3. Project Technology Options

The goal of a landfill gas (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 combined heat and power [CHP]) – LFG extracted from the landfill is converted to electricity;
- Direct use of medium-British thermal unit (Btu) gas – treated LFG is used as a direct source of fuel;
- Upgrade to renewable natural gas (RNG) – LFG is cleaned to produce the equivalent of natural gas, compressed natural gas (CNG) or liquefied natural gas (LNG).

Table 3-1. Operational Project Technologies

Project Technology	Projects[1]
Electricity Projects	
Internal combustion engine (reciprocating engine)	296
CHP	43
Gas turbine	29
Microturbine	8
Combined cycle	5
Steam turbine	4
Stirling cycle engine	1
Medium-Btu Direct-use Projects	
Boiler	46
Direct thermal	31
Leachate evaporation	12
Greenhouse	4
RNG Projects	
Pipeline Injection	62
Local Use	9

In CHP applications, LFG is used to produce electricity and heat. Direct-use applications include heating greenhouses, firing brick kilns and providing fuel to chemical and automobile manufacturing businesses. Table 3-1 provides a breakdown of technologies used in operational LFG energy projects in 2021.

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. For additional information on select technology costs and emissions, see the report *Evaluating the Air Quality, Climate & Economic Impacts of Biogas Management Technologies* by EPA's Office of Research and Development in collaboration with other programs.

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. March 2021.

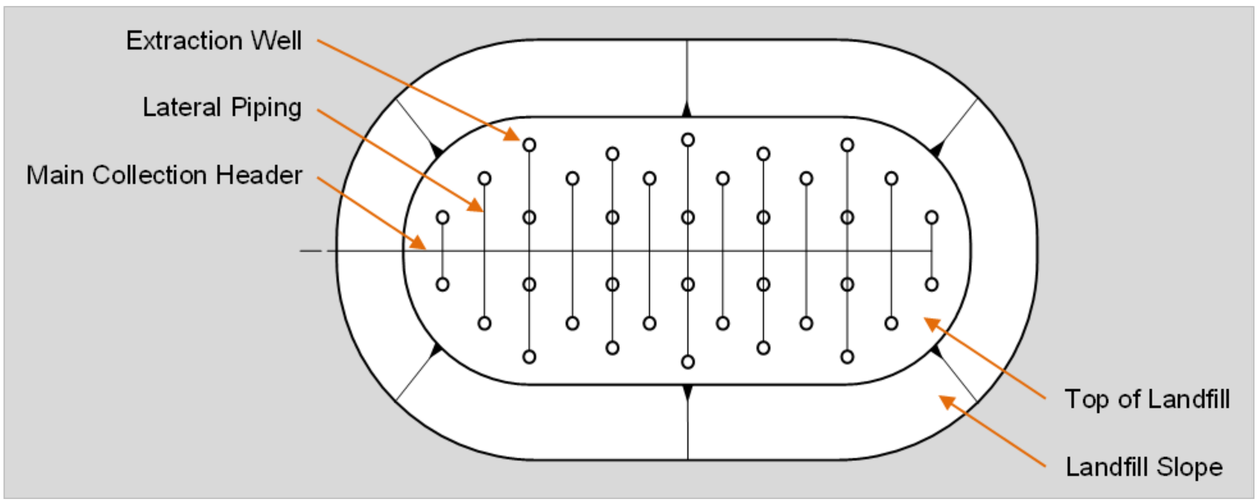
3.1 Design Factors

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

Gas collection systems (GCSs) can be configured as vertical wells, horizontal trenches or a combination of both. Advantages and disadvantages of each type of well are noted in Table 7-2 of Chapter 7. 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 GCS should be designed so that the operator can monitor and adjust the gas flow if necessary.

Figure 3-1. Sample LFG Extraction Site Plan



For more information about designing a GCS, see Chapter 7.

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. Landfills that are selling gas for beneficial use and are subject to gas collection and control requirements under federal MSW landfill rules (40 CFR part 60 subpart XXX, federal or state plan implementing 40 CFR part 60 subpart Cf, or 40 CFR part 63 subpart AAAA) are required to develop a site-specific treatment monitoring plan and keep records of the parameters noted in the plan.

- Treatment systems for LFG electricity projects typically include a series of filters to remove contaminants that can damage components of the engine or turbine and reduce system efficiency.
- Minimal treatment is required for direct use of LFG in boilers, furnaces or kilns.

