3. Project Technology Options

The goal of an LFG energy project is to convert LFG into a useful form of energy. Hundreds of LFG energy projects currently operate in the United States, involving public and private organizations, small and large landfills and various types of technologies. The most common LFG energy applications include:

- Electricity (power production and cogeneration) – LFG extracted from the landfill is converted to electricity
- Direct use of medium-Btu gas – treated LFG is used as a direct source of fuel
- Upgrade to vehicle fuel or pipeline-quality (high-Btu) gas – LFG is converted to produce the equivalent of natural gas, CNG or LNG

For example, LFG is used to produce electricity and heat in cogeneration applications. Direct-use applications include heating greenhouses, firing brick kilns and providing fuel to chemical and automobile manufacturing businesses. Table 3-1 shows a breakdown of technologies used in operational LFG energy projects in 2017.

The remainder of this chapter provides a brief overview of design factors and technology options for LFG energy projects, followed by a discussion of considerations in technology selection.

Table 3-1. Operational Project Technologies

Project Technology	Projects[1]
Electricity Projects	
Internal combustion engine (reciprocating engine)	360
Cogeneration	47
Gas turbine	31
Microturbine	12
Steam turbine	11
Combined cycle	9
Stirling cycle engine	2
Medium-Btu Direct-Use Projects	
Boiler	58
Direct thermal	43
Leachate evaporation	13
Greenhouse	6
Upgraded LFG Projects	
High-Btu	36
Alternative fuel (CNG or LNG)	6

For more information about LFG collection, flaring and treatment system components, see Chapter 1.

[1] U.S. EPA LMOP. Landfill and LFG Energy Project Database. June 2017.

3.1 Design Factors

Selecting the best technology options for a project involves consideration of several key design factors, beginning with estimating the LFG recovery potential for the landfill. In general, the volume of waste controls the potential amount of LFG that can be extracted from the landfill. Site conditions, LFG collection efficiency and the flow rate for the extracted LFG also significantly influence the types of technologies and end use options that are most feasible for a project. Design considerations for gas collection and treatment systems are presented below.

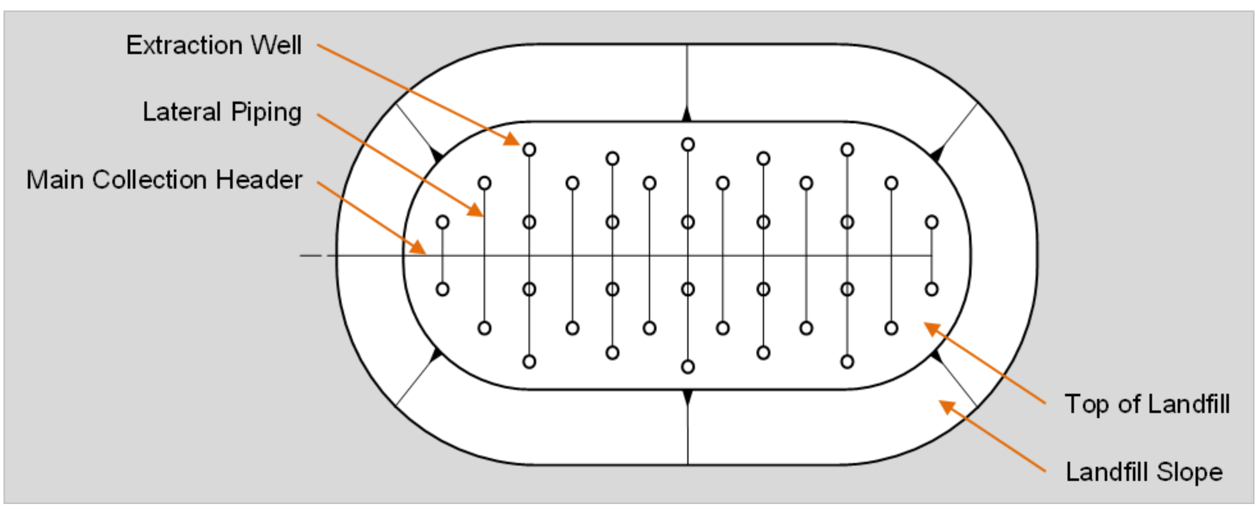
Gas Collection Systems

Collection systems can be configured as vertical wells, horizontal trenches or a combination of both. Advantages and disadvantages of each type of well are listed in Table 3-2. Regardless of whether wells or trenches are used, each wellhead is connected to lateral piping that transports the LFG to a main collection header, as illustrated in Figure 3-1. The collection system should be designed so that the operator can monitor and adjust the gas flow if necessary.

Table 3-2. Advantages and Disadvantages of Vertical and Horizontal LFG Collection Wells

Vertical Wells		Horizontal Wells	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
▪ Minimal disruption of landfill operations if placed in closed area of landfill ▪ Most common design ▪ Reliable and accessible for inspection and pumping	▪ Increased operation and maintenance required if installed in active area of landfill ▪ Availability of appropriate equipment ▪ Delayed gas collection if installed after site or cell closes	▪ Facilitates earlier collection of LFG ▪ Reduced need for specialized construction equipment ▪ Allows extraction of gas from beneath an active tipping area on a deeper site	▪ Increased likelihood of air intrusion until sufficiently covered with waste ▪ More prone to failure because of flooding or landfill settlement

