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Techno-economic performance of biogas-fueled micro gas turbine cogeneration systems in sewage treatment plants: Effect of prime mover generation capacity

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ABSTRACT

The optimum size of Micro Gas Turbine Cogeneration Systems (MGT-CGSs) in a Sewage Treatment Plant (STP) in terms of its economic performance was investigated. A STP operating in a cold region was adopted as a model and was scaled down to obtain different size ratios. It was also assumed to operate in different regions to obtain different heat demand patterns. MGT-CGSs with power output capacity of 30, 65 and 200 kW were simulated to utilize biogas produced by the STP. Instead of multiple units of the same size of MGT-CGSs, combination of different sizes of MGT-CGSs was also investigated. Life Cycle Cost Analysis was carried out to compare the economic performance of MGT-CGSs. It was found that optimum combination of three types of MGTs (MGT-Combined) stated above had the highest power generated and efficiency. However, MGT-Combined also had larger power generation capacity and low usage ratio, thus resulting in higher capital investment. Although all configurations of MGT-CGSs can generate Net Present Value, optimum configuration was obtained when the rated fuel input of MGT-CGS is approximately equal to the biogas production of the STP. However, when heat demand fluctuates throughout the year smaller size of MGT is preferred.

1. Introduction

The world is ever facing two major threats related to energy use, firstly the rapid depletion of fossil fuels and secondly, environmental disruptions both globally and domestically. Two measures to overcome these increasing problems are renewable energy and energy efficient technologies. Utilization of biomass by the use of a cogeneration system (CGS) is one example of an efficient application of renewable energy.

For many years Sewage Treatment Plants (STPs) have practised anaerobic digestion to convert wet biomass to biogas [1] and [2]. Anaerobic digestion has been used continuously in STP because its objective is not only to produce biogas, but is an important process for reducing and stabilizing sludge. Although biogas is produced in STP, its utilization is limited to cover the heat demand of the plant, and a large amount of the remaining biogas is not fully utilized. For instance, there are 1900 STPs in Japan, but only less than 30 facilities use the biogas to generate electricity [1] and [2]. This is because the amount of biogas produced in middle- and small-scale STPs is small, and on top of that there are only few commercially available prime movers (PMs) with an output of less than a few hundred kilowatts. Since more efficient small-scale micro gas turbines (MGTs) are being developed, interest has grown on them because of their multi-fuel capability, high-power density, low emissions and low maintenance requirements [3].

MGTs are generally classified as gas turbines that have power output less than 300 kW. Although the range (0–300 kW) is small, different sizes of MGTs have significant difference in performance and capital cost. When size increases, efficiency increases and capital cost per-kW decreases, and therefore larger MGT is preferable as compared to multiple smaller MGTs. However, if a larger MGT is employed, but only part load operation is required, then efficiency will decrease drastically. Part load will be needed if MGT

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Nomenclature

A	area, m^2
C	cost, US$
c_p	specific heat, kJ/kgK
i	discount rate, -
v	amount of influent sludge, m^3/s
n	number of years
NPV	Net Present Value, US$
PWF	Present Worth Factor, -
Rev	revenue, US$
t	temperature, K or ^{o}C
U	overall heat transfer coefficient, kW/m^{2}K
Q	heat energy, kW
η	efficiency, -
ρ	density, kg/m^3

Subscript

a.b	administration building
amb	ambient
b. p	biogas production
eq	equipment
d	anaerobic digestion
fuel	fuel
h.d	total heat demand
ins	installation
O&M	Operation & Maintenance
s	sludge
s.h	sludge heating
s.i	influent sludge
t.l	tank losses

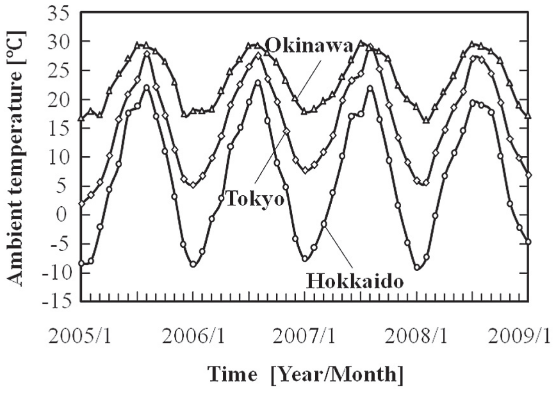
Abbreviations

CGS	Cogeneration System
MGT	Micro Gas Turbine
NPV	Net Present Value
PM	Prime Mover
STP	Sewage Treatment Plant

power generation capacity is higher than the load, and also when power or thermal load of a plant itself varies throughout the year. As such, there is a possibility that multiple smaller MGTs that operate at full load can be a better solution.

There are quite a number of studies conducted related to the effect of sizing of CGS or Trigeneration System (TGS) in general. Fragaki et al. reported on the analysis of the economic and optimum size of CGS with gas engine as the prime mover in the UK scenarios [4]. Oh et al. introduced a mixed integer linear programming model as a method to obtain optimum CGS configuration [5]. Mixed integer nonlinear programming model was proposed generally optimize the size of CGS and TGS [6] [7],. A generic deterministic linear programming model was proposed as an optimum sizing method for CGS [8]. Cho et al. proposed a simple sizing method for CGS using Load Duration Curve method [9]. Gamou et al. studied optimal unit sizing of CGS considering transient energy demand of a building [10]. Cardona et al. proposed a simple method for sizing a TGS using only a few actual data [11]. A new method to evaluate adequate size of thermal energy storage in a TGS was also proposed [12]. Multi-objective approach was introduced by Gimelli et al. in designing an optimum CGS [13]. Effect of the size of CGS integrated with a biomass fueled gas generator and piston engine on the techno-economic performance was also reported [14].

A study was also carried out by Galanti et al. on thermoeconomic analysis of optimum size of MGT, but without CGS configuration [15]. There are also a few studies conducted related to the effect of MGT with CGS configuration. Optimization of size and unit number by annual profit method for a commercial building was reported in Ref. [16]. Ferreira et al. investigated economic performance of MGT-CGSs with various sizes. Different sizes of MGT models that consider variables including compressor & turbine efficiencies, turbine inlet temperature, and compression ratio were developed and their economic performance were then investigated



Temperature Condition	Average ambient temperature [°C]
Continental	-9.5~25.0
Temperate	5.1~29.0
Tropical	15.7~29.9

Fig. 1. Ambient temperature conditions studied for various heating demand calculations.

Table 1
Basic design parameters of a Sewage Treatment Plant.

Population covered	[people]	100,000
Monthly average electricity demand	[kW]	638
Digester tank total volume		
Tank A (2 units)	[m^3]	6,438
Tank B (2 units)	[m^3]	3,650
Average		
Wastewater amount	[m^3/month]	1,564,000
Digestion coefficient	[%]	62
Biogas production	[m^3/month]	129,654
Influent sludge		
Sludge amount	[m^3/month]	7,533
Solid concentration	[%]	4.0
Organic contents	[%]	80.8

Table 2
Scaled down parameters studied for various scale ratio of STPs.

Scale		0.25	0.50	1.0
Population covered	[people]	25,000	50,000	100,000
Average electricity demand	[kW]	160	319	638
Digester tank total volume (2 units)	[m^3]	2524	5044	10088
Average influent sludge amount	[m^3/month]	1883	3766	7533
Average biogas production	[m^3/month]	32415	64827	129654