_{x,T} - R_T] \times (1 - O_{x,T}) \qquad (1)$$

CH_4 emissions = CH_4 emitted in year *T*, Gg

T = inventory year

x = waste category or type/material

R_T = recovered CH_4 in year *T*, Gg

$O_{X,T}$ = oxidation factor in year *T*, (fraction)

The CH_4 recovered must be subtracted from the amount of CH_4 generated. Only the fraction of CH_4 that is not recovered will be subject to oxidation in the landfill cover layer.

The actual transformation of degradable material in the landfill to CH_4 and CO_2 is by a chain of reactions and parallel reactions. A full model is likely to be very complex and vary with the conditions in the SWDS. However, laboratory and field observations on CH_4 generation data suggest that the overall decomposition process can be approximated by first order kinetics and this has been widely accepted.

The FOD model is built on an **exponential factor** that describes the fraction of degradable material which each year is degraded into CH_4 and CO_2.

One key input in the model is the amount of degradable organic matter (DOCm) in waste disposed into the landfill. This is estimated based on information on disposal of different waste categories (municipal solid waste (MSW), sludge, industrial and other waste) and the different waste types/material (food, paper, wood, textiles, etc.) included in these categories, or alternatively as mean DOC in bulk waste disposed.

The equations for estimating the CH_4 generation are given below. As the mathematics are the same for estimating the CH_4 emissions from all waste categories/waste types/materials, no indexing referring to the different categories/waste materials/types is used in the equations below.

The basis for the calculation is the amount of Decomposable Degradable Organic Carbon (DDOCm) as defined in Equation 2. DDOCm is the part of the organic carbon that will degrade under the anaerobic conditions in the landfill. The index *m* is used for mass. DDOCm equals the product of the waste amount (W), the fraction of degradable organic carbon in the waste (DOC), the fraction of the degradable organic carbon that decomposes under anaerobic conditions (DOCf), and the part of the waste that will decompose under aerobic conditions (prior to the conditions becoming anaerobic) in the landfill, which is interpreted with the methane correction factor (MCF).

$$DDOCm = W \bullet DOC \bullet DOCf \bullet MCF \qquad (2)$$

Where:

$DDOC_m$ = mass of decomposable Decomposable Degradable Organic Carbon deposited, Gg

W = mass of waste deposited, Gg

DOC = degradable organic carbon in the year of deposition, fraction, Gg C/Gg waste

DOC_f = fraction of DOC that can decompose (fraction) under anaerobic conditions

MCF = CH_4 correction factor for aerobic decomposition in the year of deposition (fraction)

The FOD equations are:

$$DDOCma_T = DDOCmd_T + (DDOCma_{T-1} \bullet e^{-k}) \qquad (3)$$

$$DDOCm\ decomp_T = DDOCma_{T-1} \bullet (1-e^{-k}) \qquad (4)$$

$$CH_4\ generated_T = DDOCm\ decomp_T \bullet F \bullet 16/12 \qquad (5)$$

T = inventory year

$DDOCma_T = DDOC_m$ accumulated in the landfill at the end of year *T*, Gg

$DDOCma_{T-1} = DDOC_m$ accumulated in the landfill at the end of year (*T*-1), Gg

$DDOCmd_T = DDOC_m$ deposited into the landfill in year *T*, Gg

$DDOCm\ decomp_T = DDOC_m$ decomposed in the landfill in year *T*, Gg

k = reaction constant, $k = \ln(2)/t_{1/2}$, (y^{-1})

$t_{1/2}$ = *half-life time (y)*

$CH_4\ generated_T$ = *amount of* CH_4 *generated from decomposable material*

F = fraction of CH_4*, by volume, in generated landfill gas (fraction)*

16/12 = molecular weight ratio CH_4/C *(ratio)*

With the first order reaction, the amount of product is always proportional to the amount of reactive material. This means that the year in which the waste material was deposited in the SWDS is irrelevant to the amount of CH_4 generated each year. It is only the total mass of decomposing material currently in the site that matters.

This also means that when we know the amount of decomposing material in the landfill at the start of the year, every year can be regarded as year number 1 in the estimation method, and the basic first order calculations can be done by these two simple equations, with the decay reaction beginning on the 1st of January the year after deposition.

Half-lives for different types of waste vary from a few years to several decades or longer. The FOD method requires data to be collected or estimated for historical disposals of waste over a time period of 3 to 5 half-lives in order to achieve an acceptably accurate result. It is therefore good practice to use disposal data for at least 50 years as this time frame provides an acceptably accurate result for most typical disposal practices and conditions.

A typical graph example of the methane production, based on the FOD method, is illustrated below. In the graph one can see the effect that the k constant, (reaction constant, $k = \ln(2)/t_{1/2}$, (y^{-1})), has on the calculations [36].

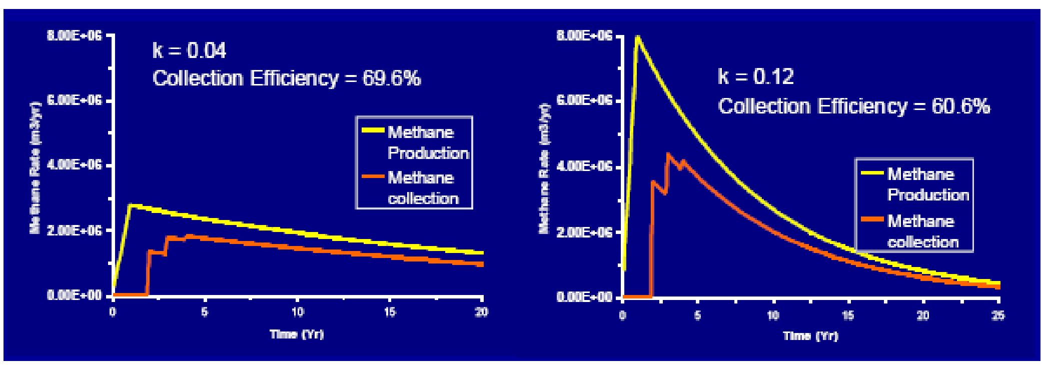


Figure 2: Methane emissions curves based on the FOD method [36]

1.2.2 Methane as GHG

GWP Potential of methane [32], [34]

Global-warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question, to the amount of heat trapped by a similar mass of carbon dioxide. **Carbon dioxide has a GWP of exactly 1** (since it is the baseline unit to which all other greenhouse gases are compared).

A GWP is calculated over a specific time interval, commonly 20, 100 or 500 years. For example, the 20 year GWP **of methane is 72**, which means that if the same mass of methane and carbon dioxide were introduced into the atmosphere, that methane will trap 72 times more heat than the carbon dioxide over the next 20 years.

The substances subject to restrictions under the Kyoto protocol either are rapidly increasing their concentrations in Earth's atmosphere or have a large GWP.

The GWP depends on the following factors:

- the absorption of infrared radiation by a given species
- the spectral location of its absorbing wavelengths
- the atmospheric lifetime of the species

Thus, a high GWP correlates with a large infrared absorption and a long atmospheric lifetime. The dependence of GWP on the wavelength of absorption is more complicated. Even if a gas absorbs radiation efficiently at a certain wavelength, this may not affect its GWP much if the atmosphere already absorbs most radiation at that wavelength. A gas has the most effect if it absorbs in a "window" of wavelengths where the atmosphere is fairly transparent. The dependence of GWP as a function of wavelength has been found empirically.

Because the GWP of a greenhouse gas depends directly on its infrared spectrum, the use of infrared spectroscopy to study greenhouse gases is centrally important in the effort to understand the impact of human activities on global climate change.

A substance's GWP depends on the time horizon over which the potential is calculated. A gas which is quickly removed from the atmosphere may initially have a large effect but for longer time periods as it has been removed becomes less important. **Thus, methane has a potential of 25 over 100 years but 72 over 20 years**; conversely sulphur hexafluoride has a GWP of 22,800 over 100 years but 16,300 over 20 years (IPCC TAR). The GWP value depends on how the gas concentration decays over time in the atmosphere. This is often not precisely known and hence the values should not be considered exact. For this reason when quoting a GWP it is important to give a reference to the calculation.

Commonly, a time horizon of 100 years is used by regulators.

Table 2: GWP values and lifetimes from 2007 IPCC 4th Assessment Report (2001 IPCC 3rd AR-TAR, in parenthesis)

	Lifetime (years)	GWP time horizon		
		20 years	100 years	500 years
Methane	12 (12)	72 (62)	25 (23)	7.6 (7)
Nitrous oxide	114 (114)	289 (275)	298 (296)	153 (156)
HFC-23 (hydrofluorocarbon)	270 (260)	12,000 (9,400)	14,800 (12,000)	12,200 (10,000)
HFC-134a (hydrofluorocarbon)	14 (13.8)	3,830 (3,300)	1,430 (1,300)	435 (400)
Sulfur hexafluoride	3,200 (3,200)	16,300 (15,100)	22,800 (22,200)	32,600 (32,400)

Under the Kyoto Protocol, the Conference of the Parties decided **(decision 2/CP.3) that the values of GWP calculated for the IPCC Second Assessment Report (SAR) are to be used** for converting the various greenhouse gas emissions into comparable CO_2 equivalents when computing overall sources and sinks. **Based on the SAR, the GWP of methane for 100y time horizon is set to 21.**

Methane as a Greenhouse Gas

There is much more carbon dioxide (CO_2) in the Earth's atmosphere than methane. But methane's global warming potential (GWP) – or warming potency compared to carbon dioxide (see Table 2) – is 25. That means it's 25 times more effective at trapping heat in the atmosphere than CO_2 over a 100-year period. So adding one tonne of methane to the atmosphere would have the same effect as adding 25 tonnes of CO_2.

Recent research however, indicates that methane is more potent than 21 or 25 times of CO_2. Results suggest that gas-aerosol interactions play an important role in methane's GWP, and hence a larger value would allow better optimization of climate change mitigation policies [37].

Table 3: GWP values – new data [37]

	Kyoto Protocol (100 y horizon)	Reality (100 y horizon)	
		IPCC 4th AR, 2007	*New data*
GWP of CH_4	21	25	34

Luckily, methane lingers in the atmosphere for only 11 to 12 years, compared to up to 200 years for CO_2. With a greater potency and shorter lifetime, the impact of methane can be reduced more rapidly. This may become very important if, in the next few years, there is an increased demand for the reduction of greenhouse gases in the atmosphere.

Sources of methane [33]

Methane is lighter than air, colourless and – despite one might think – is odourless. It is a truly universal gas. It can occur naturally in wetlands, it's made by animals, and it can be released as a result of human activities such as agriculture, fossil fuel production and landfilling of waste. It can also be found in many homes – that's because the natural gas that many of us cook and heat our homes with, is about 85 % methane.

Methane is also known as marsh gas. That's because it is produced when plants and other organic matter decompose in the absence of oxygen (anaerobically), such as when they are under water. This anaerobic decomposition by microorganisms (called methanogens) takes place in wetlands, swamps and marshes and is estimated to produce some 30% of atmospheric methane levels.

Methane is also produced in the gut of termites (5% of global emissions) and by microorganisms in the ocean (2%). **Landfilling accounts for about 10-11% of global methane production.**

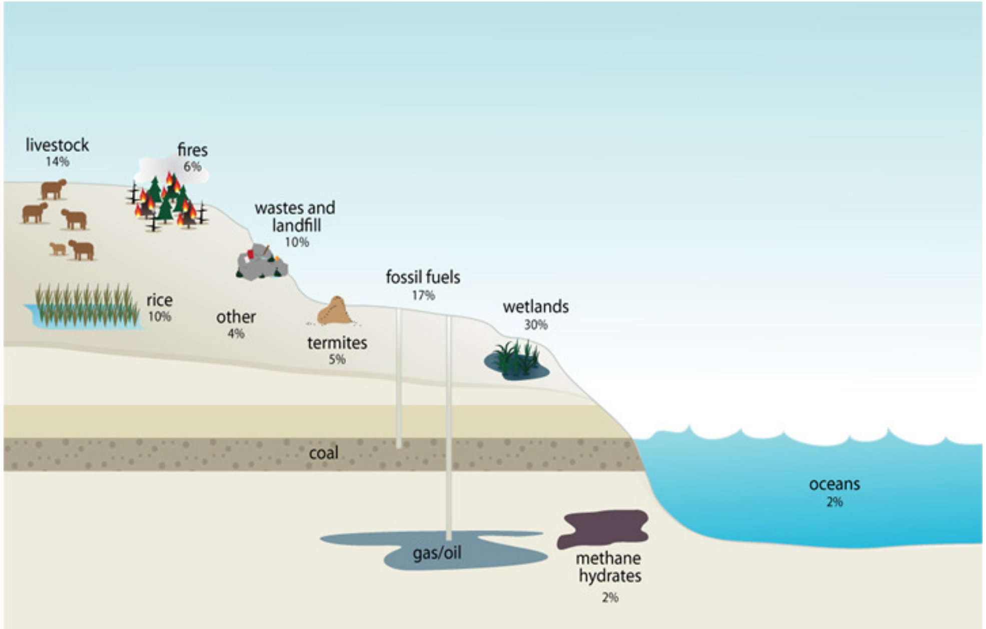
Special concern is paid on anthropogenic sources of methane, since these are easier to control. Landfills are a key issue because a quite large percentage of the produced methane can be collected and utilised. Besides, the overall design and operation of the landfill may help in reducing methane production.

One should also bear in mind, that landfill gas does not only contain methane, but also CO_2, a GHG itself; so eliminating landfill gas fugitive emissions receives extra importance.

As it is obvious from Eq.1, one may "target" recovery and oxidation in order to minimise the actual amounts of landfill gas emitted.

The way to target the "R" (recovery) factor relates both with the design philosophy of the landfill and/or the design of landfill gas collection system. Also, the operation of the landfill plays an important role in the "R" factor.

The way to enhance oxidation will be discussed as well. It should be stressed though, that the "O" factor is often forgotten; it will be demonstrated how it may offer significant reductions to the overall landfill gas emissions reduction.


livestock
14%
fires
6%
wastes and
landfill
10%
fossil fuels
17%
wetlands
30%
rice
10%
other
4%
termites
5%
coal
oceans
2%
gas/oil
methane
hydrates
2%

2 Best Management Practices (BMP) to reduce GHG emissions from Landfills

2.1 BMPs for Enhancing the "R" factor (Recovery Factor)

2.1.1 New landfill design concepts

2.1.1.1 Bioreactor Landfills – Anaerobic Bioreactor

Description

The anaerobic bioreactor landfill, (also simply known as bioreactor landfill), is a conventional landfill where leachate and/or other sources of moisture are introduced to accelerate degradation of organic waste. The aim is to obtain as rapid waste degradation and gas development as possible. The concept is based on the knowledge that waste has to be kept sufficiently wet to achieve a fast degradation. Waste moisture contents close to field capacity are considered by some to be optimal for promoting degradation **[23, 39].**

This is most often achieved through the recirculation of the collected leachate to the waste body. Leachate recirculation also provides better interaction between microorganisms, soluble nutrients and insoluble substrates, leading to an optimization of the degradation process [17]. Other sources of water may also be added to bring the landfill to optimum water content [18, 19].

