Water and Sanitation Initiative

Guidance Note on Landfill Gas Capture and Utilization

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GUIDANCE NOTE
ON LFG CAPTURE AND UTILIZATION

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1. Introduction

As part of the Inter-American Development Bank (IDB) strategy to promote good practices in municipal solid waste (MSW) management and knowledge sharing activities in Latin America and the Caribbean (LAC), the IDB Water and Sanitation Division (INE/WSA) is developing a MSW management working paper series. The first paper, which focuses on landfill gas (LFG) capture from MSW and utilization, is included in this Guidance Note.

The LAC region is highly urbanized, with an average of 75 percent of its 500 million inhabitants living in mainly large cities. The resulting concentration of solid waste leads to corresponding waste management problems. Most LAC cities still dispose of MSW in open dumps, creating leachate contamination of surface and ground water and releasing LFG into the atmosphere. The largest and most prosperous cities in the region have begun to improve disposal practices, but only 23 percent of the total amount of collected waste is currently disposed of in sanitary landfills. Legal enforcement has not been enough to guarantee good practices.

LFG is a byproduct of the anaerobic decomposition of biodegradable MSW residues. The gas typically contains 50 percent methane (CH_4), with a high energy content of 36 megajoules (MJ) per cubic meter (m^3) of CH_4. Methane is a potent greenhouse gas (GHG) with 21 times the global warming potential of carbon dioxide (CO_2). An estimated 8 percent of methane emissions released into the atmosphere comes from landfills. If LFG is captured and used for energy production, GHG emissions are reduced and a non-conventional source of energy displaces fossil fuel use. Consequently, LFG capture projects have played a significant role in the Kyoto Protocol, particularly as part of the Clean Development Mechanism (CDM). Several cities in Argentina, Chile, Brazil, Peru, Uruguay, and Mexico actively collect LFG, but only three of these countries use it for energy generation. In North America and Europe more than 1,450 LFG plants are used to generate energy, and many more are coming on-line each year. Thus there is a significant opportunity to increase LFG recovery and utilization in landfills in the LAC region under the appropriate market conditions.

Experience has shown that only well-managed and -operated landfills generate the expected amount of LFG. Taking into account the projects that have received CDM approval in the MSW sector, the under-delivery on LFG extraction and methane emission reductions has been between 10% and 80% (Terraza, Guimares, and Willumsen, 2007). Reasons include not only modeling errors but also deficiencies in operational practices, including daily caps, final caps, leachate management systems, compaction level, and pumping pressure. This under-delivery has created an incentive for local authorities and operators to improve their final disposal practices.

The objective of the IDB as a development agency is not only to reduce GHG emissions but also to generate and improve final disposal practices. Given the current limited development of LFG projects in LAC and the potential demand for LFG investment and corresponding energy supplies and carbon emission reduction, the IDB prepared this "Guidance Note on LFG Capture and Utilization" to promote LFG capture and utilization initiatives in the LAC region.

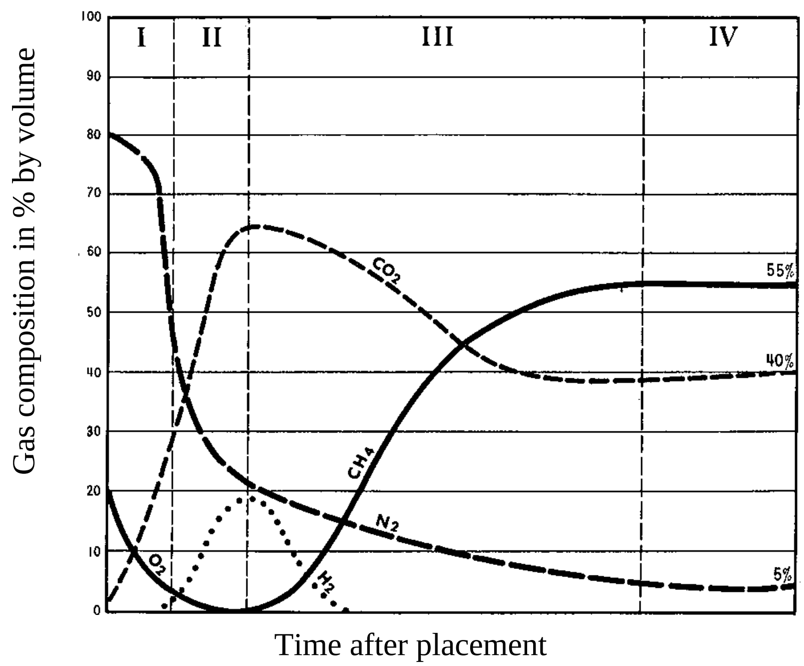
Objective. With this Guidance Note, the IDB intends to introduce an updated tool on LFG production, flaring, and utilization for energy purposes. The main objectives of the Guidance Note are to (i) promote best practices in LFG capture and utilization in the LAC region, (ii) disseminate existing case studies and analyze reasons for under performance, (iii) estimate current project design, construction, and operational costs, and (iv) evaluate the CDM experience with LFG projects so far.

Target Groups. The target audience for this Guidance Note includes technical staff from client governments, SWM operators (both public and private), consulting firms, nongovernmental organizations (NGOs), local organizations, and task managers from multilateral organizations.

2. LFG Generation

Generation of LFG is a complicated biological process, with essential microbial activity. LFG is generated as a result of the biodegradation of organic carbon in waste. Approximately 1.87 m^3 of LFG is produced per kg of degraded organic carbon (with a content of 50 percent CH_4). Organic material in the waste is decomposed in four main phases (figure 1).

Figure 1. LFG Generation after Waste Disposal



Source: Farquhar and Rovers, 1978; Emcon Associates 1990.

The LFG is generated by anaerobic (without oxygen) decomposition of the degradable organic waste. The four main phases are listed below.

Phase I: Aerobic

Typical time frame: A few days to a few weeks

Phase II: Anaerobic, non-methanogenic

Typical time frame: One month to 1 year

Phase III: Anaerobic, methanogenic, unsteady

Typical time frame: A few months to 2 years

Phase IV: Anaerobic, methanogenic, steady

Typical time frame: 10 to 50 years

After the anaerobic phase, the waste will finally stabilize after 30 to 50 years. The composition of the main components in LFG is shown in Table 1.

Table 1. Composition of the Main Gases and Trace Components in LFG

Gas component	**Chemical name**	**Variation**	**Average**
Methane (combustible)	CH_4	40–60%	50%
Carbon dioxide	CO_2	25–50%	42%
Nitrogen	N_2	3–15%	7%
Oxygen	O_2	0–4%	1%
Hydrogen (combustible)	H_2	0–1%	0.5%
Argon	Ar	0–0.4%	0.1%
Hydrogen sulphide	H_2S	0–200 parts per million (ppm)	30 ppm
Total chlorine	Cl	0–200 ppm	20 ppm
Total fluorine	F	0–100 ppm	20 ppm

LFG Production. LFG production varies considerably from one plant to another, depending on the situation in the individual country and landfill. The production rate (m^3 of LFG/tons x hour or year) depends on of the following parameters:

1. **Temperature in the landfill.** Methane bacteria find optimum mesophyll conditions at 35^o C. This temperature is found in deep landfills. In shallower landfills (10–15 meters deep) the temperature is normally as low as 20^oC. In general increased temperature accelerates microbiological activity up to that optimum temperature level.
2. **Moisture content of the waste.** Methane generation bacteria live in the water film around the waste particles. Sufficient water is needed to cover the organic particles. Moisture can accelerate bacterial activity or smother it completely if the waste is completely saturated.
3. **Waste composition.** The composition of MSW varies from country to country. Middle- and low- income countries generally produce more vegetable waste and less paper than

developed and industrialized countries. The composition of the waste affects the decomposition rate: the faster the organic material decomposes, the higher the rate of LFG production (m^3 LFG/tons x year).

4. **Waste age.** LFG production reaches its maximum capacity after 3–8 years and normally decreases after 15–30 years, when it is no longer profitable to extract the gas for energy purposes.
5. **Waste structure.** Because degrading microorganisms are active in the water film around the waste particles, smaller particles of organic materials produce more LFG.
6. **Landfill cover.** Landfills must be covered to keep out atmospheric air, which will disturb the anaerobic conditions. The cover material should allow penetration of rainwater to maintain adequate humidity in the waste.

Gas Generation Models. Since 1980 several models have been developed to estimate LFG production and extraction. These models include the simple zero order model, the first order model, and the most recent, the multi-phase model, described below.

1. **Zero order model.** In the zero order model, landfill gas generation in a given amount of waste is assumed to be constant over the time it takes to degrade the decomposable part of the organic material. This model does not include the effect of age of the waste and is therefore only applicable for estimating national and global emission.

2. **First order model.** This model is often called the Scholl Canyon Model, as it was used at the Scholl Canyon Landfill in the United States (Emcon Associates and Jacobs Engineering Co., 1976). In the first order model, LFG generation in a given amount of waste is assumed to decay exponentially over time using the following equation:

$$Q_{CH4i} = k * L_o * m_i * e_{-kt}$$

where Q_{CH4i} = annual methane (CH_4) generation in the year *i* of the calculation (m^3/year), and k = methane generation constant (the k value is related the half-life of waste degradation t_2 according to the formula t_2 = l(n)/k), L_o = methane generation potential/kg, and m_i = waste mass disposed of in year *i*.

The U.S. Environmental Protection Agency (EPA) Model LandGEM 3.02 is based on this equation.[1] The model was developed with input for normal MSW in the United States, and only the amount of waste per year has to be entered into the spreadsheet. The model cannot be used worldwide unless the default values are changed for a specific country. The EPA has also developed models for Mexico and other Central America countries.[2]

The first order model calculates LFG production in a landfill. Not all LFG produced is collected. Collection efficiency is determined by such factors as the space between wells, horizontal versus vertical gas extraction pipes, final cover material on the landfill, and suction pressure. Depending on the specific conditions in a landfill, collection efficiency is normally between 50 and 90 percent.

Accurate results depend on site-specific data. As shown in section 7 in this Guidance Note, in most CDM landfill gas projects there has been a considerable difference between estimated and extracted LFG from the LFG plants.

3. **Multiphase model.** The multiphase model is a first order model that calculates waste amount, carbon content, and the constant k for individual types of waste. The L_o is not used explicitly, as the content of degradable carbon is used in the equation to calculate the methane production and emission. The first such model developed used three phases: slow, moderate, and fast degradable materials, but newer versions use other sub-divisions as well like the GasSim Model[3], which uses the estimation from the multiphase model. Different versions of the multiphase model are used by other waste and LFG experts, who have incorporated their experience in in-house versions.

   The latest and possibly the best model is that of the Intergovernmental Panel on Climate Change (IPCC).[4] This model is also called the IPCC First Order Decay Model, as it calculates the emission of methane in tons per year from the decay of biodegradable carbon in the waste. The model was developed for use in connection with the United

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[1] Available on the website http://www.epa. gov/ ttn/ catc/ products.html.
[2] Available on the website http://www. epa. gov/ lmop/international.htm#models.
[3] Available on the website http://www.gassim.co.uk.

Nations Framework Convention on Climate Change (UNFCCC) rules for emission reduction from landfills in CDM projects.[5] Specific rules and requirements can be found in EB 39 Report, Annex 9, page 1, "Tool to determine methane emission avoided from dumping waste at a solid waste disposal site", which gives the following equation:

$$BE_{CH4,SWDS,y} = \varphi \cdot (1-f) \cdot GWP_{CH4} \cdot (1-OX) \cdot \frac{16}{12} \cdot F \cdot DOC_f \cdot MCF \cdot \sum_{x=1}^{y} \sum_{j} W_{j,x} \cdot DOC_j \cdot e^{-k_j \cdot (y-x)} \cdot (1-e^{-k_j})$$

where BE $_{CH4,SWDS,y}$ = the methane generation from the landfill; φ = the model correction factor to account for model uncertainties; f = the fraction of methane captured at the Solid Waste Disposal Site (SWDS) and flared, combusted or used in another manner; GWP_{CH4} = the Global Warming Potential (GWP) of methane, valid for the relevant commitment period; OX = the oxidation factor (reflecting the amount of methane from SWDS that is oxidized in the soil or other material covering the waste), F = the fraction of methane in the SWDS gas (volume fraction); DOC_f = the fraction of degradable organic carbon (DOC) that can decompose; MCF = the methane correction factor; $W_{j,x}$ = the amount in tons of organic waste type *j* prevented from disposal in the SWDS in the year *x*; DOC_j = the fraction of degradable organic carbon (by weight) in the waste type *j*; k_j = the decay rate for the waste type *j*; J = the waste type category (index); *x* = the year during the crediting period, running from the first year of the first crediting period (x = 1) to the year y for which avoided emissions are calculated (*x* = *y*); and *y* = the year for which methane emissions are calculated.

Using the step-by-step instructions for the IPCC model on the website, the location (continent/country) can be determined, and the related default values mentioned above will appear. Site-specific data rather than default values should be used for the most accurate results. This model estimates LFG emission, which is approximately the same as the production. As mentioned for the first order model, however, collection

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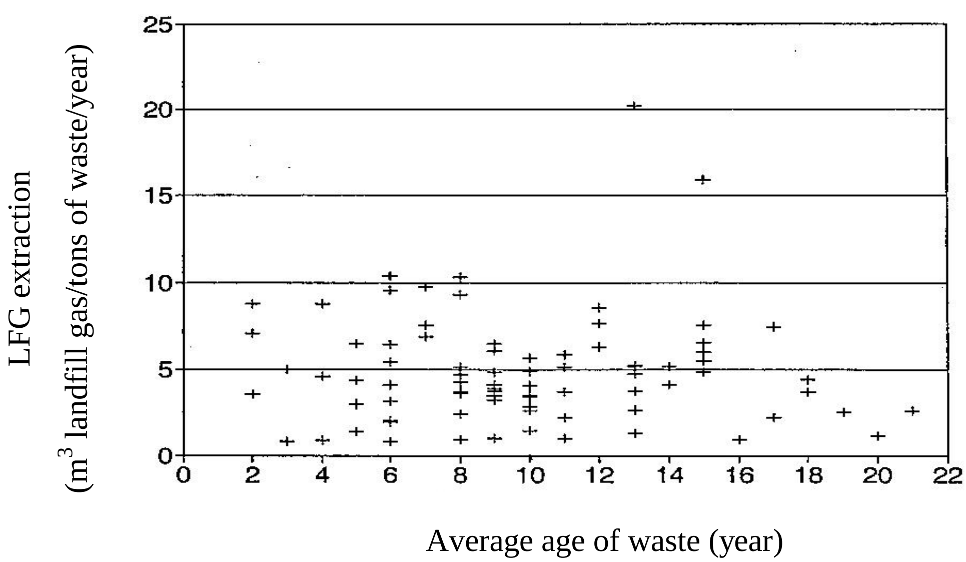
[4] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Waste, Section 3 on the website http://www.ipcc-nggip.iges. or.jp/public/2006gl/vol5.html.
[5] UNFCC website: www.unfccc.int.

efficiency for the multiphase model must be determined to calculate potential LFG extraction from the landfill.

