Farah Nazifa Nourin
Department of Mechanical Engineering,
University of Wisconsin-Milwaukee,
115 E. Reindl Way,
Glendale, WI 53212
e-mail: fnourin@uwm.edu

Ahmad I. Abbas
Department of Mechanical Engineering,
University of Wisconsin-Milwaukee,
3200 N. Cramer Street,
Milwaukee WI, 53211
e-mail: aiabbas@uwm.edu

Mohammad D. Qandil
Department of Mechanical Engineering,
University of Wisconsin-Milwaukee,
3200 N. Cramer Street,
Milwaukee WI, 53211
e-mail: mdqandil@uwm.edu

Ryoichi S. Amano[1]
Fellow ASME
Department of Mechanical Engineering,
University of Wisconsin-Milwaukee,
115 E. Reindl Way,
Glendale, WI 53212
e-mail: amano@uwm.edu

Analytical Study to Use the Excess Digester Gas of Wastewater Treatment Plants

This study presents an analytical method that can be used to enhance the power production rate and the energy-saving at wastewater treatment plants. The digester used at wastewater treatment plants produces digester gas by anaerobic digestion, with which biofuel production can be achieved. Biofuels can be used to meet some of the energy requirements of the wastewater treatment facility through combined heat and power (CHP) gas engines (cogeneration). Using micro gas turbine (MGT), a CHP technology can be introduced in wastewater treatment plants (WWTPs). The combination of MGTs and absorption chillers is a promising technology as it produces electricity, heating, and cooling simultaneously. The study demonstrated how the waste heat of MGTs could be used to drive absorption chillers. In this analytical study, a detailed technical and economic analysis is provided on the trigeneration system, i.e., the integration of MGTs and absorption chillers driven by waste digester gas of the wastewater treatment plants. It can meet the heating and cooling demands of the plants, which promote the reduction of utility costs. The technology presented is also useful for other thermal energy users. [DOI: 10.1115/1.4047603]

Keywords: combined power and heat (CHP), micro gas turbine (MGT), wastewater treatment plant (WWTP), trigeneration system; alternative energy sources, energy conversion/systems, energy from biomass, power (co-) generation

Introduction

Power consumption is increasing day by day around the world. It is necessary to reduce energy consumption and increase energy efficiency both in industries and in residential buildings. It is a challenge for the world to expand the usage of renewable energy. Climate change is also a concerning issue that encourages everyone to embrace renewable energy sources. Only 17% of U.S. electricity is generated from renewable energy sources [1].

The U.S. Department of Energy (DOE) promotes converting waste to energy, especially sludges from the municipal wastewater treatment plants (WWTPs). At many facilities, wastewater treatment plants use digester to stabilize the sludge that is removed from the wastewater during treatment. The purpose is to reduce the mass of the sludge and convert it into a non-hazardous form so that it may be handled or used with minimal health hazards. This stabilization can be performed by using anaerobic digestion. In this process, a significant fraction of the organic matter is broken down into hydrocarbons, such as carbon dioxide (CO_2), methane (CH_4), and traces of other contaminant gases, which is accomplished in the absence of oxygen. About half of the amount is then converted into biogases, while the remainder is dried and becomes a residual soil-like material. The biofuel can be used to meet some of the energy requirements of the wastewater treatment facility through combined heat and power (CHP) gas engines (cogeneration). Using micro gas turbine (MGT), a CHP technology can be introduced in WWTPs. The waste heat of MGTs can be further used to drive absorption chillers. The combination of MGTs and absorption chillers is a promising technology as it produces electricity, heating, and cooling simultaneously. It is also useful to other thermal energy users.

According to the U.S. Department of Energy CHP Installation Database, the microturbine market share has reached 25% of capacity from 100 kW to 5 MW [2] (Fig. 1). Several researchers reported on CHP, and the use of digester gas in CHP as fuel [3–7]. Tourlidakis et al. [8] investigated CHP generation for small municipality areas for heating purposes in Northern Greece. They examined the replacement conventional heating system with CHP. CHP with the combination of heating and cooling network was studied by Sdringola et al. [9]. Their case study shows the synergy between CHP and heating and cooling potential. Saidi et al. [10] reported a comparative study of CHP for the food industry basing on the system covers space heating and cooling and power. A supervisory control system is established by Cho et al. [11]. They used a feed-forward control system for CHP operation. The transient process of micro-CHP was examined by Ippolito and Venturini [12]. Hwang [13] investigated the energy benefits of the absorption chiller integrated with MGT. Abbas et al. [14] presented a study for net-zero-energy wastewater treatment plants and achieved the goal; they utilized the anaerobic digester gas into a CHP system.

The microturbine technology works based on the Brayton cycle (Fig. 2). The compressed ambient air enters the combustion chamber and then routed through a recuperator. Recuperator is a non-mixing exhaust to an air heat exchanger. Microturbine utilizes a portion of exhaust heat with the assist of the recuperator to preheat the combustion air. As a result, less fuel can be required to achieve the exhaust temperature. It also leads to increased efficiency in fuel to electric energy. The compressor, turbine, and generator are mounted on a single shaft, so they produce electrical power while drawing air to maintain the overall process. The faster the shaft spins in the magnetic field, and the more electrical output is obtained by the generator [15].

An absorption chiller can be installed with microturbine as it is a heat-operated refrigeration equipment. The cooling capacity of it is generated using waste heat. The WWTP has the benefit of using the excess digester gas (EDG) to implement CHP as the WWTP produces EDG during its process. Digester gas has the prospective to

[1]Corresponding author.

Contributed by the Advanced Energy Systems Division of ASME for publication in the Journal of Energy Resources Technology. Manuscript received May 21, 2020; final manuscript received June 8, 2020; published online July 29, 2020. Editor: Hameed Metghalchi.

