CHAPTER 4

Landfill Gas Energy Utilization Technologies

There are several ways to effectively utilize LFG for energy; however, the primary applications are direct use and electricity generation technologies. This chapter provides an overview of LFGE utilization technologies, including emerging technologies that are not yet widely used but may prove feasible in certain situations. This chapter also discusses how to evaluate and select potential energy utilization technologies and concludes with a discussion of LFG treatment options.

Table 4-1 shows the installed generating capacity for electricity projects in Australia, Canada, the United Kingdom and the United States and in developing countries or countries in transition based on recently available data. In addition to these operational electricity projects, the CDM and JI databases show that an additional 219 megawatts (MW) of generating capacity is planned at landfill sites that have registered their projects with the UNFCCC.

Table 4-1. Installed Electric Generating Capacity from LFGE Plants for Select Countries

Country	Developing/Transitioning Countries		Australia	Canada	United Kingdom	United States
	CDM	JI				
Capacity (MW)	242	13	164	67	1,012	1,730

Sources: United Nations Environmental Programme (UNEP) CDM Pipeline spreadsheet and JI Pipeline spreadsheet as of 1 October 2011; Australian Department of Sustainability, Environment, Water, Population and Communities - Map of operating renewable energy generators in Australia as of 6 August 2010; Department of Energy and Climate Change, Digest of United Kingdom Energy Statistics (DUKES) as of 2010; Global Methane Initiative (formerly prepared under Methane to Markets Partnership) Landfill Subcommittee Country-Specific Profile and Strategic Plan for Canada as of 2005; U.S. EPA LMOP Landfill and LFG Energy Project Database as of 30 September 2011.

Although a similar level of recent detailed statistics is not available for all of the other types of projects, data on direct-use projects are available from a few GMI Partner Countries. Canada reported 10 direct-use projects in 2010 used for heating and industrial applications at refineries and gypsum manufacturing plants.[1] The United States reports 152 direct-use projects on line as of September 2011; these projects are used in multiple sectors of the economy—from institutions such as schools, hospitals, and military bases, to commercial greenhouses and aquaculture, to manufacturing of cement, paper, food and automobiles.[2] According to the CDM and JI databases, 38 projects are currently flaring their LFG and have been issued credits by the UNFCCC and another 50 projects are registered with the UNFCCC. These 88 projects provide significant opportunity for increased LFGE utilization in direct-use or electricity projects.

Both in-country and foreign project developers must consider that LFGE projects, even those using the same or similar technologies, vary widely in terms of costs as a result of project- and country-specific factors such as business risk, duties and taxes, availability of materials,

Project Feasibility

The feasibility of an LFGE project for a particular landfill will depend on numerous technical and economic considerations, such as waste composition and volume, quality and quantity of LFG, availability and location of a suitable end user, project capital and operation and maintenance (O&M) costs, and financing options.

[1] Global Methane Initiative (formerly prepared under Methane to Markets Partnership) Landfill Subcommittee. 2005. *Country-Specific Profile and Strategic Plan for Canada.* http://www.globalmethane.org/documents/landfills_cap_canada.pdf.

[2] U.S. EPA LMOP. Landfill and LFG Energy Project Database. http://www.epa.gov/lmop/projects-candidates/.

labor costs, permitting and possible project revenue streams. In addition, foreign project developers must also consider currency risk. (See Chapter 7, Project Economics and Financing, for a more detailed discussion of LFGE project cost considerations.)

4.1 Direct-Use Technologies

Figure 4-1. Installing a HDPE LFG pipeline for the Brazil MARCA Landfill in Cariacica, Brazil

In the United States, Australia, and many European countries such as Sweden, Germany and the Netherlands, LFG has been commercially used in place of a conventional fuel such as natural gas, fuel oil or coal for more than 30 years.[3] While LFG has been used for less time in other countries, direct-use technologies have proven to be both viable and environmentally beneficial. In this application, the collected LFG is used on site or sent to a nearby end user through a dedicated pipeline typically constructed of high density polyethylene (HDPE) (see Figure 4-1) or other materials such as stainless steel. The length of the pipeline will primarily determine the economic feasibility of the project. Pipelines constructed within 8 kilometers (km) of the landfill are often economically viable, but longer pipelines can prove economical based on the amount of LFG collected, the fuel demand of the end user, and the price of the fuel the LFG will replace. Pipelines must include facilities to remove condensate, either before it enters the pipe or at stages along the way. LFG can be combusted in boilers or other equipment that can be modified to utilize LFG, such as dryers, space heaters, kilns, furnaces, reformers, gas chillers and other thermal applications. LFG use is well suited for operations that have a steady and continuous demand for fuel. Batch processes that have fluctuating energy demands are not as desirable, as decreased LFG demand would result in excess flared LFG.

Boilers

Boilers use LFG as a fuel to produce steam or hot water (see Figure 4-2). The steam produced by the boiler can be used for space heating, process heating or electricity generation via a steam turbine.

Existing boilers usually require modifications to the burner and to the fuel train (for example, integrating the LFG fuel supply piping) to utilize LFG, but virtually any commercial or industrial boiler can be retrofitted to fire LFG or co-fire LFG with another fuel. The equipment for retrofitting boilers is commercially available and widely used, but site-specific considerations must be taken into account during the engineering and design phase. In particular, the quantity of LFG available must be considered and compared with the facility's steam needs and

Figure 4-2. LFG Water Boiler System at the Gaoantun Landfill in Beijing, China

[3] U.S. EPA LMOP. Landfill and LFG Energy Project Database. http://www.epa.gov/lmop/projects-candidates/index.html. and IEA Bioenergy. 2003. "Municipal Solid Waste and its Role in Sustainability." http://www.ieabioenergy.com/media/40_IEAPositionPaperMSW.pdf.

the boiler's capacity.[4] The costs associated with retrofitting boilers will vary depending on boiler type, fuel use, and age of the unit.