Gas Extraction in Practice. The volume of LFG produced and collected from a specific amount of waste varies depending on the parameters mentioned on pages 4 and 5 above. A collection of estimates and results from 1975 to 1990 (Gendebien et al, 1991) shows that 60–400 m^3 of LFG was expected to be extracted from each ton of MSW over the entire degradation period of 50–100 years. With newer investigations building on more years of experience, a realistic total collection period will be 50–100 m^3 of LFG per ton of waste over a period of 40–80 years.

A staged global investigation (Willumsen, Bach, and Hedelselskabet, 1991) collected information around the year 1990 from approximately 250 LFG plants. The investigation included a comparison of the actual LFG extraction and the age of the waste in the landfills of 86 plants. Figure 2 shows that an average of 5 m^3 of LFG was extracted per ton of waste during the first 5 year period, after which the extraction rate started to fall.

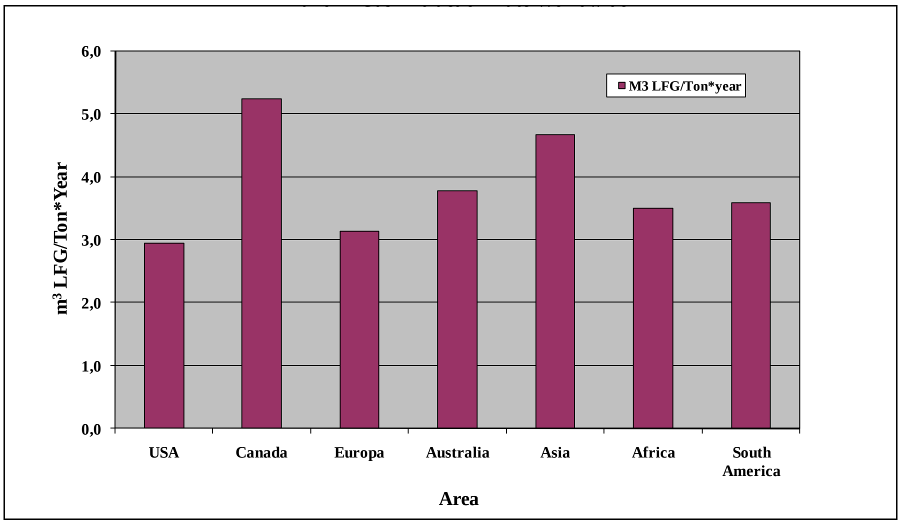
Figure 2. LFG Extraction Rate from 86 Landfills Worldwide, by Age of the Landfill



Source: Willumsen et al., 1991.

The investigation was expanded in 2003 and yielded more up-to-date information on actual LFG extraction from approximately 1,200 landfill gas to energy (LFGTE) plants worldwide. Figure 3 shows the LFG extraction rates from these landfills by continent.

Figure 3. LFG Extraction Rates from Approximately 1,200 LFGTE Plants Worldwide



Source: Willumsen, 2003.

Environmental Aspects. Produced during anaerobic decomposition in landfills, LFG contains approximately 50 percent methane (CH_4). Methane emissions from landfills contribute to the greenhouse effect. Table 2 shows that 1 ton of CH_4 contributes 21 times more to the greenhouse effect than one ton of CO_2.

Table 2. Greenhouse gases and the greenhouse effect

	Concentration in the atmosphere (ppm)	**Annual growth in the atmosphere (%)**	**Lifetime in the atmosphere (years)**	**Effect compared to CO_2 (times)**	**Relative contribution to the greenhouse effect (%)**
Carbon dioxide (CO_2)	346	0.4	40	1	50
Methane (CH_4)	1.7	1.0	10	21	19
Nitrous oxide (N_2O)	0.3	0.3	150	150	4
Ozone (O_3)	0.02	0.5	0.1	2,000	8
Freon (CFC)	0.001	5.0	100	15,000	17

Methane accounts for approximately 19 percent of the GHG in the atmosphere. Because approximately 8 percent of this methane is emitted from landfills, roughly 1.5 percent of global warming is related to emissions from landfills. Apart from the global emission effect, these emissions have a local environmental impact on air quality at landfills and in the surrounding areas. Adequate operation of LFG burning or utilization plants generally reduces this environmental impact.

Trace Components. Besides the main gases and trace components listed in table 1, LFG contains a minor volume (usually less than 1 percent) of volatile organic compounds (VOC). Even in small concentrations, VOC can be dangerous to human health. More than 100 types of VOC have been identified in LFG. Several of these are toxic or carcinogenic in heavy concentrations. These and other components have been found in concentrations above their threshold limit values (TLV).[6] The trace components occur individually, depending on the type of waste. They can often be measured in small concentrations in LFG. When emitted from a landfill, the trace components are rarefied in the atmosphere and do not normally constitute a health risk. Each of the components, however, has characteristics that in special circumstances can present a danger to life and health. Table 3 shows the most common trace components and their TLV in landfills in three European countries.

[6] The average time–weight concentrations to which nearly all workers may be exposed repeatedly for 8 hours a day or 40 hours a workweek without adverse effects.

Table 3: Most Common Trace Components in Gases Emitted from Landfills

Component	Measured concentration (ppm)	Threshold limit value (TLV) (ppm)		
		Denmark	Germany	England
Vinylchloride*	0.03–44	1	2	5
Benzene*	0.6–32	5	8	10
Chloroform*	0.2–2	2	10	10
Dichloromethane*	0.9–490	50	103	200
Toluene	4–197	75	200	100
Xylenes	2.3–139	50	101	105
Ethylbenzene	3.6–49	50	-	105
Chlorodiflourmethane	6–602	1,000	-	-
Dichlorodiflourmethane	10–486	10	-	670
Trichloroethylene	1.2–116	30	-	944
Tetrachloroethylene	0.3–110	30	-	94
Ethanol	16–1,450	1,000	-	-
Propane	4.1–630	200	-	-
Butane	2.3–626	50	-	-
Carbondisulphide	0.5–22	5	-	10
Methanethiol	0.1–430	0.5	-	-

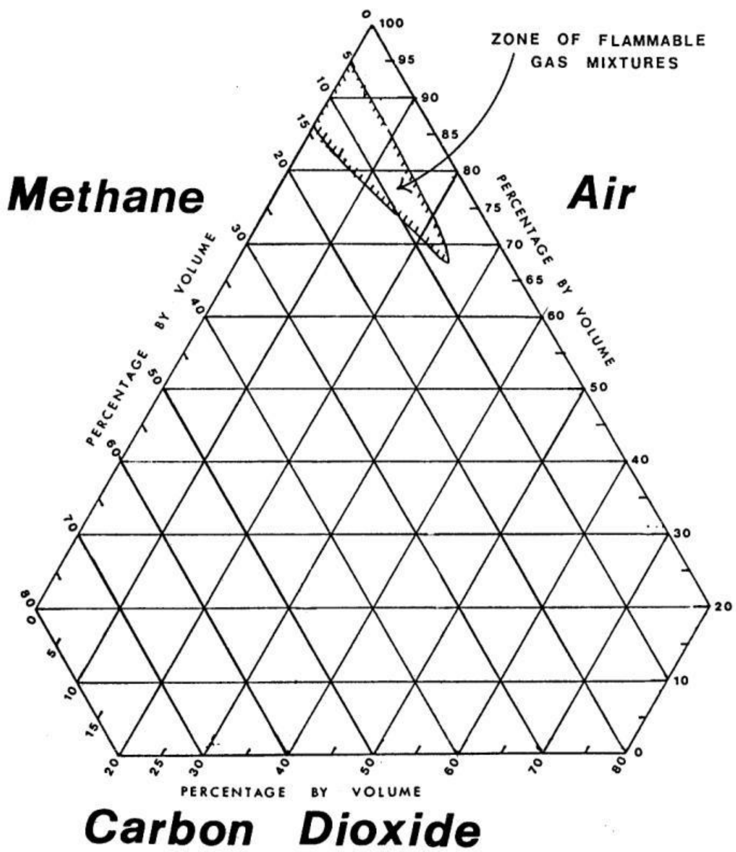
* Suspected carcinogens. Compounds not marked with an asterisk can be harmful to the central nervous system.

As the table shows, both carcinogens and other pathogens have been found in concentrations that far exceed the TLV. From a general environmental point of view, some of these compounds are hazardous. A guideline for the emission of corresponding substances from the industrial sector is that approximately 0.1 percent of the TLV is a maximum permissible concentration in the emission.

The trace components hydrogen sulfate (H_2S), chlorine (Cl), and fluorine (F) are generally problematic for gas engines in high concentrations, as they destroy oil additives and may ruin the cylinders. Silicon (Si), present in LFG from some landfills, also can be deposited in cylinders and in time damage their structure. Engine manufacturers normally set limits for the maximum concentrations of 1,000 ppm for H_2S, 30 ppm for Cl, 60 ppm for F, and 20 mg/m^3 for Si in LFG.

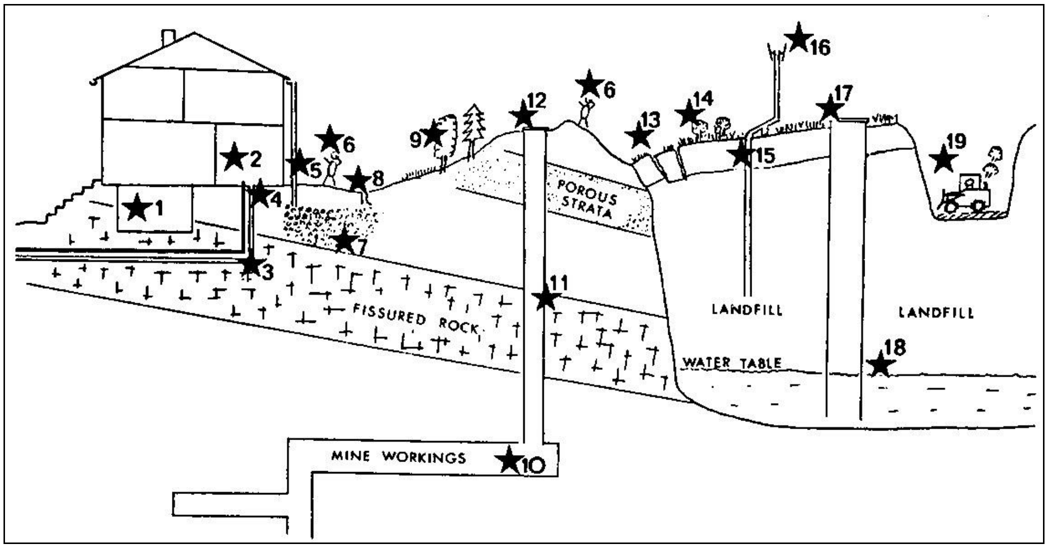
Risk of Explosion. LFG is an explosive mixture, containing 5–15 percent of CH_4 in atmospheric air, and can be ignited by a spark, match, or cigarette. Figure 4 shows the flammability limits of the methane in carbon dioxide and atmospheric air.

Figure 4. Flammability Limits for Methane in a Mixture of Carbon Dioxide and Atmospheric Air



Because of the risk of explosion, buildings should not be situated on or immediately next to landfills. Special precautions must be taken for buildings situated near landfills. If there is an impermeable membrane or layer of clay on top of the landfill, the LFG is pressed horizontally out of the landfill site and might diffuse through layers of gravel or pipelines. The LFG thus can penetrate into basements or through cracks into nearby houses, possibly leading to an explosive mixture of LFG and atmospheric air. During the past 30 years several explosions, in some cases fatal, have occurred from leaking landfill gas (Gendebein et al, 1991). Figure 5 shows a landfill with explosion risk points marked with stars.

Figure 5. Explosion Risks in and around a Landfill



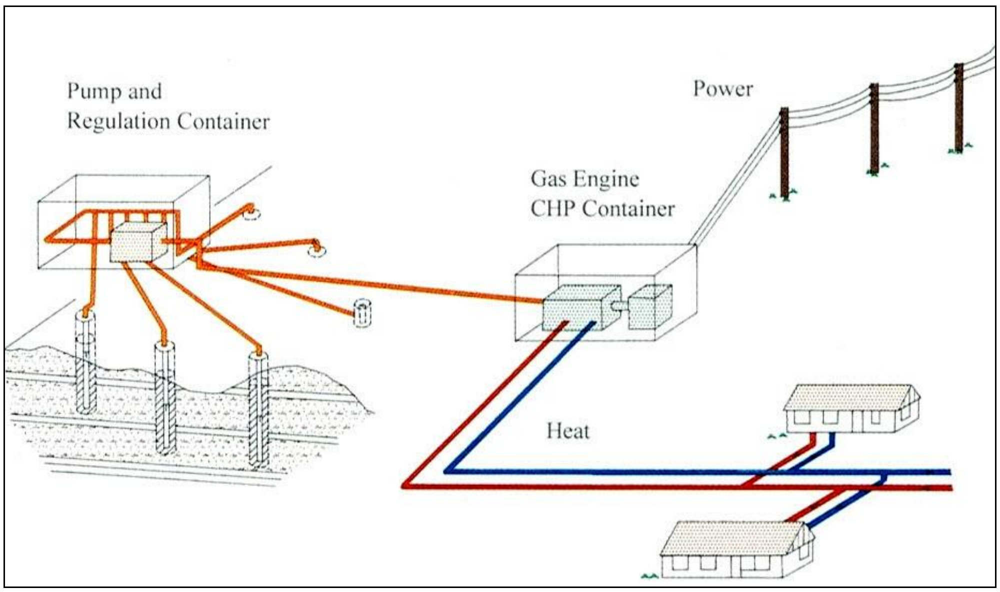
There is a risk of explosion in LFG plants from the moment the gas is extracted from the gas wells or pipes at the landfill until it is burned and destroyed in the utilization system. Explosion can occur in any of the following cases if the explosive air/gas mixture is ignited: (i) an explosive mixture of the gas compound is extracted from the landfill, (ii) the gas compound leaks into the surrounding air from the suction side of the plant, allowing air to penetrate into the closed system and resulting in an explosive gas/air mixture, or (iii) a leak in the pressure pipes causes gas emission.

LFG plants have to be protected from explosion by security and alarm systems. The oxygen (O_2) level in the LFG has to be less than 5 percent. An O_2 analyzer can control the O_2 content in the LFG, and an alarm is activated when the O_2 reaches 3 percent. CH_4 alarms have to be installed in buildings and/or containers where the LFG is present in pipes or other installations that may develop leaks. These alarms are activated if the CH_4 level exceeds 10 percent of the Lower Explosion Limit (LEL). Plants must shut down to avoid risk of explosion when the CH_4 level in the room reaches 1 percent and at 20 percent of the LEL.