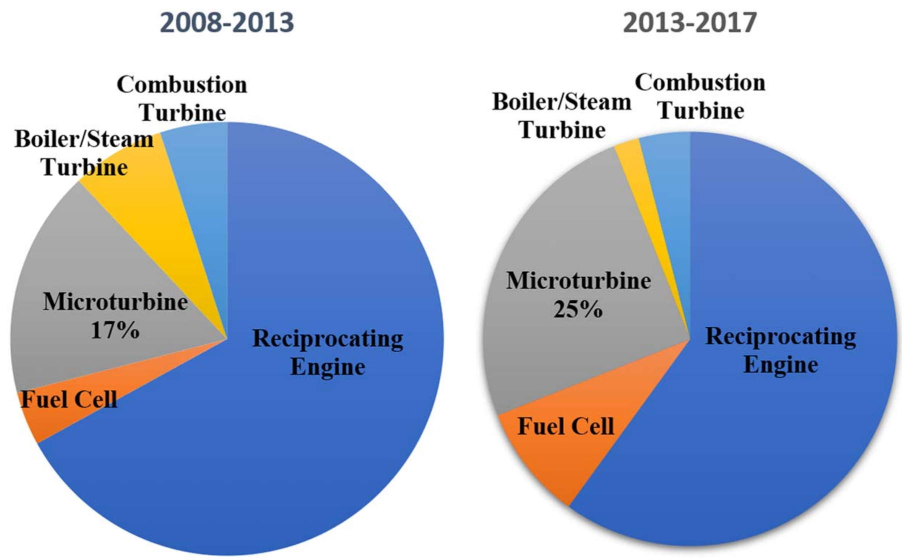

Fig. 1 CHP Installations by Technology, 100 kW—5 MW between 2008–2013 and 2013–2017 [2]

capture methane that would escape into the environment [17]. It is a form of biogas, which is a proven source of energy used in the U.S. and all over the world for decades. Nutrient-rich soil and pelletized also come as a byproduct, which can be used as fertilizer. In the study by Wisconsin, many cogeneration plants burn a combination of biomass with conventional fuels to generate electricity and heat. Figure 3 shows a typical cogeneration system.

Szega and Zymelka [19] studied the thermodynamic and economic analysis of CHP with absorption chillers. The study was conducted for real back-pressure CHP unit and single effect absorption refrigerators using water and lithium bromide as the working fluids. The research shows that after 25 years, the net present value of the combined production of cooling, heat, and power unit is a little over one million USD. The internal rate of return of capital is 14.5%. They concluded that the deterioration of the economic situation would not significantly affect the profitability of the investment as the payback period (PBP) is 13 years, and the invested amount would be returned at around half of the planned operating time. Ghaebi et al. [20] applied a dynamic and economic analysis to evaluate the CHP plant with lithium bromide (LiBr)/water absorption chiller to produce cold. Low-pressure steam (3 bar and 1 bar) powers the absorption chiller. The primary energy-savings in this system are 21,000 MWh/year. Zhang et al. [21] also investigated a trigeneration system with LiBr/water absorption chiller. The combined cooling, heating, and power system can recover the heat of the refrigeration cooling water for reheating the boiler water, which increases the energy conversion efficiency. The results show that the trigeneration system can bring a 26.6% decrease in primary energy rate consumption compared with the CHP plant and separate generation of cold.

Yun et al. [22] studied an analytic approach for defining optimal operation decisions for a power generation unit in CHP for facilities in Chicago, IL and Philadelphia, PA. Bruno et al. [23] studied a case study on a sewage treatment plant with a trigeneration system using biogas. They concluded that the best trigeneration systems are entirely replacing the existing system with a trigeneration plant that uses all the available biogas and additional natural gas to meet the heating demands of the sewage treatment plant completely.

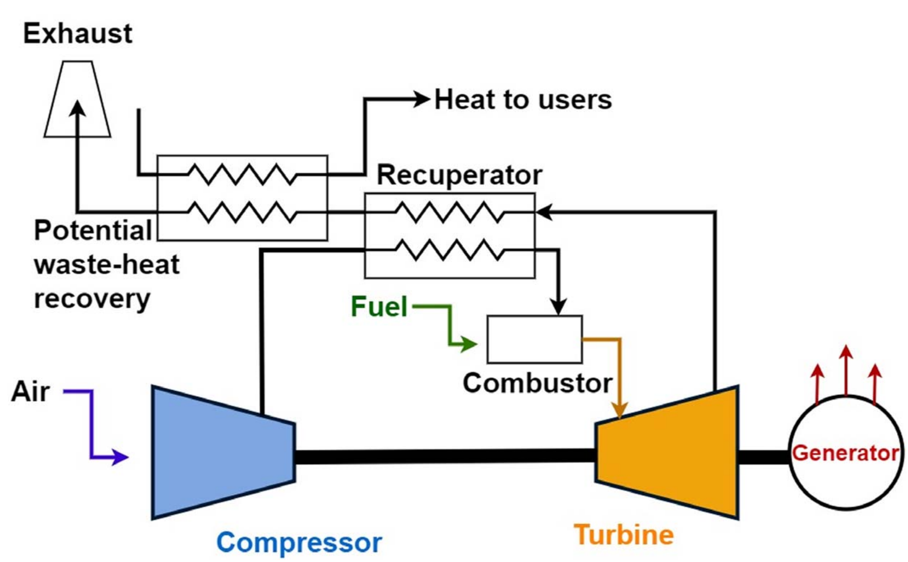

Fig. 2 Microturbine working principle [16]