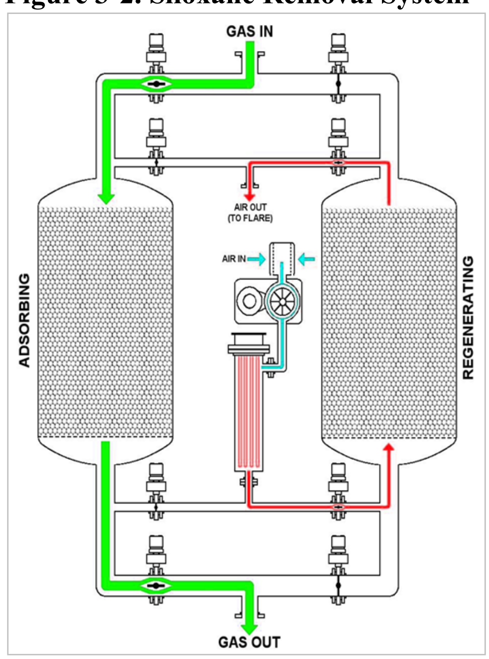
- Advanced treatment is required to produce RNG for injection into natural gas pipelines or production of alternative fuels.

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 [H_2S]), 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 municipal solid waste (MSW). The compounds tend to be at higher concentration in landfills that accept construction and demolition (C&D) materials, and additional treatment is more likely to be necessary.

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, non-methane organic compounds (NMOCs) and a variety of other contaminants in LFG to produce RNG (typically at least 96 percent methane) are discussed in Section 3.4.

Figure 3-2. Siloxane Removal System



3.2 Electricity Generation

Producing electricity from LFG continues to be the most common beneficial use application, accounting for about 70 percent of all U.S. LFG energy projects operating during 2021. 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 the gas quantity is capable of producing 800 kilowatts (kW) to 3 megawatts (MW), or where sustainable LFG flow rates to the engines are approximately 300 to 1,100 cubic feet per minute (cfm) at 50 percent methane. Multiple engines can be combined together for projects larger than 3 MW. Table 3-2 provides examples of available sizes of internal combustion engines.

Figure 3-3. Internal Combustion Engines

Table 3-2. 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: kilowatts MW: megawatts

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, also known as cogeneration, where waste heat is recovered from the engine cooling system to make hot water or from the engine exhaust to make low-pressure steam.

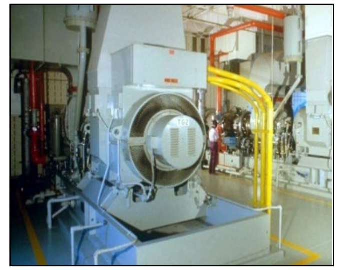
Examples

The Lycoming County Landfill Dual Cogeneration and Electricity Project in Pennsylvania, a Landfill Methane Outreach Program (LMOP) 2012 award-winning project, used an innovative permitting approach and a creative power purchase agreement. LFG is combusted in four internal combustion engines (6.4 MW total rated capacity), 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 EPA CHP Partnership's Biomass CHP 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 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 generate 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 operation and maintenance (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 (causing a high parasitic load loss).

Examples

LFG is piped 9.5 miles from the Palmetto Landfill in Wellford, South Carolina, to BMW Manufacturing's assembly plant to fuel two 5.5-MW gas turbine generators with heat recovery.

Residents from three municipalities and Waste Management, Inc., formed Green Knight Economic Corporation in Pennsylvania, 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, microturbine project costs are higher than internal combustion engine project costs based on a dollar-per-kW installed capacity.[2] However, reasons for using microturbines 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.

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 unit and about 12.2 percent better than the 30-kW unit

Examples

The Renewable Energy Anaerobic Digester (READ) project at the University of California at Davis Landfill in California began generating electricity for onsite use in April 2014. LFG is blended with biogas from the campus food waste digester for combustion in three 200-kW microturbines. The project contributes to the University's plan to reduce campus waste, generate renewable energy and transfer technology.

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 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 3-3 presents examples of typical costs for several technologies, including costs for a basic gas treatment system typically used with each technology. The costs of LFG energy generation 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 3-4 provides a summary of the advantages and disadvantages associated with each electricity-generating technology.

