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Optimal Unit Sizing of Biogas-Fuelled Micro Gas Turbine Cogeneration Systems in a Sewage Treatment Plant

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Abstract

This paper investigates the optimum size of Micro Gas Turbine Cogeneration Systems (MGT-CGSs) in a sewage treatment plant in relation to its economic performance. A sewage treatment plant in a cold region was adopted as a model, and three units of MGT-CGS with power output capacity of 30, 65 and 200kW were simulated to utilize biogas produced in-house in the plant. The energy balance of the system was first studied, and economic performance using Net Present Value method was carried out. It was found that a configuration with optimum combination of 3 types of MGTs (MGT-Combined) stated above had the highest power generation efficiency. However, MGT-Combined needed more units of MGT resulting in higher capital investment. Although all configurations of MGT-CGSs studied can generate Net Present Value (NPV) in the range of US$2,640,000-3,100,00, MGT-200 had the highest NPV. MGT-200 had 15% higher NPV compared to the lowest one, MGT-30. MGT-200 can generate the highest NPV because it had the lowest capital investment cost, while having high power cost savings.

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Keywords: *Micro gas turbine; Cogeneration System; Sewage treatment plant; Biogas; Economic analysis; Sizing effect*

1. Introduction

Sewage treatment plants have utilized anaerobic digestion process for decades to reduce sludge and to produce biogas. However, biogas is usually used to supply the heating demand with a large portion of the biogas collected still unutilized. The development of small scale prime movers, the increase of electricity price, the depletion of fossil fuel, and the environmental problems resulting from combustion emissions have led to efficient utilization of biogas by Cogeneration System (CGS) that can also generate electricity while covering the heat demand. Micro Gas Turbines (MGTs) are alternative small scale prime movers in biogas utilization because of their fuel flexibility, low maintenance and emissions, and high power density.

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MGTs are generally classified as gas turbines that have power output of less than 300kW. Although the range (1 – 300kW) is small, MGTs of different sizes have significant differences in terms of performance and capital cost. When size increases, efficiency increases and capital cost decreases, and therefore a larger MGT is preferable compared to multiple assembly of smaller MGTs. However, if a larger MGT is employed, when part load operation is required, efficiency decreases drastically. As such, there is a possibility that multiple or an assembly of smaller MGTs that run at higher load is a better solution.

There are studies on the effect of sizing of CGS in general. Zhang et al. studied on the general optimal planning of CGS [1]. Aikaterini et al. reported on the analysis of the economic and optimum size of CGS with gas engine as the prime mover in UK scenarios [2]. Mixed integer nonlinear programming model was proposed by Hongbo et al. to optimize the size of general CGS [3]. Satoshi et al. studied optimal unit sizing of CGS considering transient energy demand of a building [4]. A study was also carried out by Leandro et al. on the thermo-economic analysis of optimum size of MGT, but without CGS configuration [5]. There are a few studies on the effect of MGT with CGS configuration. Optimization of size and unit number by annual profit method for a commercial building was reported in [6]. Ana et al. investigated the economic performance of MGT-CGSs with various sizes using MGT numerical models [7]. Sizing of MGT-CGSs for sewage treatment plant was carried out by Basrawi et al. but only energy performance was evaluated [8]. From literature review, no study has been reported on the effect of sizing of MGT-CGSs in sewage treatment plant that considers energy and economic performance.

Thus, the objective of this study is to clarify the optimum size of MGT-CGSs for a sewage treatment plant considering also its economic performance. A sewage treatment plant in a cold region was adopted as a model, and MGT-CGSs with power output capacity of 30, 65 and 200kW simulated to utilize biogas produced in the plant. Then, energy balance and economic analysis using Net Present Value method were carried out.

Nomenclature

C	Cost, US$	*NPV*	Net present Value, US$		
i	Interest or discount rate, %	*Rev*	Revenue, US$		
n	Year,				
subscript		*O&M*	Operation & Maintenance		
elec. sav.	Electricity saved	*ins*	Installation	*eq*	Equipment

2. Materials and Methods

2.1. Sewage Treatment Plant Model

A sewage treatment plant located in Hokkaido, Japan was adopted as the model plant. Basic parameters are shown in Table 1. The plant can produce monthly average of 130,000m^3 biogas from a population of 100,000. This plant is equipped with two-stage anaerobic digester tanks that operates under mesophilic temperature condition. Heat and power demand of the plant are as shown in Fig. 1.