In addition to the burner and fuel supply piping modifications, retrofits include either automatic or manual process controls to control the fuel feed and the operation of the boiler. Typical approaches include:

- Installing automatic process controls and a dual-fuel train to blend LFG with other fuels to sustain a co-firing application or to provide for immediate fuel switching in the event of a loss in LFG pressure to the unit. This retrofit will ensure uninterruptible steam supply and provide users with the flexibility of dual-fuel firing.
- Installing manual controls on the boiler in lieu of an automatic process control system. This retrofit is best suited for scenarios where the boiler does not need immediate uninterruptible steam supply if there is a loss of LFG pressure to the boiler, or where other units in the system are available to provide back-up steam supply. In this case, manual controls are implemented and the boiler operating system is not integrated in an automatic process control system.[5]

LFG has been used in a wide range of boiler sizes, from small package boilers used to heat maintenance buildings, schools and hospitals to large industrial units, providing steam for pulp and paper, automobile and other large manufacturing processes. LFG is corrosive (unless very well dried) and may affect conversion of standard boiler equipment. Table 4-2 shows the estimated sizes of LFG boiler installations in the United States for specific applications.

Use of LFG in Boilers

For more information about the use of LFG in boilers, see the LMOP fact sheet on boiler retrofitting.

Table 4-2. Typical LFG Boiler Sizes

Technology/Application	Energy Demand (MJ/hr)	Estimated LFG Flows (m^3/hr)*
Small Package Boiler: School, Hospital or On-site Landfill Heating	200 to 6,700	11 to 350
Mid-Sized Hospital Boiler	17,000 to 22,200	880 to 1,200
Industrial Steam Boiler	9,600 to 160,000	510 to 8,500

* Assuming 50 percent methane in the LFG. Source: U.S. EPA LMOP Landfill and LFG Energy Project Database as of April 2011.

Examples: LFG Used in Boilers

As of 2011, the Gaoantun Landfill in Beijing, China had an average gas flow of 2,500 cubic meters per hour (m^3/hr) at 60 percent CH_4. A portion of the LFG is used in a boiler to supply hot water in the washroom at the landfill. See Appendix A for a case study of the Gaoantun Landfill.

The Three Rivers Regional Landfill in South Carolina, USA uses LFG to fuel a boiler to provide steam for the Kimberly-Clark Beech Island paper mill.

[4] U.S. EPA LMOP. 2009. *Adapting Boilers to Utilize Landfill Gas: An Eivronmentally and Economically Beneficial Opportunity*. http://epa.gov/lmop/documents/pdfs/boilers.pdf.

[5] Global Methane Initiative. 2010. *Landfill Gas Energy Technologies.* http://www.globalmethane.org/Data/1022_LFG-Handbook.pdf.

Furnaces, Dryers and Kilns

Furnaces, dryers and kilns can use LFG as a replacement for or supplement to conventional fuels (see Figure 4-3) in cement, brick and ceramics, iron and steel, wood products manufacturing and other sectors. For small applications (such as local brick or pottery plants) LFG may supply all or most of the energy needs. For plants with larger energy consumption, there often will not be a sufficient supply of LFG to meet 100 percent of the fuel needs at the manufacturing plant, and so LFG is often used as a supplementary fuel. In these scenarios, LFG provides cost savings to industries with highly energy intensive processes, especially for manufacturers relying on imported or unstable fuel supplies.

Figure 4-3. Glass Studio at the EnergyXchange Renewable Energy Center in North Carolina, USA

Typically, only very limited gas treatment (for example, condensate removal and filtration) is required for these uses, but some modification of combustion equipment may be necessary to accommodate the low heating value of LFG. From an environmental standpoint, the equipment that combusts the fuel must have a suitable retention time and temperature to ensure adequate destruction efficiency of trace gas components in the LFG.

In addition to industrial uses, some municipalities have used LFG to fuel rotary drum dryers or sludge incinerators for their local wastewater treatment plants. Often landfills and wastewater treatment infrastructures are adjacent to one another and LFG can offset wastewater treatment costs for the municipality. For example, the pelletized, treated and dehydrated biosolids can be sold to fertilizer manufacturers[6]. Table 4-3 shows the typical sizes of LFG direct thermal projects in the United States.

Table 4-3. Typical Sizes of Other LFG Direct Thermal Projects

Technology/Application	Estimated LFG Flows (m^3/hr)*	Installations in United States
Dryers: Municipal Sludge Dryers	470 to 1,300	4
Dryers: Industrial Applications	1,400 to 3,100	3
Furnaces: Iron and Steel Industry	510 to 2,400	3
Kilns: Brick and Cement Industries	680 to 3,400	12
Community Artisan Activities (Pottery, Glassblowing and Metallurgy)	34 to 68	3

* Assuming 50 percent methane in the LFG. Source: U.S. EPA LMOP Landfill and LFG Energy Project Database as of April 2011.

✔ Examples: LFG Used for Artisan Activities and Brick Manufacturing

The Yancey-Mitchell County Landfill, located in North Carolina, USA, is the site of the EnergyXchange Renewable Energy Center where captured LFG is used to run pottery kilns and glass furnaces, in addition to supplying radiant heat for a greenhouse and other buildings located on the landfill.

LFG from the Star Ridge Landfill in Alabama, USA, is used as a fuel for the Jenkins Brick Company manufacturing plant.

See Appendix A for case studies of the Yancey-Mitchell County and Star Ridge landfills.

[6] Public Works Magazine, January 2011. *Self-Sustaining Biosolids Drying*. http://www.pwmag.com/industry-news.asp?sectionID=760&articleID=1481422.

Infrared Heaters

Infrared heaters create high-intensity energy (heat) that is safely absorbed by floors and objects in a space (see Figure 4-4). Infrared heaters are effective for spot heating and are also used for heating large areas.[7] There are two kinds of LFG infrared heaters in use: ceramic (bright) and pipe (dark or low-intensive). Ceramic infrared heaters are made up of a perforated ceramic board covered with an aluminum reflector and an electrovalve that intakes a mixture of gas and air. Ceramic infrared heaters usually operate at temperatures between 800°C and 1,000°C and have efficiencies as high as 93 percent. Pipe infrared heaters are composed of a gas burner, a radiating pipe, and a screen and operate at temperatures between 400°C and 600°C. The radiating pipe is made of steel and titanium and is covered with black silicon emulsion, which contributes to the heater's radiating capacity.

Figure 4-4. Infrared Heater at the Khmelnitsky Landfill in Ukraine

Example: LFG Used for Infrared Heating

The Khelmintsky Landfill in Ukraine uses LFG to power infrared heaters installed at the landfill garage. The infrared heaters convert LFG energy into heat energy that is safely absorbed by surfaces. The project included the design and construction of a gas collection and treatment system and installation of horizontal pipelines.