3. LFG Recovery Plant

An LFG recovery plant consists of an extraction system and a utilization system. The most common system collects LFG through vertical gas pipes and uses it for energy purposes. A gas engine/generator unit can produce electricity, or the LFG can be used in more efficient Combined Heat and Power (CHP) plants, which use the waste heat from the engines for heating. Figure 6 shows a typical LFG recovery plant system. In countries where the price of energy does not make it feasible to generate energy from LFG, the recovery plant contains only an extraction and flaring system (see pages 50 and 51).

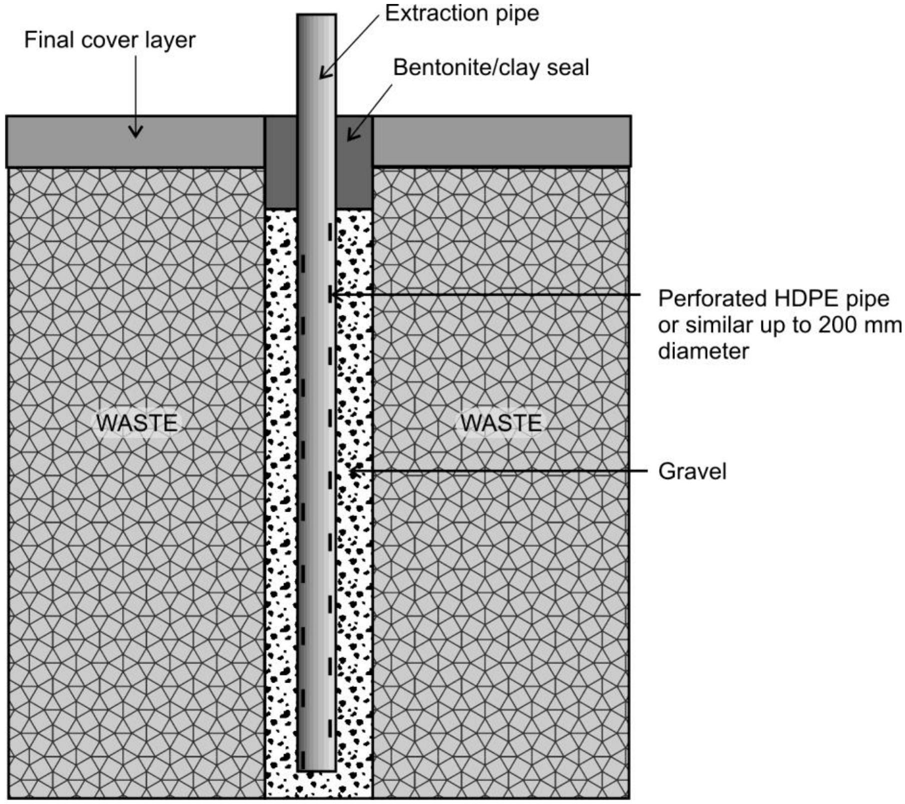
Figure 6. LFG Recovery Plant System



Source: ©Willumsen, 2009.

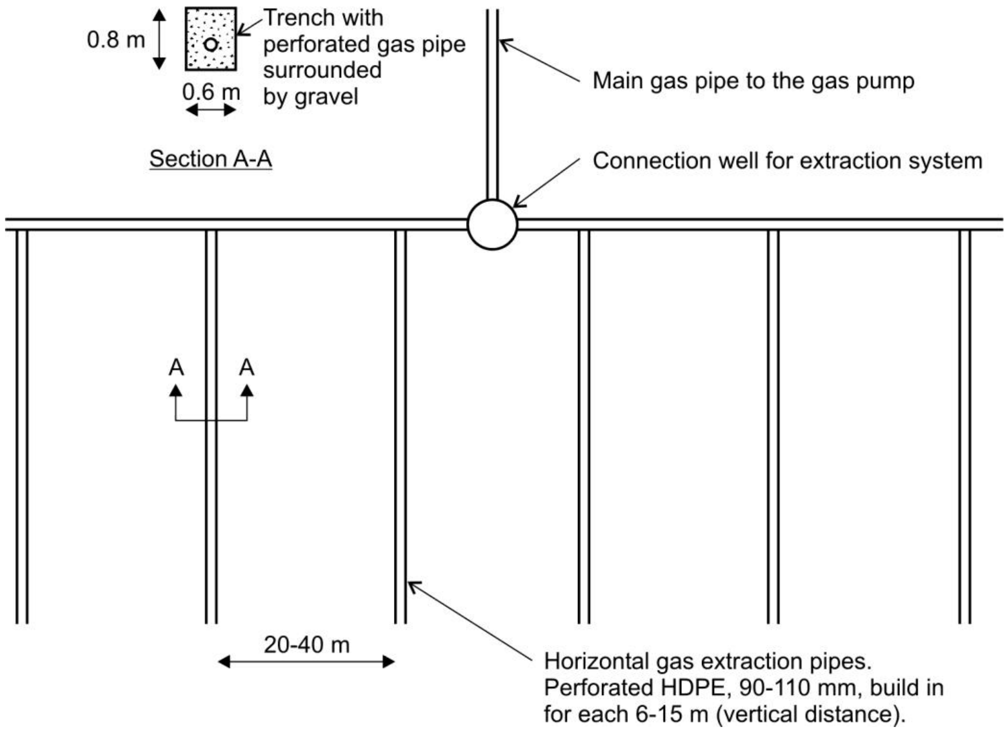
Extraction System. The extraction system in an LFG recovery plan can consist of vertical perforated pipes, horizontal perforated pipes, ditches, or, in some cases, a membrane covering the landfill under which the produced gas is collected. The most common method of active gas collection is to extract gas through vertical perforated pipes, possibly because this is the simplest method where a landfill is already established. The well is typically drilled with an auger with a diameter of 50–100 centimeters (cm). After drilling, a perforated polyethylene pipe with a diameter of 10–15 cm is placed in the middle of the hole, and gravel is filled in around the pipe. Vertical extraction wells are typically placed 40–80 meters (m) apart, depending on the landfill depth. A common operational problem with gas collection systems is well flooding. When water accumulates in the well, it is no longer functional. Pipes should therefore be sized so that pumps can be lowered into the well for water removal. Because stored condensate can prevent effective gas collection, traps to remove the condensate must be located at critical points in the collection. Figure 7 shows how a gas collection well is made.

Figure 7. Typical LFG Extraction Well



Some sites build in horizontal gas extraction pipes when the waste is disposed of in the landfill. This makes it easier to extract the gas from the beginning of production, as the gas can then be sucked out before the landfill is closed or covered. In a horizontal system, a perforated pipe is placed in the middle of a gravel-filled trench. The trench must be sloped to insure that water and leachate can be drained either into the leachate system or by separate leachate pumps installed in the gas system. Trenches are typically spaced 30–60 m apart horizontally and 10–25 m apart vertically. The upper layer of the pipes must be at least 3–4 m under the surface of the landfill to avoid atmospheric air infiltration. Figure 8 shows a horizontal gas extraction system.

Figure 8. Horizontal Perforated Pipes Used for LFG Extraction



In properly constructed landfills with finished cells, vertical and horizontal systems seem to extract the same amount of LFG. The advantage of using horizontal gas extraction pipes, however, is that they can be installed from the beginning of the cell filling and extract the LFG from the beginning, when production is high, resulting in higher total LFG extraction. The main problem with horizontal extraction pipes is that leachate can enter the pipes. This can be mitigated by an efficient drainage system. The advantage of vertical pipe systems is that they are easy to install after landfills are finished, which is not possible with horizontal pipes.

In some cases an impermeable membrane is used to cover the landfill (illustration 1). This method can collect and recover ~90 percent of the LFG generated and recovered (O'Brien, 2008). However, this is a very expensive solution generally applied in countries with strict landfill final covering requirements. Another disadvantage is that the membrane limits water penetration, reducing the moisture content of waste. This results in a drop in gas production. Water must be injected under the membrane to maintain the moisture level and gas production, but it is difficult to have a balanced water distribution supply system adequate to moisten the entire waste mass.

Illustration 1. Membrane Covering a Landfill

Photo: ©H. C. Willumsen, 2009.

LFG is extracted by a gas pump or compressor, which provides sufficient vacuum to pull gas from the landfill. A normal vacuum measures 20–100 millibars at the wellhead. The decision whether to use a pump or a compressor depends on site-specific requirements, particularly the pressure required for gas transport and the inlet pressure for the gas combustion device.

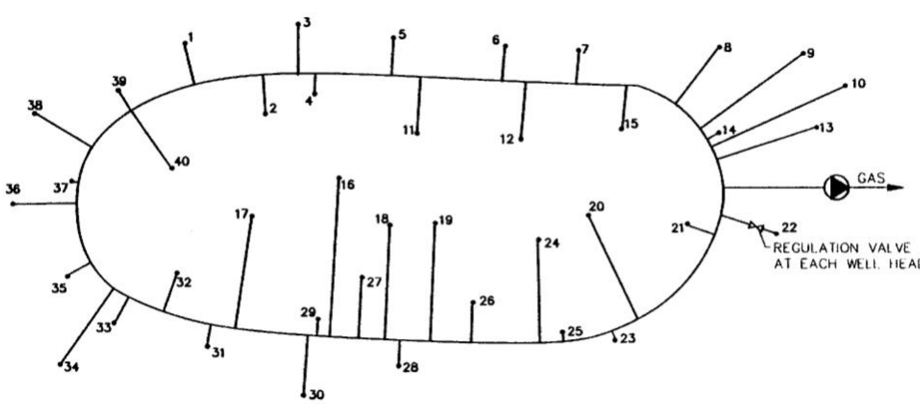
The most widely used gas pump is a radial blower, which is relatively simple and economical. Another commonly used gas pump is a rotary blower, which is reliable but more expensive than the radial blower, it can perform at higher pressure and maintain a constant vacuum and pressure when the speed is regulated by a frequency regulator. Finally, a screw compressor is used when the transmission pipe is long or the end user requires high pressure. This compressor is quite expensive but very reliable and has a long lifetime. Illustration 2 shows two rotary blowers installed in a container.

Illustration 2. Rotary Blower Installed in a Pump and Regulation Container

Photo: ©H. C. Willumsen, 2009.

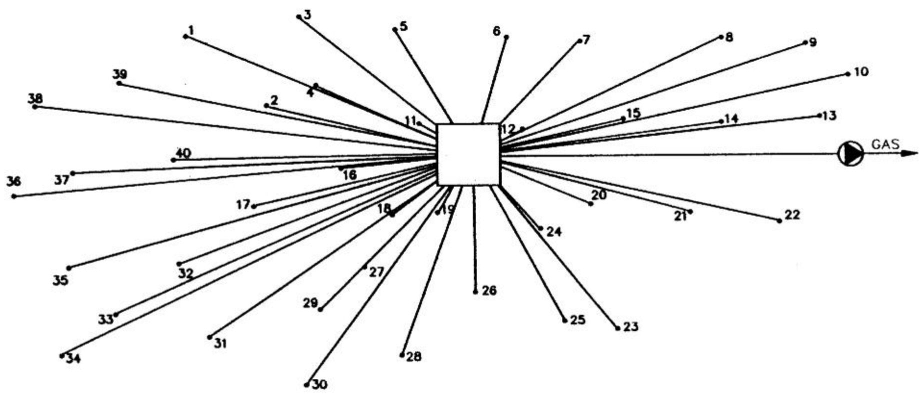
The individual wells can be connected to the pump and utilization system in several ways. The most common design is to connect the wells to a main collection pipe, which is placed in the optimal way in the landfill (figure 9). The main disadvantages of this system are the difficulty of regulating both the quality and quantity of the gas and finding the location of leaks when all the wells are connected in one large system.

Figure 9. Extraction System with Each Well Connected to a Main Collection Pipe



To reduce operational costs and improve operational efficiency, the best solution is to connect single pipes from each well to a pump and regulation house as shown in figure 10.

Figure 10. Extraction System with Each Well Connected to a Pump and Regulation House



Flaring. When the use of LFG for energy purposes is not economically feasible, the gas has to be flared off in a torch. Flaring is done for environmental reasons, essentially to reduce methane emissions and their contribution to the greenhouse effect and to reduce air emissions affecting local air quality. Flaring also reduces odors and the risk of fire and explosion.

Flares can be open or enclosed. The principle of flaring is the same for both types: to mix LFG with atmospheric air and then ignite this mix of oxygen and methane in the gas in the following combustion process: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + heat. With an open flare, the LFG is mixed with air on top of a burner. The flame is protected by an open windshield. Poor mixing and a range of different temperatures inside and at the edge of the flame result in incomplete combustion reactions. Open flares do not usually meet emission standards in many countries. They have the advantages of being inexpensive and relatively simple to operate, important factors when there are no emission standards. Open flares should only be used for test periods, start-up, running-in, or temporary use in connection to an energy plant if the energy utilization system is out of order for a shorter period.

An enclosed flare usually consists of a single burner or array of burners in a cylindrical enclosure lined with refractory material (illustration 3). This construction prevents quenching and results in more uniform burning and low emissions. Requirements for retention time and temperature vary, but the most common is a minimum of 0.3 seconds at $1{,}000^{o}C$. The destruction and removal efficiency is normally 98.0–99.5 percent for an enclosed flare.

Illustration 3. Enclosed flare for LFG

Photo: ©H. C. Willumsen 2003.

If the flare is installed in connection with an LFG project registered as a CDM project, default values for flare efficiency vary. Open flares have low efficiency with a default value of 50 percent, whereas enclosed flares are allowed to use a default value of 90 percent. In both cases the temperature in the flare has to be kept over 500°C at all times. Other specific rules have to be followed according to the methodology and requirements for CDM projects.

Energy Utilization Systems. With approximately 50 percent methane content, LFG contains approximately half of the energy of natural gas. This makes it an attractive source of energy. Combusting CH_4 in an energy plant instead of emitting it to the atmosphere results in a significant GHG emission reduction. In addition, LFG is a CO_2-neutral fuel that can replace fossil fuel and thereby help reduce CO_2 emissions to the atmosphere. Therefore, if economically feasible, LFG should be used to generate energy.

There are several methods of using LFG for energy purposes. The most common is to utilize the LFG gas as fuel in a gas engine/generator unit and produce electricity. Other methods are to use the heat from the cooling system in a combined heat and power (CHP) plant for heating and to utilize the gas in a gas boiler to produce hot water or steam for space heating or process heat.

In some cases, where hydrogen sulfide (H_2S) and/or siloxanes (chemical compounds composed of units of the form R_2SiO, where R is a hydrogen atom or a hydrocarbon group) are above acceptable concentrations for gas engines and boilers, the LFG may need to be treated for these trace components.

Other uses of LFG include its direct use, upgraded to natural gas quality, as fuel for vehicles, and in fuel cells, or directly for leachate evaporation. Table 4 lists some of these uses and the numbers of systems worldwide.