Figure 3-1. Sample LFG Extraction Site Plan



LFG Treatment Systems

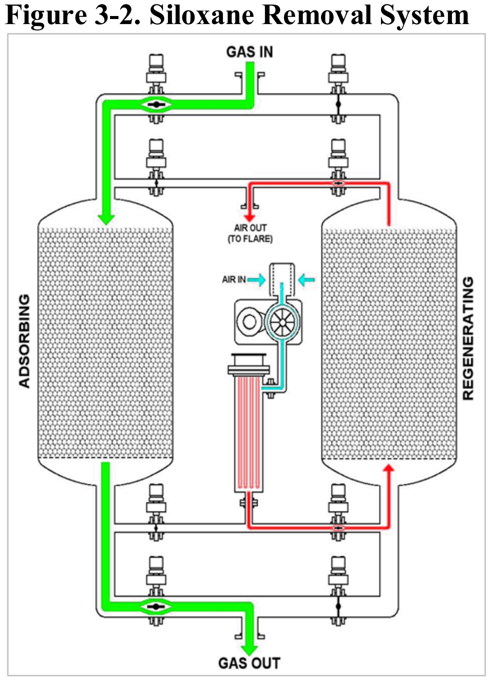
Before LFG can be used in an energy conversion process, it must be treated to remove condensate, particulates and other impurities. Treatment requirements depend on the end use.

- Treatment systems for LFG electricity projects typically include a series of filters to remove contaminants that can damage components of the engine and turbine and reduce system efficiency.
- Minimal treatment is required for direct use of LFG in boilers, furnaces or kilns.
- Advanced treatment is required to produce high-Btu gas for injection into natural gas pipelines or production of alternative fuels.

Treatment systems can be divided into primary 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 using equipment often referred to as "knockout" devices. It is common to use gas cooling and compression to remove water vapor or humidity from the LFG. Gas cooling and compression have been used for many years and are relatively standard elements of active LFG collection systems. 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, including both physical and chemical treatments. The type of secondary treatment depends on the constituents that need to be removed for the end use. Two of the trace contaminants that may have to be removed from LFG are siloxanes and sulfur compounds.

- ***Siloxanes*** are found in household and commercial products that end up in solid waste and wastewater (a concern for landfills that take wastewater treatment sludge). 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 performance and increasing maintenance costs. The need for treatment depends on the level of siloxane in the LFG and on manufacturer recommendations for the technology selected. Removal of siloxane can be both costly and challenging, so the decision to invest in siloxane treatment is project dependent.
- ***Sulfur compounds***, which include sulfides and disulfides (for example, hydrogen sulfide), are corrosive in the presence of moisture. These compounds will be at relatively low concentrations, and the LFG may not require any additional treatment at landfills accepting only typical MSW. The compounds tend to be at higher concentration in landfills that accept C&D materials, and additional treatment is more likely to be necessary.

Figure 3-2. Siloxane Removal System



The most common technologies used for secondary treatment are adsorption and absorption. Adsorption, which removes siloxanes from LFG, is a process by which contaminants adhere to the surface of an adsorbent such as activated carbon or silica gel. Figure 3-2 illustrates a common type of adsorption. Other gas treatment technologies that can remove siloxanes include subzero refrigeration and liquid scrubbing. Absorption (or scrubbing) removes compounds (such as sulfur) from LFG by introducing a solvent or solid reactant that produces a chemical/physical reaction. Advanced treatment technologies that remove carbon dioxide, NMOCs and a variety of other contaminants in LFG to produce a high-Btu gas (typically at least 96 percent methane) are discussed in Section 3.4.

3.2 Electricity Generation

Producing electricity from LFG continues to be the most common beneficial use application, accounting for about three-fourths of all U.S. LFG energy projects. Electricity can be produced by burning LFG in devices such as an internal combustion engine, a gas turbine or a microturbine.

Internal Combustion Engines

The internal combustion engine is the most commonly used conversion technology in LFG applications because of its relatively low cost, high efficiency and engine sizes that complement the gas output of many landfills (see Figure 3.3). Internal combustion engines have generally been used at landfills where gas quantity is capable of producing 800 kW to 3 MW, or where sustainable LFG flow rates to the engines are approximately 300 to 1,100 cfm at 50 percent methane. Multiple engines can be combined together for projects larger than 3 MW. Table 3-3 provides examples of available sizes of internal combustion engines.

Figure 3-3. Internal Combustion Engines

Table 3-3. Internal Combustion Engine Sizes

Engine Size	Gas Flow (50% Methane)
540 kW	204 cfm
633 kW	234 cfm
800 kW	350 cfm
1.2 MW	500 cfm

cfm: cubic feet per minute kW: kilowatt MW: megawatt

Internal combustion engines are efficient at converting LFG into electricity, achieving electrical efficiencies in the range of 30 to 40 percent. Even greater efficiencies are achieved in CHP applications where waste heat is recovered from the engine cooling system to make hot water, or from the engine exhaust to make low-pressure steam.

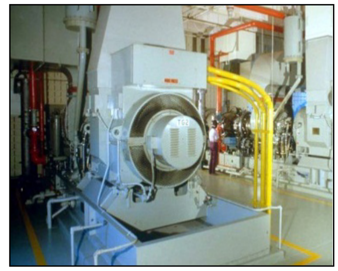
Examples

The Lycoming County Landfill Dual Cogeneration and Electricity Project in Pennsylvania, an LMOP 2012 award-winning project, used an innovative permitting approach and a creative power purchase agreement. LFG is combusted in four internal combustion engines (6.2 MW total), which supplies 90 percent of the landfill complex's power and thermal needs and 80 percent of the electricity needs of the Federal Bureau of Prisons' Allenwood Correctional Complex. The county receives revenue for the project, and the Bureau gains power price stability and can count the LFG use toward meeting federal renewable energy requirements.