The benefits of the bioreactor landfill are potentially [20, 21]:

- Reduce the period needed for long term maintenance and monitoring;
- Decrease of long term care cost and risks
- Increase rate of settlement providing more capacity or a more stable surface for final use of the site;
- Reduce leachate treatment cost because some treatment takes place within the landfill body;
- Increase rate of gas generation improving the viability of gas utilization. Enhanced degradation in bioreactor landfills accelerates LFG generation. Compared to conventional landfills, decomposition reaches a higher peak at the year of closure and then declines more rapidly. For anaerobic bioreactors, CH_4 generation rates typically increase 200- 250% [18, 22].

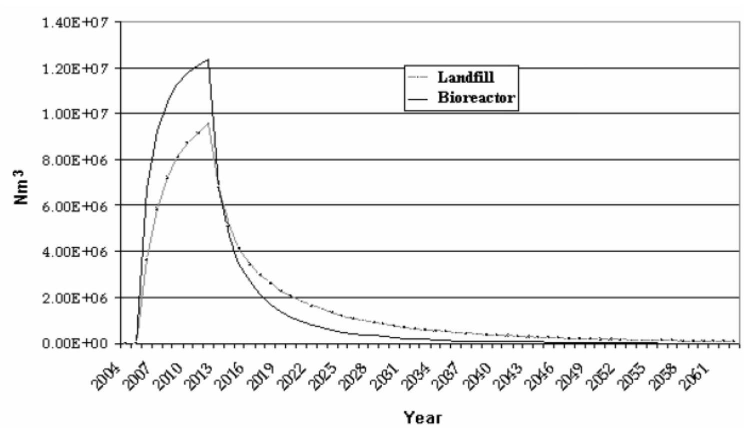


Figure 3: Comparison of model results (for a case study) of biogas production for bioreactor and conventional landfill [39]

The main benefit of the bioreactor landfill is that a major part of the degradation and the associated emissions take place early in the life of the landfill when the technical systems (leachate collection and treatment; gas collection and utilisation) are at their most efficient. However, it must be borne in mind that gas collection efficiency may be low in recently deposited wastes until they are capped and abstraction infrastructure installed. It may be advisable in such circumstances to delay raising moisture contents until a suitable infrastructure is in place [24].

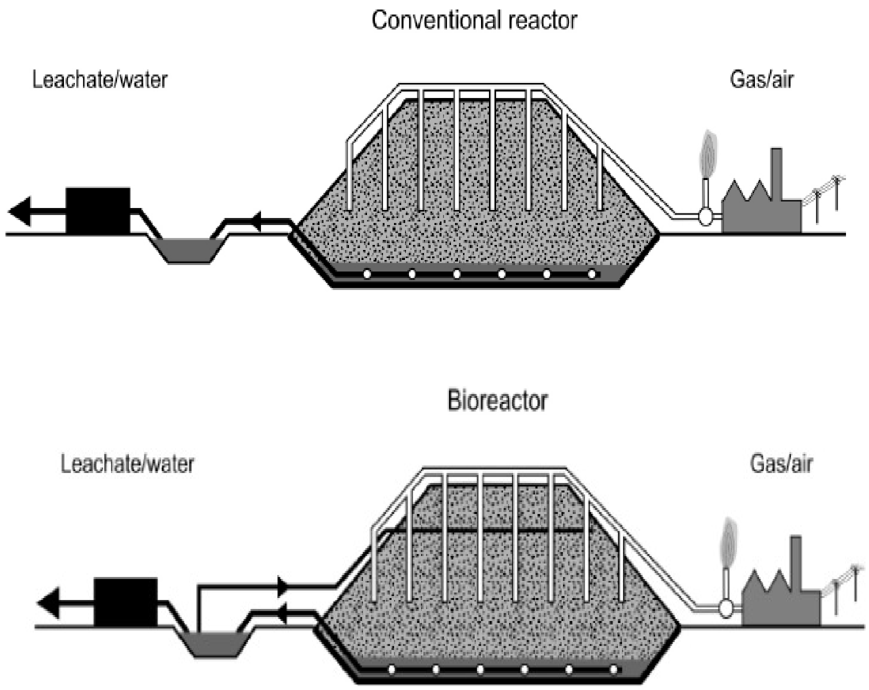


Figure 4: Main technical differences between conventional landfill and bioreactor landfill [25]

Feasibility

Application of Bioreactor technology is feasible to any landfill as long as it is proved that leachate recirculation and excessive LFG production do have additional environmental impact. It is most feasible for big landfills where economies of scale can be achieved. [3]

The conditions favourable to implement bioreactor technology are: [21]

- Limited precipitation infiltration into the waste, either due to a dry climate or an impermeable cover;
- An adequate quantity of water-based liquid is available that can be accepted at the landfill for a fee, or can be obtained at no cost or very little cost, and the source does not infringe on other uses;
- Nearby facility that can beneficially use the methane; and
- High leachate treatment costs.

Conditions that bioreactor technology may not be advantageous are: [21]

- Landfills in wet climates with permeable or semi-permeable covers;
- An adequate quantity of water for the bioreactor is not available, or the water needs to be diverted from other needs, or there is a significant cost to supplying the water;
- Landfills where much of the organic matter has been removed due to aggressive source separation, or where the organic matter is mainly wood and/or newspaper; and

- Leachate can be treated at low cost

Implementation of bioreactor technology requires increased commitment of landfill operators.

Implementation Recommendations

Implementation of bioreactor technology can be started at the design stage or at a later stage by installing a leachate recirculation system in a conventional landfill section. Leachate is usually collected in a lagoon or tank from where it is injected either at the surface or via preinstalled infrastructure at depth [25]. However, it is advisable to install or adapt first the biogas and leachate collection systems, so as to collect the increased amounts of biogas and leachate, and then to proceed to liquid addition [18]. In any case, the conventional landfill that will be converted to a bioreactor landfill must be equipped with the appropriate lining.

Another important issue is the sizing of the LFG collection system. Since it is expected increased LFG generation, the LFG collection system must be sized accordingly to capture the produced amounts of LFG; otherwise the BMP will not serve the purpose of implementation. Leachate collection system also requires appropriate sizing, to collect the added amount of leachate.

In addition, when bioreactor technology is applied, it is recommended LFG system to be installed and be in operation within 180 days of liquids addition regardless whether 40 percent moisture is reached. [3]

Relative cost

Implementation of bioreactor technology in a landfill has increased investment costs in comparison to a conventional one, because of the additional costs for design, construction and operation of the landfill. However in case that the biogas produced in a landfill is not flared but it is exploited energetically the economic benefits may overlap or cover a significant part of the extra cost. As for disposal cost, it seems that the cost per ton is lower in bioreactor landfills than in conventional ones. [39]

GHG emissions benefit

There is no certain evidence that leachate recirculation in a bioreactor landfill reduces the amount of emissions to the environment from the landfilled waste. However, the emissions are concentrated during the time frame of leachate recirculation (8–10 years), during which the level of control over the emissions to the environment is the highest. Thereafter, the potential for emissions is low because the waste is already largely stabilised.

When applied appropriately the GHG emissions benefit that bioreactor technology provides is estimated medium to high. However, application of the technology without the use of an enhanced LFG collection system may lead to increased GHG emissions.

2.1.1.2 Bioreactor Landfills – Aerobic Bioreactor

Description

Aerobic waste decomposition is a faster process in comparison to anaerobic waste decomposition and theoretically it will not produce any methane emissions, thereby reducing the potential for GHG emissions at the landfill.

This type of technique is achieved by sealing the landfill with a low permeability liner and cover to eliminate the leakage of leachate. Leachate is then removed from the bottom layer of the landfill and recirculated into the landfill in a controlled manner, while air is simultaneously injected into the waste mass using vertical or horizontal wells to promote aerobic activity. Overall airspace recovery is expedited, leading to greater waste filling tonnages; however, this technique requires significant levels of operational control, as non-aerobic zones within the waste can lead to fires in the presence of air.

Essentially, this practice is a form of in-situ composting of waste through the implementation of aerobic conditions, and carries with it many of the same risks associated with composting without the same level of operational control over the waste. The practice of aerobic landfills is relatively rare and best suited to sites designed with this objective in mind.

One of the main benefits of an aerobic bioreactor is that aerobic decomposition is able to stabilise waste much quicker than anaerobic decomposition, which will provide significant airspace savings.

Feasibility

The amount of aerobic bioreactor landfill projects is limited; however, the technology is gaining in popularity and is becoming a more viable option as research progresses. Documentation and pilot project case studies on the implementation of aerobic bioreactors are available and have generally displayed successful results. However, aerobic bioreactor landfills are generally still in the experimental stage and should be undertaken only under very specific circumstances.

A main concern when implementing an aerobic bioreactor is the chance of internal fire at the landfill due to the high temperatures and increased oxygen content within the waste mass. As a result, temperatures within the landfill must be closely monitored at all times to ensure that a fire does not start. As such, high operation skill is required for this technology.

Implementation Recommendations

The implementation of an aerobic bioreactor landfill is typically only recommended for new sites that are still in the design stages. The design of the LFG collection system must be such that it can accommodate the oxygen induced conditions, which can be highly dangerous if not managed appropriately. All other landfill systems must be designed with this goal in mind, as it is typically difficult to fully implement this bioreactor design at a landfill that was not originally intended to accommodate oxygen induced conditions.

Relative cost

The costs for implementing an aerobic bioreactor landfill are generally high compared to other practices due to the large amount of infrastructure required for the technology.

Typical aerobic bioreactors require a base and surface liner, liquid addition and air pumping equipment, instrumentation, and a SCADA system to ensure the desired liquid recirculation and waste aeration is achieved.

GHG emissions benefit

GHG emission reductions are realized when the landfill waste mass is evenly aerated, anaerobic decomposition stops, and aerobic decomposition begins, which eliminates the generation of methane gas.

The amount of GHG emission reductions that may be obtained from this technology is dependent on how well the aerobic bioreactor is operated and the percentage of the waste mass that is able to aerobically decompose. Some zones of anaerobic decomposition may still exist within an aerobic bioreactor, as saturating the entire waste mass with air is generally difficult.

Typically, the overall GHG emission reductions are equal to the predicted LFG generation rate of the waste. Since this is a methane avoidance technology, there is no direct means of measuring the emission reductions beyond estimating the GHG emissions that would have occurred if an anaerobic landfill design would have been used instead, with an appropriate assumption of the volume of LFG that might have been captured in that baseline setting.

2.1.1.3 Combination of Aerobic and Anaerobic Conditions

Description

This concept incorporates the advantages of both anaerobic and aerobic decomposition. It also provides a sustainable solution for waste management by allowing resource recovery and reuse of cell infrastructure.

This technique is achieved by operating the landfill as an anaerobic bioreactor at first, for enhanced LFG production using leachate recirculation. In the second stage, air is injected into the solid waste matrix to convert the operation to an aerobic bioreactor to allow for rapid stabilisation of the waste. The landfill may be mined for materials and space recovery after the waste has stabilised, which entails the use of additional technologies to separate recyclable materials for compost or reuse.

Feasibility

It is not a widely applied concept so far, but it is gaining popularity especially in areas that rely heavily on landfilling. It is evident that high operation skill is required for this technology.

Implementation Recommendations

This concept of landfill design is recommended for new sites that are still in the design stages. The design of the LFG collection system must be such that it can accommodate the initial high LFG generation rate and then the oxygen-induced conditions afterwards, which can be highly dangerous if not managed appropriately. Landfill fires due to the high temperatures and increased oxygen content within the waste is a major concern when conditions turn aerobic.

All other landfill systems must be designed with this goal in mind, as it is typically difficult to fully implement such a design at a landfill that was not originally designed to accommodate high LFG generation rates and oxygen induced conditions. The specific infrastructure, such as a low permeability liner and cover, leachate recirculation and injection points, and air blower equipment are more feasibly implemented during the design stages of the site.

Relative Cost

The costs for implementing such a landfill design are generally higher compared to conventional landfilling given the requirement for additional infrastructure and operational control. Typical infrastructure includes a base and surface liner, liquid addition and pumping equipment, LFG recovery and utilization system, air pumping equipment, instrumentation, and a SCADA system, to ensure the desired liquid recirculation, air circulation, and LFG collection is achieved for anaerobic and aerobic conditions, respectively. The greater the rate of LFG generation, recovery, and utilisation in the initial project stages, the more cost savings that can be realized by this technology.

Additionally, the contaminating lifespan of the landfill is theoretically reduced given the increased generation rate of LFG and the potential for attenuation of leachate through recirculation.

GHG Emission Benefits

This technology reduces GHG emissions in two separate processes. First, when the waste is put under anaerobic conditions, LFG generation and collection is rapidly increased. Secondly, after LFG collection is no longer viable, the landfill is put under aerobic conditions, which produces carbon dioxide gas instead of methane gas

Overall, the prospectus for a correctly operated bioreactor should demonstrate GHG emission reductions equal to the emissions that would have resulted from a conventional anaerobic landfill, with a suitable correction for a LFG collection system, as appropriate.

2.1.1.4 Construction of Deeper Landfills

Description

Given the fact that geometry of a landfill is a factor determining largely the surface emissions arising from it, **reducing the landfill's surface area** can be used as measure to reduce LFG emissions to the atmosphere.

A good way to reduce a landfill's surface area is by increasing its height. More specifically, it is suggested to reduce the landfill surface area to the extent possible for specific volume of refuse, either by changing landfill geometry or using canyon landfills where the side slopes are blinded by the liners constructed up canyon walls thus restricting emissions. [3]

Feasibility

Construction of a deeper landfill may be feasible under specific occasions. The most important issue to be taken into consideration is the stability of the site, since deeper landfills mean greater height of waste refused. As a consequence, "taller" landfills are more visible posing a problem of visual nuisance. What is more, "taller" landfills create smaller top deck areas, reducing in that way the easiness and the capacity of filling operations.

Implementation Recommendations [3]

In order to construct deeper landfills, landfill owners and operators should assess the best possible geometry that can be achieved based on physical constraints of the landfill and surrounding area and slope stability analyses.

Relative cost [3]

The relative cost to implement this BMP is considered low and has to do basically with the assessment of constructing a taller landfill. In case that construction of a taller landfill is feasible, a further benefit may arise, since more waste is disposed of in a specific area.

