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Combined Heat and Power Microturbines

Introduction

This fact sheet provides a review of combined heat and power (CHP) technologies for use at water resource recovery facilities (WRRFs). CHP, also called “co-generation,” is defined as the concurrent production of electricity and thermal energy from a power-generating device. Individually, microturbines are on the smaller end of the spectrum of CHP units and, at 92 MW of total installed capacity, they only comprise 0.1% of the total CHP capacity in the United States (U.S. Department of Energy, 2015). Their small size and modular design allow for widespread applicability, and, in terms of number of CHP sites using microturbines as their chosen technology, microturbines comprise approximately 8% of the U.S. CHP market (U.S. Department of Energy, 2016).

Microturbines make use of a Brayton cycle, where air is first drawn into the engine and compressed to high pressure by a radial compressor and is then mixed with fuel in the combustion chamber and continuously ignited. The compressed air is used to drive a turbine that provides torque to both the compressor drawing the air in and an electrical generator. Modern microturbines also make use of a recuperator stage, where hot exhaust air passes by the compressed air entering the combustion chamber, preheating the air before combustion and increasing thermal efficiency.

Microturbines of 30 to 300 kW are an economical option, with the ability to parallel multiple modular units (U.S. Department of Energy, 2016). In December 2019, only 36 sites with a total capacity of 7.4 MW within the U.S. water resource recovery industry were demonstrating this technology and its economic benefits (U.S. Department of Energy, 2019). U.S. installations at WRRFs range in size from 30 kW to 1.6 MW (U.S. Department of Energy, 2019).

Fundamentals

Most microturbine installations use natural gas for fuel in CHP applications. This fact sheet emphasizes operation at WRRFs using anaerobic digester gas as a renewable energy source. Anaerobic digestion is a good fit for CHP because of the constant heat demand of the digesters. CHP does not provide energy efficiency benefits without a need for the heat recovered.

The electrical efficiency of microturbines is comparatively low, ranging from 25% to 29% higher heating value (HHV) and increasing with the size of the unit. Heat recovery from a microturbine is from the exhaust gas that exits the recuperator at 260 to 315 °C (500 to 600 °F). Hot exhaust gases can be used for process heating needs, such as drying or preheated combustion air, but typically a heat exchanger extracts the heat for hot water or steam. Exhaust heat recovery boosts the overall fuel to a useful energy efficiency of 65% to 70% HHV (U.S. EPA, 2015).

In WRRF applications where digester gas is used in place of pipeline natural gas, digester gas compression and treatment are required. Digester gas is saturated with moisture and may contain hydrogen sulfide and siloxanes. Siloxane cannot be tolerated by microturbines because silicon dioxide is formed during combustion of siloxane, which destroys lightweight turbine blades. Hydrogen sulfide is tolerated, but moisture removal is required to minimize corrosive conditions in the gas piping system and for pretreatment for siloxane removal.

Because of the pressure used in the combustion chamber of a microturbine, adequate fuel supply pressure is critical to microturbine operation. Microturbines require fuel supply pressures in the range of 400 to 1000 kPa (60 to 40 psig) (U.S. EPA, 2015). Safety considerations for gas compression and microturbine installations are covered in Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines (NFPA 37, 2021) and Standard for Fire Protection in Wastewater Treatment and Collection Facilities (NFPA 820, 2020) for installation at WRRFs. Enclosed gas compressor rooms are considered Class 1, Division 1, Group D hazardous-rated spaces. Ventilation at 12 AC/h reduces the Division 1 envelope to within 2 m (5 ft) of the gas-processing equipment (NFPA 820, 2020).

Digester gas production can vary at WRRFs. With this variability in fuel supply, gas storage is, in most cases, essential to maximize CHP system production and minimize flaring. Storage is also highly beneficial to a “peak-shaving” strategy, whereby CHP system operation is maximized when thermal and electric demands are greatest, minimizing the peak energy that must be acquired by other means. Microturbines will lose efficiency at partial load; for this reason, multiple smaller units can be used so that the units online will operate at full load, and individual units are cycled on and off. If an individual turbine must be operated at partial load, the thermal side is less affected because exhaust temperatures do not drop significantly, and the efficiency loss in part-load electric generation can be compensated for with heat recovery. The drop in electrical efficiency reduces microturbines’ suitability for load-following applications. Load following is an automation strategy where the output of the microturbine modulates to meet the available load. Because of the loss of efficiency at partial load and the modular nature of the microturbines, variable loads can be offset by strategically turning microturbines in an array off and on.