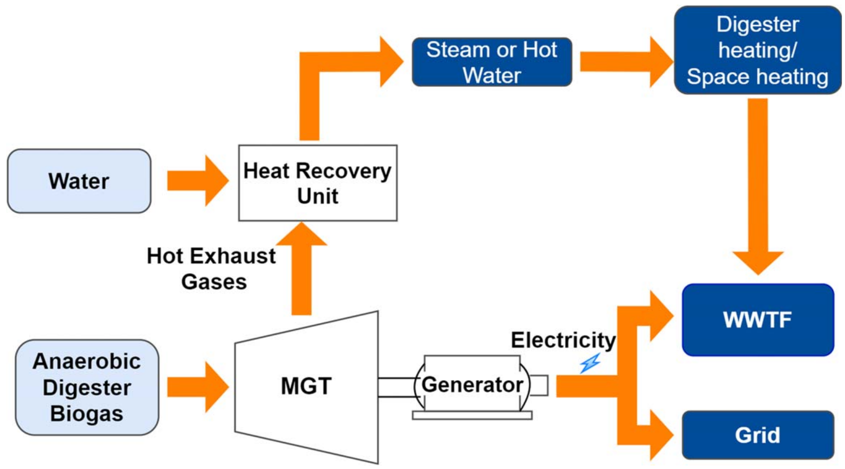

Fig. 3 Typical cogeneration system at WWTP [17]

Co-trigenerative arrangements were also attempted by several researchers. [24,25].

The authors' team performed energy assessments at several facilities in Wisconsin. The study contains the breakdown of the annual total energy cost in terms of electricity, gas, and water, facility site survey, and list of energy efficiency measures and a group of interactive measures of the facility. Before implementing the CHP system in a WWTP, multiple issues should be considered. Such issues include as to if they are with adequate concurrent thermal loads and availability of the natural gas, the compatibility of the existing system with the recoverable heat available from the prime mover, the availability of space for the CHP system [26]. Picardo et al. [27] analyzed the potential of district heating with the biogas generated from the WWTPs. They claimed that the development of this system saves energy, and 1.8×10^3 tons of CO_2 can be saved. A case study is completed in Japanese WWTP by Nakatsuka et al. [28]. This study shows that, by introducing CHP in WWTP, the CHP reduces annual costs by 35% and CO_2 emission by 1%. Another case study on adding the CHP in WWTP shows that it can save up to 46.63% of the operational cost of the plant [29]. Trendewicz and Braun [30] studied a large-scale (15.5 MW) CHP system in a large WWTP. They completed an exergy analysis and concluded that the highest contributor to exergy destruction is a waste heat recovery unit (25%). The study of Basrawi et al. [31] represents the optimization of biogas fueled cogeneration systems in WWTP.

Mosayeb Nezhad et al. [32] reported on the integrated system of both solid oxide fuel cells and MGT for wastewater treatment plants. In this integrated system, a heat exchanger is installed to transfer thermal energy to the sludge. The biogas that is not fed into solid oxide fuel cell can be used in MGT. If the produced biogas is not enough to operate the system, then natural gas should be applied. According to the authors, even though natural gas may need to use, the plant efficiency is increased by 7%. Another research group of Basrawi et al. [33] studied the techno-economic performance of biogas-fed MGT in sewage treatment plants. They suggested where heat demand fluctuates, the smaller size of MGT should use for better technical and economic performance. Somehsaraei et al. [34] developed a steady-state thermodynamic model for CHP system. The model also reported that MGT system should use on a small scale. Ge et al. [35] described the trigeneration system with MGT and absorption chiller. Their module is divided into a power and heat section, a heat diversion and refrigeration section, and a supermarket module. The module shows that with higher fuel mass flowrates the efficiency is increased. A trigeneration system was studied in the subtropical area [36]. In the subtropical area, summer is scorching. So, there is almost no heating demand. But the cooling demand is significantly high. Thus, the study shows how to maintain effective use of digester gas in summer for space cooling. The researchers concluded that a double effect absorption chiller driven by bypass of 450 °C flue gas is the best choice in this case.

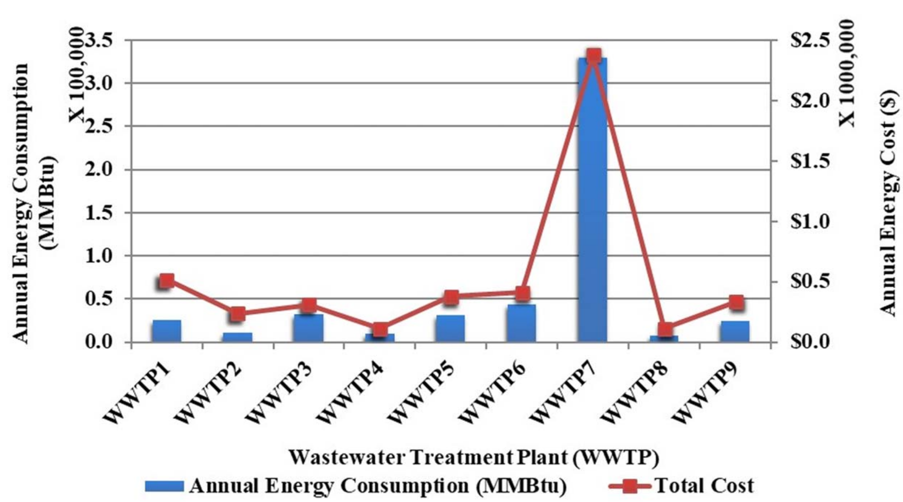

Fig. 4 Annual energy consumption and cost

Table 1 Thermal and the electric potential of WWTP-7, WWTP-8, and WWTP-9

	WWTP-7	WWTP-8	WWTP-9
Fuel required for digester load (MMBtu/day)	40	3.95	3.84
EPG (MMBtu/day)	235.52	23.28	17.10
EDG (MMBtu/day)	230.95	18.76	5.99
EP (kW)	750	75	54
HR (MMBtu/day)	69.59	6.88	3.91
AHA (MMBtu/day)	37.59	3.72	0.83

Introducing biogas-fed microturbines is one of the sources to develop the renewable energy sector. This study investigated a trigeneration system in three WWTPs and discussed the feasibility of it.

