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Characteristics of utilization of biogas technology

Introduction

Biogas is generated in the absence of oxygen by microorganisms in a process known as anaerobic metabolism. Industrial biogas is produced at sewage treatment plants, landfill sites and digestion plants for both mesophilic and thermophilic agricultural organic waste.

The chemical composition of biogas is determined by differences in organic matter and operational conditions used during anaerobic digestion.

Raw biogas consists mainly of methane (45÷70%), carbon dioxide (25÷55%), nitrogen (0.01÷5%), oxygen (0.01÷2%), hydrogen sulfide (0.005÷2%) and water (5÷10%). Biogas may also contain other contaminants such as siloxanes (0÷0.02%), ammonia (< 1%), halogenated hydrocarbons (*VOCs – Volatile organic compounds*), aromatic hydrocarbons (BTEX – *Benzene, Toluene, Ethylbenzene, and Xylenes*) and halogens.

Biogas can be utilized in several ways – either raw or upgraded. There are various biogas utilization purposes:
- the production of heat and/or steam,
- electricity production with CHP,
- as an industrial energy source for heat, steam and/or electricity and cooling,
- as vehicle fuel (in its upgraded form),
- upgrading and injection into natural gas grids,
- fuel for fuel cells.

The choice of these technologies is mainly based on compatibility with fuel quality requirements and the availability of relatively small size systems.

The vast majority of projects use internal combustion engines or turbines, in particular, with microturbine technology being used in smaller projects and niche applications. Certain technologies, such as the Stirling and Organic Rankine Cycle engines as well as fuel cells are still in the developmental phase.

Direct use

The number and diversity of direct-use biogas applications are continuously growing. Project types include:
- Boilers, which are the most common type of direct use and can often be easily converted to use biogas alone or in combination with fossil fuels.
- Direct thermal applications, which include kilns (e.g., cement, pottery, brick), sludge dryers, infrared heaters, paint shop oven burners, tunnel furnaces, process heaters, and blacksmithing forges, to name a few.
- Leachate evaporation, in which a combustion device that uses landfill gas (LFG) is used to evaporate leachate (the liquid that percolates through a landfill). Leachate evaporation can reduce the cost of treating and disposing of leachate.

The simplest and often most cost-effective use of biogas is its application as a fuel for boilers or industrial process (e.g., drying operations, kiln operations as well as cement and asphalt production). In these projects, the gas is piped directly to a nearby customer where it is used employing new or existing combustion equipment as a replacement or supplementary fuel. Only limited condensate removal and filtration treatment is required, however, some modifications of existing combustion equipment might be necessary.

The energy users' energy requirements becomes paramount when the evaluation of the sale of biogas for direct use is considered. Because no economical way to store biogas exists, all the gas that is recovered must be used when available, or it is essentially lost along with associated revenue opportunities. When a plant does not have an adequate gas flow to support the entire needs of a facility, biogas can still be used to supply a portion of the needs. For example, in some facilities, only one piece of equipment (e.g., a main boiler) or set of burners are dedicated to biogas burning. These facilities might also have equipment that can use biogas along with other fuels.

As biogas is typically a wet gas often containing trace corrosive compounds, the fuel train and possibly some burner "internals" should be replaced with corrosion-resistant materials. Stainless steel has typically been the material selected for that purpose.

A potential problem for boilers is the accumulation of siloxanes. The presence of siloxanes in biogas causes a white substance (similar to talcum powder) to build up on the boiler tubes. Where the material collects and the amount accumulated is likely to be a function of the velocity patterns in the boiler and the siloxane concentrations in the biogas. Operators' experiences to date indicate that annual cleaning is sufficient to avoid operational problems related to silicon oxide accumulation. Boiler operators may also choose to install a gas treatment system to reduce the amount of siloxanes in the biogas prior to delivery to the boiler.