Another important consideration for microturbines is the reduction in electrical efficiency as the inlet air temperatures rises. Because the inlet air is compressed, the reduced efficiency is a result of more parasitic loads being required to compress the warm inlet air. Note that this effect reduces power output and efficiency.

Techniques for inlet air cooling can be applied to microturbines. Evaporative cooling uses a fine water mist to lower the air temperature through evaporation. This technique would be applicable to high daytime temperatures at which relative humidity is moderate with separation of the wet and dry bulb temperatures.

Characteristics/Applicability

Microturbines have the following attributes that may drive their selection and application at WRRFs:

- Compact, modular design and low output capacities
- Ability to use low-energy fuel
- Low emissions
- Low maintenance compared to internal combustion engine (ICE)
- Quiet operation

Microturbines are applicable to WRRFs with digester gas available to support up to 500 kW of CHP. For CHP systems below 200 kW, microturbines are a preferred technology. Generally, digester gas production in the range of 850 to 7100 Nm^3 per day (30 000 to 250 000 scfd), corresponding to 500 kW of generating capacity, would be appropriate for microturbine systems at wastewater treatment facilities. Higher gas production supports ICE engine generators as a cost-effective CHP system.

The higher efficiency of ICE systems is offset by the high maintenance costs relative to power production for small engines. Lubricants, coolant, plugs, and regular rebuilds are associated with proportionately higher costs. If maintenance is performed using WRRF staff, the hours are significant; alternatively, contract maintenance is an ongoing expense. In WRRFs that have experience with ICE systems, the clean, quiet operation of microturbines can be a relief from engines.

In states such as California, low air emissions may be a key advantage, and, in less stringent environments, an air permit may not be required.

Microturbines can use gaseous fuels as low as 13 MJ/Nm^3 (350 Btu/scf) lower heating value (LHV) (Capstone Turbine Corporation, 2008). This attribute was used in Janesville, Wisconsin, to recover methane slip from the tail gas from a gas upgrading system. Figure 1 shows the overall digester gas utilization system at Janesville, and Figure 2 shows an example energy balance for the production of RNG for CNG vehicle fuel. Janesville is a unique application, but, in general, microturbines are more flexible in suitable fuels than ICE.