Table 4. Numbers of LFG Types and Utilization Systems Worldwide

Type	**Number**
Gas engines	581
Heat	277
CHP	187
Gas turbine	39
Leachate evaporation	17
Kilns	14
Upgraded to natural gas quality	13
Steam turbine	11
Combined cycle	7
Micro turbine	3
Vehicle fuel	2
Fuel cell	1
Total	**1,152**

Source: ©Willumsen, 2003.

The best-known use of LFG is in a gas engine running an electric generator that produces electricity. Normal-sized plants with gas engines produce between 350 and 1,200 kilowatts (kW) of electricity per engine. To produce 350 kW of electricity, 210 m^3 LFG are needed per hour, and to produce 1,200 kW, 720 m^3 of LFG are needed per hour. In a number of European countries, especially in northern and Eastern Europe where district heating systems are common in cities, it is standard practice to build CHP plants that also utilize the waste heat from the cooling water, exhaust, and oil system of the engines. A CHP plant has a total energy efficiency of approximately 87 percent, compared with approximately 37 percent when only electricity is produced. In larger plants with power production ≥ 4 megawatts (MW), gas turbines are sometimes used. In very large plants steam turbines can also be used. In recent years small gas turbines known as micro turbines have been introduced, producing as little as 30 kW of electricity.

Gas engines (illustration 4) are often used even for large-scale plants because they can be built in modules/containers of 1 MW units. Least developed countries have better local networks of distributors of gas engines and offer more reliable maintenance for gas engines than for more sophisticated technology such as gas turbines.

Illustration 4. Gas Engine/Generator Unit

Photo: ©H. C. Willumsen.

The second most common use of LFG is to heat water in a boiler system (illustration 5). Although this is a simple system, the price per kW of electricity (kW_e) is normally higher than the price per kW of heat (kW_h). Moreover, the electricity is relatively easily sold in unlimited quantities via the national power distribution network. Heat from a CHP plant is often used in district heating plants in northern and Eastern Europe. In these countries LFG can be used in central heating stations for district heating. The heat from some boiler systems is used in greenhouses, either by circulating hot water or by heating air that is blown into the greenhouses.

Illustration 5. Boiler System for Utilization of LFG

Photo: ©H. C. Willumsen.

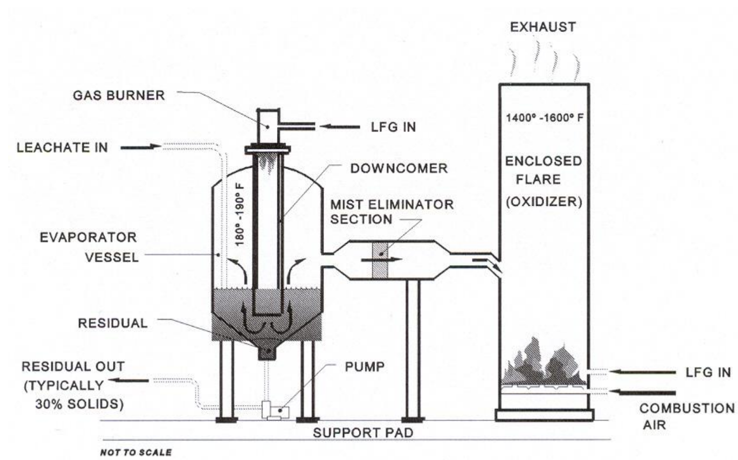
In the United Kingdom some brickyards use LFG directly in kilns instead of natural gas. LFG can also be used in cement production and below leachate evaporation is described, which is also a direct use of LFG. The advantage of direct use is that there is no technical or heat transmission loss from one machine, burner or medium to another. Therefore this tends to be a very efficient utilization scheme if the circumstances allow for it.

Treatment of leachate is one of the main environmental concerns related to landfill operation and can influence the landfill design, construction, and operational cost. Leachate can be treated in a conventional wastewater treatment plant or in some cases recirculated through the landfill for "self cleaning". Another option is to use the LFG as fuel to evaporate the leachate. Illustration 6 shows a leachate evaporation plant, and Figure 11 shows a leachate evaporation system.

Illustration 6. Leachate Evaporation at the SASA Landfill, Brazil

Source: VEOLIA Environment.

Figure 11. Leachate Evaporation by LFG



Source: Emcon/OWT, 2002.

LFG can be upgraded to the quality of natural gas to be injected into the natural gas distribution network. While this use eliminates the need for an electric generator or boiler, investment is required for a gas purification plant. Before it can be commercialized as natural gas, LFG must be treated to remove particles, liquid, CO_2, nitrogen (N_2), and trace components such as H_2S, as natural gas in most cases is nearly 100 percent CH_4. The major step in the treatment process is the removal of CO_2 in order to meet the high energy quality of natural gas for which natural gas-using burners and stoves are designed. Different systems can be used, depending on the quality requirements for the upgraded LFG, but three techniques are applied: chemical absorption, pressure swing adsorption, and membrane separation. Illustration 7 shows an LFG upgrading plant.

Illustration 7. Former LFG Upgrading Plant in Calumet, Illinois, USA

Photo: ©H. C. Willumsen, 1981.

In a few landfills LFG is compressed and then used as fuel for vehicles such as compactors, refuse collection trucks, buses, and even ordinary cars. The gas quality requirements and gas treatment methods are the same as those for upgrading to natural gas quality. The feasibility of using LFG in vehicles depends on the chosen system, tax system, compatibility of fleet size, and landfill generation/capture rate, among other factors. Investment will be relatively expensive for a system using only a few vehicles, but using all the LFG from a large landfill for vehicle fuel will require a large number of buses or cars that can run on the gas. Illustration 8 shows a filling station for upgraded LFG used as vehicle fuel.

Illustration 8. Vehicle Fuel Filling Station, Puento Hill, CA, USA

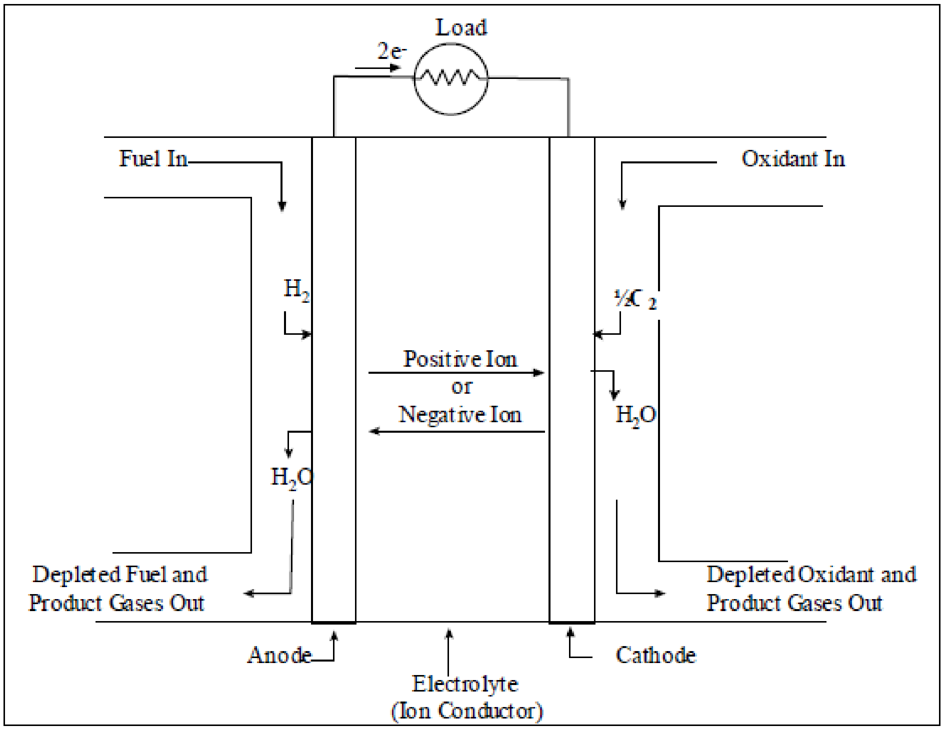
Photo: ©H. C. Willumsen.

LFG can also be used in fuel cells. Fuel cells can be compared to large electric batteries that provide a means of converting chemical energy to electricity. The difference between a battery and a fuel cell is that in a battery, all reactants are present and are slowly depleted during battery utilization, while in a fuel cell, the reactant (LFG) is continuously supplied to the cell.

The fuel cell has several advantages, including electricity conversion efficiencies of 40–50 percent, low air emissions, low labor and maintenance requirements, and low noise. Fuel cells based on LFG with a production capacity of 25–250 kW have been tested in the United States but are still not commercial. The high initial investment costs have so far made this use of LFG unprofitable.

Figure 12 illustrates the principle of a fuel cell. The fuel in this case is the H_2 from the CH_4, which is fed continuously to the anode (negative electrode), and O_2 from the atmosphere fed to the cathode (positive electrode). The electrochemical reactions take place at the electrodes to produce the electric current.

Figure 12. Diagram of a Fuel Cell



Source: U.S. Department of Energy, 2004.

Number of LFG Plants Worldwide. It is not possible to obtain exact information about the total number of LFG plants around the world. Because only a few countries have centralized data, information is fragmented among plant owners, consultants, and companies specialized in the sector. In North America centralized information is available from the U.S. EPA[7] and Environment Canada.[8] For years the Biogas Association published an overview of LFG plants in the United Kingdom. The information in this section, however, is the result of personal research conducted by Hans Willumsen in collaboration with local experts.

LFG recovery plants were first developed in 1975 in California. Many of these early plants were shut down because of decreasing gas production over the years that made LFG recovery unprofitable. Table 5 shows that development in Europe began shortly after that in the

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[7] U.S. Environmental Protection Agency Landfill Methane Outreach Program (LMOP), www.epe.gov/lmop/.
[8] Environment Canada, National Office of Pollution Prevention. *Inventory of Landfill Gas Recovery and Utilization in Canada.*

United States, and today there are more plants in Europe than in the United States. However, the capacity of the plants in Europe is half that of the plants in the United States.

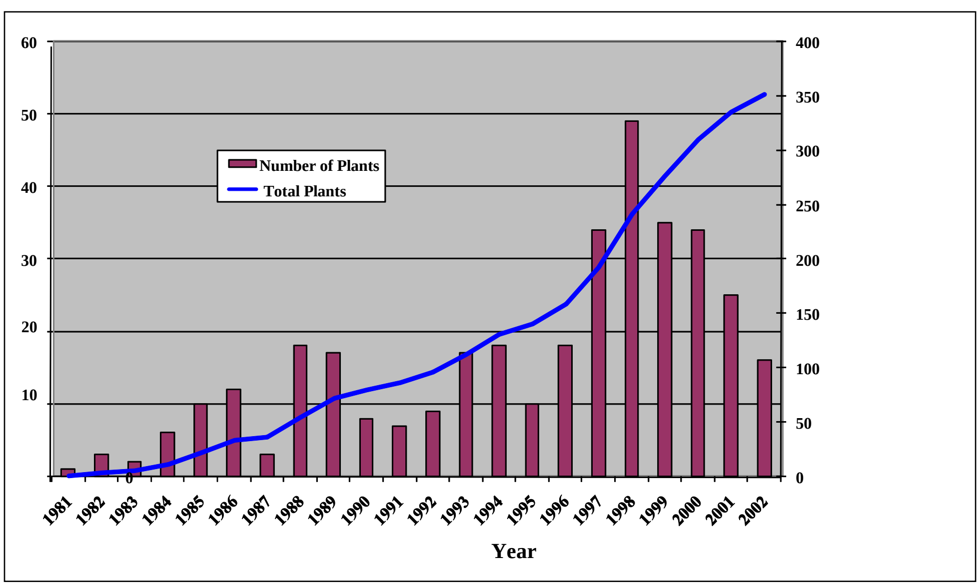
Table 5. Number, size and gas extraction for LFG plants worldwide by region

Region	Number of plants	Energy production (MW)	LFG extraction rate (m3/tons/year)
Europe	734	1,275	3.1
United States	354	2,378	2.9
Asia	19	72	4.7
Australia	18	76	3.8
Canada	15	106	5.7
South America	8	18	3.6
Africa	4	4	3.5

Source: U.S. EPA (LMOP); Environment Canada; and Willumsen, 2003.

Worldwide, approximately 1,150 plants now use LFG for energy purposes. Figure 13 gives an overview of the development of LFG plants in the United States. An estimated 1,400 plants use LFG for energy purposes.

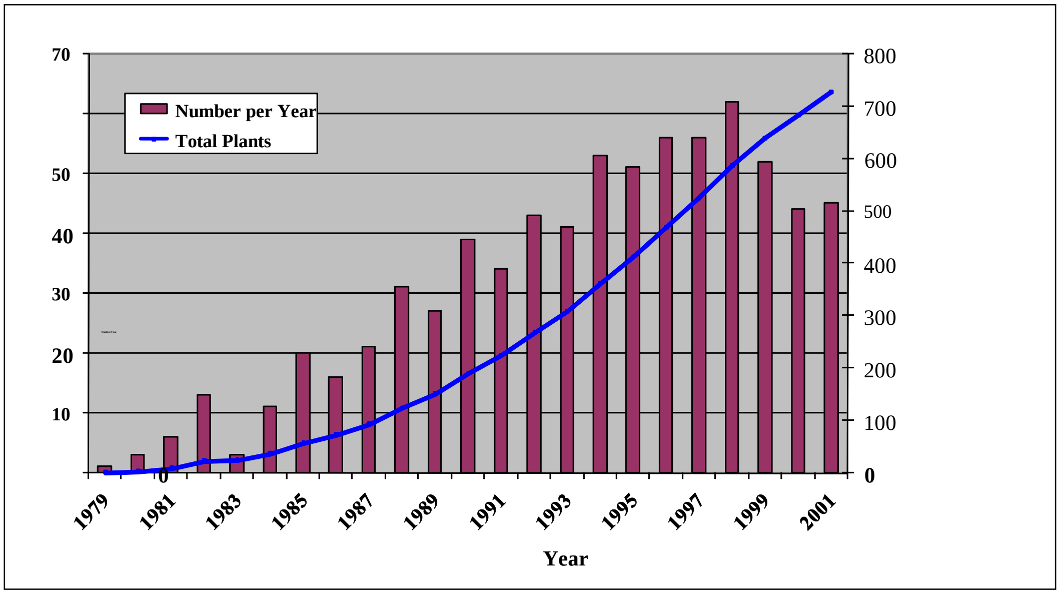
Figure 13. Annual and Accumulated Number of LFG Plants in the United States



Source: U.S. EPA (LMOP); and Willumsen, 2003.