Infrared heating, using LFG as a fuel source, has been successfully employed at several landfill sites in Canada, the United States, and the Ukraine. It is ideal when a facility with space heating needs is located at or near the landfill, such as an on-site maintenance building for sanitation workers. Depending on the location, the infrared heater may only be needed seasonally, which may limit LFG use. Infrared heaters require a small amount of LFG and are relatively inexpensive and easy to install and operate. Current heater projects use as little as 20 to 50 m^3/hr LFG, and less than 50 m^3/hr of LFG is needed to heat about 600 square meters (m^2) of space.[8] Infrared heaters require no or minimal LFG treatment, unless there are siloxanes in the gas.

Leachate Evaporation

LFG can also be used directly to evaporate leachate, which reduces leachate treatment and hauling costs by evaporating this liquid to a more concentrated and more easily disposed of effluent volume (see Figure 4-5). Leachate evaporation is a good option for landfills where leachate disposal is not available or is expensive, or where there are high volumes of leachate competing with space constraints at the landfill. However, certain byproducts of leachate evaporation (such as concentrated liquids or salts) should be safely disposed of or treated. Direct discharge leachate evaporators have low LFG requirements; modern direct discharge designs require approximately 330 m^3/hr of LFG to evaporate 1,670 liters per hour (l/hr) of leachate.[9]

[7] D.T. Mears, Optimum Utility Systems. 2001. *Biogas Applications for Large Dairy Operations: Alternatives to Conventional Engine-Generators*. http://www.manure.umn.edu/assets/cornell_biogas_applications.pdf.
[8] D.D. Dillah, January 2006. *Heating Landfill Facilities Using Infrared Heaters – Part 2 and Project 2.* http://www.epa.gov/lmop/documents/pdfs/conf/9th/dillah.pdf.
[9] Shaw LFG Specialties, LLC. 2007. *The Future of LFG Utilization*. http://www.globalmethane.org/expo_china07/docs/postexpo/landfill_zeng.pdf.

There are three categories of commercial leachate evaporation systems: spray-type dryers, direct injection-devices, and — the most commonly used — evaporation vessels. The primary features distinguishing these various leachate evaporation systems are their methods for transferring heat to leachate and treating the exhaust vapor.

Most available commercial systems use direct-contact evaporative technology, where heat is transferred by direct contact between the leachate and the hot combustion gas. Depending on the manufacturer of the evaporator, the LFG combustion unit can be located on top of the evaporation vessel, where the hot combustion gas is bubbled through a small pool of leachate at the bottom of the vessel, or on the side of the vessel, where the hot combustion gas is exhausted through submerged pipes within the vessel.

Some commercial systems use indirect transfer. In this technology, heat is transferred indirectly from an LFG burner through the walls of the heat exchanger to the leachate. Precipitated solids in the leachate may cause scale build-up on heat transfer surfaces, so regular cleaning is required for proper performance.[10]

Figure 4-5. Leachate Evaporator System at El Verde Landfill in León, Mexico

Example: Leachate Evaporation

An example of the use of leachate evaporators is at the El Verde Landfill in León, Mexico, where a 1,890 l/hr leachate evaporator has operated since 2010. See Appendix A for a case study of the El Verde Landfill.

4.2 Electricity Generation Technologies

LFG can be used as a fuel in internal combustion engines or combustion turbines driving either an electrical or gas-powered generator. The generated electricity can be used to power on-site needs such as the blowers for the active gas collection system or leachate treatment system or, more typically, be sold to the local electricity grid.[11] Electricity generation from LFG accounts for the majority of LFGE projects globally.

Internal Combustion Engine

The most common LFG utilization technology for small to relatively large LFGE projects is the internal combustion engine (Figure 4-6). Internal combustion engines are available in various sizes with electrical outputs ranging from less than 0.2 MW to more than 3.0 MW per unit.[12] Between 500 and 540 m^3/hr of LFG at 50 percent methane is necessary to generate 1 MW of electricity. Internal

Figure 4-6. GE Jenbacher Internal Combustion Engine at Simprodeso Landfill in Monterrey, Mexico

[10] Global Methane Initiative. 2010. *Landfill Gas Energy Technologies.* http://www.globalmethane.org/Data/1022_LFG-Handbook.pdf.

[11] ISWA. *ISWA Landfill Operational Guidelines*. 2nd Edition. http://www.wief.net/programs_events/ISWA_Landfill_Operational_Guidelines_2nd_Edition[1].pdf.

[12] Loening A. November 2010. "Biogas Technology Applications." http://www.globalmethane.org/documents/events_land_20101209_loening.pdf.

combustion engines that use LFG as a fuel are commercially available and may be obtained as modular units or within a complete parallel generator package. Often, containerized systems are installed in a series to allow for engines to be added or removed in response to fluctuating gas flows over time. Many manufacturers have designed engines specifically to operate on LFG and other biogases, and they should be able to provide examples of these operations.

✓ Examples: LFG Use for Electricity Generation

Examples of LFG use for electricity generation are:

- The LFGE project at the Loma Los Colorados Landfill in Santiago, Chile, started with an electricity generation capacity of 2 MW in 2009. Currently Phase II is in operation, reaching approximately 11.89 MW of installed capacity. Phase II will include an additional 9.9 MW, and Phase III will consist of the installation of an additional 21.78 MW capacity.
- São João Landfill in São Paulo, Brazil has been operating an LFGE system since 2007 with an installed capacity of 22 MW. See Appendix A for a case study of São João Landfill.

Gas Turbines

A larger LFGE technology example is the gas turbine. LFG-fired gas turbines are similar to natural gas turbines except that, because of the lower pipeline quality value, twice the number of fuel regulating valves and injectors are used.[14] The majority of gas turbines currently operating at landfills are simple cycle, single-shaft machines. Gas turbines are generally larger than internal combustion engines and are available in various sizes from 1 MW to more than 10 MW (see Figure 4-7).[15] Although smaller gas turbine units or "microturbines" (1 MW) have been used at landfills, they are not normally the primary generating unit. Most LFGE projects using turbines in the United States are in the 3 to 5 MW range, which require sustainable LFG flows in excess of 2,000 m^3/hr. Gas turbines are available as modular and packaged systems. Modular systems allow for flexibility in responding to changes in LFG quality and flow.

Figure 4-7: Dual Gas Wide Wobbe Fuel Assembly and Fuel Injectors on a Solar LFG Turbine[13]

Gas turbines require a high pressure fuel supply in the range of 165 to 200 pounds per square inch gauge (psig); thus, a fuel gas compressor (FGC) must precede the turbine. The FGC is the more sensitive piece of equipment for the efficient long-term reliability of the facility. Requirements for the compression stage will typically govern the level of LFG processing that will be necessary to ensure reasonable operating and maintenance costs for the facility. The required LFG pressure can consume a significant portion of the power being generated, resulting in lower energy conversion efficiencies (parasitic losses).

