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Research Paper

Thermoeconomic analysis of a biogas-fueled micro-gas turbine with a bottoming organic Rankine cycle for a sewage sludge and food waste treatment plant in the Republic of Korea

Taehong Sung, Sunhee Kim, Kyung Chun Kim *

School of Mechanical Engineering, Pusan National University, Busan 46241, Republic of Korea

HIGHLIGHTS

- Partial-load performance of MGT and ORC is studied.
- Economic aspects of each system for the target biogas plant are analyzed.
- Various plant operating parameters are discussed.
- System economic performance is compared to a biogas upgrade system.

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ABSTRACT

Biogas plants experience changes in biogas production due to seasonal weather changes, waste composition variation, operating methods, and other factors. These natural changes affect the economics of the subsystems. Generally, profit can be produced by selling the raw gas or the purified biomethane to the local gas distribution network, or by selling generated electricity in a dedicated power plant. Biogas plants are basically designed for sewage treatment and processing food waste produced from nearby urban areas. In this study, we analyzed the thermoeconomics of a biogas-fueled micro-gas turbine (MGT) system, which is coupled with a bottoming organic Rankine cycle (ORC) for a target biogas plant in Busan, Republic of Korea. Both systems were designed for heating a biodigester using heat in the exhaust gas. For the MGT, we considered a series of commercial multi-unit systems, and the partial-load performance was derived from the performance curves. For the ORC, we first designed an exergy-optimized cycle using n-pentane, a widely used working fluid, and then the partial-load performance was analyzed. The economic parameters were expressed based on the system size. We analyzed the system economics based on the annual utilization ratio (the produced power to the available maximum power) and the net present value (NPV). The effect of system control, methane concentration, and overhaul periods were analyzed. A membrane biogas upgrade system is considered for the comparison. In particular, we have found the followings: first, the biogas power generation systems showed the optimal system scales to provide the maximum NPVs according to the seasonal changes; second, the economics of the system were very sensitive to changes in the biogas methane ratio, electricity prices and overhaul periods; and third, in Korea, where electricity prices are low and natural gas prices are high, the competitiveness of power generation system is very low compared to a system that sells biogas directly.

1. Introduction

Biogas is produced through an anaerobic digester (AD) by cracking organic contents in landfill waste, sewage sludge, food waste, and other sources [1]. The produced biogas mainly consists of methane and carbon dioxide, which can be directly used for heating, or it can fill the role of natural gas like in vehicle fuel after scrubbing the carbon dioxide and sulfur oxides [2]. Biogas also reduces greenhouse gas emissions according to the applied substitute systems [3], and it can be another solution for diversifying national energy resources [4]. The digestate can also be used as a fertilizer [5]. Therefore, a large number of biogas plants have been built [6], despite the additional cost and some well-known problems.

* Corresponding author.
E-mail address: kckim@pusan.ac.kr (K.C. Kim).

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Nomenclature

A_i	surface area of anaerobic digester [m^2]
AB	annual benefit [$/year]
AC	annual cost [$/year]
AD	anaerobic digester [–]
AUC	all-unit control [–]
B_i	annual benefit [$]
BMP	biomethane price [$/Nm^3]
BUS	biogas upgrade system [–]
C_i	annual cost [$]
CC	combined cycle [–]
CHP	combined heat and power [–]
CI	compression ignition [–]
C_p	specific heat of sludge [kJ/kg-K]
η	efficiency [–]
i, IR	interest rate [–]
IC	investment cost [$]
ICE	internal combustion engine [–]
GT	gas turbine [–]
K	Stodola's coefficient [–]
KRW	South Korean Won [–]
LHV	lower heating value [MJ/kg]
LNG	liquefied natural gas [–]
NPV	net present value [–]
PB	payback period [–]
P	pressure [MPa]
MGT	micro-gas turbine [–]
*dot*M	mass flow rate [kg/s]
O.C.	operating coefficient [–]
ORC	organic Rankine cycle [–]
OUC	one unit control [–]
ϱ	density [kg/m^3]
$\dot{Q}$	heat rate [kJ/s]
SI	spark ignition [–]
SMP	system marginal price [$]
SOFC	solid oxide fuel cell [–]
T	temperature [°C]
U_i	heat transfer coefficient [W/m^2-K]
$\dot{V}$	volumetric flow rate [N m^3/day]
$\dot{W}$	power output [kJ/s]
x	system size [kW]