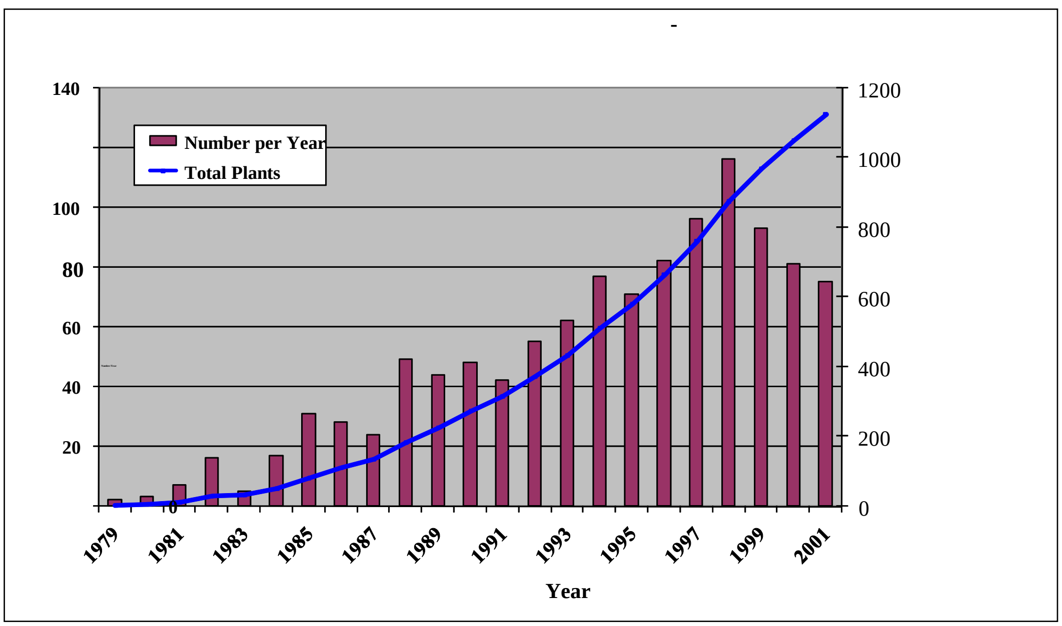
Figures 14 and 15 show the development of LFG plants in Europe and worldwide.

Figure 14. Yearly and accumulated number of LFG plants in Europe



Source: Willumsen, 2003.

Figure 15. Annual and Accumulated Number of LFG Plants Worldwide



Source: U.S. EPA (LMOP) and Willumsen, 2003.

Table 6 gives a global overview of LFG production by country, including only operating energy utilization plants. The information for some countries should be treated with caution, however, as it is not possible to obtain exact data from all of the countries. The total capacity of all LFG plants worldwide is approximately 4,000 MW.

Table 6. LFG Extraction and Utilization Plants Worldwide, by Country

Country	**Number of plants**	**Energy production (MW)**	**Amount of waste (million tons)**	**Extraction rate**	
				m^3/LFG/ hour	**m^3/tons/year[a]**
Australia	18	76	101	43,657	3.8
Austria	15	22	28	8,820	2.8
Brazil	7	11	12	4,000	2.9
Canada	15	106	120	72,000	5.3
China	4	4	4	2,160	4.7
Czech Republic	6	7	8	2,700	3.0
Denmark	23	22	20	5,913	2.6
Finland	14	12	20	6,500	2.8
France	26	30	35	12,400	3.1
Germany	182	270	380	78,500	1.8
Greece	1	13	20	7,400	3.2
Hong Kong	8	32	28	14,620	4.6
Italy	135	362	240	115,150	4.2
Korea	3	16	14	7,000	4.4
Latvia	1	5	5	2,850	5.0
Mexico	1	7	7	3,800	4.8
Netherlands	47	62	100	26,575	2.3
Norway	30	28	13	5,790	3.9
Poland	19	18	15	5,000	2.9
Portugal	1	2	2	900	3.9
South Africa	4	4	4	1,600	3.5
Spain	14	36	51	20,700	3.6
Sweden	61	55	35	12,950	3.2
Switzerland	7	7	8	2,988	3.3
Taiwan	4	20	20	10,972	4.8
Turkey	1	4	8	2,200	2.4
UK	151	320	400	180,000	3.9
United States	354	2,378	2,850	958,400	2.9
Total	**1,152**	**3,929**	**4,548**	**1,615,545**	**3.1[h]**

[a] Calculated by (extraction rate in m^3/LFG hour x 24 hours x 365 days)/(amount of waste in million tons x 1,000,000)
[b] Average
Source: U.S. Environmental Protection Agency Landfill Methane Outreach Program (LMOP), Environment Canada, and Willumsen, 2003.

4. Project Preparation

The preparation of an LFG project consists of a feasibility study, test pumping to determine actual gas quantity and quality, and the design itself.

Feasibility Study. The aim of a feasibility study is to determine the legal and economic possibility of establishing an extraction and utilization system for LFG. In developing countries that are eligible for the CDM but have no regulatory requirements in place for gas extraction, prefeasibility studies include the option of extraction and flaring only to reduce CH_4 emissions. The feasibility study should help the landfill owner decide whether to establish a landfill gas plant with or without a utilization system.

To estimate the gas yield at a specific landfill, it is necessary to have historical records of the quantity and composition of waste disposed of each year during the filling period. This information has to be obtained from the landfill operator. Unfortunately, it can often be difficult to get accurate information, especially if the landfill is more than 5–10 years old. This can be even more difficult when dealing with uncontrolled dumps in developing countries. When the historical information is available, gas production can be calculated from a model, as described in pages 5–8 of this Guidance Note. Once expected gas extraction volumes over the years are estimated, it is possible to make the first draft of the LFG recovery system and associated costs. The complexity and sophistication of the extraction system depend on local conditions, level of technical expertise, labor costs, and so on. More complex systems may include automatic measuring and a regulation system to optimize the gas extraction. The feasibility study must also include an analysis of revenue aspects, including contact with potential energy buyers. Energy prices can differ considerably from country to country depending on the local availability of fossil fuel or other types of energy, tax policy, and support (direct or indirect) to power and/or heat from renewable energy.

An important part of the feasibility study is the economic analysis, which includes the total investment, the yearly income from energy sales, and the O&M cost. From this information the yearly net income can be calculated and the Net Present Value (NPV) and Internal Rate of Return (IRR) determined.

A chapter of the feasibility study should be dedicated to evaluating the local energy and SWM regulatory framework in order to confirm that no norms impede either the construction of the LFG capture plant or the commercialization of energy. Particular emphasis should be given to the analysis of the landfill operation contract between the municipality and the operator and to the legal LFG ownership.

Test Pumping. Test pumping is often recommended because it not only yields actual data from a landfill section but also helps verify the estimations made from the gas model. Test pumping should include at least three vertical gas wells for LFG extraction and some pressure probes between the gas wells to determine the area of the suction influence. The test pumping must run continuously over 6–8 weeks and requires experienced people to analyze the results and conduct the final study before the project can be evaluated. Illustration 9 shows typical test pumping equipment.

Illustration 9. Test Pumping Equipment with Blower and Flare

Photo: ©H. C. Willumsen.

Design. The design of an LFG project consists of a detailed description and drawings of the system. Introductory sections can include the following:

- General information about the project location, client, and consultant
- A general description of LFG plants

- An overall description of the specific LFG plant with the planned extraction and utilization system
- Instructions for bidders with information and requirements valid for the bidding procedure
- General and special conditions for the total project
- Time and payment schedule

The technical part of the design is generally divided into two sections: the extraction and the utilization systems. The extraction system normally includes the following:

- Leveling of the landfill to determine the level of wells and pipes and the slopes for pipes
- Drilling of gas wells, including installation of a perforated gas extraction pipe in the well
- Dimensioning of horizontal gas pipes from the wells to a pump station
- A water knockout system for condensate
- Dimensioning of the pump/compressor for the gas extraction and distribution
- A manual or automatic regulation system for the gas extraction
- Electrical installations
- A control system
- A security and alarm system

The utilization system normally includes the following:

- Dimensioning of the gas transmission pipeline
- The gas installation
- Dimensioning and description of the energy utilization system, which can be a power plant, a CHP plant, a boiler plant, or another more specialized utilization system
- Electrical installations
- A control system
- A security and alarm system
- Environmental installations, noise, emission, and so on

The design of the detailed installations, including electrical steering, regulation, and control systems for a CHP plant or boiler plant, is normally done by the LFG contractor or the producer of the equipment. A design by consultants is normally a functional description with requirements for the system, material, performance, and so on. The design specifications from the consultant have to be prepared in enough detail to serve as the basis of the technical section of the tender document.

5. Construction of an LFG Plant

Different options for developing an LFG project require different types of contracts. In general, construction of an LFG plant can be executed as a conventional owner project, a design-built project, a design-build-operate (DBO) project, or a build-own-operate (BOO) project.

Conventional Owner Project. In most cases the owner of a landfill is also the owner of the LFG produced from the landfill. The owner procures a consultant/engineering firm with experience in LFG recovery plants to design, tender, and supervise the construction of the LFG plant. The owner can profit from the energy sale revenue and, if the plant is approved as a CDM project, from the CO_2 credit (Certified Emission Reductions, or CER). In a conventional owner project, the owner has total control over the design and equipment. The disadvantage is that the owner takes all the financial and other risks for the plant during the project lifetime.

Design-Build Project. In a design-build project, as in a conventional owner project, the owner of the LFG resource invests in the LFG plant. The responsibility for designing and building the LFG recovery system, however, is handed over to a main contractor, normally a company with an engineering and construction department and experience in LFG recovery systems. The responsibility for the design and construction may also be shared between a consultant and a construction company, both with the necessary experience. In some cases such a project is delivered as a turnkey project, in which everything is included and the LFG plant is functioning and ready for operation when the owner takes over the plant.

The design-built project is established by a single entity, which has complete responsibility for the project execution. The advantages from the owner's point of view are that this centralization tends to shorten the building period, limit the technical risks, and ensure a fixed price. The disadvantage can be that the owner has less control of the design and material used for the project and the costs might be more expensive than those "estimated" in a conventional owner project.

Design-Build-Operate (DBO) Project. DBO projects are similar to design-build projects but include a contract in which the contractor includes the O&M of the LFG plant over a certain number of years. The owner's risks are limited because the price is fixed during the contract period. The disadvantage can be that the owner has limited influence and control over the LFG plant performance and related revenues, but different types of contracts for O&M that can limit this risk.

Build-Own-Operate (BOO) Project. In a BOO project the owner of the LFG resource establishes a contract with a developer, who gets a concession/license to recover the LFG from the landfill. In this type of contract the capital investment is made by the BOO contractor. Such a contract can be made in many different ways, but the landfill owner normally gets some kind of royalty, for example, a percentage of the income from energy sales or, if the project is under the CDM, from the CER. Some BOO contracts are limited to a certain period, after which the LFG plant is transferred to the owner, who takes over the plant for O&M. This arrangement is called a build-own-operate-transfer (BOOT) project).

Bidding Documents and Process. A landfill owner who decides to install an LFG recovery plant can select among the contract options described in the previous section. The type of bidding document depends on the type of contract chosen. As a general rule, clear evaluation criteria are important for all types of bidding. These criteria should include price, experience with the same type of project, financial capability, personnel capability (CVs) of all staff involved, and references from previous projects involving construction of LFG plants and all parts of the LFG collection system, pump/compressor system, regulation system, and utilization system including the relevant energy utilization. The same criteria apply to sub-consultants/-contractors if used.

For a *conventional owner project*, the design documents described on pages 35–37 are used as the main part of the technical specifications of the bidding document. Normally the bidding documents are divided into different packages, e.g., drilling of wells, pipelines, pump/compressor system, and utilization system. This "packaging" allows the owner to get proposals from different contractors with specific competencies in each discipline. The bidding documents must include requirements for expertise and experience in the individual disciplines. Procurement can be done through an open international competitive bidding process in which companies submit proposals for executing the specified work. For this type of procurement, the owner of the project must have a fully dedicated SWM team with the necessary technical expertise.

For a *design-build project*, the bidding documents do not include a comprehensive detailed description and drawings for the technical specifications of the project. Instead, they include a functional description of the system requirements and expected quality, as well as the requirements for the performance of the components and equipment. The detailed design is executed by the contractors but should be approved by the owner/investor. Depending on to the size of the contract, this procurement process may involve a prequalification phase followed by a bidding phase. An invitation for prequalification is announced, and contractors submit their expressions of interest along with their qualifications, experience, and so on. Qualified companies are then invited to submit proposals according to the bidding document.

For a *DBO project* the bidding document is a comprehensive package including a functional description of the system requirements, the expected quality, and the requirements for the performance of the components and equipment. A DBO bidding document also should require specific proven experience in LFG plant operation. The detailed design will be carried out by the contractors and approved by the owner/investor.

As for the previous types of projects, the bidding document for a *BOO project* involves a comprehensive package. Requirements are similar to those for a DBO project, but the owner has to set specific criteria for the royalties to be offered by contractors.

Construction. Construction work normally includes the following activities, in the order listed:

- Drilling and installation of gas wells, including water/leachate pump installation, if necessary, and in some cases, installation of a horizontal gas extraction system
- Installation of gas collection pipes and a condensate system between the wells and the gas pump system
- Installation of a pump/compressor for the gas extraction and distribution
- Installation of a manual or automatic regulation system for the gas extraction
- Installation of electrical, control, security, and alarm systems
- Installation of the energy utilization system

Illustrations 10–16 show the steps in building an LFG plant.

Illustration 10. Drilling equipment for a gas well and installation of the gas pipe

Photo: ©H. C. Willumsen, 2000.

Illustration 11. Connecting a horizontal gas pipe to a gas pipe in a well

Photo: ©H. C. Willumsen, 2000.

Illustration 12. Covering horizontal gas pipes for protection against frost

Photo: ©H. C. Willumsen, 2000.

Illustration 13. Installation of a container with a compressor and gas cooling system

Photo: ©H. C. Willumsen, 2000.

Illustration 14. Connection of gas pipes to a pump and regulation container

Photo: ©H. C. Willumsen, 2000.

Illustration 15. Connection of gas pipes to a pump and regulation container

Photo: ©H. C. Willumsen, 2000.

Illustration 16. Installation of measuring equipment on an enclosed flare

Photo: ©H. C. Willumsen, 2000.

If the LFG project is a *conventional owner plant*, the owner's consultant should supervise construction by following the work step by step, checking the installations, and participating in meetings for coordination of the work and time schedule among the different contractors. For a *BOO project*, supervision is the responsibility of the contractor, who is also the investor, but the owner's consultant should be involved in regular overall supervision, making sure that construction progress follows the agreed schedule in accordance with local regulations.

Commissioning. Before the LFG plant starts up for commercial use, the contractor has to commission the plant. Commissioning is a final check and test of the operational condition and performance of the entire plant and all its components. If the plant is a *conventional owner* project with several contractors, the owner's consultant coordinates the commissioning. In the other contract options, the main contractor is entirely responsible for the commissioning. In *design-build and DBO projects*, the owner's consultant should participate in the commissioning and check the commissioning result to make sure that the equipment is operating properly. For a

BOO project the contractor as investor is completely responsible for the work and the equipment performance, although it is recommended that the consultant participate in the start-up process. It is very important that the owner's consultant have extensive experience in building and operating LFG plants.