GHG emissions benefit [3]

The GHG emissions benefit that can be achieved with the implementation of this BMP is considered medium if landfills emitted GHG at their maximum allowable level on all areas of the landfill. In case however that GHG emission rate is the same for a deeper landfill as it was for a shallower one, the GHG emissions benefit is considered high.

2.1.1.5 Construct a Bale Landfill

Description

This practice suggests baling waste prior to landfilling. Waste is inserted into a baler, is mechanically compacted, wrapped with low density polyethylene (LDPE) and placed in landfill. Baling waste prevents air and water from entering the waste, consequently reducing the waste decomposition rate and therefore GHG emissions. What is more, baling waste offer appropriate conditions for the development of a large amount of organic fatty acids, which lower the pH to below suitable levels for methane production and stabilising the same time the waste [30]. In that way, **short term** GHG emissions are significantly reduced; however, there is no evidence which are the long term GHG emission impacts arising from baling waste.

Feasibility

Implementation of this practice requires equipment purchase and space to house the baling and wrapping machine. It is feasible both for small and large landfills, since space demands for the baling and wrapping machine are not great. However, the liquids produced by compacting and baling waste should be collected and treated appropriately. Often, such liquids are trapped inside the LDPE wrapping, offering some moisture necessary to begin anaerobic decomposition.

Apart from the case of Mesomouri, Chania that waste is baled and stored, and a pilot case study in Alexandroupolis, there are no documented cases of baling-wrapping of MSW documented in Greece. [31]

Implementation Recommendations

There are two methods for baling waste. The first produces rectangular bales, whereas the second produces cylindrical. Most studies support the use of rectangular bales, as they result in less GHG emissions than cylindrical bales; they have higher density and higher processing capacity of machinery and they offer a more efficient use of space.

However, it should be stressed that operating a "bale" landfill may have some difficulties because of the fact that Greek landfills are usually deep, with slopes. So after filling up landfill basement extra care on stability issues should be paid. Also, to fill up any gaps among the bales possibly some ordinary (not baled) MSW may be used.

It is suggested that after closure of an active cell, vertical wells to extract trapped landfill gas should be constructed. It would not be wise to leave the landfill without an active gas collection system for a long time and extra care on developed pressures should be paid. Leachate production is expected quite low, on the other hand, since no rain can enter the LDPE wrapping.

Relative cost

Implementation of this BMP appears to have increased capital cost, basically because of the purchase of baling and wrapping equipment. As for the operational cost of a "balefill", it appears to be similar to that of a conventional landfill. The relative cost to implement this BMP is expected to be low.

GHG emissions benefit

Given its characteristics, this BMP can provide low to medium reduction to short term GHG emissions. However, further investigation is required to assess the method's impact on long term GHG emissions.

2.1.1.6 Segregate Organic Wastes in Dedicated Cells

Description

A practice to enhance the decomposition of organic waste and collect faster the produced landfill gas (thus enhance the recovery factor and reduce emissions in the long term, possible when the landfill aftercare period has ended), is to segregate organic wastes and landfill it in separated cells.

Given that organic waste degrades fast, fast and increased LFG production is expected in those cells. In that way, there enhanced gas collection systems can be applied and efficiently collect the produced amounts of LFG.

Feasibility

This practice is more appropriate for large landfills where there is enough space to manage organic waste separately and there is the possibility to maintain multiple active cells.

One can argue that treating source separated organic waste (SSOW) to produce compost or high quality biogas, is preferable. That is of course a correct argument, so this method may be applied when a system for treating SSOW is not yet in place, or when a source separation system has not been initiated yet. In the latter case, special equipment at the landfill site should be put in place to perform the segregation (i.e. trommels, screens, etc.)

Implementation Recommendations

When implementing this practice it is recommended to install enhanced LFG collection systems, to deal efficiently with the increased and faster produced amounts of LFG. Also, if no segregation at source is performed (dedicated bin), then special equipment should be purchased.

Relative cost

Implementation of this BMP includes additional cost of segregated organic collection or separation equipment, construction, operation and management of a separate organic cell and installation of an enhanced gas collection system in the separate cell. As a result, the relative cost to implement this BMP is expected to be high.

GHG emissions benefit

The GHG emissions benefit accruing from the implementation of this BMP is largely determined by the amount of the waste streams to be separately landfilled, the composition and the current proportion of the materials in the disposed waste stream at each landfill. However, the GHG emissions benefit is expected to be medium if an enhanced gas control system is installed in the single organic cell.

The GHG benefits may be improved if segregation is done efficiently and the produced amount of LFG from the dedicated cells has a concentration of CH_4 above 40% v/v. In this case, LFG utilisation for energy production may be considered.

2.1.2 BMPs for LFG Collection Systems

Undoubtedly, a very important mitigation measure to reduce the GHG emissions arising from a landfill is through enhanced collection of the produced LFG. In that way it is minimized the amount of LFG escaping to the atmosphere. The most common approach related to LFG collection is to install vertical wells after the end of operations in a cell/landfill. Despite the heterogeneity of landfills, this approach seems to result in adequate gas collection, without however excluding the possibility of ameliorating the collection rates. Aim of this section is to provide a number of alternatives practices contributing to the increase of the collection rates.

2.1.2.1 Horizontal Collectors

Description

A first approach to increase the capture rates of LFG produced in a landfill is by installing horizontal collectors in the early life of a landfill's cell so as to control its surface emissions. The horizontal collectors are installed across the landfill surface in trenches within the refuse and connected to the piping system at the outside slope of the landfill. [3] What is more, if the horizontal collectors are installed beneath the landfill cap or at the landfill perimeter, areas that LFG is usually concentrated, they can play a role of interceptors, by capturing the produced LFG and by do not let it escape to the atmosphere. [4]

Horizontal collection systems consist of perforated piping in gravel filled trenches constructed during the operating life of the landfill at vertical intervals of 15–25 meters and horizontal intervals of 60–70 meters. [4] Being buried, the collectors are sufficiently protected to allow gas collection while the cell is still in filling mode. The pipes used are usually sloped to promote drainage of condensate and leachate to designated collection points, and designed to accommodate settlement (as much as practicable) of the waste. In order to be easier for the operators to monitor the wells, the wellheads of the collectors are installed at the outside of the fill area.

More specifically and in order to increase the amount of LFG that is captured, when it comes the time to install the horizontal network, it is suggested to install pipes with varying length spaced according to waste density in the particular area. For example, piping near the landfill perimeter would have a tighter spacing requirement than within the landfill interior. This task can be accomplished with the best way by alternating the length of adjacent horizontal collectors between short and long. [3]

The main advantages of horizontal collectors are their compatibility with active landfill operations and their relative ease of installation. [14] Moreover, they can collect LFG in the deepest portion of the waste, if employed in the earliest stage of cell development, and LFG collection can begin much earlier than waiting to install vertical collectors after the cell is filled with refuse. In addition, horizontal collectors have greater functionality during the rehabilitation design. However, the main disadvantages of horizontal extraction collectors are high effects from waste settlement, the low recovery efficiency rate per well and the inability to be adjusted after the closure of the site. [3, 5]

Feasibility [3, 4]

Horizontal collectors may constitute a valuable solution for how to collect LFG from a cell or a landfill before the time it reaches a final or interim grade, when the installation of vertical wells is more feasible.

The most important parameter determining whether to install horizontal wells or not is what will be the LFG production during the time that the cell or landfill remain active. In that way, horizontal collectors are not suitable for cells or landfill that reach final or interim grade quickly and where vertical wells can be employed. Another parameter of crucial importance for the installation of horizontal collectors is the geometry of the fill sequence, since long and relatively consistent areas are needed to effectively install them. Furthermore, this type of collectors can be applied to sites where LFG production is slow to mature (i.e., dry sites) and in shallow landfills, namely those that waste deposits do not exceed 10 meters, where usually the installation of vertical wells is neither sufficient nor effective**.** However, they may not be feasible in refuse areas with high liquids content in the waste since the horizontal alignment of the collector is more susceptible to water inundation.

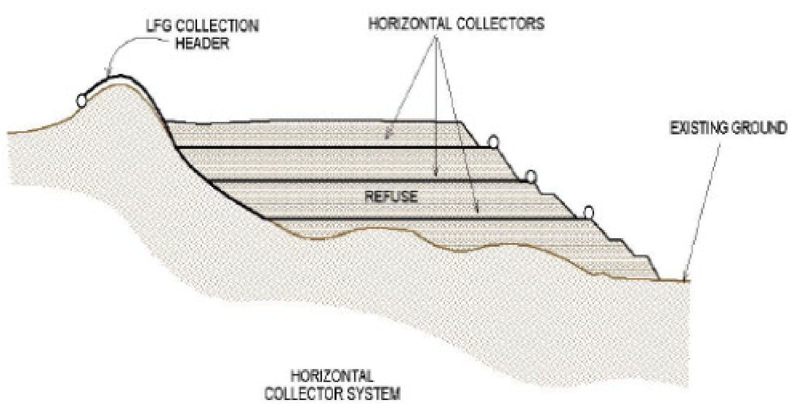


Figure 5: Typical Horizontal Layout [15]

Implementation Recommendations

Horizontal collectors should be installed as the filling progresses so the collectors are geometrically distributed throughout the waste mass. Their installation must be coordinated with fill planning since it has the potential to impact landfill operations, and poor coordination can result in damage or even destruction of the collectors. [3]

Another important element is that horizontal collectors demand active extraction of LFG so as to work properly. However, vacuum should not be applied until it is guaranteed that LFG production has begun. In addition, the vacuum should not be applied unless it is guaranteed that air infiltration into the landfill is limited. An effective way to ensure this is the adequate disposal of waste above the collectors, which may be up to 30 feet thick. Otherwise, if the vacuum is applied right after the installation of the collectors, without having production of LFG, or without having disposed adequate amount of waste above them, the pipes may collect air, influencing in that way the effectiveness and the radius of influence of the collectors, the anaerobic conditions, but also posing a severe danger of fire in the landfill. Given the aforementioned facts, it is suggested to monitor the quality of the collected LFG, so as to evaluate the system's performance, but also to ensure the landfill's anaerobic conditions.

Relative cost

The cost for horizontal collectors may be quite low in comparison to vertical ones. The factor contributing mostly to this is the construction cost, since no drilling works are required for the horizontal collectors.

Horizontal collectors provide a cost-effective way to control LFG emissions from the very beginning of a landfill's life. What is more, in case that the system functions properly, there might be a reduced need for installation of vertical wells, saving in that way some of the money used to install horizontal collectors.

GHG emissions benefit

Horizontal collectors are quite appropriate for collecting the LFG generated during the early life of a landfill or cell. In addition, when installed accordingly they can collect the produced LFG which moves up and concentrates in the surface of the landfill.

The GHG emissions reduction benefit of horizontal collectors is regarded as medium.

2.1.2.2 Mixed horizontal and vertical LFG collection system

Description

The installation of a mixed LFG collection system aims to reap off the benefits of both collection systems' and to minimize, if not to eliminate, their drawbacks. More specifically, the main advantage of horizontal collectors is the possibility of early gas collection. However, this type of collection is not so efficient as the one of vertical wells, since refuse permeability is greater horizontally than vertically, and they are the vertical wells that apply vacuum in the horizontal plane. In that way, horizontal collectors can be installed so as to create a horizontal layer of efficient gas collection, but vertical vacuum distribution is not as good for these collectors. A good way to increase vertical vacuum distribution is through tighter vertical spacing of horizontal wells to cover gas collection throughout a landfill. Despite the greater efficiency of vertical wells, this type of collection is not the best for cells or landfills that are still in operation, since they can interfere with filling operations or even be destroyed.

The horizontal collectors of a mixed LFG collection system can collect LFG across the horizontal plane of active landfill areas, including near surface gas, whereas the vertical wells collect gas from areas that are at or near final or interim grade or are in areas which are not active for filling. In that way it is guaranteed adequate interim control during the operations and increased efficiency after the completion of a cell or a landfill.

Feasibility

In spite of having significant advantages and being feasible for most landfills, the installation of mixed collection systems can also face serious problems. More specifically, the installation of horizontal collectors requires coordination with landfill operations. Moreover, the collectors must be accurately surveyed to prevent future damage from operations or drilling into the refuse. In addition, mixed systems seem to be inconvenient at many sites because vertical wells are installed in smaller increments as areas reach grade or become inactive. Furthermore, the overall cost of collection system could be expensive, depending heavily on the number of vertical wells to be drilled.

Implementation Recommendations [3, 6]

This BMP is more appropriate for large landfills that take years to fill a section. In addition, it is recommended for sites with a thick layer of solid waste. In such cases, horizontal pipes may be connected with vertical wells at numerous levels to facilitate the gas discharge to well. Such an option has the economic advantage of a reduced number of wells.

Relative cost

This BMP appears to have an increased cost in relation to simple systems because of the higher horizontal collector costs and multiple drill rig mobilizations for vertical wells. In case that the landfill is very deep, some vertical wells can be avoided. However, for deep landfills, it should be assessed the efficiency and function of the horizontal collectors, which are usually crushed because of the overlying weight of waste. A proposed measure to ensure the functionality of horizontal collectors is the use of metal pipes; a fact that rises significantly the system's cost.

The relative cost of this BMP is expected to be medium to high for full implementation of the combined systems approach.

GHG emissions benefit

This BMP provides a good early LFG collection. The relative GHG emissions reduction is expected to be medium.

2.1.2.3 Increase of collection well/trench density [3, 7]

Description

This BMP is achieved by implementing a LFG collection well or trench density greater than what currently exists on site or is typically proposed by designers prior to installation.

Most LFG system designers use various tools, models and experience to estimate the expected radius of influence (ROI). For landfills with typical clay cap and liner the ROI for vertical wells is about 30-60 m, with the possibility of spacing to be greater in landfills with composite liners and caps, and horizontal collectors, whereas for horizontal trenches is about 15 to 30 m [4, 7]. Among others, the main parameters determining the spacing of the vertical wells and of the horizontal trenches are:

- The thickness of the waste;

- The water content of the waste;
- Type of daily and intermediate landfill cover;
- The length and placement of the perforated well pipe;
- The diameter of the well;
- The use of well bore seal(s);
- The distance from the top of the perforations to the landfill surface;
- The vacuum available. [3]

Taking into consideration the parameters given above, it is determined the number and the spacing of LFG collectors, so as to provide adequate coverage in a cell or a landfill.

A common practice for LFG system designers is to overlap to some degree the ROI for neighboring wells and trenches so as to guarantee vacuum throughout the waste mass. However, collectors can fail for a variety of reasons, and there is always uncertainty in estimating the radius of influence. Therefore, there may be room for reducing the spacing of wells (and increasing the overlap of the radii of influence) in a conservative LFG system design.