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[13] Middough. City of Toledo, OH Landfill Gas 10 MW Combined Cycle Cogeneration Facility. http://www.middough.com/Business/Industrial/Energy.aspx.
[14] SCS Engineers. 1997. *Comparative Analysis of Landfill Gas Utilization Technologies.* http://www.nrbp.org/pdfs/pub07.pdf.
[15] Ibid, Loening.

Combined Heat and Power

Some electricity projects can increase their operating efficiencies by incorporating cogeneration systems. Combined heat and power (CHP) or cogeneration systems generate electricity and capture waste heat to provide thermal energy. Thermal energy cogenerated by LFG electricity projects can be used for on-site heating, cooling, or process needs, or piped to nearby industrial or commercial users to provide a second revenue stream for the project.[16] CHP is often a better economic option for end users located near the landfill or for projects where the end user has sufficient demand for both the electricity and the waste heat.[17]

Example: LFG Use for CHP

An example of LFG as a fuel source for CHP is YTV Ämmässuo Landfill in Finland. This project utilizes LFG for district heating and power generation.

Biomass CHP Catalog of Technologies

For additional information about CHP, see the U.S. EPA Combined Heat and Power Partnership's Biomass CHP Catalog of Technologies.

4.3 Emerging LFG Recovery Technologies

In addition to the commonly used direct-use and electric generating technologies discussed above, there are several emerging technologies that show promise for LFGE recovery internationally. These technologies are not used on a wide-scale basis but may prove technically and economically feasible under certain conditions.

LFG Conversion to High-Pipeline Quality Gas

LFG can be purified to produce the equivalent of pipeline-quality gas (natural gas), compressed natural gas (CNG), or liquefied natural gas (LNG). The pipeline-quality gas can be injected into a natural gas pipeline and used for industrial purposes. CNG and LNG can be used to fuel vehicles at the landfill or supply vehicle fleets designed to use these fuels. It is necessary for gas fuel produced from LFG to satisfy fuel quality standards set by regulatory agencies or by independent organizations for LFG-derived fuels to be considered interchangeable with gas fuels.[18] To meet these standards, extensive LFG treatment is needed to greatly increase the methane content of the gas and decrease the carbon dioxide, nitrogen, oxygen and moisture contents. Current gas treatment technologies are relatively expensive; membrane or pressure swing absorption gas purification processes require additional gas compressors to be installed, and the O&M of these systems can be relatively complex. LFG purification projects have generally been implemented only at very large landfills or where there is a high demand for CNG or LNG and occur more often in the United States than other countries. In addition, tight management of gas collection system (wellfield) operation may be needed to limit intrusion of oxygen and nitrogen into LFG. The primary cause for the presence of oxygen and nitrogen

Additional Information

Additional information on the conversion of LFG to high-quality pipeline gas can be found in Chapter 3 of the LMOP LFG Energy Project Development Handbook.

[16] U.S. EPA Combined Heat and Power Partnership. *Catalog of CHP Technologies.* http://www.epa.gov/chp/documents/catalog_of_%20chp_tech_entire.pdf.
[17] U.S. EPA. 2012. *Landfill Gas Energy: A Guide to Developing and Implementing Greenhouse Gas Reduction Programs*. http://www.epa.gov/statelocalclimate/documents/pdf/landfill_methane_utilization.pdf.
[18] Pierce, J. SCS Engineers. 2007. *Landfill Gas to Vehicle Fuel: Assessment of Its Technical and Economic Feasibility.* SWANA 30th Annual Landfill Gas Symposium (4-8March, 2007), Monterey, California. http://www.scsengineers.com/Papers/Pierce_LFG_to_Vehicle_Fuel_SWANA2007.pdf.

in LFG is air that is drawn through the surface of the landfill and into the gas collection system. Air intrusion can often be minimized by adjusting well vacuums and repairing leaks in the landfill cover.

Pyrolysis Furnace

Pyrolysis is a type of low-temperature waste incineration that occurs under near anaerobic conditions. Pyrolysis technology can be used to destroy semivolatile organic compounds in waste materials such as infectious wastes from hospitals. In a pyrolysis furnace, the waste material is converted to a combustible gas or liquid that can then be used to help fuel the furnace. A furnace can use LFG as a supplemental fuel source and does not require a large amount of LFG—a gas flow as low as 170 m^3/hr may be sufficient.

Anaerobic Digestion

Although not an LFGE recovery technology, anaerobic digestion (AD) of MSW is being demonstrated at some landfill sites as an alternative to landfilling and capturing methane emissions from the waste stream. AD is also used in some communities to process separately collected food waste streams. Two primary methods of AD are in-vessel or in-ground designs. The in-vessel design, which includes a constructed aboveground container to hold the organic wastes (see Figure 4-8), is widely used in the sewage treatment industry. The aim of in-vessel designs for MSW is to accelerate the decomposition rate at the thermophylic stage to achieve elevated methane production rates. In contrast, in-ground designs, such as covered, in-ground anaerobic reactors (CIGAR), install a flexible cover over the organic fraction of MSW; this design is widely used in animal manure or industrial wastewater projects. For MSW, in-ground designs would require liquefying the organic fraction of waste before it is circulated through the reactor. Typically, the MSW in the reactor is inoculated with leachate and the waste decomposition would occur at lower temperatures, typical of the mesophylic stage of decomposition. The organic fraction of MSW (or separately collected food waste) is used as a feedstock in an enclosed digester, where it is decomposed by bacteria under controlled anaerobic conditions to produce digester gas, which contains medium-to-high concentrations of methane, and is typically used to produce electricity. With digesters, virtually 100 percent of the gas produced is captured and used (whereas the gas collection efficiency from landfills is lower).