Commissioning includes preparing documents used for systematic tests of all components of the plant. During commissioning all components and equipment should be tested and the results entered in the prepared documents to be kept for future documentation of the function.

Start-up and Running-in. Once the installation is finished and tested during commissioning, the start-up and running-in period begins. The experience of both the contractor and the consultant is key during this phase. Running in and optimizing a plant can take from a few weeks to a few months to ensure the maximum energy output from the gas extraction from the landfill and the entire system. A system equipped with an automatic measuring and regulation control system is easier to run and results in more efficient energy extraction, although the investment costs of such a system are generally high.

6. Economics

A key step in LFG project development process is the evaluation of economic feasibility. This process may be complex if the evaluation includes an analysis of different utilization scenarios and their related technological choices and costs. Environmental priorities and local market conditions affect the cost of the project. Unless national or local requirements demand establishing an LFG plant for environmental reasons, the plant will be built only if it is profitable for the investor. A clear determination of the revenues from the energy sale and from a CDM project (if eligible) are also be essential.

This section explores the following parameters included in the economic evaluation:

- Preparation costs (including CDM project development)
- Investment costs for the extraction system and different utilization systems
- Operation and maintenance costs for different LFG systems
- Revenues for different utilization systems
- Revenues from CDM projects

Preparation Costs. All the information for the feasibility study must be collected through visits and meetings with the landfill owner, operator, and other stakeholders. Such a study may cost between US$15,000 and US$30,000, depending on the complexity of the data and the plant (personal communication from H. Willumsen, LFG Consult; Johannessen and Willumsem, 1999).

Costs related to the test pumping process typically range between US$40,000 and US$70,000, depending on the local availability of drilling and pumping equipment (personal communication from H. Willumsen, LFG Consult; Johannessen and Willumsem, 1999).

If the project is eligible to be developed as a CDM project, the associated costs are typically approximately US$50,000, which includes the Project Design Document (PDD), registration fee, validation, and legal work.

The design cost depends on the size of the LFG plant and the type of utilization system (flaring, electricity, or heat production). Normally the cost of the design and the preparation of bidding documents, permits, and overall supervision is approximately 10 percent of the total investment costs (personal communication from H. Willumsen, LFG Consult; personal communication from H. Willumsen, LFG Consult; World Bank, 2004).

Investment Costs. Investment costs depend on the size of the LFG plant and the chosen technology. This section outlines the investment costs for the technology options described in Section 3.

The *LFG extraction system* consists of collection and suction systems. For the collection system, the costs of vertical and horizontal gas collection pipes are similar. A vertical system normally requires four–six wells per hectare. A landfill containing a million tons of waste that is 10 meters deep requires twice as many wells as a landfill containing a million tons of waste that is 20 meters deep because the area of the latter is only half that of the 10 meter-deep landfill. The total length of the drilling and pipes is almost the same, but the connection piping between wells and the pump system for the shallow landfill covering the larger area requires more pipes and therefore a higher investment cost. A deep landfill is therefore an advantage from an economic point of view and for better biological activity. A vast majority of landfills have problems with high leachate/water levels in the wells, requiring installation of pumps to remove the water. The investment cost for the collection system including pumps normally ranges between US$30,000 and US$50,000 per hectare (personal communication from H. Willumsen, LFG Consult, 2003; Johannessen and Willumsem, 1999; SCS Engineers, 2005;).

The *gas pump system* can consist of blowers or compressors. Unless the LFG has to be conveyed long distances to the consumers, the blower costs relatively less in terms of investment and O&M than the compressor. The gas also has to be drained for condensate and cleaned for particles. Depending on the end use and the content of trace components in the LFG, more expensive systems may be needed to purify the LFG. The investment costs for a blower, manual regulation system, normal gas cleaning, and measuring and control system are normally between US$75 and US$200 per m^3 of LFG per hour (personal communication from H. Willumsen, LFG Consult; Johannessen and Willumsen, 1999; SCS Engineers, 2005; World Bank, 2004).

A flaring system is needed to destroy the LFG. For environmental reasons, enclosed flares are recommended. The investment cost for an enclosed flare, including the necessary regulation and control system, normally ranges between US$40 and US$80 per m^3 of LFG per hour (personal communication from H. Willumsen, LFG Consult; Johannessen and Willumsem, 1999; SCS Engineers, 2005; World Bank, 2003; World Bank, 2004). Table 7 summarizes the investment costs for the *collection and flaring system*.

Table 7. Investment Costs for a Collection and Flaring System

Equipment	**Costs (US$)**
Collection system	30,000–50,000/ha
Gas pump system	75–200/m^3LFG/hour
Flare system	40–80/m^3LFG/hour

The LFG can be used for energy purposes in different types of *utilization systems*. More than 500 LFG plants worldwide are equipped with gas engine/generator systems, and the investment costs are well defined. The variability range is determined by factors including the manufacturer and location. The investment costs for a total gas engine/generator unit built in a container normally range between US$1,100 and US$1,700 per kW_e installed (personal communication from H. Willumsen, LFG Consult; Johannessen and Willumsem, 1999; SCS Engineers, 2005; World Bank, 2004; World Bank, 2003; US EPA, 2009).

If the power plant has to produce more than approximately 4 megawatts of electricity (MWe), a gas turbine is sometimes used as a power plant. The investment costs are approximately US$1,000 per kWe installed (LFG Consult, 2003). In recent years micro turbines have been developed with a power production capacity of 30–250 kW. This more expensive type of gas turbine carries an investment cost of approximately US$3,000–US$5,000 per kW_e (LFG Consult, 2003; Wheless, 2009).

If the LFG is used in a *boiler plant*, it may be necessary to invest in a transmission pipe from the landfill to the boiler plant. Depending on the individual situation, the investment cost is typically US$100–US$125 per meter of gas pipeline. The boiler plant itself normally costs between US$30 and US$50 per kW_h.

The *direct use* situation is similar to a boiler plant with an investment for a transmission pipe and then installation of a furnace(s), which normally will range between US$20 and US$40 per kW_h.

A *leachate evaporation system* is an expensive installation but useful if cleaning the leachate is costly. To evaporate 1 m^3 of leachate, 250–300 m^3 of LFG are required. The investment ranges between US$7,000 and US$10,000 per m^3 of leachate per day (LFG Consult, 2003; World Bank, 2004).

For the *natural gas network*, various methods and systems are available for upgrading LFG to natural gas quality, depending on the gas quality required after upgrading the LFG and the content of trace components in the LFG. Investment costs range from US$1,800 to US$4,000 per m^3 of LFG per hour (Personal communication from H. Willumsen, LFG Consult; Persson, 2003; IEA Bioenergy, n.d.; IEA Bioenergy, 2009).

In most cases the cost of upgrading is given as the total price including investment costs and O&M over 10–15 years. The price for cleaning 1 m^3 of LFG is between US$0.05 and US$0.2 per m^3 of LFG. Table 8 summarizes the investment costs for different energy utilization systems.

Table 8. Investment Costs for Energy Utilization Systems

Equipment	**Costs (US$)**
Gas engine/generator units	1,100–1,700/kW_e installed
Gas turbine	1,000/kW_e installed
Micro turbine	3,000–5,000/kW_e installed
Transmission pipeline for LFG	100–125/m
Boiler plant	30–50/kW_h installed
Direct use	20–40/kW_h installed
Leachate evaporation	7,000–10,000/m^3 leachate x day
Upgrading to natural gas quality	1,800–4,000/m^3 LFG x hour

The investment costs for use of LFG as *vehicle fuel* are similar to those for the natural gas network because the LFG has to be upgraded in the same way.

The investment costs for use of LFG in a *fuel cell* include the cost of an upgrading system similar to the one used for a natural gas network, again because the LFG has to be upgraded in the same way. It is difficult to specify the cost of the fuel cell itself, as this technology has been used in only a few plants.

O&M costs include the labor costs for the daily operation, repair costs, and the cost of spare parts for regular maintenance and unplanned damage to the equipment. The annual O&M

costs for an LFG plant with extraction and flaring range between 4 percent and 8 percent of the investment costs (Terraza et al, 2007; U.S. EPA, 1996). The annual O&M costs for an LFG plant with extraction and a gas engine/generator or gas turbine system range between 10 percent and 12 percent of the investment costs (Terraza et al, 2007; personal communication from H. Willumsen, LFG Consult; Johannessen and Willumsem, 1999; SCS Engineers, 2005; World Bank, 2004; LFG Consult, 2003; US EPA, 2009; IEA Bioenergy, 2009). The O&M costs for leachate evaporation depend on the size of the plant but range between US$4 and US$10/m^3 of leachate evaporated (Personal communication from H. Willumsen, LFG Consult; World Bank, 2004).

If the LFG is upgraded (cleaned) to natural gas quality, O&M is usually included in the total annual costs, based on the cost to clean 1 m^3 of LFG. O&M costs range between 17 percent and 21 percent of the investment costs for flaring and power production (Personal communication from H. Willumsen, LFG Consult; US EPA, 2009; Wheless, 2009; De Hullu et al., 2008). Table 9 summarizes the O&M costs for different LFG systems.

Table 9. O&M Costs for Different LFG Systems

Equipment	**O&M costs**
LFG plant with flaring system	4–8 % of total investment costs
LFG plant with electricity production	10–12% of total investment costs
Leachate evaporation	US$4–US$10/m^3 of leachate evaporated
LFG plant with upgrading to natural gas	17–21% of total investment costs

Revenues. LFG can generate income when sold as fuel used for electricity or heat production. In recent years the value of the GHG reduction from destroying methane through flaring or using it as fuel in an energy plant can be credited as CER if the LFG plant has been approved through the UNFCCC system (see Section 7).

Sale prices for energy vary hugely worldwide. This variation depends largely on the countries' own fuel resources (fossil fuels including coal, oil, and gas or renewable energy sources such as hydro and biomass). Countries with such resources often have lower (sometimes highly subsidized) energy costs than countries without these resources and therefore depend on imports.

Most electricity today is delivered by large power companies owned by the public or private sectors. The price of electricity is to some degree controlled by the government, even for privately owned power plants. When a power company or power distribution company has to buy electricity from small producers such as LFG plants, the price is often lower than the price for electricity from large generators. This difference is due in part to the need for the power plant and/or distribution utility to have the capacity to operate the plant and maintain the distribution system. A normal range for North America and Europe is usually between US$0.01 per (off-peak) kilowatt hour (kWh_e) and US$0.08 per (peak) kWh_e, with an average of approximately US$0.05 per kWh_e (Willumsen, 2004: Gendebein et al., 1991; personal communication from H. Willumsen, LFG Consult; Johannessen and Willumsem, 1999).

Often, however, offers from distribution utilities undervalue the grid system benefits of "distributed generators" such as LFG plants. These benefits include their proximity to loads, which helps relieve pressure on (and benefits) the sub-transmission systems, and their relative contribution to system reliability. The spread of "smart grid" technologies will make the deployment of distributed generators more attractive.

In a number of countries, power companies are obliged to buy electricity. Many countries provide direct or indirect subsidies for renewable energy sources in order to promote power generation with reduced CO_2 emissions. For example, subsidies for selling electricity range from US$0.004 per kWh_e in the United States to US$0.09 per kWh_e in Germany (Personal communication from H. Willumsen, LFG Consult; *Biogas Barometer*, May 2007).

To make landfill gas recovery feasible without subsidies in Western countries, the "thumb rule" indicates that produced electricity needs to be sold at a price of US$0.04 per kWh_e or higher. For small landfills (less than 500,000 tons or approximately 150 tons/day), the produced electricity needs to be sold at US$0.06 per kWh_e or higher to make landfill gas recovery feasible.

The price for sale of heat or LFG for direct use is more variable, because heat prices can vary more depending on local circumstances. Typically, the price is half or less of the electricity price, ranging from US$0.005/$kWh_h$ to US$0.04/$kWh_h$.

If an LFG project is approved by the UNFCCC under the CDM, the CER can be sold to generate additional revenue. The price of 1 ton of CO_2 equivalent (CO_2e) varies over time depending on the market. In the free market, the price increases when there is a need for extra CO_2 quotas. The most common way to sell CO_2 offsets, however, is for the owner of the CER from the LFG to sell it for a fixed price per ton of CO_2e over a 7- or 10-year period. The price is negotiated on case by case basis, but in 2008 an average price was approximately US$12 per ton of CO_2e. This corresponds to US$0.05 per kWh_e, which is extra income on top of that generated from the sale of electricity and/or heat.

CER can also be obtained from LFG flaring. The methane is destroyed by flaring, and the GHG reduction from the flared methane is the same as that for an energy plant. This situation has encouraged many landfill owners in the developing world to install LFG recovery plants, consequently improving the environmental and sanitary quality of the final disposal service. This is a typical positive externality of the Kyoto Protocol.

Flaring vs. Energy Utilization. Some Western countries require minimizing methane emission from landfills by extraction and flaring or utilization in energy plants. Few developing countries, however, have regulatory requirements enforcing LFG recovery. Therefore LFG plants have been established only where the energy price was high enough to secure an income that could yield a profit for the investor.

The Kyoto Protocol and the CO_2 trading system have created a new type of project in which income is generated only from LFG flaring. The investment costs for an LFG plant with electricity production are 30-40 percent higher than those for an LFG flaring plant. Project feasibility is not guaranteed in every type of landfill, however. Even flaring projects need at least 500–1,000 m^3 LFG/h to make them feasible, depending on local circumstances. The feasibility depends largely on the main variables, but to make an LFG plant with power production more profitable than the same LFG plant with flaring only, the total energy price for electricity must be between US$0.06 and US$0.1 per kWh_e if the income from CER is US$12. If the electricity price is lower, it is more profitable to invest in a flare system only. Nevertheless, the investor should bear in mind that the income from CER will stay at the same level for several years, while energy prices will probably increase and allow higher profitability over time, but this requires a willingness to risk equal or even lower energy prices. Finally, from a global emission point of view, producing energy from LFG replaces fossil fuel and thus increases emission reduction.

7. Landfill Gas and the Clean Development Mechanism

In 1992 at the United Nations Conference on Environment and Development in Rio de Janeiro, 192 countries ratified the UNFCCC, which encourages industrialized countries to stabilize GHG emissions. The convention entered into force in 1994.

The Kyoto Protocol[9] is an international agreement linked to the UNFCCC that was ratified in 1997. The detailed rules for implementation of the Protocol were adapted in Marrakesh in 2001, and the Protocol entered into force in 2005. The Kyoto Protocol sets binding targets for 37 industrialized countries and the European Community, the so-called Annex B countries, to reduce GHG emissions by an average of 5 percent over a 5-year period (2008–2012) against 1990 levels. Non-Annex B countries, which include all countries in the LAC region, have no quantity commitment under the Protocol.

