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Analysis of the Performance of a Biogas Cogeneration System in a Sewage Treatment Plant in a Cold Region*

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Abstract

The use of biogas by a cogeneration system (CGS) is a promising technology as an efficient method of energy utilization. Sewage treatment plants (STPs) are facilities that have been continuously producing biogas, and therefore the potential of application of a biogas-fuelled CGS in an STP is estimated to be very high. However, there have been few reports on efficient utilization of biogas by a CGS, especially in cold regions. Since ambient temperature in a cold region is low and varies greatly, heat demand in the STP is also great and varies greatly throughout the year. Thus, auxiliary components such as a boiler, heat pump and gas storage system are also required to cover the total heat demand throughout a year. In the present study, adopting an actual STP in a cold region and a micro gas turbine as the CGS prime mover, performance of a biogas-fuelled CGS was investigated. The performances of four possible arrangements of the CGS with different auxiliary components were compared to the performance of a conventional system. It was found that all CGS arrangements could cover the total heat demand by only using biogas produced in the facility. The CGS arrangements could reduce electrical power demand by 23~31%, recover 74~78% of the energy of biogas produced, and utilize almost 100% of the biogas. The CGS arrangements with a heat pump were more efficient than the CGS arrangements with a boiler. CGS arrangements that include a gas storage system will enable efficient utilization of biogas and recovered exhaust heat.

Key words: Biomass, Biogas, Micro Gas Turbine, Cogeneration System, Cold Region, Operation Method

1. Introduction

The world is now facing twin energy-related threats, the treat of not having adequate and secure supplies of energy and the treat of environmental disruption caused by consuming too much fossil fuel(1). Research on energy saving technology and utilization of renewable energy has therefore become important. One of the applications that combine these technologies is a biogas-fuelled cogeneration system (CGS). Biogas production technology has been available for many decades, but it has not been widely utilized due to the availability of cheap fossil fuel. However, interest has recently been shown in biogas since it is a renewable and carbon neutral fuel. The "Biomass Nippon Strategy" was established in Japan in December 2002 for using all biomass produced as a product or as energy(2). While measures outlined in the European Union Biomass Action Plan in Europe will lead to an increase in biomass use, biomass consumption will reach approximately 150

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Mtoe in 2010[3].

One facility that has very high potential for biogas utilization is a sewage treatment plant (STP) because it has been continuously using anaerobic digestion for degradation and stabilization of sludge [4]~[6]. However, only a small portion of biogas produced has been used as fuel to cover heat demand of these facilities, and a large amount of unutilized biogas has been incinerated. Since environmental and energy issues have become important, many commercial biogas-fuelled engines have been developed, and utilization of biogas by CGSs has been increasing [3], [5]~[8]. However, there have been few studies on efficient utilization of biogas by CGS, especially in cold regions.

Ambient temperature in a cold region is low and varies greatly, and total heat demand for anaerobic digestion as well space heating of administration building is therefore also great and varies greatly throughout the year. On the other hand, biogas produced in the plant is almost constant and there is a possibility that a biogas-fuelled CGS cannot cover the total heat demand, especially in winter. Thus, installation of other auxiliaries such as a boiler, heat pump and gas storage system are needed to cover the total heat demand throughout the year. Study on a CGS and its arrangement in an STP in a cold region is important to ensure that biogas produced is efficiently converted to heat and electrical power.

In the present study, an actual STP in a cold region was used as an analysis model and a previously studied micro gas turbine (MGT) was used as the prime mover of the CGS. Four various possible arrangements of the CGS with different auxiliary components were proposed and their performances were compared to that of a conventional system. The performance of the CGS arrangements was investigated on the basis of reduction of electrical power demand, biogas energy recovery efficiency and reduction of unutilized biogas.

Nomenclature

A	Heat transfer area, m^2
c_p	Specific heat, kJ/kgK
COP	Coefficients of performance
K	Overall heat transfer coefficiency, kW/m^{2}K
LHV	Lower heating value, kJ/m^3
m	flow rate, m^3/s or kg/s
Pe	Electrical power, kW
Q	Heat, kW
t	Temperature in celcius, °C
T	Absolute temperature, K
$Unit$	Unit of the CGS, -
η	Efficiency, -

Subscript

$a.b$	Administration building
amb	Ambient
b	Boiler
$b.e.r$	Biogas energy recovery
$b.p$	Biogas production
CGS	Cogeneration system
$conv.$	Conventional system
d	Digestion
ehr	Exhaust heat recovery of the CGS
$g.c$	Gas compressor

h	Higher heat source
h.d	Heat demand
HP	Heat pump
i.c	Ice crusher
i.m	Ice maker
l	Lower heat source
MH	Methane hydrate storage
r.b	Remaining biogas
r.h.d	Remaining heat demand
re	Refrigerator
red	Reduction of electricity
s	Sludge
s.h	Sludge heating
s,i	Influent sludge
t.l	Losses from digester tanks
u.b	Unutilized or unused biogas
u.ehr	Unutilized exhaust heat recovery