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

Technology	Typical Capital Costs ($/kW)*	Typical Annual O&M Costs ($/kW)*
Internal combustion engine (> 800 kW)	$2,000	$300
Small internal combustion engine (< 800 kW)	$2,900	$320
Gas turbine (> 3 MW)	$1,700	$190
Microturbine (< 1 MW)	$3,400	$330

* 2020 dollars kW: kilowatt MW: megawatt

[3] U.S. EPA LMOP. *LFGcost-Web*, Version 3.5.

Table 3-4. 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 historically 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 may 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 direct-use energy 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 3-5 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 3-5. 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 $240,000 to $516,000.
- 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 $120,000 to $250,000.

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 RNG, it must be between medium-Btu gas and RNG in terms of heating value. This option eliminates the cost of a boiler retrofit and reduces maintenance costs for cleaning deposits associated with the use of medium-Btu LFG; however, there are costs associated with cleaning LFG to a level closer to RNG.

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 is burned in three boilers to produce steam for up to 31 buildings on the campus.

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

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

Figure 3-7. Infrared Heater

Infrared heating, using LFG as a fuel source, is ideal for facilities with space heating needs that are located at or 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.

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

Figure 3-8. Greenhouse

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 the technology used, such as boilers.

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

Prince William County, Virginia uses a portion of the County's LFG to heat maintenance and fleet buildings and a school bus garage with infrared heaters.

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 was used at this site to power two craft studios, four greenhouses, a gallery and a visitor center.

Leachate Evaporation

Leachate evaporation is a good option for landfills where leachate disposal at a water resource recovery facility (WRRF) is unavailable or expensive. There are two common evaporation technologies, both of which can use LFG as the fuel source. Submerged combustion evaporators combust LFG within the evaporation vessel. Concentrator evaporators pull a low-pressure waste heat from flares, LFG-fired engines or turbines or a combination of these; the waste heat then mixes with the leachate in the concentrator to evaporate it.

Figure 3-10. Submerged Combustion Leachate Evaporator

Both technologies are used to evaporate leachate to a more concentrated and more easily discarded (or recirculated) effluent volume, and can be purchased by the landfill owner or leased from a vendor who may provide O&M via a service contract.

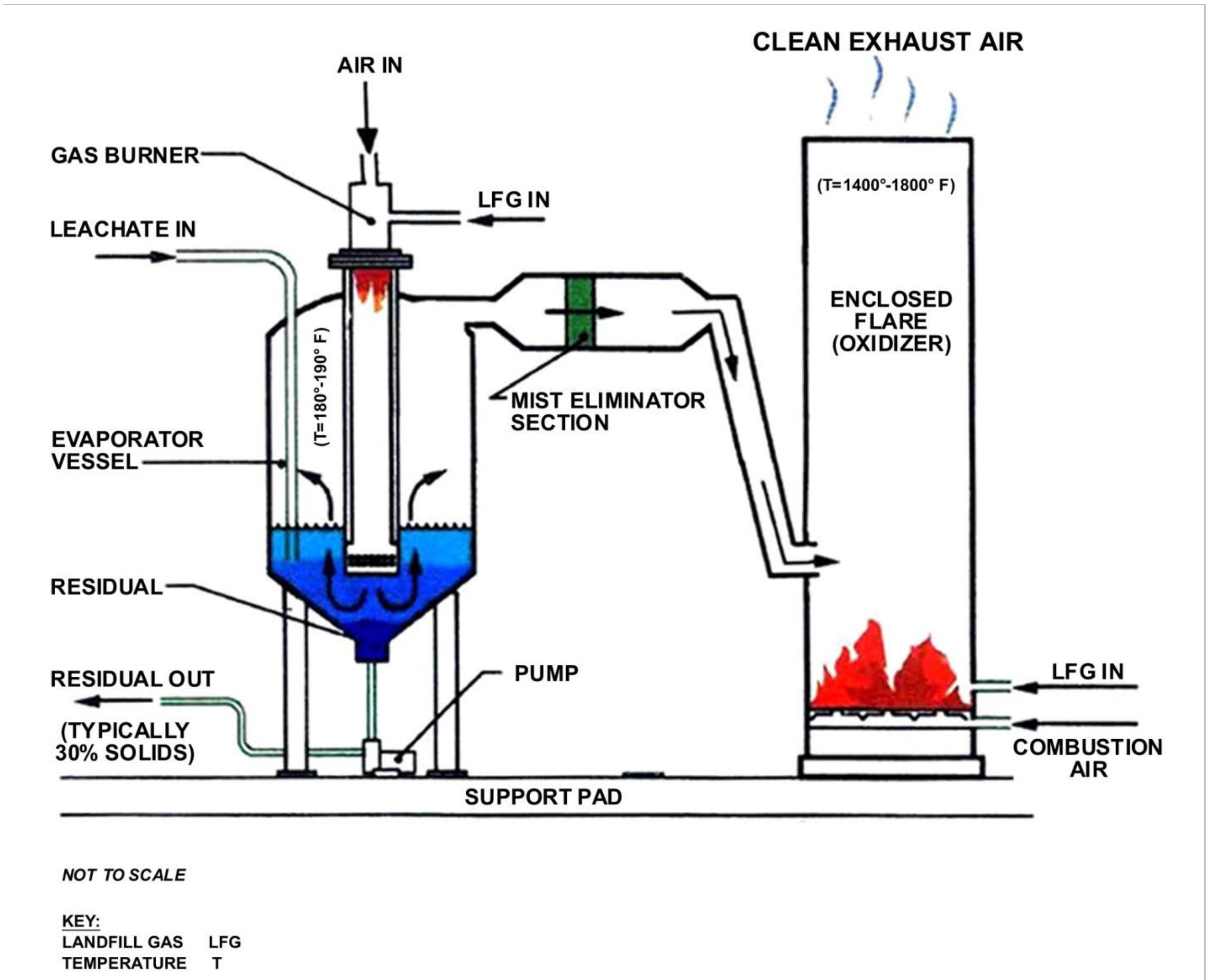
Landfill leachate can contain per- and polyfluoroalkyl substances (PFAS), a group of persistent man-made chemicals that exist in many of the waste materials placed in MSW landfills. EPA is identifying solutions to address PFAS in the environment, including researching PFAS in landfill leachate. More information about PFAS, actions EPA is taking and other resources are available on EPA's PFAS website.