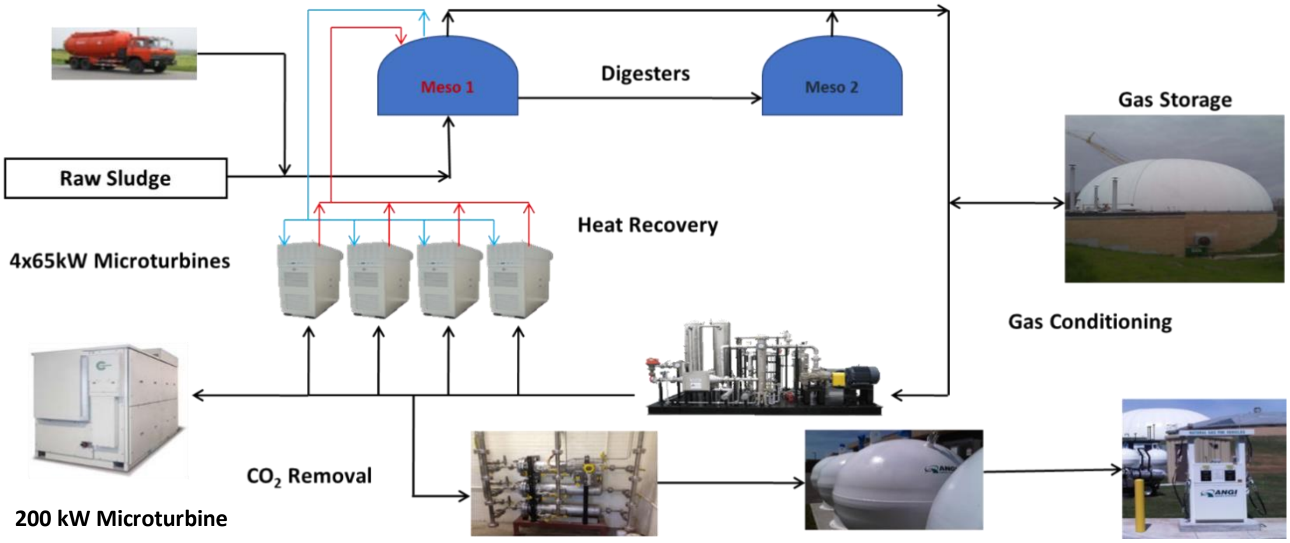

Figure 1. Janesville, Wisconsin, Digester Gas System Featuring Microturbines (Reprinted with permission from Janesville Wastewater Utility)

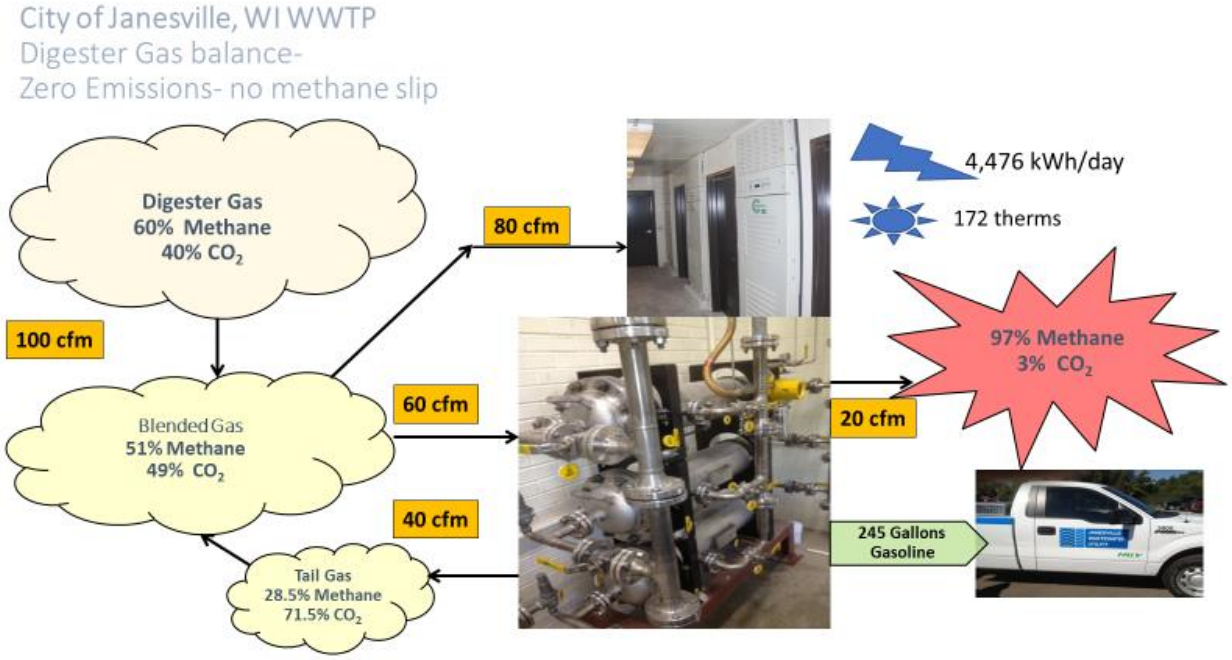

Figure 2. Energy Balance for Janesville, Wisconsin (100 cfm = 170 Nm^3/hr; 245 gal = 927 L) (Reprinted with permission from Janesville Wastewater Utility)

Heat recovery from microturbines is straightforward, with units having either integral heat recovery for hot water production, external heat exchangers, or ducting to direct hot air applications. Heat recovery is not a component of the cooling system as is the case for engine systems. Hot exhaust is diverted away from the heat exchanger if not needed, and the exhaust temperature is monitored and water flow is diverted to prevent the stack from getting too cool.