Abbreviations

CGS	Cogeneration system
HP	Heat pump
MGT	Micro gas turbine
MH	Methane hydrate storage
STP	Sewage treatment plant

2. Materials and methods

2.1 Biogas-fuelled CGS in a wastewater treatment facility in a cold region

Ambient temperature of a cold region that was used in the analysis is shown in Fig. 1. The ambient temperature was that of the coldest prefecture in Japan, Hokkaido, and the city that was selected was Kitami [9]. As shown in Fig. 1, ambient temperature in the analysis period of January 2004~January 2008 varied throughout the year with annual average of 6.3°C, highest temperature was 35.1°C and lowest temperature of -23°C. It should be noted that the temperature used for calculation was the average ambient temperature.

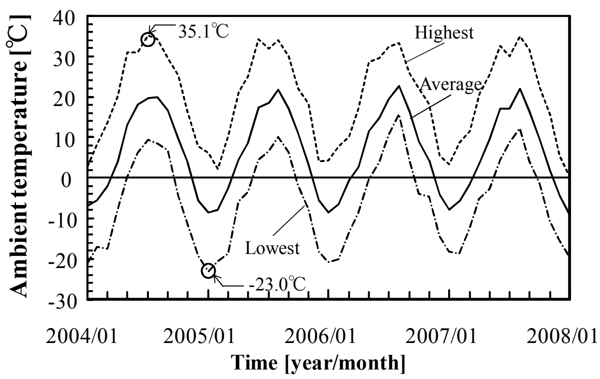

Fig. 1. Monthly average, highest and lowest ambient temperatures in the analysis period.

The design parameters of the model anaerobic digestion plant and its influent sludge temperature are shown in Table 1[10]. A two-stage digestion system that was operated under mesophilic conditions with a digestion period of 30 days was used. This is a typical anaerobic digestion system that is used in STPs in Japan [11]~[12]. The model anaerobic digestion can treat 246 m^3/day of sludge from a population of 100000.

The total heat demand of the facility can be divided into heat for heating sludge $Q_{s.h}$, digester tank heat loss $Q_{t.l}$, and heat for space heating of the administration building $Q_{a.b}$. It can be calculated by the following equation:

$$Q_{h.d} = Q_{s.h} + Q_{t.l} + Q_{a.b}. \tag{1}$$

Table 1. Design parameters of the model anaerobic digestion plant.

Population covered	[people]	100 000		
Digestion tank total volume				
Tank A	[m^3]	6 440		
Tank B	[m^3]	3 650		
		Minimum	Maximum	Average
Wastewater amount	[m^3/day]	38 900	75 100	51 200
Sludge amount	[m^3/day]	185	316	246
Biogas production	[m^3/day]	3 410	4 950	4 260
Influent sludge temperature	[°C]	9.3	18.6	14.2

Heat for heating sludge can be calculated by the following equation:

$$Q_{s.h} = m_s \cdot c_{p,s}\left(t_d - t_{s.i}\right), \tag{2}$$

where m_s is the flow rate of the sludge [kg/s], $c_{p,s}$ is the specific heat of the sludge [kJ/kgK], t_d is the digestion temperature [°C] and $t_{s.i}$ is the influent sludge temperature [°C]. The specific heat of the sludge was assumed to be equal to the water because the solid concentration of the sludge is always less than 6% and the water content is very high[13]~[14]. In order to obtain optimum digestion under a mesophilic condition, digestion temperature must be maintained in the range of 30~37°C [12], [15]. Thus, temperature of the sludge in the digester tank was assumed to be constant at 37°C in the calculation. The digester tank heat loss $Q_{t.l}$ and the heat for space heating of the administration building $Q_{a.b}$ can be calculated by the following equations:

$$Q_{t.l} = K \cdot A\left(t_d - t_{amb}\right), \tag{3}$$

$$Q_{a.b} = K \cdot A\left(t_{a.b} - t_{amb}\right), \tag{4}$$

where K is the overall heat transfer coefficiency [kW/m^2K], A is the heat transfer area [m^2], $t_{a.b}$ is the temperature inside the administration building [°C] and t_{amb} is the ambient temperature [°C]. It should be noted that $t_{a.b}$ was assumed to be constant at 23°C. The parameters used for the calculation are shown in Table 2. All of the parameters were obtained from an actual materials and dimensions of the facility.