Methods

From 2017 to 2019, the authors' team conducted research through the onsite visits at nine WWTPs in the state of Wisconsin. Authors complete pre-assessment analysis before the field-assessment, after the completion of the onsite assessment of energy-savings recommendation data. The annual energy consumption and annual energy cost collected from the utility bills of the nine plants are shown in Fig. 4.

In this analytical study, an absorption cooling system is integrated into MGT. The excess biogas from the digester performs as a fuel of MGT, and the waste heat from MGT was used for an absorption chiller and a boiler. The chilled water was used to condense water in the biogas pre-treatment before its combustion in the MGT. It was also used to cool the combustion air entering into MGT. Besides, the chilled water can also be used for air-conditioning purposes. This trigeneration system leads to power generation, space heating, and cooling.

Following calculations have been done to get the amount of EDG:

$$Fuel\ requied\ for\ digester\ load = \frac{Total\ digester\ heat\ load}{\eta_B} \tag{1}$$

$$EPG = Excess\ gas\ flow\ rate \times Gas\ lower\ heating\ value \tag{2}$$

$$EDG = EPG - (EPG \times \%\ of\ gas\ used\ for\ digester\ heat\ load) \tag{3}$$

$$EP = EPG \times Electric\ efficiency \tag{4}$$

$$HR = \frac{EP}{Power\ to\ heat\ ratio} \tag{5}$$

$$AHA = HR - Digester\ heat\ load \tag{6}$$

$$\begin{aligned} AES = AHA \times (&No.\ of\ heating\ weeks\ per\ year \\ &\times Heating\ days\ per\ week \\ &+ No.\ of\ cooling\ weeks\ per\ year \\ &\times Cooling\ days\ per\ week) \end{aligned} \tag{7}$$

$$ACS = AES \times R_g \tag{8}$$

The rate of selling electricity generated is different from the rate of purchasing it from the utility provider. Therefore, indirect annual energy-saving is

$$AES_{electricity} = \frac{ACS}{R_E} \tag{9}$$

$$PBP = \frac{Implementation\ Cost}{ACS} \tag{10}$$

Results and Discussion

Three WWTPs (WWTP-7, WWTP-8, and WWTP-9) were considered in this study by using excess digester gas for analyzing annual energy and cost-saving. WWTP-7 is a massive plant with a capacity of 32×10^3 gallons per day (MGD), WWTP-8 is a small plant with a capacity of 3.16 MGD, and WWTP-9 is the smallest one with a capacity of 1.5 MGD. According to the plant personnel, the average digester gas of WWTP-7, WWTP-8, and WWTP-9 is 392,535 ft^3/day, 38,800 ft^3/day, and 28,500 ft^3/day, respectively. The lower heating value for digester gas was considered 600 Btu/ft^3 [37]. As listed in Table 1, the energy content of the digester for WWTP-7, WWTP-8, and WWTP-9 is 236 MMBtu/day, 23 MMBtu/day, and 17 MMBtu/day, respectively. The study assumes 50% of the summer and winter operation. The excess digester gas achieved from these plants is 190 MMBtu/day, 19 MMBtu/day, and 6 MMBtu/day, respectively. According to the U.S. Environmental Protection Agency (EPA) CHP Partnership, the electricity efficiency and power to heat ratio are considered 26% and 0.88, respectively [38].

According to the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, CHP is suitable where digester gas is available in the process of anaerobic digestions. Biogas is a product of anaerobic digestion, which is formed by the anaerobic

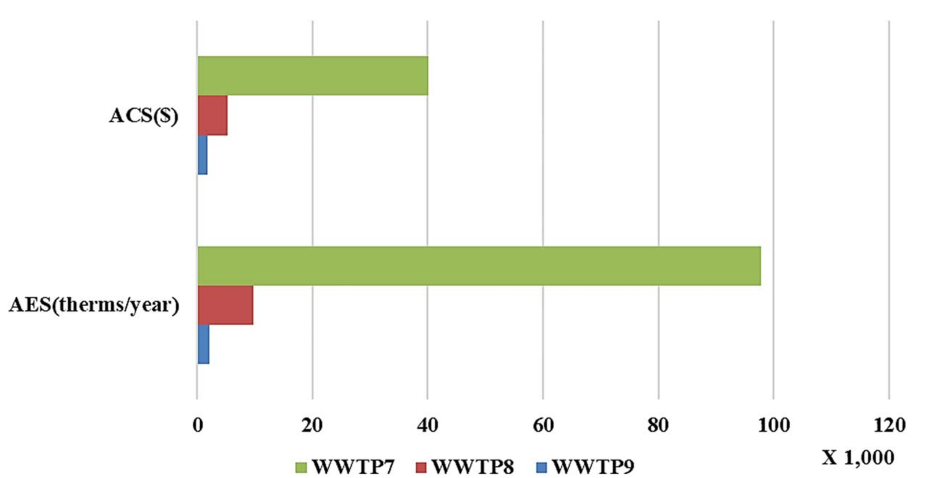

Fig. 5 Annual energy and cost-savings in terms of using additional heat available