2.2. Energy System in the Sewage Treatment Plant In the conventional energy system, a boiler was often used to utilize the biogas to cover the heat demand of the plant, but a large portion of the biogas produced was incinerated. The main advantage of the MGT-CGS is that it can convert biogas to electricity while covering heating demand. However, since heat demand in winter is high, boiler is still needed to operate in parallel. Energy system with MGT-CGS in the sewage treatment plant is shown in Fig. 2. The biogas produced is supplied to a boiler and MGT-CGS. The amount of biogas supplied is adjusted depending on the heat demand. The boiler and heat by-product of the MGT-CGS' operation cover the total heat demand, whereas the electricity generated by the MGT-CGS covers a portion of the power demand.

Table 1 Basic parameters for the model plant

Population covered	[people]	100,000
Digester tank Tank A (2 units)	[m^3]	6,438
Digester tank 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 amount	[m^3/month]	7,533
Influent solid concentration	[%]	4.0
Influent organic contents	[%]	80.8

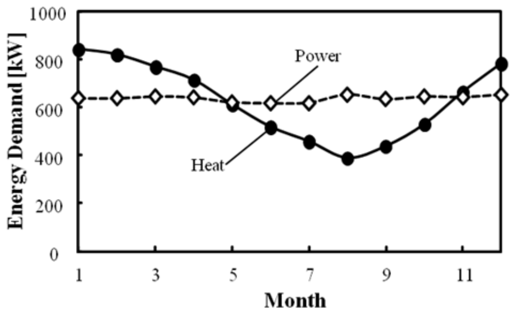

Fig. 1 Heat and Power demand of the model plant

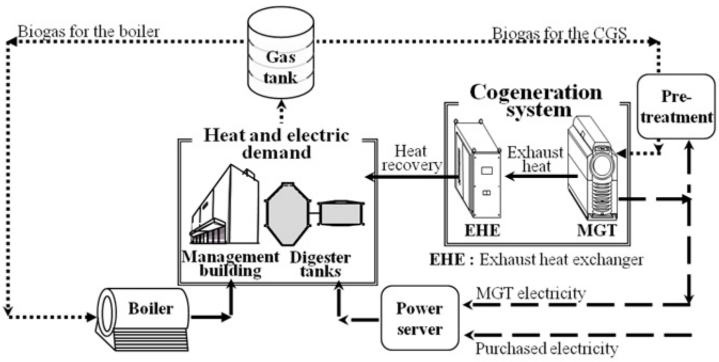

Fig. 2 Energy System in the sewage treatment plant

2.3. Performance of the MGT-CGS and Operation Strategies

The main components of MGT-CGS were a MGT and a heat exchanger. For the MGT, three MGTs of different sizes were considered, MGT-30, MGT-65 and MGT-200. A heat exchanger with temperature exchange efficiency of 80% was assumed to be used for each MGT. The recovered exhaust heat from the exhaust heat exchanger was analyzed using NTU-efficiency-Capacity Ratio relationship. Power generation efficiency, exhaust heat recovery efficiency and energy efficiency of MGT-CGS are shown in Fig. 3 [8]. Fig. 3 shows the efficiency when each MGT-CGS is operated within 1-240kW. Heat/Power Ratio of each MGT are also shown in Fig. 3. Fig.3a shows that when the load is in the range of 0-30kW, MGT-30 has the highest efficiency. When the load is between 30-65kW, MGT-65 achieves the highest efficiency, and when the load is higher than 200kW, MGT-200 yields the highest efficiency. Thus, another one option that can be proposed is to combine these 3 sizes of MGTs and operate them at their highest efficiency only, instead of using multiple unit but one size of MGT only.

2.4. Economic Analysis

Net Present Value (NPV) analysis considers time value of money in evaluating the economic performance of all MGT-CGSs. The main parameters required for calculation are shown in Table 2. Cash flow throughout the life cycle were calculated based on the present value. The NPV for 25 years of life cycle of the investment on the energy system can be calculated by the following equation

$$NPV = Rev_{elec.sav.} - \left(C_{eq} + C_{ins} + C_{O\&M}\right) \tag{1}$$

The cost of MGT-CGS varies depending on its generation capacity. Overnight costs are reported in a number of literature and are shown in Fig. 4. As shown in Fig. 4, equipment cost decreases when the power generation capacity decreases. The installation cost was also considered, and assumed to be 20% of the equipment cost. In addition, O&M cost was assumed to be 0.01US$/kWh.