Submerged combustion evaporators (Figures 3-10 and 3-11) are available in sizes to treat 10,000 to 40,000 gallons per day (gpd) of leachate. Capital costs for a 30,000-gpd system are approximately $2.3

million.[4] Some economies of scale are realized for O&M costs of larger vessels; for a 30,000-gpd system the O&M costs range from 4 to 6 cents per gallon. The lower end of this range represents when the system is purchased while the higher end includes costs for a third-party system operator under a long-term lease.

Concentrator evaporator (Figure 3-12) capacities range from 10,000 to 144,000 gpd. An example 25,000-gpd system in which the landfill owner operates the system instead of a third party has a total cost of 6 cents per gallon, which includes operating cost and capital recovery.[5]

Figure 3-11. Submerged Combustion Leachate Evaporation Diagram



4 Cost estimate provided by LMOP Partner APTIM LFG Specialties. December 2020.

5 Weigold, J, Heartland Technology. MSW Management. March 2021. A Cogeneration Solution for Evaporating Landfill Leachate.

Figure 3-12. Concentrator Type of Leachate Evaporator – Heartland's Low Momentum-High Turbulence (LM-HT®) Evaporator Using Heat from Both (1) Engine Exhaust and (2) LFG Flare

Photo courtesy of Heartland Water Technology

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 J.J. Brunner Landfill in Zelienople, Pennsylvania and the Three Rivers Regional Landfill in Pontotoc, Mississippi. 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 3-6.

Table 3-6. 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 RNG

LFG can be upgraded to RNG by removing carbon dioxide and other constituents. RNG can be used as a substitute for natural gas in a variety of applications including vehicle fuel (e.g., CNG or LNG), electricity generation, thermal energy or as a feedstock for chemicals (e.g., methanol). RNG can be delivered to end users via pipeline injection, used locally at CNG or LNG fueling stations at or near the landfill or transported to either an injection point or fueling station via a tube trailer ("virtual pipeline"). Some projects may use more than one of these delivery mechanisms.

While not a new concept (the first U.S. LFG-to-RNG project started up in 1975), the prevalence of this project type increased steadily between 2005 and 2017 and then began a sharp upward trend in 2018 with more new LFG-to-RNG projects coming online than other uses. In addition to financial incentives, RNG pipeline injection projects capitalize on the RNG being versatile for numerous end uses and accessible to non-local energy demands.