For more information about CHP, see the CHP Partnership's Biomass Combined Heat and Power Catalog of Technologies and the Catalog of CHP Technologies.

Gas Turbines

Figure 3-4. Gas Turbine



Gas turbines, as shown in Figure 3-4, are typically used in larger LFG energy projects, where LFG flows exceed a minimum of 1,300 cfm and are sufficient to generate a minimum of 3 MW. Gas turbine systems are widely used in larger LFG electricity generation projects because they have significant economies of scale. The cost per kW of generating capacity drops as the size of the gas turbine increases, and the electric generation efficiency generally improves as well. Simple-cycle gas turbines applicable to LFG energy projects typically achieve efficiencies of 20 to 28 percent at full load; however, these efficiencies drop substantially when the unit is running at partial load. Combined-cycle configurations, which recover the waste heat in the gas turbine exhaust to capture additional electricity, can boost system efficiency to approximately 40 percent. As with simple-cycle gas turbines, combined-cycle configurations are also less efficient at partial load.

Advantages of gas turbines are that they are more resistant to corrosion damage than internal combustion engines and have lower nitrogen oxides emission rates. Additionally, gas turbines are relatively compact and have low O&M costs compared with internal combustion engines. However, LFG treatment to remove siloxanes may be required to meet manufacturer specifications.

A primary disadvantage of gas turbines is that they require high gas compression of 165 pound-force per square inch gauge (psig) or greater. As a result, more of the plant's power is required to run the compression system (creating causing a high parasitic load loss).

Examples

LFG is piped 4 miles from the Arlington Landfill in Arlington, Texas, to the Fort Worth (Village Creek) Wastewater Treatment Plant and is used to co-fire two 5.2-MW gas turbine generators with heat recovery.

Residents from three municipalities and Waste Management, Inc., formed Green Knight Economic Corporation, an independent non-profit organization that invested the revenue from the sale of the LFG generated by a 9.9-MW power plant with three gas turbines.

Microturbines

Figure 3-5. Microturbine

Microturbines have been sold commercially for landfill and other biogas applications since early 2001 (see Figure 3-5). Generally, costs for a microturbine project are higher than for internal combustion engine project costs based on a dollar-per-kW installed capacity.[2] However, several reasons for using microturbine technology instead of internal combustion engines include:

- Require less LFG volume than internal combustion engines
- Can use LFG with a lower percent methane (35 percent methane)
- Produce lower emissions of nitrogen oxides
- Can add and remove microturbines as gas quantity changes
- Interconnection is relatively easy because of the lower generation capacity

[2] Wang, Benson, Wheless. 2003. *Microturbine Operating Experience at Landfills.* Solid Waste Association of North America (SWANA) 26th Annual Landfill Gas Symposium (2003), Tampa, Florida.

LFG was not treated sufficiently in early microturbine applications, which resulted in system failures. Typically, LFG treatment is required to remove moisture, siloxanes and other contaminants. This treatment is composed of the following components:

- Inlet moisture separator
- Rotary vane type compressor
- Chilled water heat exchanger (reducing LFG temperature to 40ºF)
- Coalescing filter
- LFG reheat exchanger (to add 20 to 40ºF above dew point)
- Further treatment of the moisture-free LFG in vessels charged with activated carbon or other media (optional)

Microturbines typically come in sizes of 30, 70 and 250 kW. Projects should use the larger-capacity microturbines where power requirements and LFG availability can support them. The following benefits can be gained by using a larger microturbine:

- Reduced capital cost (on a dollar-per-kW of installed capacity basis) for the microturbine itself
- Reduced maintenance cost
- Reduced balance of plant installation costs — a reduction in the number of microturbines to reach a given capacity will reduce piping, wiring and foundation costs
- Improved efficiency — the heat rate of the 250-kW microturbine is expected to be about 3.3 percent better than the 70-kW and about 12.2 percent better than the 30-kW

Example

The Fort Benning Landfill in Fort Benning, Georgia is the site of a 250-kW capacity microturbine project that has generated electricity for onsite use by the U.S. Army since November 2011. The project is part of the U.S. Department of Defense's high-priority environmental and energy goals.

When declining LFG flows led its original reciprocating engine project to close in the mid-1990s, the All Purpose Landfill in Santa Clara, California partnered with a third-party developer for a new 750-kW capacity microturbine project which started up in late 2009. The project has three 250-kW units and contributes to power purchaser Silicon Valley Power's Renewable Energy Portfolio.

Electricity Generation Summary

Table 3-4 presents examples of typical costs for several technologies, including costs for a basic gas treatment system typically used with each technology. The costs of energy generation using LFG can vary greatly and depend on many factors, including the type of electricity generation equipment, its size, the necessary compression and treatment system, and the interconnect equipment. Table 3-5 provides a summary of the advantages and disadvantages associated with each electricity-generating technology.

Table 3-4. Examples of Typical Costs[3]

Technology	Typical Capital Costs ($/kW)*	Typical Annual O&M Costs ($/kW)*
Internal combustion engine (> 800 kW)	$1,800	$250
Small internal combustion engine (< 800 kW)	$2,500	$270
Gas turbine (> 3 MW)	$1,500	$160
Microturbine (< 1 MW)	$3,000	$280

* 2013 dollars kW: kilowatt MW: megawatt

3 U.S. EPA LMOP. *LFGcost-Web*, Version 3.2.

Table 3-5. Advantages, Disadvantages and Treatment Requirements Summary (Electricity)