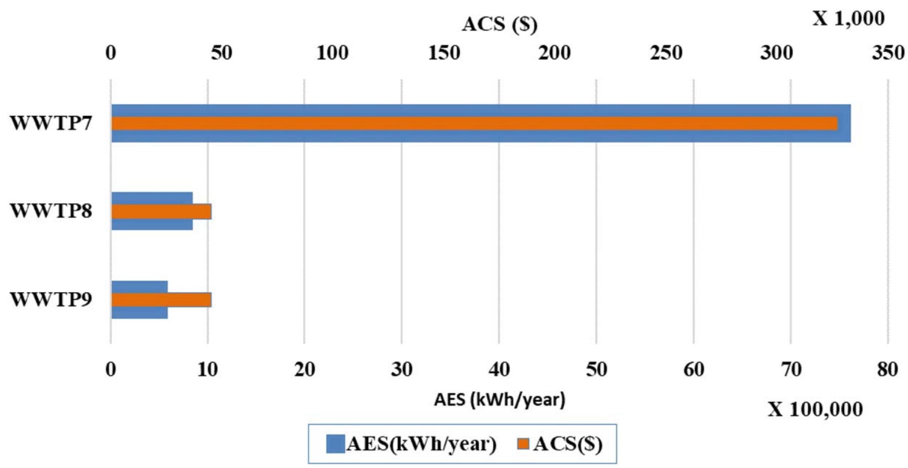

Fig. 6 Annual electricity and cost-savings in terms of CHP application

Table 2 Implementation cost and a payback period of CHP installation

	WWTP-7	WWTP-8	WWTP-9
MGT (kW)	6 × 120	2 × 60	1 × 60
Implementation cost ($)	2,880,000	480,000	240,000
PBP (year)	7.84	9.5	9.39

microorganisms. The microbes feed off carbohydrates and fats. It produces methane as a byproduct and carbon dioxides as metabolic waste products. Biogas helps to generate green energy from waste and reduces the volume of waste disposed of in landfills. It also promotes greenhouse gas emission and maximizes the biogas production. Figures 5 and 6 represent the annual electricity-savings and cost-savings as a function of space heating, cooling, and CHP application. With regard to the energy-savings and cost-savings with additional heat available (AHA), WWTP-7 shows the highest value as it the largest plant considered than WWTP-8 and WWTP-9. The lowest annual cost-savings (ACS) and energy-savings for WWTP 9 are due to the most economical digester gas. In terms of CHP application for WWTP-7, the annual cost-savings are lower than the annual energy-savings (AES) due to the small unit price of electricity of this plant.

According to Figs. 5 and 6, the total energy-savings from AHA and CHP application for WWTP-7 are 10,389,633 kWh, and cost-saving of $367,508. Annual energy and cost-savings for WWTP-8 is 1,038,523 kWh/year, and $50,532, whereas the WWTP-9 can save 570,352 kWh/year, which is $25,564. For WWTP-7, WWTP-8, and WWTP-9, 6 × 120 kW MGT, 2 × 60 kW, and 1 × 60 kW need to be installed, respectively. According to the U.S. Environmental Protection Agency (EPA) CHP Partnership [38] guide, the average cost per kW is $4000. The simple PBP for WWTP-7, WWTP-8, and WWTP-9 is 7.84 years, 9.5 years, and 9.39 years, respectively (see Table 2).

Hybrid Optimization Model for Multiple Energy Resources (HOMER) Pro software [39] was used for analyzing the capacity of the turbine and biogas consumption. It is developed by the National Renewable Energy Laboratory (NREL) in the United States. Figure 7 shows the simulation results of the output capacity of the microturbine of these three WWTPs for every month. The power output for WWTP-7 is around 1200 kW in every month. In the cases of WWTP-8 and WWTP-9, it is around 120 kW and 90 kW, respectively. The electricity production (EP) depends on the biogas consumption of the plants. Thus, it is required to keep tracking of the biogas consumption. According to Fig. 8, for