Capital costs of RNG processing equipment are approximately $6,200 to $8,300 per standard cubic foot per minute (scfm) of LFG (2020 dollars). Electricity demand to operate these systems is often a significant portion of the O&M costs, consuming 0.009 kilowatt-hours per cubic foot of LFG processed. Total O&M costs including electricity, pipeline injection fees, labor and parts, and supplies range from $1.4 million for a 1,000-scfm LFG project to $7.4 million for a 6,000-scfm LFG project (2020 dollars).[6] These costs are just for conversion of LFG to RNG so do not include fueling station costs. Project costs depend on the purity of the product gas (RNG) required by the receiving pipeline or end user, concentrations of non-methane constituents in the raw LFG and the size of the project. Some economies of scale can be achieved when larger quantities of RNG can be produced.

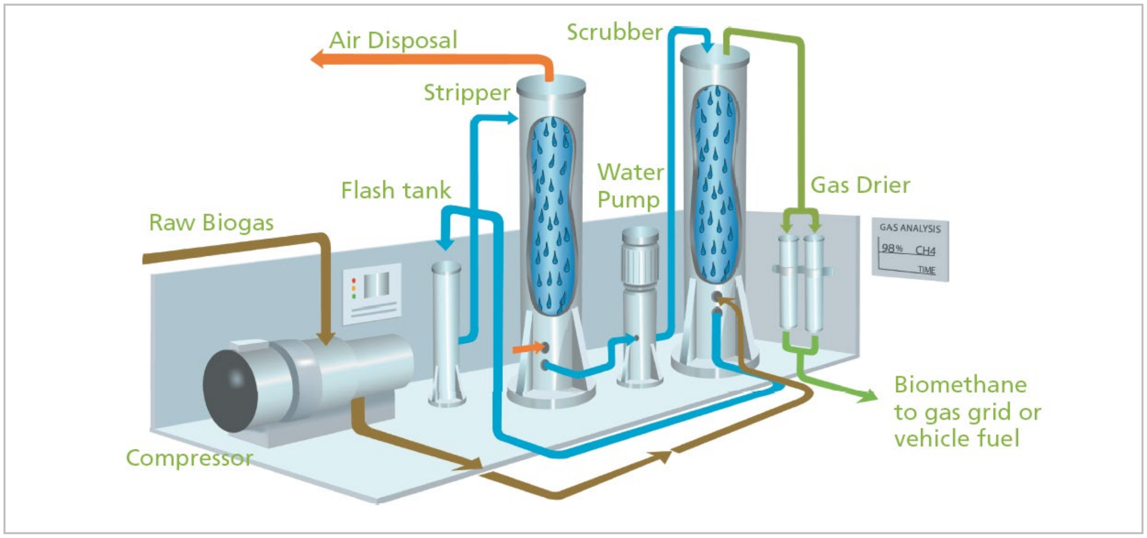
LFG (or other biogas) can be converted into RNG by increasing its methane content and, conversely, reducing its carbon dioxide, nitrogen and oxygen content. The exact specifications will depend on how

6 U.S. EPA LMOP. *LFGcost-Web*, Version 3.5.

and where the RNG product will be used. In the United States, four methods have been commercially employed (beyond pilot testing) to remove carbon dioxide from LFG:

- ***Water Scrubbing.*** Water scrubbing (or water wash) consists of a high-pressure biogas flow into a vessel column where carbon dioxide and some other impurities, including H_2S, are removed by dilution in water that falls from the top of the vessel in the opposite direction of the gas flow. Figure 3-13 illustrates a water scrubbing process. 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 as tail gases. Generally, no chemicals are required for the water scrubbing process. 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 RNG product is considered.

Figure 3-13. Water Scrubbing Unit Flow Schematic[7]



- ***Solvent Scrubbing.*** Solvent scrubbing involves use of a chemical solvent such as amine or a physical solvent like Selexol to strip carbon dioxide and H_2S from the raw biogas. Carbon dioxide is adsorbed into the solvent and methane passes through as the RNG product. In a chemical solvent system the solution is heated to release the carbon dioxide into the tail gas while in a physical solvent system the solvent is depressurized to release the carbon dioxide. NMOCs are generally hundreds to thousands of times more soluble than methane, while carbon dioxide is about 15 times more soluble than methane. Solubility is enhanced with pressure, facilitating the separation of NMOCs and carbon dioxide from methane in the process of creating the RNG product.
- ***Pressure Swing Adsorption (PSA).*** A typical PSA plant employs compression, moisture removal and H_2S removal steps but relies on a molecular sieve to remove carbon dioxide along with low-level impurities. A difference in molecular size allows methane to pass through into the RNG product while the media capture carbon dioxide, low-level impurities and, to a lesser extent, nitrogen. The media are depressurized after saturation to release the carbon dioxide, impurities and nitrogen into the