Subscripts

ad	anaerobic digester
amb	ambient
bg	biogas
bm	biomethane
bus	biogas upgrading system
eg	MGT exhaust gas
eV	ORC evaporator, evaporation
mgt	micro-gas turbine
orc	organic Rankine cycle
supply	supply
t	year
tb	ORC turbine
wf	ORC working fluid

Some of the problems are that ADs crack only a part of the organic contents, the reaction is slow, a large digestion chamber is required, the process is vulnerable to inhibitors, the quality of the produced gas is low, and the presence of siloxane can be critical for energy devices [7]. In the Republic of Korea, a total of 92 biogas plants are in operation as of 2015, and 21 more plants are planned or under construction [8], which indicates rapid growth in this field. The Korean Government is also considering a mandate on blending conventional natural gas with 2% biogas (BG2) [9]. However, the biogas technologies in Korea were evaluated as unsuccessful, mainly due to a lack of knowhow, deficient technologies, and policies [10]. Kim et al. [10] found that plant dimension, energy balance, and operation knowhow were lacking.

This study focuses on biogas utilization technologies rather than the production system. Several applications like heating and power generation can use raw biogas after stripping sulfur oxides. Power generation systems with flexible fuel requirements are being considered, such as compression ignition (CI) engines, spark ignition (SI) engines, micro-gas turbines (MGTs), and high-temperature fuel cells [11,12]. For example, Somehsaraei et al. [13] analyzed the performance of MGT for different methane concentrations and found that the electrical efficiency decreased only 0.4% for a 60% methane concentration compared to typical natural gas. This efficiency decrement increases the required fuel heat rate, but the rated power can be sustained by decreasing the compressor surge margin by only 0.3%. Similar fuel flexibility is reported for an SI engine. Staniforth and Ormerod [14] reported that an SOFC can operate directly with a wide range of raw biogas concentrations, but the performance shows quite complex characteristics because the reaction at the anode depends on the partial pressure of each component and the unreacted gas is discharged. Porpatham et al. [15] reported that the brake power in an SI engine is decreased and the hydrocarbon emission is increased because the high carbon dioxide content delays the combustion duration and the fuel is partially combusted. Chandra et al. [16] also reported similar performance degradation for an SI engine.

Considering these power systems, various proposed solutions for biogas plants have mainly focused on the system economics. Lantz [17] presented an economic comparison between CI engines, SI engines, and MGTs for different system capacities, assuming that the price model is a power law to reflect the market situation in Sweden. He concluded that the CI engine has the best economic performance among the systems considered, but all of them had poor economic performance overall and required a significant amount of subsidies. He also pointed out that additional heat integration to AD could alleviate the required subsidies by increasing the operating temperature to a thermophilic temperature.

Kang et al. [18] compared the economics of two gas turbine systems for combined heat and power (CHP) and combined cycle (CC) systems and found that the CHP system is more economical, but the system economics is quite dependent on the level of heat demand. Kang et al. [19] analyzed the effect of co-firing of natural gas and found that the heat value of biomethane is not enough for a conventional power system, and the external natural gas supply can complement natural fluctuations in the biogas production. They also found that the introduction of natural gas decreased the system economics and that the heat sale is essential for good economic performance. Akbulut [20] analyzed the economics of farm-scale biogas plants that included AD, CHP, and other accessories, but he did not consider the detailed performance of CHP units and their partial-load economics. Trendewicz and Braun [21] analyzed the economics of a SOFC-based CHP system for sewage sludge treatment plants based on the performance and lifetime cost. They compared the results with competing technologies and found that GT provides the best economic performance, and a large system has better economic performance due to the reduced capital cost.