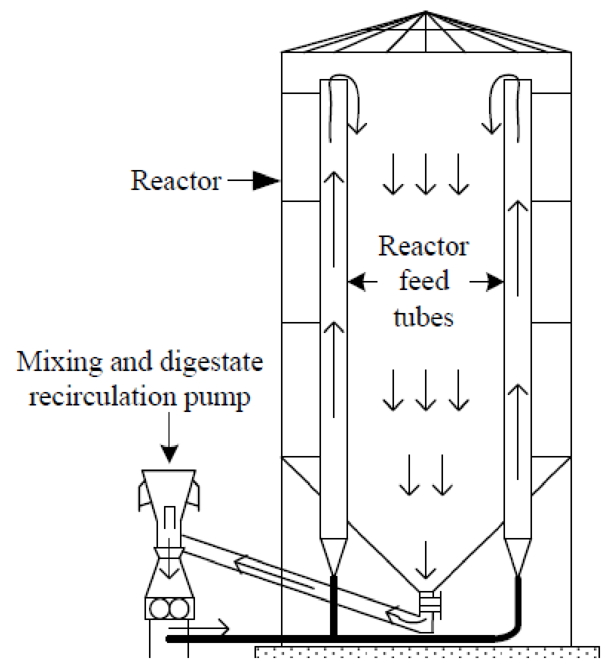

Figure 4-8. Schematic of a Dranco system In-Vessel Anaerobic Digester[19]

[19] "Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste." California Integrated Waste Management Board.

4.4 Selection of Suitable Technologies

For landfills pursuing LFGE recovery, the primary choices are electricity generation technologies or the direct use of LFG as a fuel. The best type of energy recovery technology for a particular landfill will depend on a number of factors. General considerations for selecting appropriate LFGE technologies include:

- Guarantee of waste delivery (composition and volume)
- Distance to the grid
- Local and regulatory framework
- Quantity and duration of LFG recovery potential
- Presence of nearby potential end users for direct use of LFG
- Ability to sell electricity to the grid (infrastructure and regulatory framework)
- On-site needs for heat or electricity
- Capital expenditures and operating costs of utilization system options, including gas treatment and transportation issues and costs
- Financial considerations (expected revenues from the sale of LFG for electricity or direct use, carbon credits, other financial incentives, mode of financing, and return on investment) — see Chapter 7
- Availability of local suppliers to provide and service equipment
- Availability of skilled operators to operate and maintain equipment
- Ability to secure contracts (energy purchase and sales and gas rights agreements) — see Chapter 5

Direct Thermal Use Considerations

The major benefits of direct thermal applications are that they maximize utilization of the gas, require limited treatment, and allow for blending with other fuels. Direct thermal applications have been demonstrated for a wide range of project sizes as long as there is a match between the quantity of LFG available and the demands of a prospective end user, or adequate LFG to supplement the primary fuel consumption of the end user. Direct thermal applications may be most useful when electricity regulations or markets restrict the sale of electricity generated from LFG (see Chapter 5 for additional information on electricity markets).

Factors to consider in evaluating the suitability of a direct thermal project include:

- ***Energy requirements of the end user in terms of quantity and quality of LFG.*** The quantity of LFG available and its methane content must be considered and compared with the facility's heat or steam needs and rated heat input capacities of the combustion equipment. End users with large daily or seasonal fluctuations in fuel demand are less desirable, as LFG is produced at the site at a relatively constant rate and it is not feasible to store LFG for delayed consumption at the facility.[20] In addition, the gas quality and type of LFG treatment needed for the specific end use must be considered in analyzing economic feasibility.
- ***Retrofit Requirements to Accommodate LFG.*** There are also considerations for the end user on designing equipment that either co-fires LFG and other supplementary fuels or that uses LFG as primary fuel with natural gas or other fuel as a back-up source only. The fuel train configuration will

[20] ESMAP. 2004. *Handbook for the Preparation of Landfill Gas to Energy Projects in Latin America and the Caribbean*. http://www.esmap.org/esmap/node/1106.

need to be modified to add an LFG burner and control system to accommodate the fuel sources selected, as discussed in Section 4.1. Burner modifications and changes in the process control systems will also be required for boiler applications. Kilns such as those used in the brick and cement manufacturing industries typically tolerate a wide range of fuel quality and may have lower retrofit costs.

- ***Location of the end user.*** The location of the end user will dictate the necessary length and location of an LFG pipeline. The landfill must be located relatively near an end user (generally less than 10 or 15 km) to achieve an adequate return on investment for this type of LFGE project, as the capital and operating costs of a dedicated pipeline longer than 10 km can make the net cost of delivered LFG less competitive with traditional fuels. However, a longer distance may be economically feasible, depending on the amount of gas recovery at the landfill, the energy load of the end-use equipment, and fuel prices.[21] Additionally, the end user's location will determine the route of the pipeline. Crossing railroads, waterways, or major roadways will factor into the cost and feasibility of pipeline construction.
- ***Cost considerations.*** The costs associated with gas treatment, pipeline and conversion of equipment to utilize LFG, as well as O&M, must be considered. The economics of an LFGE project improve the closer the end user is to the landfill. Furthermore, pipeline right-of-way issues will influence costs and the price at which LFG can be delivered and sold to the end user.[22] In addition, the end user must invest in equipment that is capable of switching between LFG and traditional fuels to manage the long-term uncertainty and variability of LFG flow, as well as pipeline quality value. The long-term financial stability of the end user should also be considered. (To recover the project investment cost, a 10- to 15-year project lifetime is usually required.) Refer to Chapter 7 for more information on project costs.

Factors to consider in determining suitability of on-site LFG usage include:

- ***Infrared heater or other space heating considerations.*** The low volume of LFG required for infrared heater projects or small boilers used for heating schools or administrative buildings and the seasonal nature of heating requirements may make these projects cost prohibitive on their own if the landfill does not already have a gas collection and flaring system. However, infrared heaters work well when paired with another flaring and or energy project at the site because the infrared heater can use a small amount of leftover gas that would otherwise be flared.
- ***Leachate evaporation considerations.*** Leachate evaporation systems are generally economically feasible only at sites where there is an adequate supply of LFG to evaporate the volume of leachate generated and the costs for alternative methods of leachate treatment and disposal are high. A typical landfill requires approximately 0.15 m^3 to evaporate 1 liter of leachate.[23] Evaporators are available in a range of sizes, and some economies of scale are realized for larger size vessels.

[21] World Resources Institute. 2002. *Opportunities with Landfill Gas*. http://pdf.wri.org/gpmdg_corporate_guide_02.pdf.
[22] U.S. EPA. 2012. *Landfill Gas Energy: A Guide to Developing and Implementing Greenhouse Gas Reduction Programs*. http://www.epa.gov/statelocalclimate/documents/pdf/landfill_methane_utilization.pdf.
[23] Instytut Nafty i Gazu. 2010. *Landfill Gas Energy Technologies*. http://www.globalmethane.org/Data/1022_LFG-Handbook.pdf.