The Conference of Parties (COP) is the overall authority that provides official guidance to the CDM. An Executive Board (EB) gives the COP suggestions and recommendations.

CO_2 Trading. The industrialized countries should meet their GHG emission targets through national actions, but the Kyoto Protocol allows them also to meet their commitments though the following three market-based "flexible mechanisms":

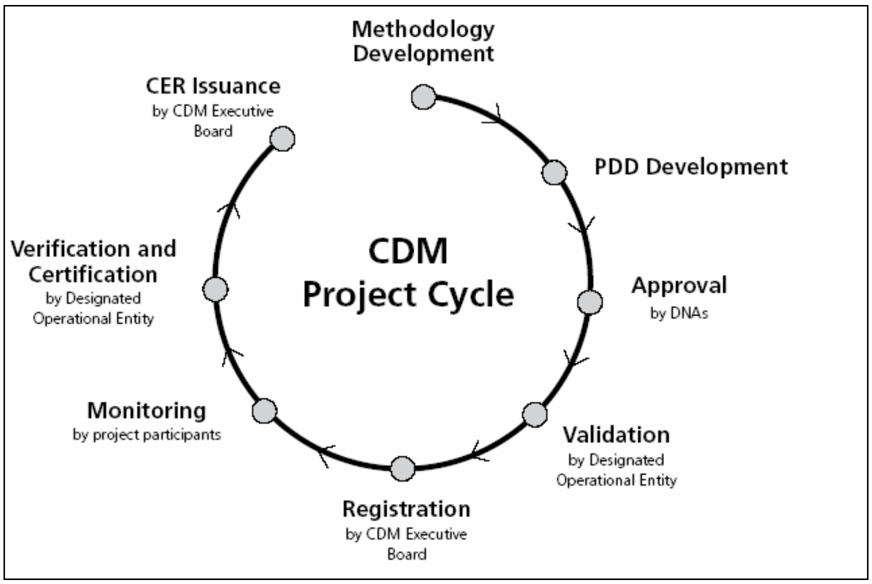
1. Emission trading (ET) is the trading of emission permits called Assigned Amount Units (AAUs) among industrialized (Annex B) countries.
2. Joint Implementation (JI) allows an Annex B country to invest in an emission reduction project in another Annex B country and be credited with the reduction (in Emission Reduction Units, or ERU). The project in the second Annex B country might yield the same emission reductions for a lower investment cost than a more expensive project in the country with the obligation to lower the emissions.

- The CDM allows an Annex B country with an emission reduction obligation to implement an emission reduction project in a Non-Annex B (developing) country and earn saleable credits (CER). The CER can then be bought by the investor, typically a

[9] www.unfccc.int/kyoto_protocol/items/2830.php.

fund, owned by an Annex B country or in most cases a number of countries that can use the credit to reduce GHG emissions in their own country or countries. Figure 16 illustrates the CDM project cycle. The flexible CDM can be used for LAC countries, as explained below.

Figure 16. CDM Project Cycle



Source: UNFCCCC.

Project Design Document. The CDM project cycle begins with a PDD[10] written by the project participants (developers), who often hire specialized consultants for this task. The PDD is a kind of feasibility study that must strictly follow the requirements and methodology[11] for each type of project. For LFG projects, the Approved Consolidated Methodology (AMC0001: Consolidated baseline and monitoring methodology for landfill gas project activity) is normally used. The methodology includes several tools that are revised frequently.

The PDD includes a general description of the project and a description of the baseline methodology, which must include a demonstration of the additionality for the CDM project. Additionality is the extent of the emission reduction below what would have occurred in the absence of the CDM project. The PDD also includes an estimate of emission reductions, the

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[10] The PDD form can be found at www.cdm.unfccc.int/Reference/PDDs_Forms/PDDs/index.html, and the PDD guidelines can be found at www.cdm.unfccc.int/Reference/Guidclarif/index.html.
[11] Methodologies: www.cdm.unfccc.int/methodologies/index.html.

monitoring methodology and plan, the time schedule and crediting period, a description of expected environmental impacts, and stakeholder comments.

In all Annex B and Non-Annex B countries, a Designated National Authority (DNA)[12] acts as the local CDM officer. The DNA has to verify that the project activity described in the PDD is voluntary and consistent with sustainable development in the host country (the country where the project activity will take place).

Validation of CDM Projects. The CDM Executive Board (EB) has certified Designated Operational Entities[13] (DOE) that are accredited to validate CDM projects. The project developer has to choose a DOE for validation of the PDD. Before sending the PDD to the EB for registration, the DOE visits the host country and the project parties (for a CDM-LFG project, the DOE also visits the landfill to investigate and evaluate the information in the PDD).

The validator writes a Validation Report and sends it to the developer. In most cases the PDD has to be revised in accordance with the questions and guidance from the DOE. If methodology and tools change between the time the PDD is written and the Validation Report is sent, the PDD has to be revised according to the new requirements. This means that the validation period can easily be 6 months to 1 year or more.

Registering a CDM Project. When the DOE decides that the project activity and PDD are valid, (s)he submits the PDD and the Validation Report to the EB, requests registration of the project, and pays a registration fee. Normally the EB registers projects within 8 weeks, unless one of the parties or the EB requests a review. In such case registration can take up to 6 months.

Establishing a CDM–LFG Plant. An LFG plant can be established in different ways, as described in Section 5. In a conventional owner project, the landfill owner builds, owns, and operates the plant and keeps the revenues from the sale of CER and in many cases from the energy production. The owner of the landfill can also use an LFG contractor to build and operate the LFG plant. In some cases the contractor makes the investment and is allocated all or part of

[12] A list of Designated National Authorities (DNA) can be found at www.cdm.unfccc.int/DNA/index.html.
[13] A list of Designated Operational Entities (DOE) can be found at www.cdm.unfccc.int/DOE/index.html.

the revenue. To document the emission reduction achieved by a CDM-LFG plant, it is necessary to install monitoring equipment according to the requirements for a CDM–LFG project and described in the PDD, which in some cases are more comprehensive than those for a normal LFG plant.

Monitoring and Verification. Once the LFG plant has been registered and built and has been running and monitored for 1 year, the DOE visits the plant to verify the emission reduction achieved. The verification consists of reviewing the performance record, collecting measurements and analysis, testing the accuracy of monitoring equipment and the calibration methods and results for the equipment, and interviewing the owner, operator, and other project participants. Based on the verification results, the DOE issues a report that is sent to the EB, stating the amount of CER achieved from the project activity. This document is made available to the public on the UNFCCC website, as are all the other documents related to the project. After 15 days the EB issues the CER, unless a party or the EB requests a review, which has to be conducted within 30 days.

8. Existing LFG Plants and Under-delivery

As noted earlier, more than 1,200 LFG plants are now operating and utilizing LFG for energy purposes. Since CDM and JI projects were introduced, several LFG plants with flaring only have been established, as these projects now can produce revenue from selling the CO_2 credits. Therefore, actual cases around the world can be studied for their experience and results.

Although LFG recovery projects are some of the most profitable renewable energy sources, in many cases LFG plants have failed to deliver the LFG amount estimated from design studies. These plants did not go bankrupt because business was probably good enough that the payback period lasted longer than expected but still yielded a positive NPV over a reasonable number of years. No accurate information is available on the number of LFG plants that failed to deliver the expected LFG amount, but the estimate during the past 30 years is nearly 75 percent.

One of the problems for LFG projects is that it looks simple to drill some wells in a landfill and then extract the LFG and use it in a boiler or a gas engine. Many new and inexperienced companies got started on this assumption but then learned that a landfill is an anaerobic digester with a complex biological system that is sensitive to many parameters. Problems can arise with leachate in the landfill, condensate in the pipe system, poor compaction of the waste, poor cover material on top of the landfill, trace components in the gas.

It is difficult or impossible to obtain information from owners of LFG plants on the difference between their estimated and actual LFG extraction, but CDM projects in recent years allow a closer look at this discrepancy. For these plants all the gas extraction is estimated in the PDD before construction, and during operation the monitoring programs give exact information on the LFG extraction, LFG utilization through energy production and/or flaring, and emission reduction as a result of the CDM–LFG projects.

A 2007 survey of six LFG projects by the World Bank showed a difference in estimated and actual performance. All but one project showed an under-performance rate of between 20 percent and 90 percent (one plant under-estimated performance in the design and produced approximately 100 percent more than expected). The results of this investigation are shown in Table 10.

Table 10. Estimated vs. Actual LFG Extraction for Six LFG Plants, 2007

	Sao Paulo Brazil	Buenos Aires Argentina	Monterrey Mexico	Maldonado Uruguay	Liepaja Latvia	Olavarría Argentina
Estimated $m^3 \times 10^3$ LFG/year (2006)	215,000	116,500	15,340	1,963	696	3,408
Actual in $m^3 \times 10^3$ LFG/year (2006)	103,000	13,100	41,230	1,496	561	677
Difference in $m^3 \times 10^3$ LFG/year	–112,000	–103,400	+15,890	–467	–135	–2,731
Difference in %	–48	–89	+104	–24	–20	–80
Gas extraction from waste, 10^3 x tons	20,000	25,000	8,700	335	41	180
Actual extraction rate in 2006, m^3/tons x year (at 50% CH_4)	5.15	0.52	3.59	4.47	13.70	2.25
Worldwide range in m^3/tons x year	3–6 m^3 LFG/tons x year (at 50% CH_4)					

Source: Terraza, Willumsen, and Guimaraes, 2007.

The comparison of actual LFG extraction with data from existing LFG plants worldwide done in the investigation described on page 8 in Section 2 showed an LFG extraction rate of between 3 and 6 m^3 of LFG/tons per year. Table 10 shows a similar rate in four of the landfills listed. Buenos Aires yields only 0.52 m^3LFG/tons x year because of the high level of leachate in the landfill that hinders extraction of the LFG. Liepaja yields 20 percent less LFG than estimated but still produces 13.7 m^3 LFG/tons x year, higher than the worldwide range, possibly because the waste is only 1–2 years old compared with 5–10 years for the other plants.

Another survey (SCS Engineers, 2007) was conducted by the Carbon Fund Unit in the World Bank in 2007. Of the 14 CDM and JI projects investigated, 3 were included in the survey shown in table 11, but the results showed the same trend of lower actual than estimated LFG extraction. Table 11 shows that the average actual extraction for the 14 LFG plants was only 39.6 percent of the extraction estimated in the PDD. The result is when taken the measurements from the individual plants each year summarize them and compare with the estimated LFG extraction, which gives a total number of 25 reports during the 5-year period.

Table 11. Estimated vs. Actual LFG Extraction for 14 LFG Plants, 2007

Year	Number of LFG projects reporting each year	Estimated LFG extraction (m^3/h)	Actual LFG extraction (m^3/h)	Comparison of estimated and actual LFG extraction (%)
2003	1	558	334	59.9
2004	3	23,655	13,308	56.3
2006	8	51,557	20,027	38.8
2006	11	48,808	14,820	30.4
2007	2	2,317	1,725	74.5
Total	25	126,895	50,214	
Average	5			39.6

Source: SCS Engineers, 2007.

In the two surveys discussed above, a more detailed investigation of each LFG plant found over-expectation of LFG extraction in some cases an under-performance in others. In many cases both over-expectation and under-performance were responsible for the difference in the estimated and actual LFG extraction.

Both surveys found that many of the models or parameters used in the models were too optimistic. Collection efficiency was over-estimated in many cases (up to 80 percent when 50 percent or less would have been more realistic). Some landfills were very shallow, with poor waste compaction, accumulated leachate in the landfills and gas wells, much of the organic materials burned by fires, and porous cover material that allowed penetration of atmospheric air. Because construction and especially operation of an LFG plant can lower the extraction rate, it is very important to have a good O&M system and experienced O&M staff, as well as to follow up on any irregularities as soon as they appear.

By the end of 2008, there were 89 CDM–LFG projects registered at the UNFCCC. Their estimated CO_2e and corresponding LFG extraction can be found in the PDDs. Forty-nine of the registered LFG projects have been running for more than a year, and the results from the monitoring program have been verified by the DOE. These can be found on the UNFCCC website and are shown in table 12, where the estimated and monitored emission reduction is the amount counted from the start of the individual LFG plants until the year mentioned in the table.

Table 12. Comparison of Estimated and Monitored Emission Reductions of Registered LFG Projects from the Verified CER

Registration year	Number of LFG projects with monitoring reports	Estimated emission reduction (tons of CO_2e)	Monitored emission reduction (tons of CO2e)	Monitored emission reductions as a percentage of estimates
2005	8	11,120,000	1,275,000	11.5
2006	20	20,647,000	8,436,000	40.9
2007	15	4,642,000	2,711,000	58.4
2008	6	818,000	310,000	37.9
Total	49	37,226,000	12,733,000	34.2

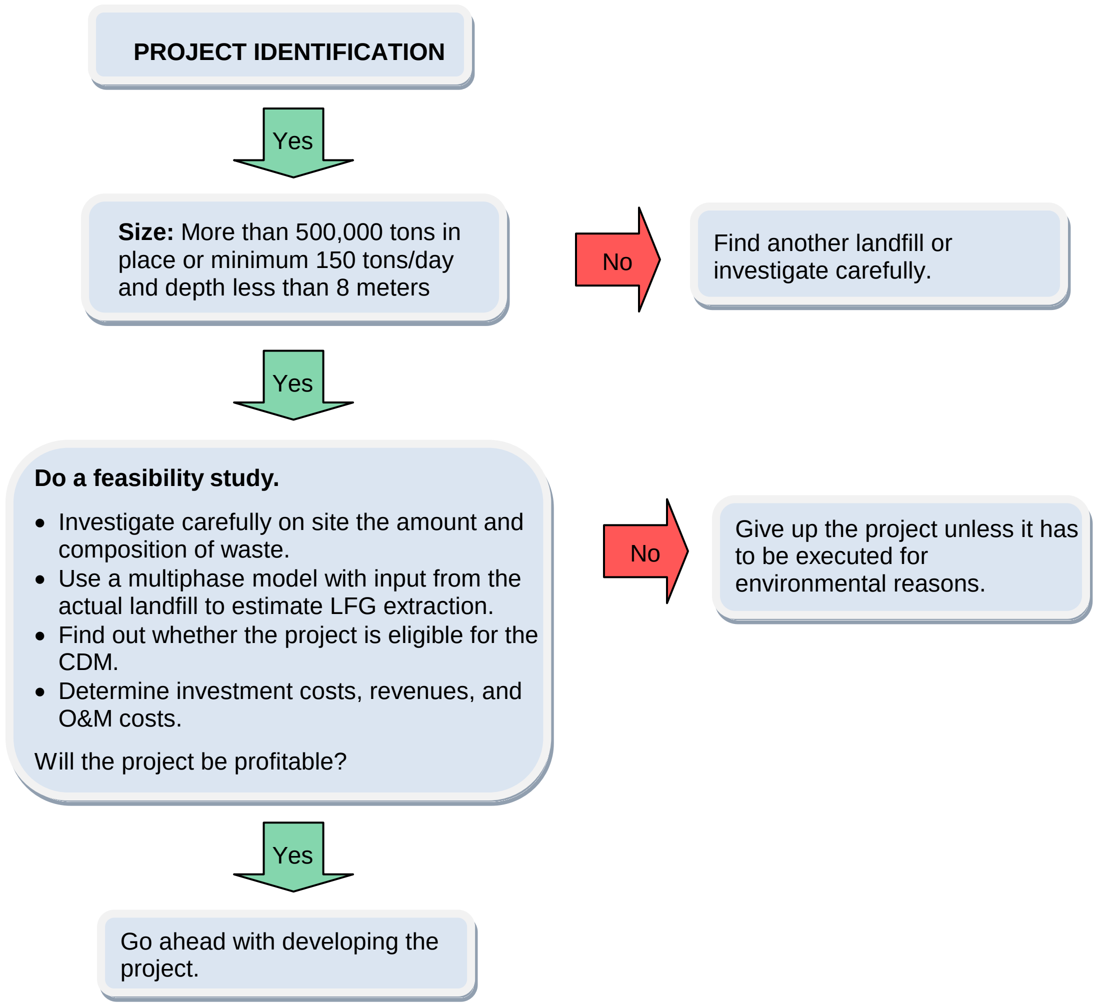
Source: Peterson et al., 2009.