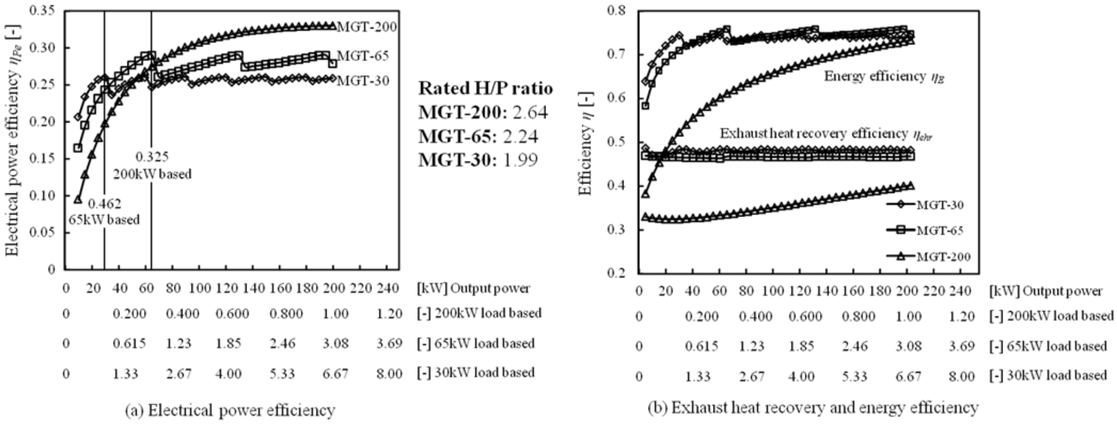

Fig. 3 Part load performance of all MGT-CGSs

The main revenue for MGT-CGSs is electricity saving, but it is a serie of cash flow in the future. Present Worth Factor (PWF) needs to be calculated to obtain its present value. PWF can be calculated by the following equation

$$PWF_x = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{2}$$

Table 2 Main parameters for economic analysis

Currency	1yen=US$0.01
Commercial and institutional tariff	0.128 US$/kWh
Discount rate	1.48%
Lifetime	25 years
O&M Cost	0.01 US$/kWh

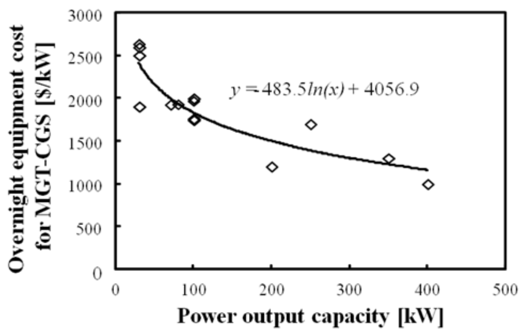

Fig. 4 Overnight equipment cost for MGT-CGS

3. Results and Discussion

3.1. Capacity and Unit of MGT-CGSs needed

To cover the heat demand, the number of units of a MGT-CGS assembly needed is shown in Table 3. MGT-30 needs the highest number of units which is 11, whereas MGT-200 needs the lowest number of unit which is 2. Only one unit is needed to run at part-load for MGT-30, MGT-65 and MGT-200. MGT-Combined also needs low number of units, 4 units where 3 units needed to operate at part-load. However, in terms of generation capacity, MGT-Combined has the highest generation capacity which is 495kW. This indicates that MGT-Combined will incur the highest capital cost because it has more units of MGTs. The usage rate of MGT-Combined was also the lowest and this shows that MGT installed was not frequently used.

Table 3 MGT-CGSs unit and total power generation capacity for each configuration

	Full load [Unit]	**Part load, Usage Rate, Part load ratio** [Unit] ,[-], [-]	**Total** [Unit]	**Total** [kW]
MGT-30	10	1, 0.51, 0.48	11	330
MGT-65	5	1, 0.47, 0.48	6	390
MGT-200	1	1, 0.44, 0.47	2	400
MGT-Combined				495
MGT-30	0	1, 0.14, 0.43	1	
MGT-65	0	1, 0.25, 0.81	1	
MGT-200	1	1, 0.41, 0.61	2	

3.2. Power Generation and Economic Performance

Fig. 5(b) shows annual average power generated by all MGT-CGSs. As shown in Fig. 5(a), MGT-30 yields the lowest amount of power generation, whereas MGT-Combined has the highest amount of power generation. This is basically related to the power generation efficiency as shown in Fig. 5(a). Although MGT-30 can run at full load, it still operates with the lowest efficiency because the rated efficiency is low. On the other hand, MGT-Combined has the most efficient MGT-CGS configuration with the highest efficiency.