In designing and assessing the economic feasibility of projects utilizing biogas in boilers, several factors in addition to the boiler retrofit must be considered. For example, the quantity of biogas available must be considered and compared to the facility's steam needs and boiler capacities. Fortunately, the level of biogas clean-up required for boiler use is minimal, and only large particles and moisture need to be removed. Other compounds in biogas, such as siloxanes, do not damage boilers or impair their function.

Conversion of biogas to electricity or CHP

Biogas to CHP (Combined heat and power) is an energy production method. The efficiency of installations using biogas in the CHP unit is higher, and their number is growing, whereas the thermal efficiency is always higher than electrical efficiency for all CHP units. The energy use of biogas plants in cogeneration can involve the application of reciprocating gas engines, gas turbines and microturbines.

CHP plants using gas-powered reciprocating engines usually produce hot water or saturated steam. Heat is recovered from the heat exchanger on the engine casing, oil cooler and exhaust heat exchanger. CHP operation can also be used in gas turbines, involving a simple cycle gas turbine with a heat recovery heat exchanger which recovers the heat in the turbine exhaust and converts it to useful thermal energy, typically in the form of steam or hot water. Combined cycle operation occurs when high pressure steam is generated from recovered exhaust heat and then used to create additional power employing a steam turbine.

Gas turbines are mostly used in combined heat and power systems of more than 1 MW (only a few types of gas turbines of less than 1 MW are available). At the same time, it should be realized that units of the smallest size, feature low efficiency and relatively high unit investment costs.

Microturbines can also be used in CHP systems. In these applications, the waste heat from microturbine exhaust is used to produce hot water (up to 93°C). This option can replace a relatively expensive fuel, such as propane, needed to heat water in colder climates to meet space-heating requirements. The sale or use of microturbine waste heat can significantly enhance project economy. Hot water can be used to heat building space, to drive absorption cooling, and to supply other thermal energy needs in a building or industrial process.

The Sterling engines can also be operated in a CHP mode, but only with hot water. In this mode, the waste heat produced as a byproduct of the electricity generation process is recovered and utilized.

Reciprocating engines (ICE)

The reciprocating internal combustion engine represents the most widely used technology for electricity generation from biogas. The reason is mainly both the power and the economic feasibility of the system. These engines represent a prevalent and consolidated technology, and the related economic risks are very low compared to other technologies.

Gas-powered reciprocating engines, also called gas-powered internal combustion engines, are the modified versions of medium- and high-speed engines powered by liquid fuels. The modifications applied in gas-fuelled engines typically include: changes in the shape of head and the top part of pistons, adding a gas and liquid fuel system, expansion of the engine cooling system and the exhaust heat removal system.

There are many manufacturers worldwide that produce generators. Major manufacturers, offering highly-reliable generators and a wide range of products, include CATERPILLAR (USA) and Jenbacher Energie (Austria), DEUTZ (Germany) and WAUKESHA (USA) are also worth mentioning.

Turbines

Gas turbines represent the second most frequently used technology for biogas energy production, even though the number of installations is significantly lower than that of the ICEs. Compared with an internal combustion engine of the same size, a gas turbine features lower generation efficiency and a markedly lower power to heat ratio (cogeneration ratio). On the other hand, a gas turbine is significantly lighter (e.g. a 1 MW turbine weighs approx. 1 tonne, whereas an ICE of the same size – approx. 10 tonnes) and smaller. In a gas turbine, the only source of heat is the exhaust gas which can still be converted to useful energy.

Gas turbines operate based on a thermodynamic Brayton Cycle. The term "gas" refers to the atmospheric air that is taken into the engine and used as the working medium in the energy conversion process. This atmospheric air is first drawn into the engine where it is compressed, heated, and then expanded for power generation. The power produced by the expansion turbine and consumed by a compressor is proportional to the absolute temperature of the gas passing through the device.

A gas turbine that uses biogas is very similar to a natural gas turbine, except that it requires twice the number of fuel-regulating valves and injectors, which is the effect of low heating value.