Advantages	Disadvantages	Treatment
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 or remove engines to follow gas recovery trends	▪ Relatively high maintenance costs ▪ Relatively high air emissions ▪ Economics may be marginal areas with low electricity costs	At a minimum, requires primary treatment of LFG; for optimal engine performance, secondary treatment may be necessary
Gas turbine		
▪ Cost per kW of generating capacity drops as the size of the gas turbine 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 areas with low electricity costs	At a minimum, requires primary treatment of LFG; for optimal turbine performance, secondary treatment may be necessary
Microturbine		
▪ Requires lower gas flow ▪ Can function with lower percent methane ▪ Low nitrogen oxides emissions ▪ Relatively easy interconnection ▪ Ability to add and remove units	▪ Economics may be marginal in areas with low electricity costs	Requires fairly extensive primary and secondary treatment of LFG

3.3 Direct Use of Medium-Btu Gas

Figure 3-6. Boiler and Cement Kiln

Boilers, Dryers and Kilns

The simplest and often most cost-effective use of LFG is as a medium-Btu fuel for boiler or industrial processes such as drying operations, kilns and cement and asphalt production. In these projects, the gas is piped directly to a nearby customer for use in combustion equipment (Figure 3-6) as a replacement or supplementary fuel. Only limited condensate removal and filtration treatment are required, although some modifications of existing combustion equipment might be necessary.

The end user's energy requirements are an important consideration in evaluating the sale of LFG for direct use. All gas that is recovered must be used as available, or it is essentially lost, along with associated revenue opportunities, because storing LFG is not economical. The ideal gas customer, therefore, will have a steady annual gas demand compatible with the landfill's gas flow. When a landfill does not have adequate gas flow to support the entire needs of a facility, LFG can still be used to supply a portion of the needs. For example, only one piece of equipment (such as a main boiler) or set of burners is dedicated to burning LFG in some facilities. In other cases, a facility might co-fire or blend LFG with other fuels.

Before an LFG energy direct-use project is pursued, LFG flow should be measured, if possible, and gas modeling should be conducted as described in Chapter 2. For more details about project economics, see Chapter 4.

Table 3-6 provides the expected annual LFG flows from landfills of various sizes. While actual LFG flows will vary based on age, composition, moisture and other factors of the waste, these numbers can be used as a first step toward assessing the compatibility of customer gas requirements and LFG output. A rule of thumb for comparing boiler fuel requirements with LFG output is that approximately 8,000 to 10,000 pounds per hour (lb/hr) of steam can be generated for every 1 million metric tons of waste in place at a landfill; accordingly, a 5 million metric ton landfill can support the needs of a large facility requiring about 45,000 lb/hr of steam.

It may be possible to create a steady gas demand by serving multiple customers whose gas requirements are complementary. For example, an asphalt producer's summer gas load could be combined with a municipal building's winter heating load to create a year round demand for LFG.

Table 3-6. Potential LFG Flows Based on Landfill Size

Landfill Size (Metric Tons Waste-in-Place)	Annual LFG Flow (MMBtu/yr)	Steam Flow Potential (lb/hr)
1,000,000	100,000	10,000
5,000,000	450,000	45,000
10,000,000	850,000	85,000

MMBtu/yr: Million British thermal units per year   lb/hr: pounds per hour

Equipment modifications or adjustments may be necessary to accommodate the lower Btu value of LFG, and the costs of modifications vary. Costs will be minimal if retuning the boiler burner is the only modification required. The costs associated with retrofitting boilers will vary from unit to unit depending on boiler type, fuel use and age of unit. Retrofitting boilers is typically required in the following situations:

- Incorporating LFG into a unit that is co-firing with other fuels, where automatic controls are required to sustain a co-firing application or to provide for immediate and seamless fuel switching in the event of a loss in LFG pressure to the unit. This retrofit will ensure uninterruptible steam supply. Overall costs, including retrofit costs (burner modifications, fuel train and process controls), can range from $200,000 to $400,000.
- Modifying a unit that has a surplus or back-up steam supply so that the unit does not rely on the LFG to provide an uninterrupted supply of steam (a loss of LFG pressure can interrupt the steam supply). In this case, manual controls are implemented and the boiler operating system is not integrated into an automatic control system. Overall costs can range from $100,000 to $200,000.

Another option is to improve the quality of the gas to such a level that the boiler will not require a retrofit. While the gas is not required to have a Btu value as high as pipeline-quality gas, it must be between medium- and high-Btu. This option eliminates the cost of a boiler retrofit and reduces maintenance costs for cleaning deposits associated with the use of medium-Btu LFG.

As described in Section 3.1, Design Factors, a potential problem for boilers is the accumulation of siloxanes. The presence of siloxanes in the LFG causes a white substance to build up on the boiler tubes. Operators who experience this problem typically choose to perform routine cleaning of the boiler tubes. Boiler operators may also choose to install a gas treatment system to reduce the amount of siloxanes in the LFG before it is delivered to the boiler.

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

Examples

The NASA Goddard Flight Center became the first federal facility to burn LFG to meet energy needs.

LFG captured from the Lanchester Landfill in Narvon, Pennsylvania, is used for multiple purposes, including boilers, heaters, thermal oxidizers, ovens, engines and turbines.

For the St. John's LFG Energy Project in Portland, Oregon, LFG provides a stable, competitively priced fuel source for lime kilns. Other benefits include lower utility costs and lower emissions.

In Blythe, Georgia, a Clay Mine LFG Application involves the use of LFG to fuel flash drying operations in the processing of mined clay.

Infrared Heaters

Infrared heating, using LFG as a fuel source, is ideal for facilities with space heating needs that are located near a landfill (Figure 3-7). Infrared heating creates high-intensity energy that is safely absorbed by surfaces that warm up. In turn, these surfaces release heat into the atmosphere and raise the ambient temperature. Infrared heating applications for LFG have been successfully employed at several landfill sites in Canada, Europe and the United States.