Electricity Generation Considerations

The geographic limitations and need for equipment modification associated with direct use can be overcome by using LFG to fuel electricity generation equipment located at the landfill. In general, internal combustion engines have proven to be the most cost-effective and reliable technology for electricity generation from LFG, especially for moderately sized projects. Gas turbines are an option for LFGE projects that can support generation capacity of at least 3 to 5 MW.[24] Other factors that should be evaluated in considering electricity generation from LFG, include:

- ***Electrical conversion efficiency.*** Electrical conversion efficiency is an indication of what portion of the energy value of the LFG can be converted into electrical power. Electrical conversion efficiency varies based on the selected technology. Internal combustion engines have a higher efficiency than most gas turbines. However, very high altitudes or high ambient temperatures reduce the efficiency of internal combustion engines.
- ***Power generation potential.*** Reliability of the power generation equipment and the supply of the fuel to the LFGE plant will determine the actual amount of power generation.
- ***LFGE plant maintenance and repair.*** The need and extent of any recommended spare parts must be assessed based on the availability of these parts in the specific country, as well as the time that may be required to import the parts.[25] Operating the LFGE plant in accordance with equipment specifications and conducting regularly scheduled maintenance will reduce the wear on system parts and allow plant operators to plan for outages, thereby reducing plant downtime. Developing a plan for routinely conducting and tracking analysis of engine oil is important to help the plant operators assess operational problems early in the process.
- ***Ability to respond to changes in LFG quantity over time.*** The modular nature of internal combustion engines and gas turbines provides flexibility for incremental capacity increases in response to greater production of LFG.[26] Internal combustion engines or microturbines can be added in smaller incremental stages than gas turbines for a lower capital cost.
- ***Availability of an electric grid interconnection point.*** Typically, LFGE projects rely on existing infrastructure to deliver electricity to the market because the costs of building extensive new infrastructure are prohibitive. The project developer should examine the availability and types of nearby power lines and electrical substations. Nearby power lines that are suitable to provide a connection to the power grid and substations are advantageous for project development. Interconnection can be a considerable investment cost and will require careful investigation into permits and approvals that can vary greatly, depending on the location and site-specific requirements.
- ***Cost considerations.*** Costs include capital and labor costs to purchase and install all equipment needed to treat the gas and generate electricity as well as ongoing O&M costs (labor and materials used to operate the system and perform routine maintenance and repairs, including periodic equipment overhauls). Internal combustion engines have a comparatively low capital cost per kilowatt (kW), but have higher O&M costs than gas turbines. [27] Refer to Chapter 7 for more information on project costs.

[24] World Resources Institute. 2002. *Opportunities with Landfill Gas*. http://pdf.wri.org/gpmdg_corporate_guide_02.pdf.
[25] Ibid.
[26] ESMAP. 2004. *Handbook for the Preparation of Landfill Gas to Energy Projects in Latin America and the Caribbean*. http://www.esmap.org/esmap/node/1106.
[27] ISWA. *ISWA Landfill Operational Guidelines*. 2nd Edition. http://www.wief.net/programs_events/ISWA_Landfill_Operational_Guidelines_2nd_Edition[1].pdf.

4.5 Treatment of LFG

Before collected LFG can be used in a conversion process, it is usually treated to remove moisture (condensate) not already captured in the condensate removal systems, along with particulates and other impurities. Treatment requirements depend on the end use application. The primary treatment option for both electricity and direct-use technologies is moisture removal since LFG is saturated and can be corrosive to equipment. Minimal treatment is required for direct use of LFG in boilers, furnaces or kilns. Treatment systems for LFG electricity projects typically include a series of filters to remove contaminants that could damage components of the engine and turbine and reduce system efficiency. The focus of this section is on the treatment conducted before direct-use and electricity projects.

Types of Treatment Systems

Treatment systems can be divided into primary treatment processing and secondary treatment processing. Most primary processing systems include de-watering and filtration to remove moisture and particulates. Dewatering can be as simple as physical removal of free water or condensate in the LFG through a relatively simple device — a condensate knockout pot (see Figure 4-9). The condensate knockout pot slows the gas velocity sufficiently for gravity settling or "knock-out" of liquid to occur. Knockout pots should be located as close to the inlet to the gas booster as practicable. The liquid can then be drained or pumped to a discharge storage tank. Knockout pots are capable of handling large gas flows (greater than 10,000 m^3/hr) and of removing more than 1 liter per minute of water.[28]

Figure 4-9. Knockout Pot Upstream of Flare at Gaoantun Landfill, China

It is common in new projects to remove water vapor or humidity in the LFG by using gas cooling and compression. Cooling the LFG causes condensation of the water vapor, which in turn results in dehumidification. The condensate is separated out in a trap installed after the cooling equipment and removed via a siphon or pump. Typical temperatures for gas cooling range from -4° to 10°C. Gas compression prior to cooling serves to further dehydrate the air. Gas compression is commonly specified by the distance to the energy recovery systems and by their input pressure requirements, and commonly ranges from less than 100 to nearly 700 kilopascal (kPa). LFG dehumidification results in increased efficiency and protects LFG equipment. Chlorinated and halogenated compounds and other water-soluble compounds are also removed with the condensate.[29]

Secondary treatment systems are designed to provide much greater gas cleaning than is possible using primary systems alone. Secondary treatment systems may employ multiple cleanup processes depending on the gas specifications of the end use. These processes can include both physical and chemical treatments. The type of secondary treatment depends on the constituents that need to be removed for the desired end use. Two trace contaminants that may have to be removed from LFG are:

[28] United Kingdom Environment Agency. *Guidance on Gas Treatment Technologies for Landfill Gas Engines*. http://publications.environment-agency.gov.uk/pdf/GEHO0311BTON-e-e.pdf.
[29] ESMAP. 2004. *Handbook for the Preparation of Landfill Gas to Energy Projects in Latin America and the Caribbean*. http://www.esmap.org/esmap/node/1106.

- ***Siloxanes:*** Siloxanes are found in household and commercial products that find their way into solid waste and wastewater (a concern for landfills that accept wastewater treatment sludge). The siloxanes in the landfill volatilize into the LFG and are converted to silicon dioxide when the LFG is combusted. Silicon dioxide (the main constituent of sand) collects on the inside of internal combustion engines and gas turbines and on boiler tubes, potentially reducing the performance of the equipment and resulting in significantly higher maintenance costs. The need for siloxane treatment depends on the level of siloxane in the LFG (which varies among landfills) and on manufacturer recommendations for the energy technology selected. The removal of siloxane can be both costly and challenging, so the decision to invest in siloxane treatment is project dependent. Figure 4-10 depicts the diagram of one type of siloxane removal system. Figure 4-11 shows the siloxane removal technology as installed at a landfill.