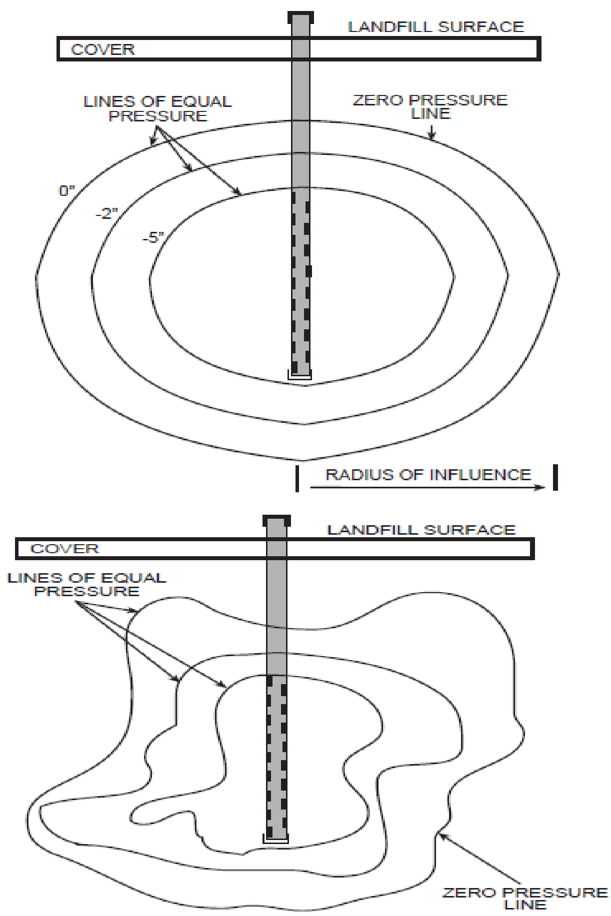


Figure 6: Theoretical and Actual ROIs

LFG collection generally increases as more collection wells or trenches are installed, as long as the radius of influence of the extraction points is appropriately taken into account. For LFG extraction systems that may be subject to air intrusion, the use of additional extraction points can allow the overall system to operate at a lower vacuum, thus reducing air intrusion and increasing LFG extraction coverage. More specifically, wells and trenches near the perimeter or edge of a landfill are more prone to air short-circuiting and therefore less likely to operate at high vacuum. These wells should be installed at a relatively close spacing and operated at lower relative vacuum than the interior wells or trenches. However, wells on the interior of a landfill do not have the same air short-circuit potential. Hence it may be possible to operate these at much higher vacuum, and as such, not as many vertical wells are required. Therefore, fewer interior wells could be installed and still place adequate vacuum on the landfill. It must be shown that any reduced spacing in the interior does not jeopardize control of LFG within the entire extent of the refuse. [3,7]

Feasibility

The increase of collection well/trench density is feasible in most landfills. This BMP should be applied when it is measured that the collected amount of LFG is not the one expected initially. In this case collection well/trench density should increase so as to collect a higher percentage of the LFG produced.

If a LFG collection system has yet to be installed, additional wells and trenches can be implemented in the design, but should always be measured against potential recovery and with consideration for expected zone of influence around each of the extraction points, which is a function of landfill conditions and intended operations of the LFG extraction system. The implementation of this BMP is relatively simple for both closed and active sites. [3, 7]

Implementation Recommendations

Increasing the LFG collection well or trench density is applicable for any landfill site, active or closed, that has an existing collection system installed. Increase of horizontal collection trench density can be accomplished during filling activities for active sites, or can be implemented as shallow trenches post-filling. Increasing the vertical LFG extraction well density simply involves installation of additional wells and connection to the LFG collection system. [3, 7]

However, it is suggested increase of collection well/trench density to be applied initially on a limited basis and to be monitored. Tracking the increase in total and per well gas flows will help determine if larger scale employment will be successful. There is a point of diminishing return with this BMP, as additional collectors do not increase the amount of extracted methane because they are simply drawing gas from other wells rather than from an uncollected reservoir. Competing vacuums between neighboring wells can also increase operation and maintenance costs. [3]

Relative cost

An increase of collection well/trench density raises the cost of the LFG collection systems. The cost-effectiveness of this BMP is ultimately dependent on the amount of LFG not collected under the existing or less conservative design. Despite the fact that relative costs of installing additional LFG collection wells and trenches can vary substantially based on site-specific conditions and the applicable design, the relative cost for implementation of this BMP is expected to be medium.

GHG emissions benefit

Implementation of this BMP improves LFG collection, consequently reduces the GHG emissions to the atmosphere. When applied appropriately in sites with relatively poor extraction point coverage, it can increase LFG recovery while reducing air infiltration; if the initial coverage is at a high resolution, additional extraction points may increase collection further, but at diminished relative return. However, this BMP is resource intensive and possible gains should be balanced against the required expenditures.

Given that LFG collection is the simplest and most direct way to control LFG emissions, this BMP can provide a medium to high reduction GHG benefit.

2.1.2.4 Deep, Multi-Depth Vertical Wells

Description [3, 16]

This BMP suggests the installation of multiple vertical wells for different depths in the same bore hole. Given the fact that the deeper a well is imbedded in refuse, the greater is the vacuum that can be applied before the well will short-circuit with ambient air, this BMP aims to operate the deeper zones at greater vacuum than the shallower ones. In that way it is increased the captured amount of LFG from the deeper parts of the landfill. What is more, if additional gas is present as evidenced by positive pressure in the well, shallower wells can be brought online sequentially from bottom to top. This pressure condition can exist because of the reduced vertical versus horizontal permeability of refuse.

A variation of closely spaced, deep, multi-depth vertical wells is to alternate the pattern between deep wells and shallow single depth wells. This pattern helps take care of the problem of shallow wells having a reduced radius of influence compared to deep wells. It also reduces the construction cost from drilling deep vertical wells. [3]

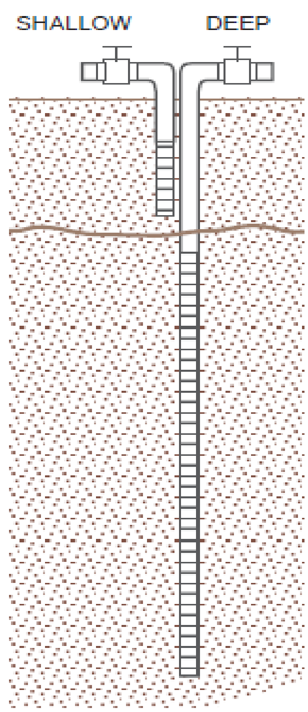


Figure 7:Multi-depth vertical well [6]

Feasibility [3]

This BMP is more feasible for deep unlined or clay-lined landfills with evidence of lateral gas migration. In addition, this BMP can provide useful solution to sites with steep slopes, where shallow wells are prone to short circuiting. By splitting the well into multiple depth casings and maintaining greater depth to the perforated sections, the short-circuit path for deep wells is longer hence greater vacuum can be applied to them.

Implementation Recommendations

Important element for the realization of this BMP is the spacing of vertical wells. Designers are encouraged to elaborate spacing of wells conservatively. An evaluation of the possible deep well zone vacuum is indispensable and in case that the ROI can be doubled, based on the longer short-circuit path, then alternating deep and shallow wells can be constructed.

It is very common practice vertical wells to be installed in the active fill area of a landfill, causing in most occasions problems in the operation procedures. In order to overcome such problems, it is suggested to extend the vertical well by the height of a refuse lift, place dirt around the well, and fill refuse around the dirt. Wells extended in this manner have the advantage of being deep in refuse; however they are costly to protect and prone to failure.

Relative cost [3]

The relative cost for the implementation of this BMP is considered as low since the multi-depth vertical wells can be implemented over traditional vertical wells for a nominal cost increase. This nominal cost includes additional materials of construction, and additional wellhead(s), monitoring port(s), and control assemblies.

There are some economies of scale because one borehole is essentially used for two wells, except when using the alternate pattern type design where two boreholes are used.

GHG emissions benefit

Main benefit of this BMP is the increase in the amount of LFG collected; consequently, it is reduced the amount of GHG emitted to the atmosphere. The benefit from the implementation of this BMP is considered low for shallow landfills, but medium for deeper ones.

2.1.2.5 Maximize Borehole and Well Diameters

Description

Maximization of borehole and well diameters can provide a useful way to increase the LFG amount collected, since smaller diameter wells may act as a limiting factor to LFG collection. The usual diameters for borehole and well diameters are 500 to 1000mm and 100 to200mm, respectively.

Apart from the fact that wells with bigger diameter can collect more LFG, another important advantage they have is greater resistance. Consequently, they are not so vulnerable to hits and pinches and they can accommodate the insertion of pumps for leachate removal.

As for boreholes, larger diameter acts as safety factor against settlement and diminishes the plugging of piping perforations due to fine material. In addition, they guarantee enough space for well installation, even an amount of refuse will fall back into the borehole. What is more, large diameter boreholes offer greater surface perimeter area to apply vacuum to the refuse. Another important element is that larger diameter boreholes may benefit the conduct of deep wells, since it is less likely drilling refusal to limit the depth of a well, because larger items can be extracted through the borehole.

Deep vertical extraction wells should be installed in a minimum of a 500mm boreholes with a provision to increase the borehole to as large as 1000mm in areas with excessive liquids. It is also important to use a high quality pipe for wells, including higher grade, i.e., thicker wall HDPE or steel pipe in areas with expected high gas temperatures consistently over 150 degrees F.

Feasibility

This BMP can be applied in all vertical well systems. It is most feasible for extraction wells where high gas production is expected and for landfills with high risk of settlement.

Implementation Recommendations

In order to implement this BMP, it is required to review site conditions and to select the appropriate pipe and borehole sizes. In every case, it is suggested the system to be designed conservatively and to select the largest diameters for both.

Relative cost [3]

In comparison to the cost of conventional LFG systems, the relative cost for the implementation of this BMP is considered medium, since it includes the purchase of more expensive pipes and greater costs for the drill of larger boreholes and backfill materials.

GHG emissions benefit

The benefit from the GHG emissions reduction that arises from the implementation of this BMP is considered low. Despite the fact that larger pipes can collect more LFG, the main reason to implement this practice is to ensure system's capability to collect LFG and not to act as a limiting factor.

2.1.2.6 Enhanced Seals on LFG Wells and Boreholes

Description [3]

Active LFG extraction requires the application of vacuum, the amount of which is greatly determined by the seal between the perforated collection zone and the nearest source of air infiltrating the landfill. The most usual source of air infiltration for vertical wells is the well borehole, whereas for horizontal collectors is the well trench.

In order to avoid air infiltration phenomena, designers use bentonite or bentonite soil mixtures near the surface of vertical wells as part of the well boring backfill. Compacted backfill soil can be an alternative choice, however, it may not be practicable and it can damage the well casing pipe.

There are three different techniques to seal a well's connecting pipes:

- Bentonite clay seal,
- Compacted clay seal, and
- Plastic well bore seal.

Given the fact that seal is critical for proper well performance, it is common to use multiple seals (designers suggest two or three), with potential combinations to be:

- Bentonite – Bentonite
- Bentonite – Clay
- Bentonite – Well Bore Seal
- Bentonite –Clay – Bentonite
- Bentonite –Clay – Well Bore Seal
- Bentonite – Bentonite – Well Bore Seal.

The first bentonite seal is placed deep in the borehole, with the other seals to be installed closer to the landfill surface. Closed landfills that use a clay cap usually have a clay seal in the well borehole that matches the cap depth.

A good surface seal appears to be more effective at minimizing surface emissions and borehole air intrusion.

Feasibility

The first two techniques provided above are feasible for both vertical and horizontal collection systems, whereas the third is feasible only for vertical wells.

Implementation Recommendations

Given the importance that seals have, designers are suggested to use a minimum of two seals, with the use of additional seals not to be a problem. However, the use of bentonite may be problematic in dry conditions, causing the bentonite to desiccate and crack.

Relative cost

The relative cost for implementation of this BMP is considered low, since it requires only additional materials and labor for the installation.

GHG emissions benefit [3]

If this BMP is implemented to wells having proper ROI, it can achieve a medium to high GHG emission benefit in comparison to improperly sealed ones.

2.1.2.7 Dewatering of Gas Wells

Description [3]

Dewatering of gas wells is considered as a BMP given the inability of wells to pull gas through liquid. The most common liquids appearing in gas collection wells are leachate and LFG condensates. Keeping liquids out of wells is considered as an indispensable element for the proper performance of a LFG collection system. The best way to achieve this is by not let them enter the wells.

A common measure to block liquids from entering the wells is to place a Bentonite seal opposite perched water in the refuse. However, in order this method to be effective, levels of perched water have to be determined, so as to place accurately the seal. Other measures to prevent liquids from entering the wells are the conduct of field investigations of liquid levels into the site, so as to avoid these areas, and the installation of solid pipes in depths and areas that liquids are suspected. What is more, lateral collectors should always be sloped away from the well head to avoid condensate backflow.

Another issue arising from the accumulation of liquids is the biological build-up on the well screen or the filter pack. As a result, dewatering becomes more difficult and subsequently gas collection reduces. In order to overcome such problems, they have been developed a few methods to flush the screens and filter packs. Despite the effectiveness of flushing methods, the liquids used may hinder the performance of wells. For this reason, another successful alternative for this issue is the installation of leachate pumps into the wells; however, the removal process is very slow.

Feasibility

This BMP is most feasible for landfills with high level of leachate production, a factor that can affect LFG collection. In order to avoid such problems, designers are encouraged to develop the collection system in such a way so as to keep liquids out of the wells, with the most common practice to be to place the perforated wells above liquid zones.

In case that leachate/liquid removal is required, they can be used pumps; however, both operation and maintenance costs are high, and leachate infiltration can cause functional problems to pumps.

Implementation Recommendations

In order to implement this BMP, they are required well pipes with larger diameter, so as to allow installation of leachate/liquid removal pumps. As a result of the pumps' installation, they are also required other utilities such as power and compressed air to facilitate pump operation.

The cost and performance of installing pumps should be measured against those of installing a well with perforations above the leachate level. [3]

Relative cost

The relative cost for the implementation of this BMP varies depending on practice applied. In case of installing pumps, both long term costs for operation and maintenance are high, not to mention the costs for collection and disposal of the leachate.

For the case of gravity drain leachate from horizontal collectors, the relative cost is considered low. However, this approach seems to be more vulnerable in multiple factors (differential settlement, silt, etc.) that can cause its fail.