Figure 3-7. Infrared Heater

Infrared heaters require a small amount of LFG to operate, are relatively inexpensive, and are easy to install. Current operational projects (some of which have multiple heaters) use between 10 and 150 cfm. Infrared heaters do not require pretreatment of the LFG, unless siloxanes are present in the gas. One heater is typically required for every 500 to 800 square feet. Each heater costs approximately $3,000 and the cost of interior piping to connect the heaters within the building ceilings ranges from approximately $20,000 to $30,000.

Greenhouses

LFG can be used to provide heat for greenhouses, power grow lights and heat water used in hydroponic plant cultures (Figure 3-8). The costs for using LFG in greenhouses are highly dependent on how the LFG will be used. If the grow lights are powered by a microturbine, then the project costs would be similar to an equivalent microturbine LFG energy project. If LFG is used to heat the greenhouse, the cost incurred would be the cost of the piping and of the technology used, such as boilers.

Figure 3-8. Greenhouse

Artisan Studios

Artisan studios with energy-intensive activities such as creating glass, metal, or pottery (Figure 3-9) offer another opportunity for the beneficial use of LFG. This application does not require a large amount of LFG and can be coupled with a commercial project. For example, a gas flow of 100 cfm is sufficient for a studio that houses glass-blowing, metalworking or pottery kilns.

Figure 3-9. LFG-Powered Glass Studio

Examples

Infrared heaters are used in maintenance facilities at the I-95 Landfill in Virginia.

Several greenhouses have been constructed near landfills to take advantage of the energy cost savings, including the Rutgers University EcoComplex Greenhouse.

The first U.S. artisan project to use LFG was at the EnergyXchange at the Yancey-Mitchell Landfill in North Carolina. LFG is used at this site to power two craft studios, four greenhouses, a gallery and a visitor center.

Leachate Evaporation

Leachate evaporation using LFG, shown in Figure 3-10, is a good option for landfills where leachate disposal at a publicly owned treatment works (POTW) plant is unavailable or expensive. LFG is used to evaporate leachate to a more concentrated and more easily discarded effluent volume (Figure 3-11).

Figure 3-10. Leachate Evaporator

Evaporators are available in sizes to treat 10,000 to 30,000 gallons per day (gpd) of leachate. Capital costs range from $300,000 to $500,000. O&M costs range from $70,000 to $95,000 per year. When a system is owned and operated by a third party, long-term contracts will typically assess costs based on the volume of leachate evaporated. Some economies of scale are realized for larger size vessels, as shown in Table 3-7.

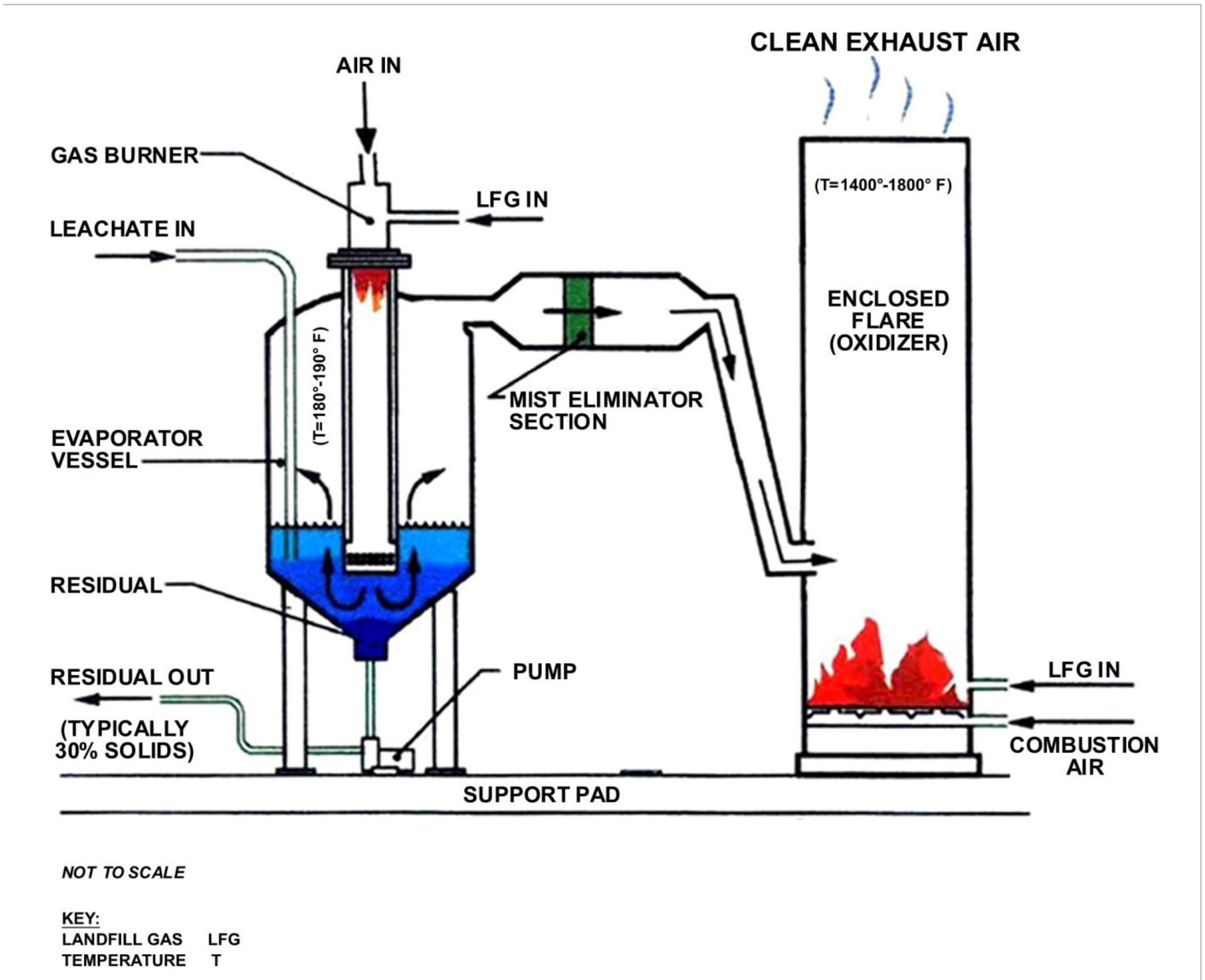
Table 3-7. Cost of Leachate Evaporation[4]