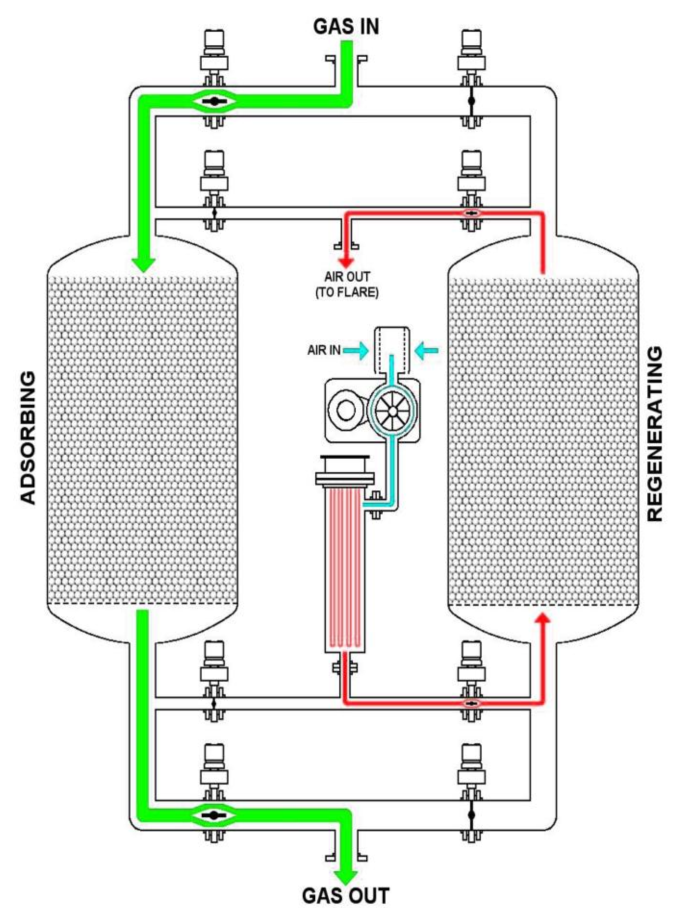

Figure 4-10. Diagram of the a siloxane removal system

Figure 4-11. Siloxane removal systems at the Lorraine power station at Oberlin, Ohio, USA

- ***Sulfur compounds:*** These compounds, which include sulfides and disulfides (hydrogen sulfide), are corrosive in the presence of moisture. These compounds will be relatively low and the LFG may not require any additional treatment at landfills accepting only typical MSW. The compounds tend to be higher in landfills that accept construction and demolition materials and additional treatment is more likely to be necessary.

The most common technologies used for secondary treatment are adsorption and absorption. Adsorption involves the physical adsorption of the contaminant onto the surface of an adsorbent such as activated carbon or silica gel. Adsorption has been a common technology for removing siloxanes from LFG. Absorption (or scrubbing) involves the chemical or physical reaction of a contaminant with a solvent or solid reactant. Absorption has been a common technology for removing sulfur compounds from LFG.

Filtration systems may be installed to provide additional LFG treatment. Particulates in the LFG stream that enter equipment can cause damage and wear. Particles can be controlled either by passing the gas stream through a filter pad (typically made of stainless steel wire or geotextile), or alternatively using a cyclone separator. Cyclones are capable of removing particles down to 15 micrometer (µm) (or even 5 µm for a high efficiency cyclone), whereas filter pads are effective down to 2 µm. Both systems are prone to blockage and thus require periodic maintenance to remove accumulated solids.

Treatment Cost Considerations

The treatment required for an LFGE project may range from the simple removal of moisture and particulates to the more expensive removal of corrosive and abrasive contaminants.[30] The specific type and application of LFG utilization equipment may require various levels of LFG treatment. The primary form of treatment for LFG is to remove some portion of the water vapor from the saturated LFG, which reduces the maintenance costs for the utilization equipment. Cleaner fuel gas can result in substantially reduced corrosion and reduced maintenance costs over the life of the equipment.[31] The level of LFG treatment and subsequent cost will depend on the gas purity requirements of the end use application. For example, siloxanes will cause fewer problems for boilers than for engines or turbines.

The tradeoff of simplified and less costly treatment is increased equipment maintenance. The treatment system is usually an upfront capital cost, whereas not using a treatment system or using a simplified treatment system will likely result in increased long-term O&M costs and ultimately equipment replacement costs. For most sites, a cooling system is recommended to cool, dehumidify, and filter the gas to remove free liquids and particulates before it is piped to engines or compressors. Other treatments for hydrogen sulfide or siloxanes depend on the project requirements and contaminant levels in the LFG.

In practice, landfill operators that have chosen not to install cooling systems have been able to run the engines, but have encountered problems with corrosion from acid formation and particulates in the combustion zone, resulting in more frequent oil changes and periodic maintenance, and in some cases extreme wear on engine cylinders. Lack of treatment causes a buildup of silicon compounds in components such as after coolers and turbochargers, which results in additional maintenance costs.

4.6 LFGE Technology and Cost Summary

Table 4-4 provides a summary of the LFGE technologies discussed in this chapter. Table 4-5 presents typical capital and annual costs for landfill gas projects, based on LFGE projects conducted in the United States.

[30] ISWA. *ISWA Landfill Operational Guidelines*. 2nd Edition. http://www.wief.net/programs_events/ISWA_Landfill_Operational_Guidelines_2nd_Edition[1].pdf.

[31] Ibid.