The biogas-based turbine systems require more inspections, cleaning and general maintenance. It requires a higher level of biogas treatment for the removal of siloxanes, which finally increases the project costs.

Gas turbines are available in sizes ranging from 500 kW to 250 MW, however at landfills most LFG energy projects are at minimum of 3 MW to more than 5 MW (where gas flows exceed a minimum of 2,300 Nm^3/h). The most common gas turbine in operation at LFG recovery projects in USA is the Centaur, manufactured by Solar Turbines, a subsidiary of Caterpillar.

A simple-cycle gas turbine for power-only generation has efficiencies approaching 40% and overall CHP efficiencies of up to 80%.

Microturbines

Microturbines are small combustion turbines that can be used in stationary power generation applications. The basic components of a microturbine are the compressor, turbine generator, and recuperator. In a microturbine, the combustion air (inlet air) is compressed using a compressor and then it is preheated in the recuperator using heat from the turbine exhaust in order to increase overall efficiency. The heated air and biogas are burned in the combustion chamber, and the release of heat causes the expansion of the gas. The expanding gas, sent through a gas turbine, turns the generator, which then produces electricity.

The size range for microturbines, available under development, is from 30 to 400 kW. The sizes of the microturbines offered by producers are as follows:

- Capstone (Chatsworth, California, USA) 30 kW, 65 kW and 200 kW,
- Ingersoll-Rand (Portsmunth, New Hampshire, England) 70 kW and 250 kW,
- Turbec (Malmo, Sweden) 100 kW,
- Elliott Energy Systems (Jennette, Pennsylvania, USA) 80 kW,
- Bosman Power (Southampton, England) 80 kW.

Microturbines have relatively low electric efficiencies, even with recuperator electric, efficiencies are typically 20÷32%, with overall CHP efficiencies of 50÷80%. Microturbines can be successfully fired on biogas provided a careful consideration is given to the way that the gas is handled and treated. For example, a microturbine can run on landfill gas with methane content as low as 30%.

Stirling engines

Traditional gas or diesel internal-combustion engines mix fuel and air inside the cylinder. The mixture is ignited causing combustion that pushes against the piston. The Stirling engine works differently. It contains a working gas (which may be air or an inert gas such as helium or hydrogen) that is sealed inside the engine and used over and over. Rather than burning the fuel inside the cylinder, the Stirling engine uses external heat to expand the gas contained inside the cylinder. As it expands, the gas pushes against the piston. The Stirling engine then recycles the captive working gas by cooling and compressing it, then reheating it again to expand and drive the pistons which, in turn, drive a generator and produce electricity.

To date, few organizations have produced trial Stirling engines using exhaust from fossil fuel combustors. Those that have been produced are designed to generate less than 200 kW of power, and none of these are commercially available. All the recent research related to Stirling engines has been focused on small-sized engines, from less than 2,5 kW (Sunpower, Inc.) to about 100 kW (MTI's ASE engine, Stirling Thermal Motors – now STM Power) and more technology-focused companies, including Tamin Enterprises, Stirling Technology Co., Whispertech, United Stirling and Stirling Energy Systems. Mechanical Technology Incorporated (MTI) is currently developing a Stirling engine called the Mod III, which could be adapted to use LFG.

The electrical efficiency of the power units is 30% with 80% efficiency in the total CHP system. The recovered heat in the form of hot water can be used for space heating either in commercial, or industrial processes.

Organic Rankine Cycle (ORC)

An alternative way of complementing the above list of technologies can be the application of a technology to convert heat energy into electricity using a system built on the basis of the ORC process.

The Organic Rankine Cycle (ORC) process is not significantly different from the traditional Rankine cycle (used for steam turbine power plants) with water circulation. The only difference is the working fluid. The ORC process utilizes an organic fluid of high molecular mass, rather than water. The above application is recommended for biogas plants with an output exceeding 300 kW, and for cases where there is no demand for heat. About 20% of the thermal energy from the associated CHP generation was available for the ORC process.