Capacity	Cost
30,000 gpd	$0.05 - $0.06 per gallon
20,000 gpd	$0.06 - $0.9 per gallon
10,000 gpd	$0.10 - $0.15 per gallon

gpd: gallons per day

4 U.S. EPA LMOP. *LFGcost-Web*, Version 3.2.

Figure 3-11. Leachate Evaporation Diagram



Biofuel Production

LFG can also be used to heat boilers in plants that produce biofuels including biodiesel and ethanol. In this case, LFG is used directly as a fuel to offset another fossil fuel. Alternatively, LFG can be used as feedstock when it is converted to methanol for biodiesel production.

Examples

Leachate evaporation is used at the Centralia Landfill in Centralia, Washington, the J.J. Brunner Landfill in Zelienople, Pennsylvania, and the Earthmovers Landfill in Elkhart, Indiana.

One example of an LFG biofuel project is located in Sioux Falls, South Dakota. The Sioux Falls Regional Sanitary Landfill supplies LFG to POET, a producer of biorefined products, for use in a wood waste-fired boiler, which generates steam for use in ethanol production.

Direct Use of Medium-Btu Gas Summary

A summary of the advantages and disadvantages of direct-use technologies is presented in Table 3-8.

Table 3-8. Advantages, Disadvantages and Treatment Requirements Summary (Direct-Use)

Advantages	Disadvantages	Treatment
Boiler, dryer and kiln		
▪ Uses 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
Leachate evaporation		
▪ Good option for landfill where leachate disposal is expensive	▪ High capital costs	Limited condensate removal and filtration treatment

3.4 Conversion to High-Btu Gas

LFG can be used to produce the equivalent of pipeline-quality gas (natural gas), CNG or LNG, subject to state regulations. Pipeline-quality gas can be injected into a natural gas pipeline used for an industrial purpose. Alternatively, CNG and LNG can also be used to fuel vehicles at the landfill (such as water trucks, earthmoving equipment, light trucks and autos), fuel refuse-hauling trucks (long-haul refuse transfer trailers and route collection trucks) and supply the general commercial market (Figure 3-12). Recent capital costs of high-Btu processing equipment have ranged from \$2,600 to \$6,000 per scfm of LFG. The annual cost to provide electricity to operate and maintain these systems ranges from \$500,000 to \$5.0 million.[5] Project costs depend on the purity of the gas required by the receiving pipeline or energy end user as well as the size of the project. Some economies of scale can be achieved when larger quantities of high-Btu gas can be produced.

Figure 3-12. CNG Stations and CNG-fueled Vehicles

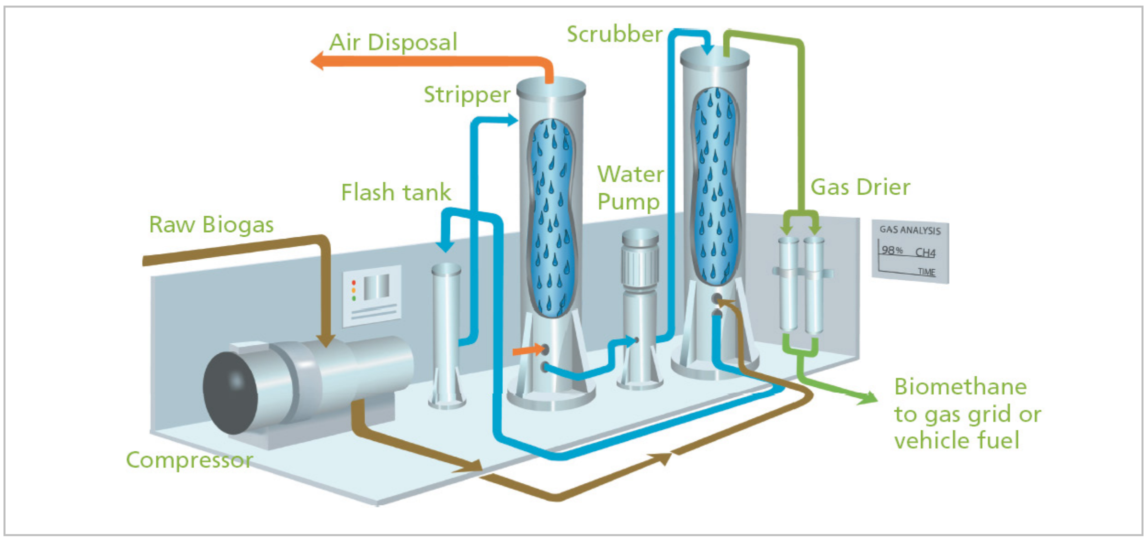
[5] U.S. EPA LMOP. *LFGcost-Web*, Version 3.2.