Table 4-4. Summary of LFGE Technologies

Advantages	Disadvantages	LFG Treatment Requirements
Direct-Use Medium Pipeline Quality		
Boiler, dryer, and process heater		
▪ Can utilize maximum amount of recovered gas flow ▪ Cost-effective ▪ Limited condensate removal and filtration treatment is required ▪ Does not require large amount of LFG and can be blended with other fuels	▪ Cost is tied to length of pipeline; energy user must be nearby	Need to improve quality of gas or retrofit equipment
Infrared heater		
▪ Relatively inexpensive ▪ Easy to install ▪ Does not require a large amount of gas ▪ Can be coupled with another energy project	▪ Seasonal use may limit LFG utilization	Limited condensate removal and filtration treatment is required
Leachate evaporation		
▪ Good option for landfill where leachate disposal is expensive	▪ High capital costs	Limited condensate removal and filtration treatment is required
Electricity		
Internal combustion engine		
▪ High efficiency compared with gas turbines and microturbines ▪ Good size match with the gas output of many landfills ▪ Relatively low cost on a per kW installed capacity basis when compared with gas turbines and microturbines ▪ Efficiency increases when waste heat is recovered ▪ Can add/remove engines to follow gas recovery trends	▪ Relatively high maintenance costs ▪ Relatively high air emissions ▪ Economics may be marginal in countries with low electricity costs	At a minimum, requires primary treatment of LFG; for optimal engine performance, secondary treatment may be necessary
Gas turbine		
▪ Economies of scale, because the cost per kW of generating capacity drops as gas turbine size increases and the efficiency improves as well ▪ Efficiency increases when heat is recovered ▪ More resistant to corrosion damage ▪ Low nitrogen oxides emissions ▪ Relatively compact	▪ Efficiencies drop when the unit is running at partial load ▪ Requires high gas compression ▪ High parasitic loads ▪ Economics may be marginal in countries with low electricity costs	At a minimum, requires primary treatment of LFG; for optimal turbine performance, secondary treatment may be necessary

Advantages	Disadvantages	LFG Treatment Requirements
Microturbine		
▪ Need lower gas flow ▪ Can function with lower percent methane ▪ Low nitrogen oxides emissions ▪ Relatively easy interconnection ▪ Ability to add and remove units as available gas quantity changes	▪ Economics may be marginal in countries with low electricity costs	Requires fairly extensive primary and secondary treatment of LFG
Direct-Use High Pipeline Quality		
Pipeline-quality gas		
▪ Can be sold into a natural gas pipeline	▪ Increased cost that results from tight management of wellfield operation needed to limit oxygen and nitrogen intrusion into LFG	Requires extensive and potentially expensive LFG processing
CNG or LNG		
▪ Alternative fuels for vehicles at the landfill or refuse hauling trucks, and for supply to the general commercial market	▪ Increased cost that results from tight management of wellfield operation needed to limit oxygen and nitrogen intrusion into LFG	Requires extensive and potentially expensive LFG processing

The costs presented in Table 4-5 were developed using U.S.EPA's LMOP LFGCost V2.3 model, which estimates the installed LFGE system costs using data from LFG projects in the United States. Analyses performed using LFGCost are considered preliminary and should be used for guidance only. The uncertainty of these costs estimates is +/- 30 to 50 percent. A detailed final feasibility assessment should be conducted by qualified LFG professionals before preparing a system design, initiating construction, purchasing materials, or entering into agreements to provide or purchase energy from an LFGE project. Furthermore, a project developer should also consider additional cost uncertainties unique to other geographic boundaries because these data represent costs from United States projects. Costs presented here may vary by country as a result of import fees, taxes, labor, materials, permitting requirements and regulations. The costs shown below do not include the costs for gas collection and flaring systems.

During the first year of operation, annual operating costs include electricity to operate compression and separator systems as well as routine O&M costs on LFG delivery and energy generation equipment. Annual operating costs can escalate based on project-specific factors such as electricity rates, local conditions and labor costs.

Table 4-5. Typical Capital and Annual Costs for Landfill Gas Projects

Technology	Capital Costs (2012 USD)		Annual Costs (2013 USD)	
Direct-Use Medium Pipeline Quality				
Direct Use — Sizing (m³/hr):	**340**	**1,020**	**340**	**1,020**
Skid-mounted Filter, Compressor and Dehydration Unit	$848,000	$983,000		
Pipeline to Convey Gas to Project Boundary[32]	$1,717,000	$1,717,000	$58,000	$85,000
Total Capital Costs Including Cost Contingency	$2,565,000	$2,700,000		
Additional Costs for Retrofitting Boilers				
Pipeline Delivery from End User's Property Boundary to Boiler[33]	$292,000	$292,000		
Metering Station	$81,000	$81,000		
Boiler Conversion for Seamless Controls	$109,000	$155,000		
Total Capital Costs Including Cost Contingency	$3,047,000	$3,228,000		
Electricity				
CHP - Engine[34] — Sizing (MW Capacity):	**1**	**3**	**1**	**3**
Gas Compression/Treatment, Engine/Generator, Site Work, Housings and Heat Recovery	$1,985,000	$5,923,000		
Gas Pipeline[33]	$173,000	$173,000	$185,000	$552,000
Water Pipelines and Circulation Pump[35]	$304,000	$304,000		
Engine-Generator Set[34] — Sizing (MW Capacity):	**1**	**3**	**1**	**3**
Gas Compression/Treatment, Engine/Generator, Site Work, and Housings	$1,665,000	$4,995,000	$184,000	$553,000
Turbine[34] — Sizing (MW Capacity):	**3**	**5**	**3**	**5**
Gas Compression/Treatment, Turbine/Generator, Site Work, and Housings	$6,340,000	$9,496,000	$398,000	$664,000
Direct-Use High Pipeline Quality				
Pipeline Injection — Sizing (m³/hr):	**1,020**	**3,400**	**1,020**	**3,400**
Gas Compressor, Separators, and Dryers for Pipeline Quality Gas	$4,094,000	$8,741,000		
Pipeline to Convey Gas to Project Site[32]	$1,717,000	$1,717,000	$266,000	$886,000
Total Capital Costs Including Cost Contingency	$5,811,000	$10,458,000		

Best Practices for Utilizing LFGE Technologies

The overall feasibility of an LFGE project for a particular landfill depends on numerous technical considerations, such as waste composition and volume, quality and quantity of LFG, and availability and location of a suitable end user. Understanding, evaluating and selecting the appropriate LFGE utilization technologies is essential for the overall feasibility and success of LFGE projects. Proven and emerging technologies offer practical solutions to effectively implement LFGE projects for direct-use and electricity generation, including the treatment of LFG to remove moisture, particulates and other impurities.

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[32] Pipelines to convey LFG to project sites were assumed to be 5 miles and exclude pipelines inside the facility.
[33] LFG pipelines inside the property boundary and within the facility were assumed to be 0.5 mile.
[34] Estimates are not provided for electrical interconnect equipment costs because they vary by location.
[35] Water pipelines were assumed to be 0.5 mile.