The comparison of O&M cost, equipment & installation cost, power cost savings, and NPV are shown in Fig. 5(b). As shown in Fig. 5(b), and as expected, MGT-Combined has the highest equipment & installation cost as shown in Section 3.1. MGT-30 that is supposed to have higher equipment & installation cost has almost the same equipment & installation cost with MGT-65 and MGT-Combined. This is due to the fact that although it has higher equipment cost per-kW, its total power generation capacity obtained in this study is the lowest. MGT-200 has the lowest equipment & installation cost because it has lower cost per-kW and its total power generation capacity also is not too high. On the other hand, power cost savings show that MGT-Combined yields the highest amount – MGT-200 saving yields US$200,000 less than MGT-Combined, and the lowest is MGT-30, approximately US$3,900,000.

Moreover, considering all costs, it was found that all MGT-CGSs have NPV in the approximate range of US$2,640,000-3,100,000. This proves that MGT-CGS is not only suitable in term of addressing energy depletion and environmental issues, it can also generate profit to investors. In addition, comparing all MGT-CGSs configuration, MGT-200 is the most optimum choice because it has the highest NPV, and also has significantly lower equipment & installation cost as compared to others. This is mainly because it has the lowest equipment & installation cost, while achieving quite high power cost savings. However, other MGT-CGSs also can generate high NPV, only US$63,000-141,000 less as compared to the MGT-200, excluding MGT-30 which has 15% less NPV. It can be concluded that the largest MGT-CGSs, MGT-200 is the most optimum option in term of economic performance because it has the lowest capital investment and has the highest NPV throughout the life cycle.

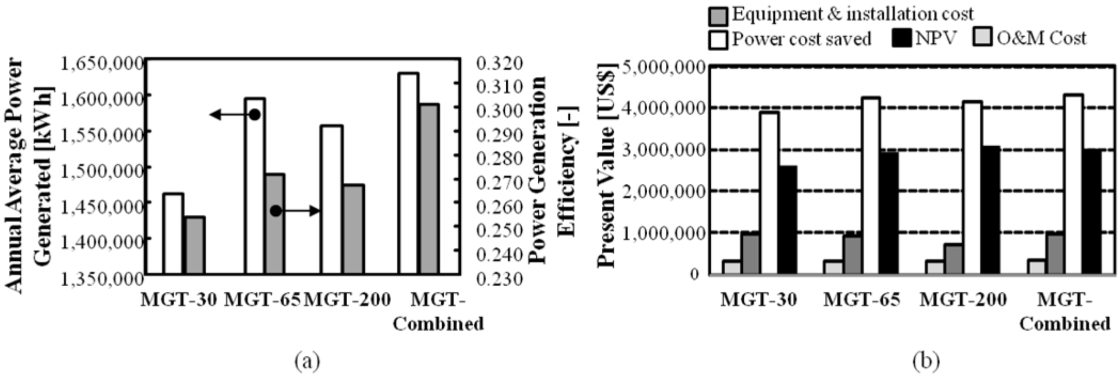

Fig. 5(a) Annual average power generated and power generation efficiency, (b) Comparison of O&M cost, equipment & installation cost, power cost savings, and Net Present Value

4. Conclusions

The most economical size of Micro Gas Turbine Cogeneration Systems (MGT-CGSs) was investigated. It was found that All MGT-CGS configurations can generate net profit and the range of Net Present Value (NPV) was US$2,640,000-3,100,00. MGT-30 yields the worst economic performance, 15% lower NPV as compared to MGT-200 because of its power generation efficiency limit. Although combination of different sizes of MGTs (MGT-Combined) can avoid lower part-load operation that results in lower efficiency, this combination needs more units of MGTs. Thus, the capital investment is higher as compared to other configurations. Although MGT-200 needs to be operated at part load, it is still the optimum size of MGT in term of economic performance. This is because it can generate the highest Net Present Value, and it also has significantly less capital investment cost as compared to others.

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Biography

Dr. Firdaus Basrawi is a Senior Leturer in Faculty of Mechanical Engineering at Universiti Malaysia Pahang. He received his BEng, MEng and his doctorate from Kitami Institute of Technology. He is currently works in Energy System field, and actively involve in publication and peer review in journals and conferences.