[7] American Biogas Council. Biogas Processing for Utilities. February 2012. Previously accessed at http://www.americanbiogascouncil.org/biogasProcessing/biogasProcessing.pdf.

tail gas. Once exhausted, the media can be regenerated through a depressurizing and purge cycle. PSA is also known as a molecular sieve process.

- ***Membrane Systems.*** A typical membrane plant employs compression, moisture removal and H_2S removal steps but relies on activated carbon or PSA to remove NMOCs and membranes to remove carbon dioxide. Removing the NMOCs 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. Differential pressure across the membrane wall is the driving force for the separation process. Project-specific RNG quality specifications and project size will help determine if a single-pass or multiple-pass membrane system is needed.

In addition to carbon dioxide removal, many RNG projects employ treatment technologies to reduce nitrogen, oxygen and other LFG constituents. 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 GCS due to the vacuum on the wellfield. 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 RNG production process and sending LFG from the perimeter wells (which often have higher nitrogen and oxygen levels) to another beneficial use or emissions control device. Adjusting the GCS to achieve a desired nitrogen level may impact the amount of LFG available — LMOP's RNG Flow Rate Estimation Tool can serve as a screening tool to help estimate normalized gas flows for RNG projects.

Nitrogen remaining in the intermediate gas stream, following any wellfield adjustments and initial treatment to remove carbon dioxide and possibly other constituents, can be removed using PSA, membrane or cryogenic distillation technologies. At least two types of PSA – an activated carbon adsorbent type (also removes oxygen) and a kinetic type – are available for nitrogen removal. A multi-stage membrane process is also available for nitrogen removal using a polyether ether ketone membrane material which preferentially separates methane from nitrogen as compared to the polyimide material used for carbon dioxide removal. Low-pressure cryogenic distillation separates methane from air gases by lowering the temperature of the gas stream to a point where the methane liquefies but nitrogen and oxygen do not.

Treatment technologies (PSA, membrane) used for removal of carbon dioxide or nitrogen can also achieve varying levels of oxygen removal. In addition, there is a stand-alone option for oxygen removal using a catalytic reactor process wherein the oxygen reacts with methane to produce carbon dioxide and water.

Examples

In Rochester, New Hampshire, LFG from the Turnkey Recycling and Environmental Enterprises (TREE) Landfill is processed into RNG and then piped 12.7 miles to the University of New Hampshire for combustion in the campus' gas turbine CHP plant.

RNG produced at the Seabreeze Environmental Landfill in Angleton, Texas is provided to OCI NV in Beaumont, Texas in a "directed biogas" project, wherein the end user extracts an amount of natural gas from the pipeline that is equivalent to the amount of RNG injected into the pipeline by the project. The OCI NV methanol plant is about 100 miles away from the landfill.

LMOP's *An Overview of Renewable Natural Gas from Biogas* document provides more details about purification processes and technologies, as well as additional information about RNG project development. LMOP's Renewable Natural Gas webpage also provides information and resources for this project type.

Compressed Natural Gas

The membrane and PSA 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 solvent scrubbing process. The estimated annualized capital and operating costs of CNG production for membrane separation processes capable of handling various gas flows range from $1.93 to $3.28 (2020 dollars) per gasoline gallon equivalent (GGE).[8]

LMOP's fact sheet *Landfill Gas to Vehicle Fuel* summarizes the benefits of and incentives for using LFG to fuel vehicles. RNG can be used to fuel all types of vehicles that run on CNG, such as refuse collection trucks, earthmoving equipment, buses, and light trucks and cars (Figure 3-14).

Examples

The Dane County BioCNG™ Vehicle Fueling Project located in Dane County, Wisconsin originally produced 100 gallons of GGE per day in 2011 for county parks and public works trucks and expanded to produce 250 GGE per day in 2013. In 2019, a new project began injecting RNG into an interstate transmission line for delivery to regional CNG fueling stations.