Support Equipment—Fuel System

Microturbines can burn a wide range of liquid and gaseous fuels. This fact sheet discusses the fuel system requirements for using digester gas as the microturbine fuel. Digester gas produced from municipal anaerobic digesters contains siloxane at levels that will damage microturbines, and siloxane must be removed for digester gas to be used in a microturbine.

Digester gas is fully saturated with water because it is produced within anaerobic digesters. Digester gas piping is designed to collect and trap condensed moisture from the gas, but digester gas should be further dried as part of an overall treatment system.

Hydrogen sulfide (H_2S) is an odorous gas component of digester gas that forms corrosive sulfuric acid in the presence of moisture and contributes sulfur dioxide (SO_2) to exhaust gases, which may threaten air quality.

Siloxane is typically removed by activated carbon. The carbon must be dry to adsorb siloxane, and H_2S competes for carbon adsorptive capacity, so a complete treatment system includes removal of H_2S, moisture, and siloxane.

Most anaerobic digesters operate at a pressure of 1 to 4.5 kPa (4 to 18 in) H_2O. Microturbines require digester gas fuel to be delivered at 400 to 1000 kPa (60 to 140 psig) (U.S. EPA, 2015). Digester gas compression equipment is typically included as part of the overall gas treatment train. Hydrogen sulfide removal typically requires moist gas that can be incorporated ahead of compression and subsequent treatment steps. H_2S can be removed by iron-based adsorbents, activated carbon, or wet scrubbers, incorporating chemical or biological methods (or both).

The pressurized gas train includes moisture and siloxane removal before the microturbine fuel train, which may include additional filters and pressure regulators.

NFPA 820 (2020) provides fire protection standards for digester gas handling and processing at WRRFs. Digesters and gas treatment facilities are rated as hazardous spaces that may require special electrical construction depending on separation distances and ventilation.

Operations and Maintenance

Modes of Operation

As with any Brayton cycle turbine, microturbines require the compressor section to be rotating before combustion can occur. To start the microturbine, the generator is run as a motor, providing torque to the microturbine shaft until an adequate speed is reached. Power to start the units can be obtained from a grid connection; however, for black start capability, a battery pack charged by the microturbine is required.

The operating speed of microturbines and their generators is very high, up to 60 000 rpm (U.S. EPA, 2015). The bearings are often air lubricated to reduce wear, and most microturbines incorporate a generator on the same shaft to make the package as compact as possible. Microturbines without air-lubricated bearings make use of ceramic oil-lubricated bearings that require oil filters and pumps, adding to capital and maintenance costs.

The high operating speed means that a microturbine generator cannot interface directly with the grid, and units are equipped with a gearbox or solid-state electronics that convert the high-frequency output to grid frequency at 50 or 60 Hz (U.S. EPA, 2015). When the microturbine parallel to the utility it is called the grid-connect mode. Grid-connect is contrasted to standalone operation mode where the microturbine is commanded to a specific output power level and typically includes emergency battery packs that are used to provide power to remote sites when electricity is not available. Some microturbines are also equipped with dual-mode operation.

Microturbine systems are also available in two general types: simple and recuperated. The simple microturbine energy conversion efficiency is low, at approximately 15%. Commercially available microturbines for application at WRRFs are recuperated units so simple microturbines will not be discussed further. Recuperated microturbines use waste heat to heat compressed air between the compressor stage and the combustion chamber. The overall conversion efficiency is between 26% and 32% on a recuperated microturbine. With both types, waste heat capture for hot water can raise overall co-generation efficiency to 80% (U.S. Department of Energy, 2016).

Maintenance Requirements

Maintenance requirements for microturbines are fewer than those of ICEs because of the small number of moving parts and lower operations and maintenance costs associated with microturbines. These costs include routine inspections, scheduled repairs and replacement, preventive maintenance, and labor. Recommended preventive maintenance intervals range between 2000 and 8000 hours, which can be extended longer if equipment are operated above a normal temperature of 10 °C (50 °F) (U.S. EPA, 2017).