Upgrading of biogas

Biogas can be upgraded to biomethane by removing carbon dioxide (CO_2) and trace contaminants, such as ammonia (NH_3), hydrogen sulphide (H_2S), siloxanes, etc. Biomethane is a gaseous fuel with physicochemical properties similar to those of natural gas, which makes it possible to inject it into the gas grid.

As biogas is generally saturated with moisture, the appropriate treatment is needed before it is introduced into the pipeline, to avoid condensation and corrosion. Additionally, condensate knock-outs along the pipeline are necessary as condensation in the main pipeline can cause blockages.

The following technologies for CO_2 removal from biogas are employed to improve the energy value of the fuel:

- Pressure Swing Adsorption (PSA),
- Physical and chemical absorption,
- Membrane separation,
- Cryogenic treatment.

The above processes are different not only in terms of the utilized technique, but also the achievable gas quality, processing behaviour, and the experience with which these techniques have been used in biogas processing. An overview of the available processing methods is shown in the table 1.

Table 2 compares various methods of biogas upgrading to biomethane, with a particular focus on the working pressures and losses of methane released during desorption.

Table 1. Overview of CO_2 removal processes

<table>
<tr><th>Separation Method</th><th>Process</th><th>Functioning Principle</th><th>Final Methane Content</th></tr>
<tr><td>Adsorption</td><td>Pressure Swing Adsorption</td><td>Adsorption of CO_2 a molecular sieve</td><td>> 96 Vol.-%</td></tr>
<tr><td rowspan="2">Physical absorption</td><td>Pressurized Water Wash</td><td>Dissolution of CO_2 in water at high pressure</td><td>> 96 Vol.-%</td></tr>
<tr><td>Selexol®-, Rectisol®-, Purisol®- Processes</td><td>Dissolution of CO_2 in a specialized solvent</td><td>> 96 Vol.-%</td></tr>
<tr><td>Chemical absorption</td><td>Monoethanolamine (MEA) – Wash</td><td>Chemical reaction of CO_2 with MEA</td><td>> 99 Vol.-%</td></tr>
<tr><td rowspan="2">Membrane separation</td><td>Polymer membrane gas separation (dry)</td><td rowspan="2">Membrane permeability of H_2S and CO_2 is higher than CH_4</td><td>> 80 Vol.-%</td></tr>
<tr><td>Membrane gas separation (wet)</td><td>> 96 Vol.-%</td></tr>
<tr><td>Cryogenic process</td><td>Low temperature process</td><td>Phase transformation of CO_2 to liquid, while CH_4 remains gaseous</td><td>> 99,9 Vol.-%</td></tr>
</table>

Table 2. Methods of biogas upgrading to biomethane

Method	Process	Working pressure [bar]	Methane losses [%]
Adsorption	Pressure Swing Adsorption	6-10	< 2
Absorption	Pressurized Water Wash	10	< 2
	Selexol Process	7÷10	< 6.5
Chemical absorption	Monoethanolamine (MEA) – Wash	atmospheric	< 0.1
Membrane separation	Membrane gas separation	25÷40	< 3

Conclusions

Both traditional and innovative technologies have been considered. The goal of a biogas energy project is to convert biogas into a useful energy form, such as electricity, steam, heat, or pipeline-quality gas. An analysis of currently available energy technologies using biogas shows that the most effective way is the use of cogeneration. Unfortunately, for economic reasons the use of heat is often not justified because of the distance to customers. The exception is the use of CHP in sewage treatment plants where there is a significant demand for heat and electricity. In connection with the sources where there are few opportunities for heat utilization, like landfill sites and biogas plants, the most commonly used technology is the generation of electricity. The internal combustion engines are still the most widely used facilities, due to economic factors.

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