St. Landry Parish in Louisiana originally converted 50 cfm of LFG into 250 GGE of CNG per day in 2012 and expanded the project in 2015 to create a total of 630 GGE per day. In the original project, the CNG was used to fuel only government vehicles including cars, trucks and vans, but the expansion included a new satellite fueling station and a tube trailer to transport CNG there for use by a national waste company and the public.

Figure 3-14. CNG Stations and CNG-fueled Vehicles

Liquefied Natural Gas

CNG produced from LFG can be 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.

[8] U.S. EPA LMOP. *LFGcost-Web*, Version 3.5.

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 per 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.[9]

Example

In 2009, a high-tech fuel plant was opened in Livermore, California, that demonstrated 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 on LMOP's website.

Conversion to RNG Summary

The advantages, disadvantages and treatment requirements are similar for converting LFG to RNG for natural gas pipeline injection or local use vehicle projects (e.g., alternative fuel for landfill or refuse hauling vehicles, supply to the general commercial market). One advantage of using RNG for vehicle fuel is that the combustion emissions from vehicles fueled by the RNG are excluded from the RNG plant's potential to emit calculations since the LFG is not combusted on site. A disadvantage of either type of RNG project is the increased cost from tight management of wellfield operations needed to limit oxygen and nitrogen intrusion into the LFG. Treatment of LFG for pipeline-injected RNG requires extensive and potentially expensive processing; treatment for local vehicle fuel use also requires a high level of LFG processing but usually with slightly less stringent gas specifications as compared to natural gas pipeline injection.

3.5 Selection of Project Type

The primary factors in choosing the right project configuration for a particular landfill are the amount of LFG available for a project, project economics and proximity of users for the energy recovered. Table 3-7 summarizes the relationship between technology options and the amount of LFG flow available for an LFG energy project.

Table 3-7. 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

[9] 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.

Technology	LFG Flow Range (at Approximately 50% Methane)
Greenhouse	Small quantities of gas
Artisan studio	Small quantities of gas
Leachate evaporation	Direct heat – 500 cfm of LFG at 50% methane is necessary to treat ~21 gallons of leachate per minute Indirect heat – can evaporate 5,000 gpd of leachate per MW of engine capacity's exhaust heat (additional thermal energy from flaring can supplement to meet site's evaporation needs)
RNG	
Pipeline injection – eventual use for vehicle fuel, electricity generation or thermal needs	1,000 cfm and up are the most cost-effective
Local use – vehicle fuel (CNG or LNG)	Depends on project-specific conditions; based on currently operating projects CNG applications tend to use between 50 and 200 cfm while LNG uses 2,400 cfm

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

The economics of an LFG energy project depend largely on external factors, including the price at which the energy can be sold, available tax credits or other revenue streams such as renewable energy certificates (RECs) or transportation fuel credits. LMOP's Landfill Gas Energy Cost Model (*LFGcost-Web*) can help with preliminary economic evaluation of several project type options. See Chapter 5 for details on incentive and funding options for various project types.

Table 3-8 summarizes some of the criteria and other considerations for a particular project type to apply to a specific landfill.

Table 3-8. Summary of Other Criteria and Considerations by Project Type

Technology	Criteria for Project Type to Apply / Considerations
Electricity	
Any	Favorable electricity market rates or green energy incentives
	Ability to interconnect
	Policies allow and there is sufficient demand for net metering
	Local air quality regulations / non-attainment area restrictions
CHP	Heat or steam need in addition to electricity need
Medium-Btu Direct-Use	
Any	Onsite thermal needs or suitably interested end user nearby
	End user with constant fuel need not intermittent or seasonal is best fit
	Onsite or other end user equipment that is adaptable to LFG
	Fossil fuel price higher than LFG pricing or interest in paying a premium for 'green gas'
	LFG quality not conducive to RNG project

Technology	Criteria for Project Type to Apply / Considerations
RNG	
Pipeline injection – eventual use for vehicle fuel, electricity generation or thermal needs	Fossil natural gas pipeline onsite or near landfill property / ability to interconnect
	Sufficient demand from offtake agreements
Local use – vehicle fuel (CNG or LNG)	Landfill located near CNG/LNG station or other local demand (e.g., waste truck fleet)
Any	High-quality LFG
	Fossil fuel price higher than RNG pricing or favorable incentives
	Local air quality regulations / non-attainment area restrictions

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