LFG can be converted into a high-Btu gas by increasing its methane content and, conversely, reducing its carbon dioxide, nitrogen and oxygen content. In the United States, four methods have been commercially employed (beyond pilot testing) to remove carbon dioxide from LFG:

- ***Water Scrubbing.*** Water scrubbing consists of a high-pressure biogas flow into a vessel column where carbon dioxide and some other impurities, including hydrogen sulfide, are removed by dilution in water that falls from the top of the vessel in the opposite direction of the gas flow. The water scrubbing process is illustrated in Figure 3-13. Methane is not removed because it has less dilution capability. The pressure is set at a point where only the carbon dioxide can be diluted; normally between 110 and 140 pounds per square inch (psi). The water that is used in the scrubbing process is then stripped in a separate vessel to be used again, making this system a closed loop that keeps water consumption low. The gases resulting from the stripping process (the same that were removed from the biogas) are then released or flared. Generally, no chemicals are required for the water scrubbing process, making it an attractive and popular technology.

  It is important to note that this technology will not remove certain contaminants such as oxygen and nitrogen that may be present in the raw biogas. This limitation may be an important variable when the end use of the cleaned gas is considered.

  Figure 3-13. Water Scrubbing Unit Flow Schematic[6]

- ***Amine Scrubbing.*** Selexol, a physical solvent that preferentially absorbs gases into the liquid phase, is the most common amine used in amine scrubbing systems to convert LFG to high-Btu gas. A typical Selexol-based plant employs the following steps:
  - LFG compression (electric drive, LFG-fired engine drive or product gas-fired engine drive)
  - Moisture removal using refrigeration
  - Hydrogen sulfide removal in a solid media bed (using an iron sponge or a proprietary media)
  - NMOC removal in a primary Selexol absorber
  - Carbon dioxide removal in a secondary Selexol absorber

  The LFG is placed in contact with the Selexol liquid in a Selexol absorber tower. NMOCs are generally hundreds to thousands of times more soluble than methane. Carbon dioxide is about 15

[6] American Biogas Council. Biogas Processing for Utilities. February 2012. http://www.americanbiogascouncil.org/biogasProcessing/biogasProcessing.pdf.

times more soluble than methane. Solubility also is enhanced with pressure, facilitating the separation of NMOCs and carbon dioxide from methane.

- ***Molecular Sieve.*** A typical molecular sieve plant employs compression, moisture removal and hydrogen sulfide removal steps, but relies on vapor-phase activated carbon to remove NMOC and a molecular sieve to remove carbon dioxide. Once exhausted, the activated carbon can be regenerated through a depressurizing heating and purge cycle. The molecular sieve process is also known as pressure swing adsorption.
- ***Membrane Separation.*** A typical membrane plant employs compression, moisture removal and hydrogen sulfide removal steps, but relies on activated carbon to remove NMOCs and membranes to remove carbon dioxide. Activated carbon removes NMOCs and protects the membranes. The membrane process takes advantage of the physical property that gases, under the same conditions, will pass through polymeric membranes at differing rates. Carbon dioxide passes through the membrane approximately 20 times faster than methane. Pressure is the driving force for the separation process.

Air intrusion is the primary cause for the presence of oxygen and nitrogen in LFG and can occur when air 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. In some instances, air intrusion can be managed by sending LFG from the interior wells directly to the high-Btu process, and sending LFG from the perimeter wells (which often have higher nitrogen and oxygen levels) to another beneficial use or emissions control device. Membrane separation can achieve some incidental oxygen removal, but nitrogen — which represents the bulk of the non-methane/non-carbon dioxide fraction of LFG — is not removed. A molecular sieve can be configured to remove nitrogen by proper selection of media. Nitrogen removal, in addition to carbon dioxide removal, requires a two-stage molecular sieve pressure swing adsorption.

Compressed Natural Gas

The membrane separation and molecular sieve processes scale down more economically to smaller plants for CNG production. For this reason, these technologies are more likely to be used for CNG production than the Selexol (amine scrubbing) process. The estimated annualized capital and operating costs of CNG production for membrane separation processes capable of handling various gas flows ranges from $1.64 to $2.82 per gasoline gallon equivalent (GGE).[7]

Example

In Rochester, New Hampshire, LFG from the TREE Landfill is processed into pipeline-quality gas and piped 12.7 miles to the University of New Hampshire.

Example

The Dane County BioCNG™ Vehicle Fueling Project located in Dane County, Wisconsin, was recognized as an LMOP 2011 award winner for its successful generation of electricity from landfill methane as well as its use of excess LFG to produce CNG that fuels the county's parks and public works department trucks. The system originally produced 100 gallons of gasoline equivalent (GGE) per day and expanded to produce 250 GGE per day in 2013.

St. Landry Parish in Louisiana was recognized as a 2012 LMOP award winner for its successful LFG-to-CNG project. The Parish originally converted 50 cfm of LFG into 250 GGE of CNG per day, and expanded the project in 2015 to create a total of 630 GGE per day. The CNG is used to fuel government vehicles including cars, trucks and vans. Benefits from the project include better air quality and environmental education opportunities for the community.

7 U.S. EPA LMOP. *LFGcost-Web*, Version 3.2.

Liquefied Natural Gas

LNG can be generated from LFG that is first converted to CNG. The CNG produced from LFG is liquefied to produce LNG using conventional natural gas liquefaction technology. When assessing this technology, two factors should be considered:

- Carbon dioxide freezes at a temperature higher than methane liquefies. To avoid "icing" in the plant, the CNG produced from LFG must have the lowest possible level of carbon dioxide. The low carbon dioxide requirement favors a molecular sieve over a membrane separation process, or at least favors upgrading the gas produced by the membrane process with a molecular sieve. Water scrubbing also is an option.
- Natural gas liquefaction plants have generally been "design-to-order" facilities that process large quantities of LNG. A few manufacturers offer smaller, pre-packaged liquefaction plants that have design capacities of 10,000 gpd or greater.