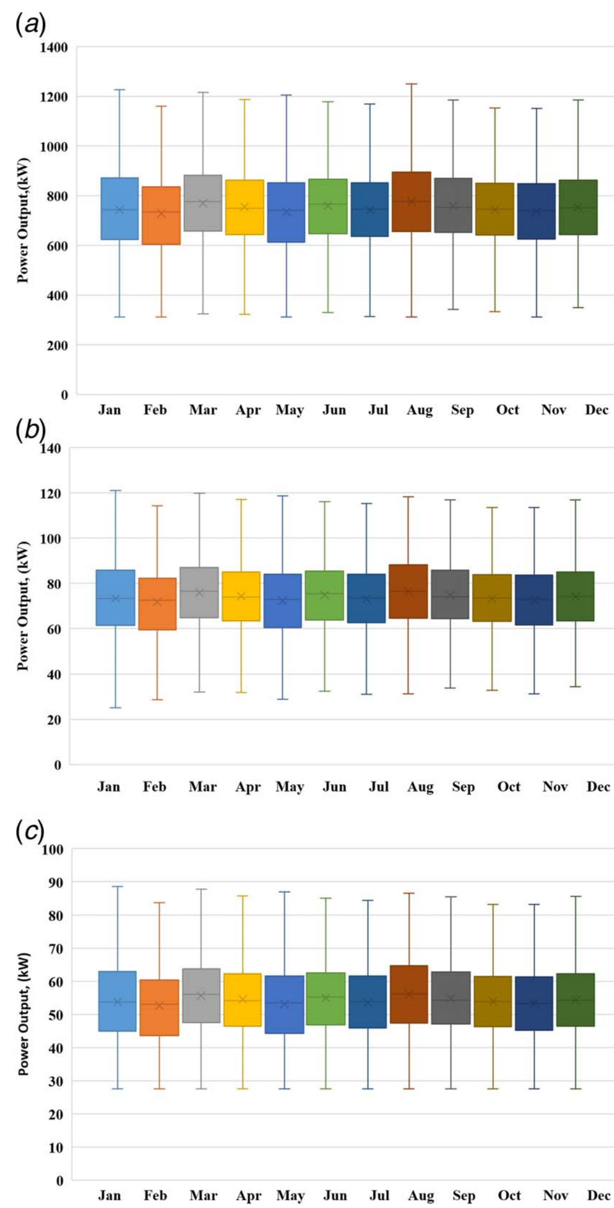

Fig. 7 Microturbine output (kW) (*a*) WWTP-7, (*b*) WWTP-8 and (*c*) WWTP-9

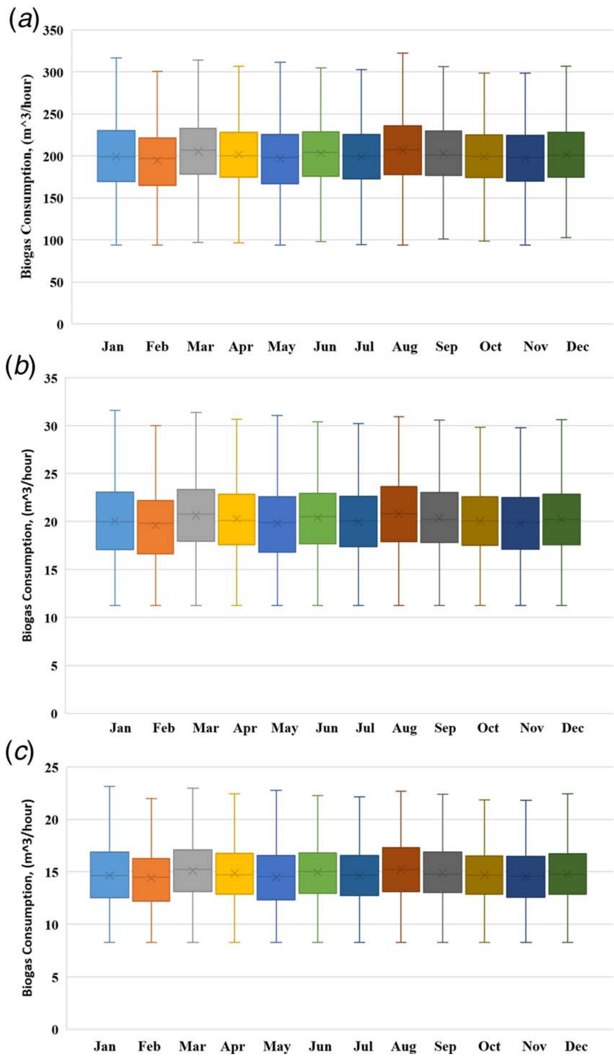

Fig. 8 Biogas consumption (m3/hour): (*a*) WWTP-7, (*b*) WWTP-8, and (*c*) WWTP-9

WWTP-7, biogas consumption is the highest in August, which relates to the EP. For WWTP-8 and WWTP-9, the highest biogas consumption is in January for both the plants, and it is relatable with the data shown in Fig. 7. Considering that turbines work for the year-round, the electrical summary is given in Tables 3 and 4.

Table 5 shows the gas emission rate for installing a CHP system in the plants. All the pollutants show the highest value for WWTP7, as it is the largest plant considered. The highest carbon dioxide and carbon monoxides are 0.000931×10^3 metric tons/year and 0.000024×10^3 metric tons/year 931 megagrams/year, and 24 megagrams/year, respectively. According to the report of the U.S. Energy Information Administration [40], the coal-powered plant emits 1127×10^3 metric tons of carbon dioxide every year. The Department of Energy reports that 46 giga watt (GW) of CHP capacity is achievable. Kaarsberg et al. [41] concluded that the CHP would result in net energy-savings of 2.6 quads and carbon emissions reductions of 74×10^3 metric tons of carbon equivalent in 2010. The district energy system and industries together can avoid the emissions of 1.4×10^3 tons of SO_2 and 0.6×10^3 tons of NOx emissions. According to the report of the U.S. Environmental Protection Agency, from June 2011, the CHP system was installed at 104 WWTPs, which represents 190 MW of capacity in 30 states of U.S. [38]. The database of U.S. DOE CHP Installation 2016 shows that the WWTPs can generate 2.41 GW of electricity at 11,676 sites [18].

Table 3 Electrical summary of WWTPs

	WWTP-7	WWTP-8	WWTP-9
Production (kWh/year)	6,571,065	648,504	474,965
Mean output (kW)	750	74	54.2
Minimum output (kW)	312	37.5	27.5
Maximum output (kW)	1250	136	99.3

Table 4 Biogas consumption statistics

	WWTP-7	WWTP-8	WWTP-9
Total fuel consumed (m3)	1,756,640	176,631	129,382
Avg. fuel per day (m3/day)	4813	484	354
Avg. fuel per hour (m3/hour)	201	20.2	14.8

Table 5 Emissions from CHP for WWTP7, WWTP8, and WWTP9

	WWTP-7	WWTP-8	WWTP-9
Carbon dioxide (kg/year)	931,470	93,878	87,485
Carbon monoxide (kg/year)	23,831	2,396	1755
Unburned hydrocarbons (kg/year)	1,265	127	93.2
Particulate matter (kg/year)	204	20.5	15
Sulfur dioxide (kg/year)	0	0	0
Nitrogen oxides (kg/year)	4,567	459	336

Conclusions

The electricity and thermal potential for introducing CHP in WWTP are discussed in this paper. The analysis achieved was gained using a reliable source of renewable energy as well as reduces the emission of greenhouse gas. Implementation cost and PBPs were calculated, which represents a high cost of implementing such a system, and it leads to a PBP of 7–10 years. For smaller plants, the implementation cost is in the order of \$200,000–\$500,000, whereas it requires about \$3,000,000 for a plant of 30 MGD. Even though this system is expensive to install, it is beneficial in the long run. From an environmental point of view, the system offers less pollution than the coal-fired system. The system is feasible, environmentally, and technically. This study provides economic research in terms of MGT price, electricity, and gas savings. Before planning to adopt the technology, it is advisable for the facility to request an incentive from the federal and state government agencies since there are several incentive programs available in each municipal and state.