GHG emissions benefit

Since flooded wells cannot collect gas, dewatering can constitute a useful solution for every well that has been watered in, providing a significant GHG emissions benefit.

2.1.3 Best Management Practices – BMPs for the design of LFG Collection Systems

2.1.3.1 Early Installation of LFG Systems

Description

Early installation of LFG systems aims to capture emissions that would otherwise escape to the atmosphere. This practice is usually applied in active cells/landfills, where operations have not completed or LFG system installation is not yet required. Early installation is usually applied using horizontal collectors or extraction wells with remote wellheads to accommodate the well being buried under future waste, and extraction wells that are protected and raised with waste filling. [3]

Feasibility

This practice is more feasible for big landfill with high disposal and degradation rates, where active cells may have enough gas production in quite short time. Typical example of landfill that requires early installation of LFG system is the Bioreactor landfill.

Implementation Recommendations

Implementation of this practice applies to landfills that do not have installed a gas collection system or to landfills with an existing collection system that requires further expansion due to increased waste disposal and gas production.

Relative cost

The relative cost to implement this practice depends on the existence or not of a LFG collection system. In case that there is not an installed system the cost is expected high, whereas for expansion of an already installed one, is expected low.

GHG emissions benefit

The GHG emissions benefit that can be achieved with the implementation of this practice depends on the site's characteristics. More specifically, for a site with an already installed collection system, that was expanded, the benefit is considered low to medium, whilst for a site that did not have a collection system at all, the benefit is expected to be high.

2.1.3.2 LFG Planning

Description

Implementation of this practice suggests the development and implementation of a LFG Master Plan for both already constructed and to be constructed landfills. With the development of a LFG Master Plan it is guaranteed compliance with the current legislative framework related to waste management and the emissions arising from it, it is ensured environmental and public health protection and long term risks are minimized. What is more, through the system's optimization it is achieved the optimal result with the lowest cost.

Feasibility

This practice is feasible for all landfills.

Implementation Recommendations

There are no specific recommendations to implement this practice. However, a LFG Master study is suggested to cover indicatively issues related to: LFG generation and recovery, optimal collection system layout, LFG monitoring system, energy recovery future landfill expansion, overall system's costs, etc.

Relative cost

The cost to implement this practice is expected to be low, especially when compared to other BMPs.

GHG emissions benefit

The emissions benefits that may arise from the drafting of a LFG Master Plan are difficult to be quantified. However, given that LFG Master Plan allows landfill operators to achieve maximum LFG control and to expand the system properly as landfill receives waste, it is expected to have a low to medium benefit.

2.1.3.3 Connection of Leachate Drainage Layer (LDL) to LFG Collection System

Description

With the connection of LFG system to the leachate drainage layer (LDL) it can be achieved LFG collection under the waste mass, along the bottom of the landfill. The connection is done by installing a lateral pipe connection, with corresponding wellhead, to an LCRS riser pipe, clean-out, or other access point.

Feasibility

This BMP can be implemented in landfills with an existing LFG collection system, which can be connected to the LDL. It is most feasible for sites that have identified significant quantities of LFG in the LDL. In addition, it is more effective for dry climate, where leachate collection pipes are not filled with liquid.

Implementation Recommendations [3]

An element of crucial importance for successful implementation of this BMP is to connect the LFG system with the high side of LDL, so as to avoid problems with leachate blockage.

What is more, the LDL should be brought online only when it is buried by waste; otherwise, there is danger of air short-circuiting, increasing the risk of fires and reducing the effectiveness of the LFG collection system.

The implementation of this BMP suggests the installation along the bottom perimeter of some cleanout/riser pipes so as to create a vacuum influence. In that way LFG migration or escape over the liner anchor trench can be prevented. However, before the application of vacuum, leachate collection pipe connections, shafts, etc., should be monitored for gas quality, quantity, and pressure.

Relative cost [3]

The implementation of this BMP is not considered expensive since the only costs arising are those of a LFG wellhead and some above grade piping.

GHG emissions benefit

This BMP offers the possibility to collect LFG amounts that are produced during the early stages of a cell's life, when LFG preferentially moves into the LDL. In that way, it can provide a medium to high GHG emissions benefit early in a landfill's life, a potential, however, that as landfill ages decreases.

2.1.4 Operate LFG Systems for Leachate Recirculation

Description

Leachate recirculation is used by many operators to increase the moisture content of a landfill, which in turn increases the rate of biological degradation in it, the biological stability of it, and the rate of methane recovery from it.

A useful way to achieve better leachate recirculation is by using the LFG collection system. Horizontal collection network seems to be more appropriate for leachate recirculation, since it is comprised of collection and distribution pipes, located in shallow trenches filled with permeable materials. Given that, they can be used to distribute leachate into the waste mass. In case of implementation of this practice, the elements of LFG collection system need to be larger so as to perform both purposes. In that way it increases also the system's ability to collect and transport larger volumes of LFG.

Feasibility

Use of LFG collection system to re-circulate leachate constitutes a common practice for landfill operators.

Implementation Recommendations

Recirculation of leachate usually requires a special approval. In addition, in order a landfill to better accommodate leachate recirculation it is required to have an enhanced LFG collection system installed, so as to correspond efficiently to the increased amounts of LFG produced by leachate recirculation.

Relative cost [3]

Use of LFG collection systems to re-circulate leachate in landfill increases the cost of LFG collection system, because they are usually required distribution layers or horizontal wells, elements that are not typical parts of a LFG system. What is more, there are additional costs for leachate collection, storage, and pumping system to accommodate the recirculation process.

The relative cost to implement this BMP is expected to be medium to high.

GHG emissions benefit

The GHG emissions benefit that arises from the implementation of this BMP is medium and has to do with the potential to capture greater amounts of LFG, since more of it is produced. However, leachate recirculation can result in increased GHG emissions without the installation of an enhanced LFG collection system.

2.2 Limit fugitive emissions (indirectly improve the “R” factor) and enhance bioxidation (maximise the “O” factor)

2.2.1 Designing for Closure and Post–Closure

Description

Proper design for closure and post-closure of a landfill are crucial parameters ensuring effective and efficient operation of LFG collection system for a long period.

It is at the closure of a landfill that operators install the last vertical wells and horizontal collectors, and enhance or substitute, wherever required, the already applied elements. What is more, operators are encouraged to upgrade wellheads and pipes to above grade, so as to allow easy access for future procedures of maintenance and monitoring.

Final cover is the element ensuring the potential of a landfill to adequately prevent from escaping and **to oxidize the LFG produced during the post closure period**. For this reason, final cover should be designed carefully and penetrations must be avoided as far as possible. If a penetration cannot be avoided, a seal should be installed in every case. What is more, final cover should be carefully inspected, maintained and repaired, wherever required, to retain its abilities.

Feasibility

This BMP involves enhancements of LFG system at closure and proper operation and maintenance of LFG and cover systems. For these reasons, this BMP is most feasible for well known and documented landfills.

Implementation Recommendations [3]

Implementation of this BMP requires the development of an operation and maintenance plan for the LFG and cover system for the closure of the landfill. The plan should also describe post-closure (aftercare) activities.

Relative cost [3]

The relative cost for closure enhancements and post closure maintenance are expected low, since they can be coordinated with LFG and closure activities.

GHG emissions benefit [3]

Despite the fact that proper design of closure and post-closure activities of a landfill can provide an effective way to reduce GHG emissions to the atmosphere, the potential for this BMP is considered low.

2.2.2 Blockage of Permeable Layer within Landfill Footprint [3]

Description

Implementation of this BMP aims to deal effectively with LFG migration up slopes and into the anchor trenches and to avoid LFG escape beyond landfill’s seal.

Given the fact that most modern landfills are designed with either a gravel layer or a geocomposite layer across the bottom of the cell and up the slide slopes, this BMP suggests the blockage of the gravel layer or the geocomposite as a measure to prevent LFG from escaping. An effective way to achieve this is by injecting sealing foam around the top of the LDL. What is more, weld of a membrane to the bottom liner covering the gravel layer or the geocomposite inside the anchor trench could be an alternative.

This BMP deals with LFG migration up slopes and into the anchor trenches and it is applicable only for landfills that have a LDL on slopes.

Feasibility

This BMP is most feasible for new cell installations but more difficult for cell retrofits. Indispensable element for the realization of this practice is the existence of a LDL on the slopes.

Implementation Recommendations [3]

This BMP is more appropriate for all new liner system installations that have a geocomposite LDL on the slopes which extends into the perimeter anchor trench. However, it should be considered for retrofit installations where there is a known problem of gas escaping through the anchor trench.

In addition, when welding a membrane to the bottom liner of a landfill, it must be shown attention to ensure the integrity of the anchor trench.

Relative cost [3]

The relative cost for the application of this BMP is expected low, especially if it is applied in a landfill from the beginning of its operation. However, the cost of material and welding the strip is higher than the one for sealing foam.

GHG emissions benefit [3]

This BMP provides a relatively small benefit concerning the reduction of GHG emissions, since it deals only with the LFG that migrates up the slope and is released to the atmosphere.

2.2.3 Designing Covers for LFG Collection

Description

Covers may play an important role in LFG collection. Covers are categorized according to the time they are applied. As a result there are daily, interim and final covers.

The relevant objectives for applying a cover are to:[8, 9]

- prevent wind-blown litter;
- prevent odours causing a problem off site;
- avoid attracting scavenging birds to the site or the air space above it;
- deter other forms of scavenging;
- reduce infiltration of rainfall;

- promote runoff from the refuse;
- prevent vermin from being attracted to or infesting the site;
- prevent flies from infesting the site;
- minimize the risk of fire on or within the site;
- ensure the visual appearance of the site is not seriously detrimental to the amenity of the locality.

Typical daily cover is comprised of 20 cm of onsite soil that has been excavated usually during the construction of the landfill. It is possible landfill operators to use alternative daily cover (ADC); however, such materials have to be tested. Specific materials that can be used as ADC are: [9]

- Ash and cement kiln dust;
- Treated auto shredder waste;
- Construction and demolition waste;
- Compost;
- Green material;
- Contaminated sediment;
- Sludge;
- Shredded tires;
- Foam products;
- Geosynthetic fabric or panel products (blankets);

Given the ADC materials above, it is clear that specific materials can save space in the landfill, can lower operating costs, but also have the advantage of being able to attenuate (e.g., adsorb, oxidise, etc.) LFG constituents and prevent their release to the atmosphere. [3, 10]

Interim covers are usually thicker than daily covers and are expected to remain effective by over an extended period of time, thus the durability of the cover material and the ability to shed surface water to drainage ditches become more crucial elements. The latter issues show with the best way that not all daily cover materials are suitable for interim cover materials.

LFG collection systems do cause problems in daily or interim cover development; however when materials of low permeability are used, a difficulty in LFG collection might be observed due to impeding gas movement at various points within the waste mass. [3]

When a landfill closes, a cover of low permeability is usually applied on it which aims to seal the site's surface by not letting water to enter the site, by preventing air intrusion and by not letting LFG to come out the site. Synthetic covers are considered as the most appropriate elements for final covers [3]**.** In all cases, covers must be inspected, maintained and repaired, when necessary, to ensure its optimal function concerning LFG emissions reduction.

Feasibility

The application of daily, interim and final covers are a common approach in Greece, especially since they are considered as mandatory by legislation. The application of covers may constitute a problem for the installation of a LFG collection system; that is why many methods have been developed (and are proven by now), for extending wells, relocating piping, and sealing final covers.

Implementation Recommendations [3]

Proper design of the cover system is a prerequisite for the optimal operation of the LFG collection system. For this reason it is suggested the cover system to be designed from the beginning in such a way to allow the proper installation, relocation, and operation of LFG collection system components, avoiding the same time the high cost of later changes.

Relative cost [3]

Implementation of this BMP requires proper design of the cover layers from the beginning of the landfill’s construction, so as to accommodate LFG system components. For this case the cost is considered low; otherwise, the cost may rise a lot. What is more, use of typical cover elements has low cost, whereas use of synthetic covers may prove quite expensive.

GHG emissions benefit [3]

Incorporation of LFG systems into cover systems design offers the potential to manage efficiently the produced LFG in a site. However, the benefit arising from the implementation of this BMP varies depending on the type of cover element used. Collected data from various reports indicates a value of 36% (overall average) of non-collected methane being oxidised in the final cover []. Therefore, the benefits may be considered as medium.

2.2.4 Limit Delays on Final Covers Systems

Description

As it has been mentioned above, it is the final cover element and the thoroughness of its installation that largely determines the vacuum applied on the LFG collection system of a site. Given that, a well applied final cover material with low permeability may increase the allowed vacuum of the LFG collection, optimizing in that way its performance and allowing greater amounts of gas to be collected.

Given the above, landfill operators are suggested to apply final covers as soon as possible after the completion of a cell, in order to increase the efficiency of the LFG collection system.

Feasibility

Application of this BMP is most feasible for cells or sites that have reached their capacity and they have available onsite final cover elements, such as soil and clay. However, it should be ensured that early final cover of an area will not affect the operations in adjacent areas.

Implementation Recommendations

Early application of final cover demands the secure consent of landfill operators that it will not affect operations in adjacent areas. Also, application of this BMP in great areas may cost a lot, and they are the operators that may need to justify this high cost.

Relative cost

The relative to cost to implement this BMP is medium and may be high when it is applied on smaller sites, which require more planning.

GHG emissions benefit [3]

Implementation of this BMP avoids the emission of LFG to the atmosphere and allows the better performance of LFG collection wells. As a result, this BMP is considered to offer a medium GHG emissions benefit.

2.2.5 Modify, Limit or Remove Daily and Interim Cover Systems

Description

Daily and interim cover materials are commonly used in many landfills to address with specific issues. However, it is their use that creates problems in LFG flow into the waste mass, especially when they materials with low permeability have been used.

An effective measure to deal with such problems can be the use materials with higher permeability, such as degrading foams or green waste. What is more, the removal of the daily cover is considered as another potential solution, suggesting the use of tarps as an alternative.

Provided the above, a smoother LFG flow and a better performance of the LFG collection wells can be achieved.

Feasibility

Implementation of this practice is feasible for all landfills, since the only things demanded are tarps, green waste or degrading foams to substitute daily covers. The most important advantage of these practices is that they do not decrease the landfill's capacity, as other covers do.

For the case of interim cover, removal is considered a valuable practice since it increases the landfill's capacity. However, this method may prove costly and may create odour related problems. What is more, the increase in landfill's capacity may not be significant because the lowest layers of soil must remain on-site since they have been mixed with waste.

Implementation Recommendations

Removal of covers should be done to the extent possible, with the materials to be stocked for later use.