Unless the nitrogen and oxygen content of the LFG is very low, additional steps must be taken to remove nitrogen and oxygen. Liquefier manufacturers desire inlet gas with less than 0.5 percent oxygen, citing explosion concerns. Nitrogen needs to be limited to produce LNG with a methane content of 96 percent. The cost of LNG production is estimated to be $0.65/gallon for a plant producing 15,000 gpd of LNG. A plant producing 15,000 gpd of LNG requires 3,000 scfm of LFG and would require a capital investment approaching $20 million.[8]

Example

In 2009, a high-tech fuel plant was opened in Livermore, California, that demonstrates the viability of LFG as an alternative transportation fuel. LFG processed from the Altamont Sanitary Landfill generates LNG that is used to fuel ~300 garbage trucks. More information about the Altamont Landfill Gas to Liquefied Natural Gas Project is available from LMOP's website.

Conversion to High-Btu Gas Summary

Table 3-9 summarizes the advantages and disadvantages of converting LFG to high-Btu gas.

Table 3-9. Advantages, Disadvantages and Treatment Requirements Summary (High-Btu)

Advantages	Disadvantages	Treatment
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

[8] Pierce, J. SCS Engineers. 2007. *Landfill Gas to Vehicle Fuel: Assessment of Its Technical and Economic Feasibility.* SWANA 30th Annual Landfill Gas Symposium (March 4 to 8, 2007), Monterey, California.

3.5 Selection of Technology

The primary factor in choosing the right project configuration for a particular landfill is the projected expense versus the potential revenue. If a suitably interested customer is located nearby, a medium-Btu option should be thoroughly examined. An energy user that requires gas 24 hours per day, 365 days a year, is the best match for an LFG energy project, since intermittent or seasonal LFG uses typically result in wasting gas during off-periods. If no such customer exists, the landfill could use its energy resources to attract industry to locate near the landfill. The landfill should work with a local department of economic development to develop a strategy for this option.

The economics of an electricity generation project depend largely on external factors, including the price at which the electricity can be sold, available tax credits or other revenue streams such as renewable energy certificates. If the purchasing utility pays only the avoided cost for the electricity, an electricity generation project may not be economically feasible. Fortunately, electricity generation projects are receiving more favorable power purchase agreements (PPAs) because of growing interest in renewable energy resources and an increasing number of states with Renewable Portfolio Standards (RPS).

Avoided costs are the costs the utility avoids, or saves, by not making the equivalent amount of electricity in one of its own facilities, and would include fuel costs and some operating costs, but not fixed costs.

The most common structure for an LFG electricity project is to sell the electricity to an investor-owned utility, cooperative or municipal entity through a PPA. Typically, the electricity, including energy and capacity, is sold at a fixed price with level of escalation, or at an indexed price based on an estimate of short-run avoided cost, or a publicly available local market price mechanism. Negotiating an acceptable interconnection agreement is important to a successful electric generation project. The interconnection agreement can be a large cost variable and discussions should begin early in the project.

If an electric generation project is selected, the next step is to choose the type of power generation, which depends on the amount of recoverable LFG, the expected quantity for at least 10 years and the gas quality. If heat or steam and electric power are needed forms of energy, then a CHP project may be the appropriate choice. Regardless of which generator type is used, the project will most likely need to be sized smaller than the amount of available gas to ensure full-load operation of equipment. Therefore, the project likely will have excess gas that will have to be flared. Table 3-10 summarizes the relationship between technology options and the amount of LFG flow available for an LFG energy project.

Table 3-10. Summary of LFG Flow Ranges for Technology Options

Technology	LFG Flow Range (at Approximately 50% Methane)
Electricity	
Internal combustion engine (800 kW to 3 MW per engine)	300 to 1,100 cfm; multiple engines can be combined for larger projects
Gas turbine (1 to 10 MW per gas turbine)	Exceeds minimum of 1,300 cfm; typically exceeds 2,100 cfm
Microturbine (30 to 250 kW per microturbine)	20 to 200 cfm
Medium-Btu Direct-Use	
Boiler, dryer and process heater	Utilizes all available recovered gas
Infrared heater	Small quantities of gas, as low as 10 cfm
Greenhouse	Small quantities of gas
Artisan studio	Small quantities of gas
Leachate evaporation	1,000 cfm is necessary to treat 1 gallon of leachate per minute
Upgraded LFG	
High-Btu/Pipeline-quality gas	400 cfm and up, based on currently operating projects
Alternative fuel (CNG or LNG)	Depends on project-specific conditions

cfm: cubic feet per minute CNG: compressed natural gas kW: kilowatt
LNG: liquefied natural gas MW: megawatt

State and local air quality regulations and limits also play a role in technology selection. Refer to local air regulations for determining restrictions on technologies. For example, internal combustion engines may not comply with nitrogen oxides emission requirements, and a gas turbine or microturbine may need to be used. Stringent emission limits for various pollutants may require more extensive pretreatment of the LFG or exhaust from gas turbines.

Regions of the country with more stringent air regulations offer opportunities for CNG or LNG applications because use of these fuels in landfill vehicles or refuse collection and transfer fleets in place of fossil fuels will lower emissions.

For more information about project economics and financing, see Chapter 4.
For more information about permitting requirements and relevant regulations, see Chapter 5.