Finally, it can be mentioned that the study gives an idea to energy engineers and plant personnel about the benefits of installation and the impact of CHP using MGT combining absorption chiller and space heating.

Acknowledgment

U.S. Department of Energy funds this project under grant DE-EE0007716.

Nomenclature

CCHP = combined cooling, heat, and power
CHP = combined heat and power
EPG = energy potential of gas (Btu/day)

HR = heat recovery (Btu/day)
IAC = industrial assessment center
Rg = average gas cost ($/therm)
RE = average electricity cost ($/kWh)

Greek Symbol

η_B = the efficiency of the boiler (%)

References

[1] 'Renewable Energy,' 2019 Wisconsin Academy of Sciences, Arts and Letters, https://www.wisconsinacademy.org/content/renewable-energy, Accessed January 8, 2020.
[2] 'U.S. MICROTURBINE CHP MARKET SHARE GROWS TO A RECORD 25%', Capstone Turbine Corporation, August 29, 2018, https://www.capstoneturbine.com/news/press-releases/detail/3625/, Accessed January 8, 2020.
[3] Cardona, E., and Piacentino, A., 2004, "A Validation Methodology for a Combined Heating Cooling and Power (CHCP) Pilot Plant," ASME J. Energy Resour. Technol., **126**(4), pp. 285–292.
[4] Khaliq, A., Kumar, R., and Dincer, I., 2009, "Exergy Analysis of an Industrial Waste Heat Recovery-Based Cogeneration Cycle for Combined Production of Power and Refrigeration," ASME J. Energy Resour. Technol., **131**(2), p. 022402.
[5] Vasquez Padilla, R., Ramos Archibold, A., Demirkaya, G., Besarati, S., Yogi Goswami, D., Rahman, M. M., and Stefanakos, E. L., 2012, "Performance Analysis of a Rankine Cycle Integrated With the Goswami Combined Power and Cooling Cycle," ASME J. Energy Resour. Technol., **134**(3), p. 032001.
[6] Liu, P., Zhu, M., Zhang, Z., and Zhang, D., 2019, "Rheological Properties and Stability Characteristics of Biochar-Algae-Water Slurry Fuels Prepared by Wet Milling," ASME J. Energy Resour. Technol., **141**(7), p. 070709.
[7] Amano, R. S., Abbas, A. I., Al-Haddad, M., and Qandil, M. D., 2019, "Energy Consumption, Energy-Saving and Emissions Reduction of Wastewater Treatment Plants (WWTPs) in Wisconsin," AIAA Propulsion and Energy 2019 Forum, Indianapolis, IN, Aug. 19–22, p. 4239.
[8] Tourlidakis, A., Malkogianni, A., and Karlopoulos, E., 2013, June, "Combined Heat and Power Generation for a Small Municipality for District Heating Purposes, Using Different Fuels," ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, San Antonio, TX, June 3–7, p. V05AT20A008.
[9] Sdringola, P., Proietti, S., Astolfi, D., and Castellani, F., 2018, "Combined Heat and Power Plant and District Heating and Cooling Network: A Test-Case in Italy With Integration of Renewable Energy," ASME J. Sol. Energy Eng., **140**(5), p. 054502.
[10] Saidi, K., Orth, U., Boje, S., and Frekers, C., 2014, June, "A Comparative Study of Combined Heat and Power Systems for a Typical Food Industry Application," ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, Dusseldorf, Germany, June 16–20, Vol. 45653, p. V03AT21A010.
[11] Cho, H., Luck, R., and Chamra, L. M., 2010, "Supervisory Feed-Forward Control for Real-Time Topping Cycle CHP Operation," ASME J. Energy Resour. Technol., **132**(1), p. 012401.
[12] Ippolito, F., and Venturini, M., 2019, "Micro Combined Heat and Power System Transient Operation in a Residential User Microgrid," ASME J. Energy Resour. Technol., **141**(4), p. 042006.
[13] Hwang, Y., 2004, "Potential Energy Benefits of Integrated Refrigeration System With Microturbine and Absorption Chiller," Int. J. Refrig., **27**(8), pp. 816–829.
[14] Abbas, A., Saravani, M. S., Al-Haddad, M., and Amano, R. S., 2018, "Net-Zero-Energy (NZE) Wastewater Treatment Plants (WWTPs)," 2018 AIAA Aerospace Sciences Meeting, Kissimmee, FL, Jan. 8–12, p. 1712.
[15] MosayebNezhad, M., Mehr, A. S., Lanzini, A., Misul, D., and Santarelli, M., 2019, "Technology Review and Thermodynamic Performance Study of a Biogas-Fed Micro Humid Air Turbine," Renewable Energy, **140**, pp. 407–418.
[16] 'Understanding CHP,' Energy Solutions Center, https://understandingchp.com/overview-2/system-schematics/, Accessed January 8, 2020.
[17] USDA, USEPA, 2014, *USDOE. Biogas Opportunities Roadmap: Voluntary Actions to Reduce Methane Emissions and Increase Energy Independence*. Washington, DC. https://bit.ly/2xEW9TV, Accessed on April 18, 2020.
[18] 'Characterization of CHP Opportunities at U.S. Wastewater Treatment Plants,' 2019, U.S. Department of Energy, https://bit.ly/2ze8uPs, Accessed on April 19, 2020.
[19] Szega, M., and Żymełka, P., 2018, "Thermodynamic and Economic Analysis of the Production of Electricity, Heat, and Cold in the Combined Heat and Power Unit With the Absorption Chillers," ASME J. Energy Resour. Technol., **140**(5), p. 052002.