Relative cost

The cost to implement this BMP includes the costs of personnel and equipment to apply tarps or foam or to remove layers of soil. However, the additional cost arising from such practices is offset by the increase in landfill's capacity. Consequently, the relative cost is considered low to medium.

GHG emissions benefit

The main benefit arising from the implementation of this BMP is the easier transfer of LFG into the waste mass. Consequently, a greater ROI for the collection wells can be achieved, indicating a little more effective LFG collection from the site. The expected GHG emissions benefit is considered low.

2.2.6 Biocovers and Biowindows

Description

As it has been mentioned above, landfill covers oxidise to some extent the LFG as it travels through the landfill's surface. This basically occurs because of the existence of methanotrophic populations in most soils. As a result, many scientists focused their research on biocover design and how to optimise and sustain methane oxidation as a cost-effective technology for controlling emissions from waste disposal sites. [26]

Biocovers are typically comprised of a coarse gas distribution layer, so as to homogenize LFG fluxes, and a layer of organic material of varying type, engineered properties and depth, aiming to support methanotrophic microorganisms to consume the methane. [3, 26] However, the biocovers may not lose their efficiency if a gas distribution layer is not applied because waste from itself is quite permeable. A variety of elements are used to create biocovers including composted wastes, wood chips, bark mulch and peat, inorganic materials such as glass beads, bottom ash or porous clay pellets, as well as mixtures of organic and inert materials [27].

Alternatively to a biocover system, the methane oxidation might take place in a biowindow system. Whereas biocovers are designed to cover all or large sections of a landfill, biowindows are relatively small units at the cover where the biofilter material is integrated into the landfill cover. [26]

Important operational parameter is the fact that biocovers are operated in a passive way, with the LFG to flow from the waste directly to the filtration material governed by pressure gradients or by diffusion when pressure gradients are low. [26]

Biofilters are another small alternative of biocovers, comprised of an inlet tube from a passive LFG vent leading to a vessel or chamber filled with a distribution layer and a "filtering" layer of organic material. [Ca] Green waste is considered as an alternative form of biocover, with its effectiveness, however, to be less than the options given above.

Feasibility

Application of biocovers is feasible for all landfills. Given the fact that LFG extraction systems do not capture all LFG produced in landfills, biocovers can be used as further mitigation measure, in conjunction with LFG extraction systems, to further reduce the environmental load from landfills. [40]

However, it must be mentioned that the effectiveness of biocovers is largely determined by their thickness, physical properties, moisture content and temperature.[28]**.** What is more, methane oxidation depends on the amount of methane being released to the landfill surface [3]**.**

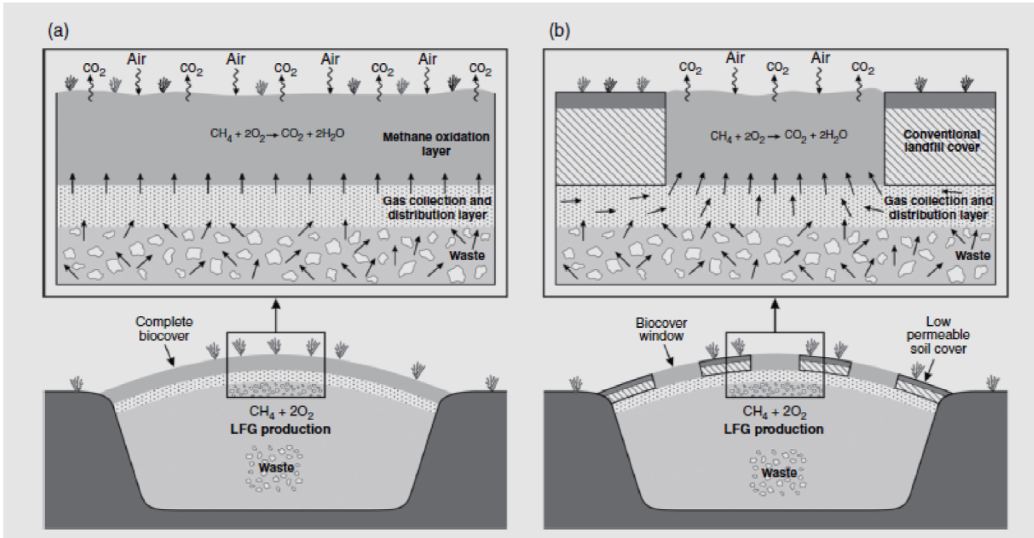


Figure 8: Designs of landfill covers intended for methane oxidation. (a) The concept of a biocover. (b) The concept of a biowindow cover system. [26]

Implementation Recommendations

Biocovers are a cost effective way to reduce GHG emissions from landfills. Research has shown that their efficiency increases when they consist of a gas distribution layer followed by an appropriate organic feedstock, such as compost. However, even without the distribution layer, biocovers can be quite effective.

As it has been mentioned above, biocovers can be implemented in most landfills. However, they appear to be more effective in small landfills, where LFG production is expected to be limited and installation of LFG collection systems is costly or for landfills that continue to emit significant amounts of LFG after their closure. Also, the efficiency of biocovers increases when they are connected with the final covering of a landfill, since they can easily be part of the final covering, minimizing in that way their required maintenance. [3, 29] An alternative approach suggests the use of biocovers as interim covers.

To be more competitive to other practices, whenever possible, it is suggested compost to be produced on site. In that way not only cost reduction is achieved, but there is also environmental benefit, reducing the transportation emissions. [3]

Relative cost

Being a “low” technology practice, application of biocovers to landfills seems to provide a number of economic advantages, including low operations and installation expenses, and low maintenance requirements. The economic advantages may be even greater in case of on-site compost production, avoiding in that way the cost of acquisition. In every case, the cost of biocovers must be similar to placing soil cover.

GHG emissions benefit

Selection of methanotrophic bacteria, landfill variables, ultimately the flow of fugitive methane through the cover system, the type and the extent of the biocover, are among the parameters determining the methane oxidation rate for landfill covers. Studies have shown that methane oxidation rate for landfill covers vary from 100 – 150 g CH_4/m^2/day (30 – 60 % removal to 250 g CH_4/m^2/day (80–100% removal). [26] .

What is more, apart methane oxidization, it has been demonstrated that properly designed landfill cover materials can degrade a wide range of volatile organic compounds, including halogenated hydrocarbons, some of which are more than a 1000-fold more greenhouse-active than methane (Scheutz and Kjeldsen, 2003, 2005; Scheutz et al., 2003, 2004, 2008) [26]

Given the above, application of biocovers in a landfill can provide medium to high GHG emissions benefit.

3 Improvement of Operations and Maintenance

Operations and maintenance play an important role in LFG systems. These systems include pipes, blowers, flares and other equipment that require a strict maintenance schedule to ensure good operation. Also, other parameters such as the barometric pressure may be controlled during operation in order to reduce LFG fugitive emissions.

3.1 Barometric Control of LFG System

Description

One of the forces responsible for LFG moves is atmospheric pressure. When atmospheric pressure is high, LFG is compressed in the void areas of waste, but when atmospheric pressure is low LFG tends to escape to the atmosphere, posing both environment and human health into danger. [11, 12, 13]

A useful method to reduce the amounts of LFG escaping to the atmosphere, when atmospheric pressure changes, is to control the LFG extraction rate. In that way, when atmospheric pressure is low and LFG tends to leave the waste mass, extraction rates can be decreased. Respectively, when atmospheric pressure is high and air tends to enter the waste mass, extraction rates can increased, ensuring also in that way less air infiltration.

In order to be most effective, the procedure must be automated and to adjust extraction rates, using a variable speed drive, based on atmospheric pressure.

Feasibility

It is the flow rate required to collect the LFG produced in a landfill that largely determines the feasibility of this practice and the ability to vary this flow rate. What is more, blowers and combustion devices used to treat LFG must be able to operate in a wide range to accommodate flow rate changes; otherwise, inappropriate choice of equipment may cause poor performance or even equipment failure. Apart from barometric variations, varying LFG generation while a landfill is filled or LFG decrease when a landfill is closed maybe the main causes of flow rate variations.

Implementation Recommendations

To implement this BMP it is required the possibility to adjust the gas extraction rate from the site. The easiest method to achieve this is by using a variable frequency drive (VFD) causing the vacuum to vary according to the desired changes in LFG flow rate.

Given the above, it is also recommended to use blowers and combustion devices with wide range of operation, so as to be able to accommodate the variations in LFG flow rates.

Relative cost

The relative cost to implement this BMP varies from medium to high depending on the desired maximum and minimum equipment performance.

GHG emissions benefit

Implementation of this BMP not only reduces to some extent the amount of LFG escaping to the atmosphere, but also limits the amount of air infiltrating a site, improving in that way the LFG quality produced. The GHG emissions benefit is expected low.

3.2 Redundant Flare Station Equipment

Description [3]

Despite being designed to operate 24 hours per day, 365 days per year, there will be times that flare systems must shutdown for service. The duration of such shutdowns is usually short, while others may last longer, especially when key equipment repair takes place and several days are required.

A few examples of shutdowns include:

Short Term Shutdowns	Long Duration Shutdowns
Adjust or replace belts on rotating equipment	Rewind an electrical Motor
Calibrating meters	Repair or replace a blower
Lubricating equipment	Repair or replace flare insulation
Replacing Thermocouples	Rebuild a flare burner
Replacing U.V. scanners	Repair/replace failed electrical equipment & controls

Given that in most cases shutdown is inevitable, the only thing can be done is to reduce downtime. One of the simplest way to correspond fast to minimize downtime is by having a thorough spare parts inventory, including consumable parts as well as entire replacement assemblies. Spare parts inventory can include consumable parts (i.e., thermocouples, U.V. scanner tubes) as well as entire replacement assemblies (i.e., a motor blower assembly). Most of the time, the thoroughness of the inventory has to do with the importance of the operation. For instance, LFG collection safety at a park is more critical than at an old and rural landfill that isn't generating much gas.

As an alternative to redundancy, increased operations, maintenance, monitoring, testing, and inspection can achieve the same objectives of minimizing system downtime and excess emissions that occur during downtime. See below "improvement monitoring" and "LFG Collection System Maintenance" for additional details.

Feasibility

It is generally suggested provision of redundant spare parts of the equipment installed in a landfill. What is more, operators of big landfills are encouraged to have already installed redundant equipment, in case that the one operating fails. However, redundant flare systems are less common because most flare systems have less than 10 days downtime per year.

In addition, implementation of this BMP is recommended for sites that flare system shutdowns may pose severe threat for the surrounding areas. For example, this BMP is recommended more for active sites – generating gas – close to residential areas, rather than for inactive sites located away from any activity.

Implementation Recommendations [3]

A good spare parts inventory is the basic recommendation to implement this BMP. This inventory should include all small parts requiring regular replacement or repair and parts that it is known in advance that it takes a lot to make them available.

For expensive parts, such as blowers or flares, it is suggested to have spare parts of lower quality to support the system so as to avoid a potential total fail of it. In addition, spare parts provide an additional degree of safety in reducing downtime. [3]

Relative cost

Despite the additional cost for acquiring spare parts, it may prove that proper equipment maintenance may extent its life significantly. In that way it can be assumed that the additional cost is depreciated. However, the cost to acquire a spare blower or a spare flare is expected to be medium and high respectively.

GHG emissions benefit [3]

Implementation of this BMP provides a low GHG emissions benefit, since most modern equipment is quite reliable. However, for the case that flares are used as backup equipment for energy recovery devices, which usually have greater downtime, the GHG emissions benefit is expected to be medium.

3.3 Maximize Capacity of Gas Mover Equipment

Description

Among the multiple operating limitations that blowers have, operating range appears to be the most important, since it has to match with the LFG collection rates, ensuring in that way proper operation of the gas collection system.

Maximization of the blower’s capacity aims at providing sufficient capacity to collect all the LFG produced in a landfill. Important part of this BMP is the proper sizing of the pipes used to and from the blower to avoid flow restrictions.

Feasibility

Implementation of this BMP is most feasible when having a reliable estimation of the expected LFG production and collection rate. In that case blower can be sized so that the LFG flow to be at the low end of its performance curve; otherwise, the blower must be sized for operation to its mid-range.

Implementation Recommendations

When it comes time for designers to select a blower, they should review the performance data for numerous units and they must seriously consider their capacity for both current and future gas collection requirements. In addition, proper pipe sizing is of crucial importance to avoid flow problems.

Relative cost

The increased cost to implement this BMP arises from the higher cost to purchase equipment of greater size and from the higher operating costs to low flow (a fact that may equate to low performance). Potential solutions to mitigate such costs would be the use of a smaller blower with provision to substitute it with a larger one in the future, if appropriate, or to use a variable frequency drive to turn the blower at a lower speed.

The relative cost to implement this BMP is expected to be medium.

GHG emissions benefit

Implementation of this BMP provides a benefit only when implemented in sites that LFG collection rates exceed the already installed blower's capacity. In that case, GHG emissions benefit is expected to be medium.

3.4 Maximize Capacity of Gas Control Equipment

Description

Use of flares is a very common practice to destroy methane and non methane organic compounds (NMOC) contained in LFG. Prerequisites for that are sufficient gas temperature, adequate oxygen presence in the exhaust and holding of combustion products for sufficient time to allow adequate destruction.

Aims of this BMP are to increase the LFG combustion capacity and to improve destruction efficiency.

Increase in combustion capacity can be achieved using a larger flare, whereas destruction efficiency can be achieved increasing gas mixing with oxygen, increasing the combustion temperature, or increasing the combustion retention time.

Consequently, it is clear that by increasing the flare size, both capacity and destruction efficiency are increased. Increasing flare size is practical provided the manufacturer can simultaneously increase the flare turndown. In that way it is achieved improved combustion capacity without castigating the low flow performance.

Feasibility

Turndown ratio is defined as the ratio of the flare's maximum capacity and the minimum amount of heat input that is necessary to achieve proper combustion and operate the flare. Flares can be made to operate between 4:1 and 8:1 turndown ratios, with a 6:1 turndown ratio to be desirable, allowing the flare size to be increased.

What is more, when very large flares are required, it is more practical to split the capacity into multiple smaller flares. In that way it is increased the minimum flare performance and it can provide partial combustion capacity when one of the flares is down.

Implementation Recommendations

To implement this BMP it should be installed either the largest flare with the greatest practical turndown or install multiple reduced size flares.

Relative cost

The relative cost to implement this BMP is considered medium to high since larger and multiple flares cost more.

GHG emissions benefit

In case that a flare is adequately sized, the benefit arising from the implementation of the practice is low. However in case that the flare's capacity is exceeded, installation of a larger flare may provide a medium to high GHG emissions benefit.