Preventive maintenance activities primarily consist of inspecting inlet air and external fuel filters and battery packs. Each battery pack must be fully charged before storage and charged again before being brought back into service. Battery packs are used in stand-alone mode. The total life of a microturbine is estimated to be 40 000 run hours (U.S. EPA, 2017).

Case Studies

Janesville, Wisconsin, Wastewater Treatment Plant

Janesville commissioned four 65-kW Capstone microturbines in November 2010. The microturbines replaced two Waukesha engine-generators. The microturbines are fueled by digester gas produced by three anaerobic digesters. Gas storage is provided by a dual membrane cover on one digester. Digester gas is treated for H_2S removal with an iron sponge followed by a skid-mounted system that includes gas compression, moisture removal, and siloxane removal. In 2012, a 200-kW microturbine and a carbon dioxide removal system were added to produce renewable natural gas (RNG) to be used as fuel for Janesville's compressed natural gas (CNG) vehicle fleet.

The Janesville digesters produce approximately 3685 Nm^3 per day (130 000 scfd) of digester gas that is used in the microturbines or to produce RNG. A recent summary of the generated energy is show in Table 1 below. The data summarized in Table 1 was provided by the Janesville Wastewater Utility.

TABLE 1. JANESVILLE GENERATED ENERGY SUMMARY

	2016	2017	2018	2019
Digester Gas Production (MMscf)	48	47	49	46
Digester Gas Production (Dtherm) (LHV)	26 068	25 730	26 696	25 382
CNG (Dtherm)	517	491	524	582
Net digester gas to microturbines (Dtherm)	25 552	25 239	26 172	24 800
Annual Generated Electricity (kWh)	1 937 800	1 817 800	1 862 296	2 007 694
Average Annual Power Generation (kW)	219	208	218	229
Overall efficiency of generation (%)	26%	25%	24%	28%
Heat Rate (Btu/kWh)	13 186	13 884	14 054	12 353
65kW microturbine hours	15 597	20 569	26 265	18 283
200kW microturbine hours	7186	6450	4254	5420
% hours 65 kW	68%	76%	86%	77%
% hours 200 kW	32%	24%	14%	23%
Average 65 kW Generation	51	45	47	57
Average 200-kW Generation	158	138	146	177
Heat Recovered 65 kW (Dtherm)	3083	3558	4780	4038
Heat Recovered 200 kW (Dtherm)	4545	3571	2478	3831

The electricity generated by the microturbines is sold to Alliant Energy under a power purchase agreement (PPA). The PPA pays \$0.12 per kWh during on-peak hours and \$0.074 per kWh during off-peak hours. The average rate paid is \$0.093 per kWh. Table 2 shows a recent energy cost and revenue summary for the WRRF.

TABLE 2. JANESVILLE ENERGY COST AND REVENUE SUMMARY

	2016	**2017**	**2018**	**2019**
Purchased Electricity Cost	$467,798	$497,490	$465,784	$495,984
Generated Electricity Revenue	$(179,708)	$(168,058)	$(172,916)	$(187,055)
Net Electricity Cost	$288,090	$329,433	$292,868	$308,929
Average Generated Revenue ($/kWh)	-0.093	-0.092	-0.093	-0.093
Average Purchased Cost ($/kWh)	0.080	0.081	0.082	0.082
WRRF Natural Gas Cost	$23,204	$31,979	$34,401	$25,834
Net Heat Recovery Summer (Dtherm)	2403	2206	2202	2202
Heat Recovery Winter (Dtherm)	4493	4199	2386	4635
Net Purchased Energy Cost	$317,927	$368,953	$330,912	$341,941
CNG revenue at $2.50 gasoline gallon equivalent*	($11,327)	($10,760)	($11,492)	($12,759)
Net Energy Cost	$299,967	$350,651	$315,777	$322,003

*1 GGE = 3.74 liter equivalents = 120 MJ

The data presented in Table 2 is based on utility bills and plant operating data provided by the city. The revenues generated from the microturbine project represent a 7-year payback for the project.

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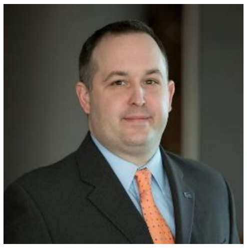

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