[20] Ghaebi, H., Karimkashi, S., and Saidi, M. H., 2012, "Integration of an Absorption Chiller in a Total CHP Site for Utilizing Its Cooling Production Potential Based on the R-Curve Concept," Int. J. Refrig., **35**(5), pp. 1384–1392.
[21] Zhang, C., Yang, M., Lu, M., Zhu, J., and Xu, W., 2012, "2012 International Conference on Medical Physics and Biomedical Engineering Thermal Economic Analysis on LiBr Refrigeration-Heat Pump System Applied in CCHP System," Phys. Proc., **33**, pp. 672–677.
[22] Yun, K., Luck, R., Mago, P. J., and Smith, A., 2012, "Analytic Solutions for Optimal Power Generation Unit Operation in Combined Heating and Power Systems," ASME J. Energy Resour. Technol., **134**(1), p. 011301.
[23] Bruno, J. C., Ortega-López, V., and Coronas, A., 2009, "Integration of Absorption Cooling Systems Into Micro Gas Turbine Trigeneration Systems Using Biogas: A Case Study of a Sewage Treatment Plant," Appl. Energy, **86**(6), pp. 837–847.
[24] Fragiacomo, P., De Lorenzo, G., and Corigliano, O., 2018, "Performance Analysis of a Solid Oxide Fuel Cell-Gasifier Integrated System in Co-trigenerative Arrangement," ASME J. Energy Resour. Technol., **140**(9), p. 092001.
[25] Hasan, A., and Dincer, I., 2020, "A New Integrated Ocean Thermal Energy Conversion-Based Trigeneration System for Sustainable Communities," ASME J. Energy Resour. Technol., **142**(6), p. 061301.
[26] American Society of Heating and Air-Conditioning Engineers, 2015, *Combined Heat and Power Design Guide*, ASHRAE.
[27] Picardo, A., Soltero, V. M., Peralta, M. E., and Chacartegui, R., 2019, "District Heating Based on Biogas From Wastewater Treatment Plant," Energy, **180**, pp. 649–664.
[28] Nakatsuka, N., Kishita, Y., Kurafuchi, T., and Akamatsu, F., 2020, "Integrating Wastewater Treatment and Incineration Plants for Energy-Efficient Urban Biomass Utilization: A Life Cycle Analysis," J. Cleaner Prod., **243**, pp. 118–448.
[29] Zuza, A., Agachi, P. S., Cristea, V. M., Nair, A., Tue, N. N., and Horju-Deac, C., 2015, "Case Study on Energy Efficiency of Biogas Production in Industrial Anaerobic Digesters at Municipal Wastewater Treatment Plants," Environ. Eng. Manage. J., **14**(2), pp. 357–360.
[30] Trendewicz, A. A., and Braun, R. J., 2012, July, "Modeling and Performance Evaluation of a Large-Scale Sofc-Based Combined Heat and Power System for Biogas Utilization at a Wastewater Treatment Facility," ASME 2012 10th International Conference on Fuel Cell Science, Engineering and Technology Collocated with the ASME 2012 6th International Conference on Energy Sustainability, San Diego, CA, July 23–26, pp. 541–552.
[31] Basrawi, M. F. B., Yamada, T., and Nakanishi, K., 2011, January, "Optimization of a Biogas-Fuelled Cogeneration System in a Sewage Treatment Plant," ASME 2011 Power Conference Collocated With JSME ICOPE, Denver, CO, July 12–14, pp. 393–402.
[32] MosayebNezhad, M., Mehr, A. S., Gandiglio, M., Lanzini, A., and Santarelli, M., 2018, "Techno-economic Assessment of Biogas-Fed CHP Hybrid Systems in a Real Wastewater Treatment Plant," Appl. Therm. Eng., **129**, pp. 1263–1280.
[33] Basrawi, F., Ibrahim, T. K., Habib, K., Yamada, T., and Idris, D. M. N. D., 2017, "Techno-economic Performance of Biogas-Fueled Micro Gas Turbine Cogeneration Systems in Sewage Treatment Plants: Effect of Prime Mover Generation Capacity," Energy, **124**, pp. 238–248.
[34] Somehsaraei, H. N., Majoumerd, M. M., Breuhaus, P., and Assadi, M., 2014, "Performance Analysis of a Biogas-Fueled Micro Gas Turbine Using a Validated Thermodynamic Model," Appl. Therm. Eng., **66**(1–2), pp. 181–190.
[35] Ge, Y. T., Tassou, S. A., Chaer, I., and Suguartha, N., 2009, "Performance Evaluation of a Tri-generation System With Simulation and Experiment," Appl. Energy, **86**(11), pp. 2317–2326.
[36] Chen, Y., Zhang, T., Yang, H., and Peng, J., 2016, "Study on Energy and Economic Benefits of Converting a Combined Heating and Power System to a Tri-generation System for Sewage Treatment Plants in Subtropical Area," Appl. Therm. Eng., **94**, pp. 24–39.
[37] Tchobanoglous, G., Burton, F. L., and Stensel, H. D., 2003, *Metcalf & Eddy Wastewater Engineering: Treatment and Reuse*, McGraw-Hill, New York, 4, pp. 361–411.
[38] "Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field', U.S. Environmental Protection Agency Combined Heat and Power Partnership, 2011, https://bit.ly/2NrsHFv, Accessed on January 14, 2020.
[39] HOMER (Hybrid Optimization Model for Multiple Energy Resources) Pro Software, https://www.homerenergy.com/
[40] "How Much Carbon Dioxide is Produced Per Kilowatt-Hour of U.S. Electricity Generation?", US Energy Information Administration, 2020, https://www.eia.gov/tools/faqs/faq.php?id=74&t=11, Accessed March 19, 2020.
[41] Kaarsberg, T. M., Elliott, R. N., and Spurr, M., 1999, "An Integrated Assessment of the Energy Savings and Emissions-Reduction Potential of Combined Heat and Power," Industry and Innovation in the 21st Century, Proceedings, USA.