3.5 Improve Monitoring

3.5.1 Description

LFG monitoring is an indispensable "landfill related" practice ensuring environmental protection and protection of human health. Legislation requires regular monitoring of LFG production, pressure, content, etc., monitoring for LFG migration and accumulation and surface emissions monitoring using portable equipment.

LFG operations typically involve monitoring gas composition and related gas parameters that may serve as performance indicators. These include:

- Methane
- Carbon dioxide
- Oxygen
- Liquid levels (e.g., condensate, leachate)
- Gas pressure and vacuum
- Gas flow
- Hydrogen sulfide
- Other trace gases

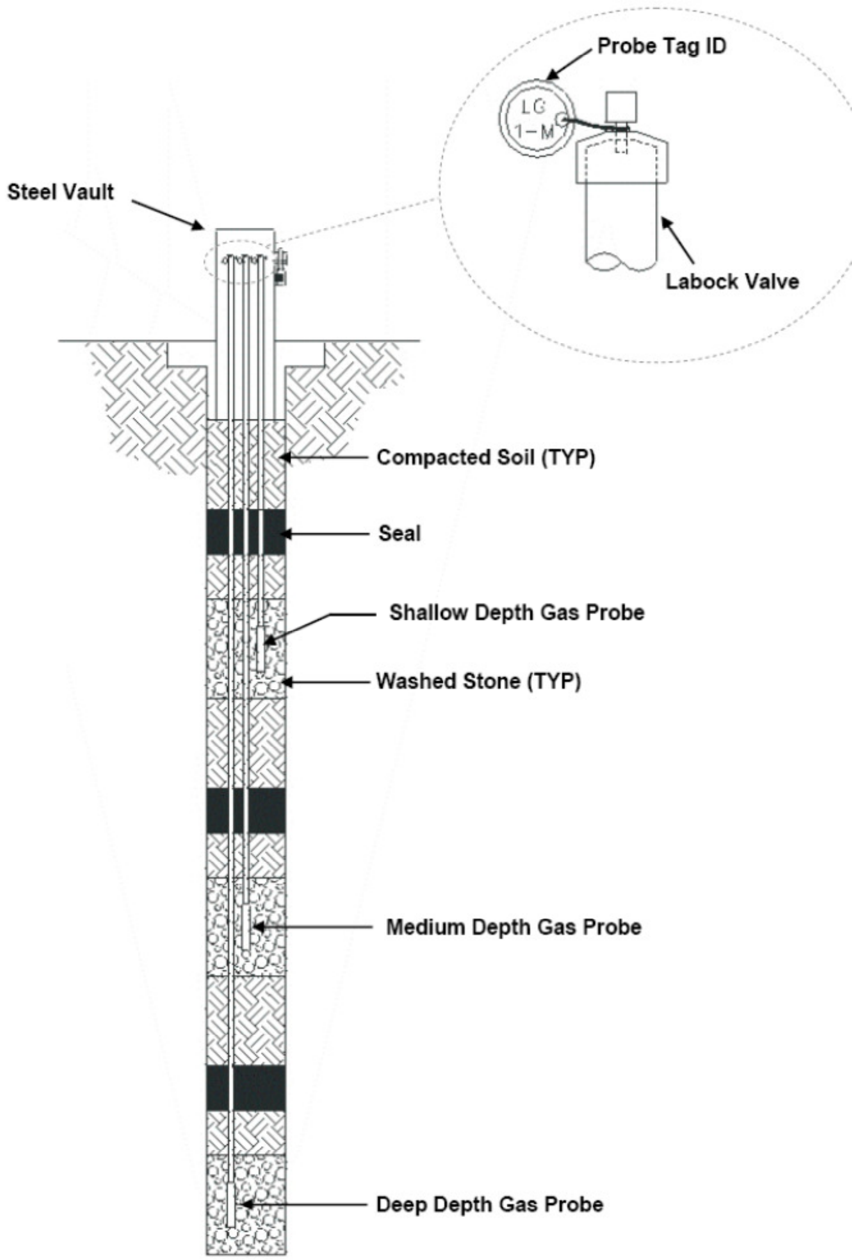
Landfills also are typically required to monitor for the subsurface movement of LFG, and to show that LFG migration control systems are working properly. This is because LFG can migrate from the landfill in all directions, can accumulate, and possibly explode under certain conditions. **LFG generally flows from areas of high pressure or concentration to areas of low pressure or concentration.**

The **monitoring of LFG surface emissions also may be necessary**, depending upon the air quality regulations in the area where the landfill is located. Specific reasons why LFG monitoring is necessary include:

- To determine whether LFG migration exists
- To assess the degree to which LFG migration has occurred
- To figure out whether there is any potential for a gas explosion
- To document how well the LFG system is operating
- To be in compliance with environmental regulations

3.5.1.1 Monitoring Probes

A primary monitoring system component is known as **the monitoring probe or well**. The purpose of such probes is to show whether LFG has migrated beyond an established boundary such as the landfill property line. Unless they are being used to collect LFG samples, monitoring probes should be placed outside the waste mass. Probes may also be located elsewhere to monitor landfill structure, specific LFG migration patterns, etc.



Monitoring probes can be driven into the soil, instead of using a borehole, if the probe depth is less than about 5 meters. Probes can also be single- or multi-depth, with multi- depth probes consisting of varying depth pipes within the same borehole. Depths should typically be determined by how deep the landfill is in the area of the probe.

The LFG probes typically monitor for the following types of indicators: methane, carbon dioxide, pressure, and balance gas (indicating nitrogen).

3.5.1.2 Monitoring points, Key Equipment and Data to be recorded

Apart from monitoring probes or wells, LFG monitoring and sampling can be conducted within the collection system piping, in buildings and structures to maintain a safe work environment, in soils near the landfill perimeter, at the landfill surface, at the extraction wells to show that the collection system is in balance, in monitoring wells, etc. Many different types of instruments are used to monitor LFG. Monitoring and sampling can be accomplished using both portable and stationary devices and instruments. Such devices typically measure LFG in terms of the percent volume occupied in the air.

A partial list of other areas where monitoring data should be collected from, as applicable, includes:

- Elevator shafts, pits and seals
- Wall space hollows and behind switch plates
- Basements and substructures
- Pilot light and fired equipment locations
- Water wells
- Foundation expansion joints and seams
- Electrical conduit
- Non-ventilated areas and small rooms
- Cracked flooring

To specifically determine methane levels, the following kinds of instruments are used:

- An organic vapour analyzer/flame ionization detector (OVA/FID)
- A combustible gas analyzer
- An infrared analyzer

Other key LFG monitoring equipment includes:

- Pressure measurement devices
- Oxygen detectors
- Flow measurement devices.

Specific knowledge about each instruments capabilities, limitations, and requirements is important. For example, an OVA/FID can also be used to measure the following:

- Low levels of VOCs or combustible gases
- Surface emissions
- Human exposure in specialized applications
- Fugitive leaks from pipes and equipment.

Portable measurement instruments are typically comprised of a detector element, an electronic circuit that responds to the detector, and a user interface such as a digital meter or analog current meter. The instrument must be calibrated to ensure accurate measurements. Also, the term indicator is sometimes used instead of the term analyzer to reflect the fact that the instrument in not that precise. For example, the presence of a combustible gas may be measured but not the actual quantity. One example is provided by the simple combustible gas analyzer or indicator (i.e., CGA or CGI). Such instruments can determine the presence of most combustible gases and, therefore, if the CGI is calibrated for methane, other gases that are present may impact the accuracy of the reading.

Typical instrument types and associated LFG application include:

- Flame ionization detector (for methane detection)
- Thermal conductivity detector (methane)
- Catalytic combustion sensor (methane)
- Infrared bench detector (methane, CO_2)
- Chemical reaction (oxygen, H_2S, CO)

As a rule of thumb, technicians should track and operate the following type of monitoring data and equipment:

- Geologic/hydrologic reports
- Gas well and probe location map
- Landfill depth information
- Barometric data from a nearby airport or installed meteorological station
- Gas monitoring instruments for oxygen, methane, CO_2, plus pressure gages

For each monitoring well tracked, the following type of specific data should be recorded:

- Date and time of readings
- Name of technician
- Weather conditions
- Atmospheric pressure
- Methane, CO_2, and oxygen gas composition
- Probe location, pressure/vacuum

In any event, data measurements should be conducted during the time of the day when LFG migration is identified to be at its highest. This is typically during **the mid-afternoon to late-afternoon period when barometric pressure is on the decline and LFG tends to migrate and vent from the landfill**.

Collecting data from the LFG wells on a consistent basis is important. This will enable operators to best achieve the goal of a balanced system. Monitoring frequency for the gas well depends upon field conditions and requirements, but should at least be performed monthly. Landfills with energy recovery, ground water protection concerns, etc., should be monitored more frequently.

Further, it may be necessary to adjust the wellhead to ensure that the gas collection system is in an approximate 'steady state' of operation. This will help to minimize the amount of air that enters the landfill through the landfill cover and other means. Balancing the well is accomplished by stabilizing the quality and rate of the LFG extracted.

It is important to note that the adjustment of one well can impact the performance of other wells at the landfill site. It is suggested that adjustment readings be started at the furthest location from the blower and flare facilities and then worked toward these facilities. In this situation, it makes sense to record all of the data before making any adjustments.

The typical data measurement categories associated with wells (wellhead) include:

- Measurement person's name
- Time and date measurements taken
- Carbon dioxide concentration (as a basis for well adjustment)
- Oxygen concentration (as a basis for well adjustment)
- Methane concentration (as a basis for well adjustment)
- Balance gas (nitrogen) concentration (as a basis for well adjustment)
- Ambient temperature
- Wellhead gas temperature (an indicator of anaerobic conditions)
- Gas velocity
- Wellhead gas flow rate before and after adjustment (key parameter)

- Wellhead vacuum before and after adjustment (to calculate and determine flow)
- Wellhead adjustment valve position (to note degree it is open or closed)
- Carbon monoxide concentration (if problem suspected)
- Hydrogen sulfide reading (if problem suspected - potentially lethal)
- Maintenance observations.

While there are many well adjustment criteria, methane quality and flow rate are the primary ones. These are indicators of the landfill's general anaerobic state and the impact of air intrusion on this condition.

In addition, landfill surface emissions monitoring may be accomplished using various monitoring devices, and applying different collection methods such as:

- **Immediate random landfill surface sweeps using an OVA/FID and a site map**: it involves observing and recording instrument readings using an OVA/FID and a site map, and following a random or predetermined pattern over the landfill. Particular attention should be given to high readings that result from damage to the landfill cap (i.e., as a result of drying, cracking, and settlement) or thin landfill cover.
- **Immediate direct landfill surface sweeps covering a defined area using an OVA (plus optional strip chart recorder or data logger)**: it involves covering a defined area involves taking data measurements similar to the random sweeps but the technician walks at a defined speed, recording readings with an OVA at a set time interval, within an established grid segment, and following a predefined pattern. A data logger or strip chart recorder may also be used.
- **Collection of an emission sample over time covering a defined landfill area using a bag sampler (OVA used to derive and average grid reading)**: it involves taking a continuous data measurement at a set sampling rate and speed. A bag sampler is used to collect the sample and methane concentration can be measured using an OVA.
- **Ambient air sampling using up-wind and down-wind integrated bag samplers** to measure total non-methane hydrocarbons (TNMHC) and track priority pollutants from the landfill

3.5.1.3 Monitoring schedule

According to legislation, biogas monitoring should be conducted once per month while the landfill is active and twice a year during the post closure period. **Implementation of the BMP suggests more frequent conduction of monitoring.** A typical schedule is presented in the following table:

Table 4: Typical schedule for LFG monitoring

LOCATION	ROUTINE	ACCELERATED	ACCELERATED SCHEDULE CRITERIA
LFG Monitoring Wells	Monthly	Weekly	Monitoring well with methane reading > 5.0% GAS
On-site Structures	Quarterly	Daily	Interior methane concentration reading of >25% LEL
Blower/Flare Station	Weekly	Daily	Adjustments made to any extraction system components (i.e., blower, extraction well)
Extraction System (first Year)	Monthly	Weekly	Adjustments necessary at extraction wells

Monitoring during the initial LFG system, (extraction system), startup maybe part of the construction acceptance tests. If the extraction system is inoperable for three or more consecutive days, a non-scheduled routine monitoring round should be conducted at all locations. Extraction system monitoring should be conducted at least monthly for the first year, depending on the stability of the extraction system flow rates, methane content, etc. With time, this monitoring frequency may be reduced.

Also, accelerated monitoring occurs when a there is a change of condition at the monitoring location. It is recommended that an additional round of perimeter and extraction system monitoring take place should the LFG system be shut down for a period of three days or more.

Accelerated monitoring schedules at the various locations are independent of each other (i.e., on-site structures can be under an accelerated monitoring schedule while the other locations remain under their respective routine monitoring schedules).

3.5.1.4 Health & Safety

When monitoring for methane gas concentrations, it is important to mind the following health and safety issues:

- Methane concentrations less than the lower explosive limit (LEL), equivalent to five percent by volume in air, may be indicative of a potential problem if corrective action is not taken;
- Methane concentrations greater than 15 percent (the upper explosive limit, or UEL) offer the potential for a methane-air explosion;
- **Good safety practices dictate that measured explosive concentrations of methane should not exceed 25% of the LEL**, or 1.25 percent methane by volume in air (25% x LEL=25 x 5/100), in structures (e.g., buildings, manholes, vaults, drainage culverts, structures housing an electric sparking device) on or near the landfill; and
- LFG displaces air as it builds up and may result in oxygen deficiency and death by asphyxiation in confined spaces and elsewhere.

In addition, a qualified worker should be responsible for the operation of the following types of field sampling instruments:

- A methane analyzer (e.g., a CGA)
- An instrument to measure hydrogen sulfide (potentially lethal gas)
- An oxygen analyzer

Such instruments and other portable electronic monitoring equipment should be rated explosion-proof and safe. Also, other gas compounds may need to be monitored (e.g., benzene, vinyl chloride) during drilling operations, and a daily record of monitoring activities should be maintained.

3.5.2 Feasibility

Implementation of this BMP is feasible for any landfill; however, it costs more and it is time consuming.

3.5.3 Implementation Recommendations

Implementation of this BMP does not require special recommendation.

3.5.4 Relative cost

The relative cost to implement this BMP is expected to be low to medium, since it includes the costs of additional surface emission monitoring and the potential costs of mitigation measures that may arise from the monitoring procedure. Consequently, if in a site is already conducted surface emission monitoring, the additional cost has to do with the increase in frequency of the monitoring procedure; as for sites that do not conduct surface emission monitoring, the implementation cost is expected to be greater, including the cost of the whole monitoring procedure.