Many case studies of LFG plants are available on the websites of the World Bank, U.S. EPA, consultants, and contractors, as well as on the Methane to Market website.[14]

Troubleshooting. Many problems and failures can occur during identification, design, construction, and operation of an LFG plant. Figure 17 lists some of the most common problems, with actions recommended at each stage.

[14] http://www.methanetomarkets.org/m2m2009/index.aspx.

Figure 17. Flowchart of Recommended Actions during LFG Project Identification, Construction, and Operation



CONSTRUCTION OF AN LFG PLANT

Type of contract

- Conventional owner project
- Design-Build or Turnkey project
- Design-Build-Operate (DBO) Project
- Build-Own-Operate (BOO) Project

Is the owner of the landfill also the investor in the LFG plant?

No

If a contractor or consortium is the investor through a BOO project, be sure to get a royalty on a certain amount or percentage of the income from the sale of the LFG or energy.

Yes

Is the owner of the LFG plant also the contractor and builder of the LFG plant?

No

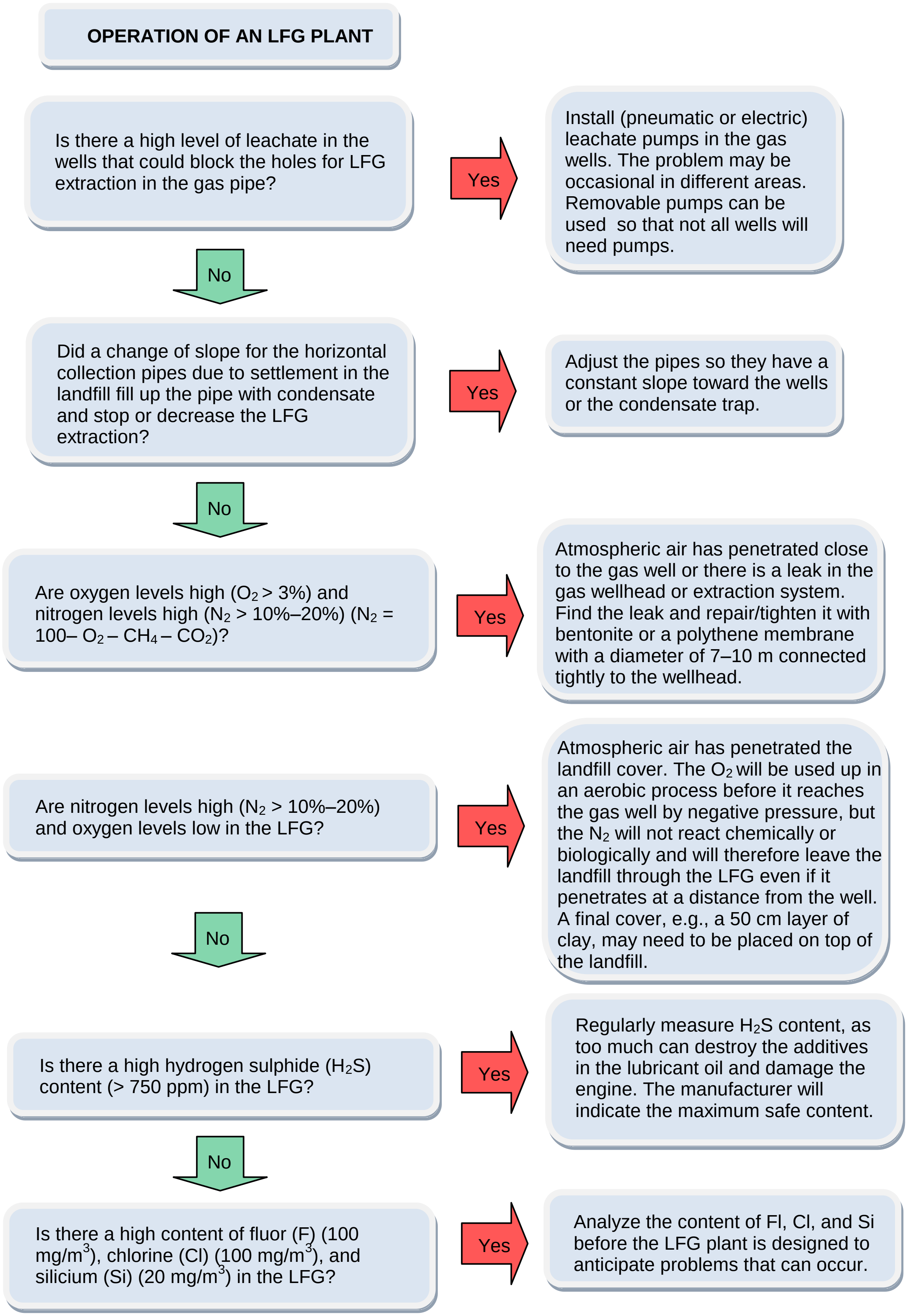
For a DBO project, the owner should pay incentive compensation to the operator so that he gets a higher payment the higher the CO_2 emission reduction and/or energy production is. During construction, the owner should keep an eye on the following:

- When drilling wells, be sure the gas pipe and gravel around it are placed correctly and not filled with mud.
- When preparing the gas well for installation of leachate pumps if a high level of leachate is present, consider two pipes in the wells, one for LFG and one for leachate.
- Make sure horizontal collection pipes have a constant slope of at least 2%.
- Place a condensate trap on all low points in the collection system.
- Make sure all equipment for extraction and utilization are designed for LFG.
- Carefully check the commissioning of all equipment, control, and alarm systems.

Yes

During supervision the owner and builder should look for the following:

- When drilling wells, be sure the gas pipe and gravel around it are placed correctly and not filled with mud.
- When preparing the gas well for installation of leachate pumps if a high level of leachate is present, consider two pipes in the wells, one for LFG and one for leachate.
- Make sure horizontal collection pipes have a constant slope of at least 2%.
- Place a condensate trap on all low points in the collection system.
- Make sure all equipment for extraction and utilization are designed for LFG.
- Carefully check all equipment, control, and alarm systems during the commissioning.


OPERATION OF AN LFG PLANT
Is there a high level of leachate in the wells that could block the holes for LFG extraction in the gas pipe?
Yes
Install (pneumatic or electric) leachate pumps in the gas wells. The problem may be occasional in different areas. Removable pumps can be used so that not all wells will need pumps.
No
Did a change of slope for the horizontal collection pipes due to settlement in the landfill fill up the pipe with condensate and stop or decrease the LFG extraction?
Yes
Adjust the pipes so they have a constant slope toward the wells or the condensate trap.
No
Are oxygen levels high (O_2 > 3%) and nitrogen levels high (N_2 > 10%–20%) (N_2 = 100– O_2 – CH_4 – CO_2)?
Yes
Atmospheric air has penetrated close to the gas well or there is a leak in the gas wellhead or extraction system. Find the leak and repair/tighten it with bentonite or a polythene membrane with a diameter of 7–10 m connected tightly to the wellhead.
Are nitrogen levels high (N_2 > 10%–20%) and oxygen levels low in the LFG?
Yes
Atmospheric air has penetrated the landfill cover. The O_2 will be used up in an aerobic process before it reaches the gas well by negative pressure, but the N_2 will not react chemically or biologically and will therefore leave the landfill through the LFG even if it penetrates at a distance from the well. A final cover, e.g., a 50 cm layer of clay, may need to be placed on top of the landfill.
No
Is there a high hydrogen sulphide (H_2S) content (> 750 ppm) in the LFG?
Yes
Regularly measure H_2S content, as too much can destroy the additives in the lubricant oil and damage the engine. The manufacturer will indicate the maximum safe content.
No
Is there a high content of fluor (F) (100 mg/m^3), chlorine (Cl) (100 mg/m^3), and silicium (Si) (20 mg/m^3) in the LFG?
Yes
Analyze the content of Fl, Cl, and Si before the LFG plant is designed to anticipate problems that can occur.

REFERENCES

Christensen, T. H., R. Cossu, R. Stegmann, eds., and H. C. Willumsen. 1996. *Landfilling of Waste: Biogas*. London: E & FN Spon.

De Hullu, Jos, et al. 2008, "IFP Project: Biogas Upgrading". PowerPoint presentation, June 10, 2008, Technische Universiteit Eindhoven, Netherlands.

Emcon Associates. 1980. *Methane Generation and Recovery from Landfills*. Ann Arbor, MI: Ann Arbor Science Publishers.

Emcon Associates and Jacobs Engineering Co. 1976. "A Feasibility Study of Recovery of Methane from Parcel I of the Scholl Canyon Sanitary Landfill" for the City of Glendale, CA, United States.

Farquar, G. H., and F. A. Rovers. "Gas Production during Refuse Decomposition". 1973. *Water, Air & Soil Pollution* 2 (4) December.

Gendebien, A., et al. 1991. *Landfill Gas. From Environment to Energy*. Luxembourg: Office for Official Publication of the European Communities.

International Energy Agency (IEA). 2009. "Turning a Liability into an Asset: The Importance of Policy in Fostering Landfill Gas Use Worldwide." Paris, France. Available at www.iea.org/textbase/papers/2009/ landfill.pdf.

____. 2009. IEA Bioenergy, *Task 37: Biogas Upgrading to Vehicle Fuel Standard and Grid Injection*.

____. 1998. "International Perspective on Energy Recovery from Landfill Gas." Bioenergy and CADDET Renewable Energy Technology Programme. Paris, France: IEA CADDET.

____. n.d. IEA Bioenergy, Biogas Upgrading and Utilization, *Task 24: Energy from Biological Conversion of Organic Waste*. Available at http://www.iea-biogas.net/Dokumente/Biogas upgrading.pdf.

International Solid Waste Association (ISWA). 2005. *Field Procedures Handbook for the Operation of Landfill Biogas Systems*. Vienna, Austria.

Johannessen, L. M., and H. C. Willumsen. 1999. *Guidance Note on Recuperation of Landfill Gas from Municipal Solid Waste Landfills*. World Bank Urban and Local Government Working Paper Series. Washington, DC, United States: World Bank.

Le Baromètre du Biogaz/Biogas Barometer: *Le Journal des énergies renouvelables* No. 179, May 2007. Paris, France: Observatoire des Energies Renouvelables/European Renewable Energy Agency (EurObserv'ER). Available at http://www.energies-renouvelables.org/observ-er/stat_baro/observ/ baro179 _a.pdf.

LFG Consult. 2003. "Draft Case Study: Landfill Gas to Energy Projects in Poland". Prepared for the World Bank, Washington, DC, United States.

O'Brien, J. K. 2008. "Landfill Gas Collection System Efficiencies". *MSW Management*, July/August.

Persson, Margareta. 2003. "Evaluation of Upgrading Techniques for Biogas". Report SGC 142. Lund, Sweden: Lund Institute of Technology.

Peterson, C., W. N. Bowden, and A. Bhaskar. 2008. "Landfill Gas Recovery System Performance". CDM Investment Newsletter, No 1/2008.

SCS Engineers. 2007. "Comparison of Forecast and Reported Methane Recovery Rates at Selected Landfills in Developing Countries". Washington, DC, USA: World Bank.

____. 2005. "Pre-Feasibility Studies for Landfill Gas Recovery and Energy Production from Specific Landfills in Brazil, Mexico, Colombia, Uruguay, and Peru". Prepared for the World Bank Environmentally and Socially Sustainable Development, Latin America and the Caribbean Region.

Terraza, H., H. Guimares, and H. Willumsen. 2007. "Design vs. Actual Performance and the Future for CDM Projects". Paper presented at the LGF Workshop: Project Design vs. Actual Performance and the Future for CDM Projects, Washington, DC, United States, April 19, 2007.

U.S. Department of Energy. 2004. *Fuel Cell Handbook*. Seventh edition. Morgantown, West Virginia, USA.

U.S. Environmental Protection Agency (EPA). 2009. LFG Energy Project Development Handbook. Available at http://epa.gov/lmop/res/handbook.htm.

____. 1996. *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook.* Landfill Methane Outreach Program, September 1996. EPA 430-B-96-0004. Available at http://www.epa.gov/lmop/res/pdf/handbook.pdf.

Wheless, Ed. 2009. “Operating Experience at Two Biogas-fired Microturbine Facilities”. Paper presented at the 28th Annual Solid Waste Association of North America (SWANA) Landfill Gas Symposium, March 7–10, 2005, San Diego, California, United States.

Willumsen, H. C. 2005. “A Review of Global LFG Recovery and Utilization”. Paper presented at the 28th Annual SWANA Landfill Gas Symposium, March 7–10, 2005, San Diego, California, United States.

____. 2004. “Landfill Gas Recovery Plants: Looking at Types and Numbers Worldwide”. *Waste Management World* 5 (7) July–August 2004.

Willumsen, H. C., L. Bach, and L. Hedeselskabet Sp. z o.o. 1991. “Landfill Gas Utilization Overview”. Paper presented at the Third International Landfill Symposium, October 14–18, 1991, Cagliari, Sardinia, Italy.

World Bank. 2004. *Handbook for the Preparation of Landfill Gas to Energy Projects in Latin America and the Caribbean*. Energy Sector Management Assistance Program (ESMAP) Ref. No. 019399 (6). Prepared by Conestoga-Rovers & Associates. Washington, DC, United States: World Bank.