3.5.5 GHG emissions benefit

The GHG emissions benefit accruing from the implementation of this BMP is difficult to be quantified, since no direct measure is applied on landfills. However, the stricter monitoring process ensures the minimization of LFG escapes and thus, application of the practice is expected to provide low GHG emissions benefit, which may be medium for landfills that do not conduct emissions monitoring.

3.6 Apply a thorough maintenance schedule of the LFG collection/monitoring system

3.6.1 Description

Thorough maintenance of the LFG system (instruments, wells, piping, blower/flare, etc) offers good functioning of the system and allows for efficient recovery of LFG. Also, when the maintenance schedule is followed severe or unexpected damages are avoided, while safety of personnel and residents is ensured.

This BMP suggests to follow the maintenance schedule as prescribed in relevant suppliers' manuals and also foresee additional maintenance periods after a failure, i.e. a slope collapse, an unexpected blower shutdown, etc.

3.6.1.1 Maintenance of the blower

The typical blower is a single-stage or multi-stage centrifugal gas compressor that is belt-driven or directly-driven by an electric motor. Proper operations and maintenance of a blower facility requires the following types of activities, on an as needed basis (i.e., daily to monthly, depending upon the facility design, system components, etc.):

- Checking the pressures and temperatures associated with blower suction and discharge to make sure there is adequate flare fuel pressure
- Checking for out of the ordinary blower vibration or temperature (weekly)
- Periodically draining condensate from the blower housing
- Running standby blowers (weekly)
- Checking drive belt wear and tension (monthly)

- Observing the levels of lubricants
- Greasing appropriate equipment parts (electric drive motor)
- Looking at the position and condition of valves (check valve, block valve)
- Determining the quality and temperature of LFG gas
- Monitoring instrument air operation
- Figuring out the status of condensate, LPG, propane, lube oil tank levels
- Monitoring overall system operations.

If maintenance is required, it is important to note all activities in a log book and on recorder strip charts, and take all appropriate corrective action as soon as possible.

3.6.1.2 Maintenance of the flare

The equipment leading up to and including the flare system are operated by a nearby electrical control panel. This includes start, stop, and reset buttons, and other switches for system operations. An electrical service panel is also typically located in close proximity.

To start the flare ignition sequence, most systems rely on a switch or button operation. Pilot fuel is lit with a spark igniter after the pilot solenoid valve is opened. The flame safeguard system verifies the existence of the pilot flame, the automatic block valve opens and the blower starts. This is followed by the ignition and operation of the main LFG flame which will establish a minimum operating temperature of 760oC. If the flare does not reach this minimum operating temperature within an established period of time, it will shut down..

Proper operations and maintenance of a flare facility requires a variety of activities, on an as needed basis (i.e., daily to monthly, depending upon the facility design, system components, etc.). A majority of the maintenance activities associated with the candlestick flare (i.e., proper fuel mixing, velocity, quality, flame condition, wear due to thermal stress) are also required for the enclosed ground flare system. The operational life of flare equipment can be maximized by operating the flare at the minimum recommended temperatures for emission control. Other specific operation and maintenance activities include:

- Checking the alarm or annunciator panel for any system malfunctions
- Observing that the flare temperature is in the proper operating range (daily)
- Inspecting the firing condition of the flare (secondary air dampers and flame)
- Checking the valve position at the flare inlet (for proper flare adjustment)
- Making sure the flame arrester is properly functioning (differential pressure)
- Observing facility flow
- Maintaining the igniter and pilot fuel systems
- Removing any condensate from the flare
- Checking the internal refractory for heat and other damage (enclosed ground flare)
- Inspecting high temperature shutdown/switch annually
- Cleaning electrical equipment controls and instrumentation annually
- Inspecting condensate equipment corrosion and other maintenance needs
- Completing a visual and audible check of overall system operations.

If maintenance is required (e.g., replacing corroded pipes, valves, etc.), it is important to note all activities in a logbook and on recorder strip charts, and take all appropriate corrective action as soon as possible. Further, it is desirable to maintain a minimum methane concentration for good combustion at the flare. About 25 percent methane is a practical minimum.

3.6.1.3 Maintenance of wells and pipes

LFG extraction wells usually consist of perforated or overlapping pipe casing placed in the solid waste. A permeable material, such as gravel, is then typically backfilled over the solid waste, and an impermeable material is placed over the gravel to prevent air infiltration. Suction is then applied to each well and trench using a blower and the LFG is extracted and transported to the processing facility.

Landfill managers should always strive to achieve a smooth, consistent well operation that promotes effective LFG recovery and control. Readings may be taken, relating to line vacuum, gas flow and quality, at key points along the main gas collection header and lateral branches. By doing so, leaking sections, poor performance, and pressure drops can be identified.

Normal operating activities associated with the wells and the conveyance piping include:

- Monitoring and adjusting LFG extraction wells;
- Inspecting landfill surface for indications that gas venting or air intrusion is taking place (e.g., settlement, openings, etc.);
- Looking at wells and conveyance piping for any needed adjustments and maintenance;
- Making sure monitoring instrumentation is operating properly; and
- Keeping thorough and accurate records and logs and scheduling appropriate maintenance services.

In terms of system maintenance, air leaks are a main concern. These may occur in the system as a result of settlement damage, conveyance piping expansion and contraction, system aging, and other factors. By comparing oxygen readings from the wellhead to access point readings, and looking for increasing concentrations, leaks can be detected and isolated. Major vacuum loss is another indicator of leaking air within the system. Such leaks are best repaired by replacing the damaged equipment. **It is recommended that oxygen not be greater than 3 to 4 percent by volume of LFG in the collection piping.**

Other maintenance activities associated with the well and conveyance systems include:

- Repairing or replacing system components (e.g., wellheads, condensate traps, valves, etc.)
- Reinstalling probes (due to loss, damage, etc.)
- Repairing and adjusting piping supports and anchors
- Re-sloping and re-leveling piping support earth berms
- Removing sludge or particulate from the liquid knockout vessel (visually inspect annually)
- Making adjustments to the landfill surface (e.g., cover and cap maintenance).

Proper selection of the type of conveyance system pipe material is also important from an operations and maintenance standpoint. In choosing which pipe material(s) is most appropriate for a given LFG system, the following factors should be considered:

- Strength (a function of pipe thickness, type, and how installed)
- Chemical resistance (to varying mixtures found in the landfill)

- Weather resistance (minimized through proper storage and installation)
- Stress cracking (due to solvent, environmental, oxidative, and thermal conditions)

Ultimately, how long a pipe material lasts will depend upon the service conditions and the durability of the material.

It is also advisable to check the well and collection systems for unusual conditions and maintenance needs. Unusual conditions would include: cracks and fissures, subsurface fires, liquid ponding, major settlement, etc. It should also be noted that the operation of extraction wells at temperatures greater than 145 degrees F or 63 degrees C may result in the weakening and possible collapse of thermoplastic well casings.

When repairs are being made to the LFG collection system it is often necessary to shutdown the blower and flare facilities as well. Such repairs should be coordinated with other shutdown procedures to minimize the down time of the overall LFG system/

3.6.1.4 Maintenance of the LFG monitoring system

In order to perform proper LFG system monitoring, the technician must possess a thorough understanding of operational principles, instrument procedures and maintenance, and the instrument operating limitations. Also, data collection personnel should ensure that the monitoring equipment is calibrated to collect the most accurate data possible. For example, readings from portable field instrumentation can be affected where there is low oxygen, or when working with explosive gases.

Using LFG monitoring probes as a specific example, accurate records should be maintained including, at a minimum, specific pipe identification (i.e., especially within a multi-depth probe scenario), probe depth, and construction information.

In addition, operational steps associated with LFG migration probe monitoring should include the following:

- Measuring and recording probe pressure/vacuum
- Checking the entire sample train for leaks
- Purging the probe piping
- Reading and recording gas composition
- Resealing the probe once monitoring complete.

3.6.2 Feasibility

Implementation of this BMP is feasible for any landfill.

3.6.3 Implementation Recommendations

Implementation of this BMP does not require special recommendation.

3.6.4 Relative cost

The relative cost to implement this BMP is expected to be low to medium, because it is common especially in very busy landfills to skip maintenance of LFG equipment and mainly focus on the leachate treatment plant. So, if a landfill does not perform any maintenance and inspection procedures on the LFG system, then after the initiation of maintenance operations at regular intervals the landfill **operation cost will increase.**

3.6.5 GHG emissions benefit

The GHG emissions benefit accruing from the implementation of this BMP is difficult to be quantified, since no direct measure is applied on landfills. However, the stricter maintenance procedures leads to better performance of the LFG system thus ensures the minimization of LFG escapes and thus, application of the practice is expected to provide low GHG emissions benefit, which may be medium for landfills that do not conduct maintenance.

4 Energy Recovery from LFG

Description

Energy recovery from LFG is considered a BMP because not only it deals efficiently with the LFG produced in a landfill, but because it offers an additional GHG benefit, by generating energy from an alternative fuel and not from fossil ones.

Energy recovery occurs by combusting LFG in internal combustion systems (Reciprocating Engines, Gas Turbines, etc.), in external combustion engines (Organic Rankine Cycle, Stirling Cycle Engines, etc.) and other technologies to produce electricity for on-site use and/or sale. [1,2,3]. What is more, with proper treatment, LFG can be enhanced and supplement natural gas network or it can be converted to natural gas (LNG) or compressed natural gas (CNG) and used as a vehicle fuel. See Figure 9 for a summary of alternative LFG energy uses.

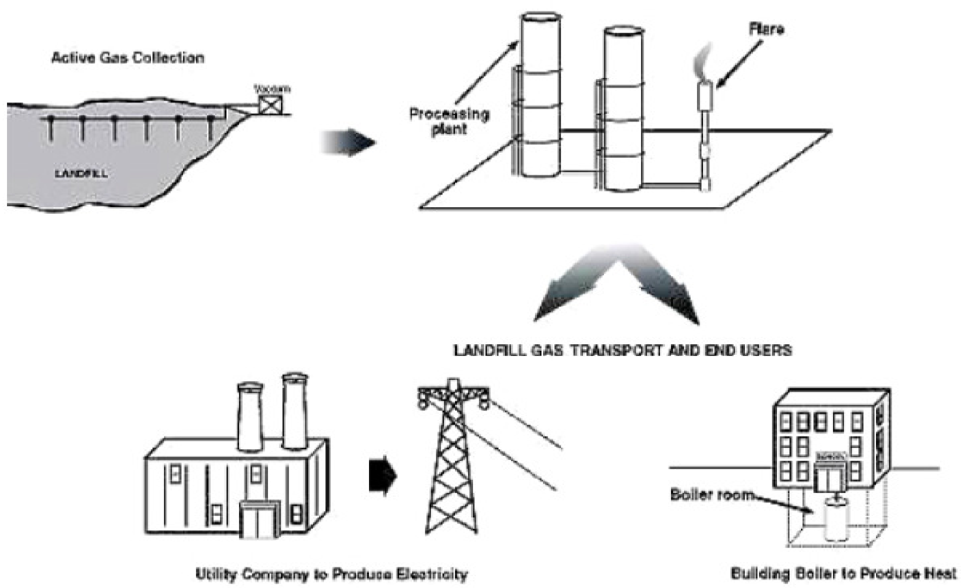


Figure 9: Summary of possible LFG uses

The energy generated from LFG can range from low-grade to high-grade, depending upon the level of processing the gas is subjected to. A brief description of the processing associated with each fuel type follows:

- **Low-grade fuel** production requires little processing, primarily involving condensate removal as part of the LFG collection system, and the use of liquid knockout vessels to reduce LFG moisture quantities
- **Medium-grade fuel** requires additional LFG treatment (e.g., compression, refrigeration, scrubbing, and/or chemical treatment) to extract more contaminated moisture and finer particles
- **High-grade fuel** requires extensive gas pretreatment to remove carbon dioxide and other gases (i.e., with no heat value) from the methane, to remove impurities such as VOCs, and also requires gas compression for gas dehydration

Typical LFG energy recovery operations include the following types of system components:

- Heat Exchangers

- Process Chillers
- Engines
- Gas Compressors
- Gas Turbines
- Electrical Generators
- Boilers

A brief description of each component follows:

Heat Exchangers are used to cool and heat LFG; examples include: a gas/chilled water exchanger used to cool LFG and capture water condensate to meet dew point specification of the gas; a gas/gas exchanger to reheat LFG back to above its dew point; air exchanges to cool LFG or water from compressors; jacket water radiators for the compressor, engine, or turbine to maintain cooling jacket oil or water within a set temperature range; cooling tower to cool compressor and engine water jacket water.

Process Chillers are used for LFG dew point suppression in order for the LFG product to meet use specification and not condense out liquids that might interfere with LFG use.

Engines are responsible for driving generators and compressors in medium BTU LFG operations, and usually require a minimum gas quality of 50 percent to function properly.

Gas Compressors are responsible for pressurizing LFG for use in engines, turbines, boilers, and gas pipelines.

Gas Turbines are responsible for driving generators to create electric power, and may be adversely impacted by corrosion and poor gas quality.

Electrical Generators are typically linked to a gas turbine or engine and are responsible for generating electricity.

Boilers are used to generate steam through the heating of water, under high or low pressure. Like turbines, boiler performance may be adversely impacted by corrosion and poor LFG quality. Delivery of consistent LFG pressure also facilitates good combustion and operation.

Feasibility

Large landfills appear to be most feasible for energy recovery projects since they have more LFG available for exploitation. In that way the project has more possibilities to be economically viable. However, it is the price of the utility sold that largely determines the viability of the whole project.

Implementation Recommendations

Energy recovery projects can be implemented where they are shown to be economically viable.

Relative cost

Implementation of this practice has high capital and operational costs. However, these costs are depreciated by the income accruing for the sale of the utility produced.

GHG emissions benefit

Implementation of this BMP displays high GHG emissions benefit. The benefit is even more obvious when LFG from old dumpsites is used for energy recovery.

5 Conclusions

Methane is a potent greenhouse gas and it is produced in landfills as a result of anaerobic decomposition of organic wastes. Methane production of landfills accounts up to 11% of global methane emissions and it is produced continuously from the landfilled waste, even when operation has seized, for hundreds of years.

Many solutions and practices exist to help reduce these emissions from landfills. A sanitary landfill is an anaerobic bioreactor, maybe not as well engineered as typical bioreactors are. However, as it was presented in this Guidance Document, simple, clever practices may increase methane capture or reduce fugitive emissions.

In order to do so, an LFG management plan should be created from the very beginning, even from the landfill design phase. This way, all the systems in the landfill (leachate collection, biogas collection, monitoring, daily operation) may be designed with the aim, among others, to reduce LFG emissions and subsequently the contribution of the landfill to global methane emissions.

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