Table 2. Parameters used to calculate heat demand.

	Overall wall area [m²]	Heat transfer coeff. of wall × 10^{-3} [kW/(m²K)]	Overall window area [m²]	Heat transfer coeff. of window × 10^{-3} [kW/(m²K)]
Digester tank A	1115	2.76		
Digester tank B	816	2.44		
Admin. building	2773	4.11	82	3.60

Since the source of biogas as biomass fuel has a widespread distribution but limited amount in each area [11], [16], the utilization method is usually limited to a small-scale biogas plant. Thus, presently usable prime movers with an output of more than a few hundred kilowatts are usually difficult. A reciprocating engine, a fuel cell and a micro gas turbine (MGT) are available as prime movers with an output power less than this capacity. Of these three, the fuel cell is the most promising technology, but it still has problems in reliability and cost [17]~[18]. Interest has been shown in the most recently developed MGTs because they have high power density, lower maintenance requirements and lower emissions than those of a reciprocating engine [19]~[20]. Moreover, an MGT has a high heat-to-power ratio, which is suitable for application in a cold region. Thus, the prime mover of the CGS used in the present study was an MGT. The performance of an MGT-CGS in a cold region was analyzed in a previous study, and the same model was used in the present study. Its design parameters are shown in Table 3 [21]. It had a rated electrical power output of 28 kW and a rated heat recovery of 55 kW.

Table 3. Basic specifications of the micro gas turbine cogeneration system.

MGT			
Ambient pressure	101.3 kPa	Rated speed of biogas compressor	450 ~1200rpm
Turbine outlet temperature	593 ° C	Biogas inlet outlet pressure	0.02~6bar
Compressor & turbine efficiency	0.76	Flow rate	~ 30Nm³/h
Combustion efficiency	0.99		
Recuperator efficiency	0.74	**Exhaust heat exchanger**	
Mechanical efficiency	0.97	Effectiveness	0.80
Rated revolution speed	96,300 rpm	Cold water inlet temperature	80 ° C
Rated electrical power output	28 ± 2 kW	Cold water mass flow rate	1.616 kg/s
Electrical efficiency	26 ± 2 %	Capacity ratio	0.054 ~ 0.063
Pressure ratio	3.4	Rated heat recovery	55kW
NOx emission	<9ppmV@ 15 %O_2		

2.2 MGT-CGS arrangements

The overall system of the biogas-fuelled CGS in the facility is shown in Fig. 2. The system was arranged to cover total heat demand by only utilizing all biogas produced. The biogas produced was supplied to the CGS for covering a part of the heat demand.

When the heat demand is high, especially in winter, auxiliary components such as a boiler or heat pump (HP), will also be operated. The remaining biogas will be used as the input of the boiler, whereas electrical power generated from the CGS will be used as the input of the HP. Gas storage will also be used in some arrangements for using the biogas remaining in summer to be efficiently used in winter.

Four main arrangements of the CGS were investigated in the present study. Details of the arrangements are shown in Table 4. The first arrangement (A1) was the simplest arrangement. In this arrangement, percentages of biogas supplied to the CGS and the boiler are adjusted depending on the season. All biogas produced monthly is consumed by the CGS and boiler, but more biogas is supplied to the boiler in winter and less in summer.

However, since the heat demand is low in summer, there is a possibility that the exhaust heat recovered by the CGS cannot be fully utilized in the facility. The CGS units operated in this arrangement are in a range of 0~11.

The second arrangement (A2) includes the CGS, a boiler and a gas storage system. It is similar to A1, but a gas storage system is also installed in the system. Since heat demand in summer is low, in order to avoid unutilized recovered exhaust heat, a part of the biogas produced in summer is not used but is carried over to winter. The CGS units operated in this arrangement are less than those in A1, in a range of 4~8.

The third arrangement (A3) includes the CGS and state-of-art heat supply technology, the HP. All biogas produced monthly is consumed by the CGS to convert the biogas into electrical power as well as heat. An insufficient heat demand, especially in winter, is covered by the HP with some of the electrical power produced by the CGS being used as its input. However, since the heat demand in summer is low, there is a possibility that the exhaust heat recovered from the CGS in summer is not fully utilized. The CGS units operated in this arrangement are in the range of 7~11.

The forth arrangement (A4) includes the CGS, the HP and the gas storage system. It is similar to A3, but gas storage is also considered for using the remaining biogas in summer to be efficiently used in winter. Since the heat demand in summer is low, some of the biogas produced in summer was not used but was carried over to winter. The CGS units operated in this arrangements are in the range of 5~11.

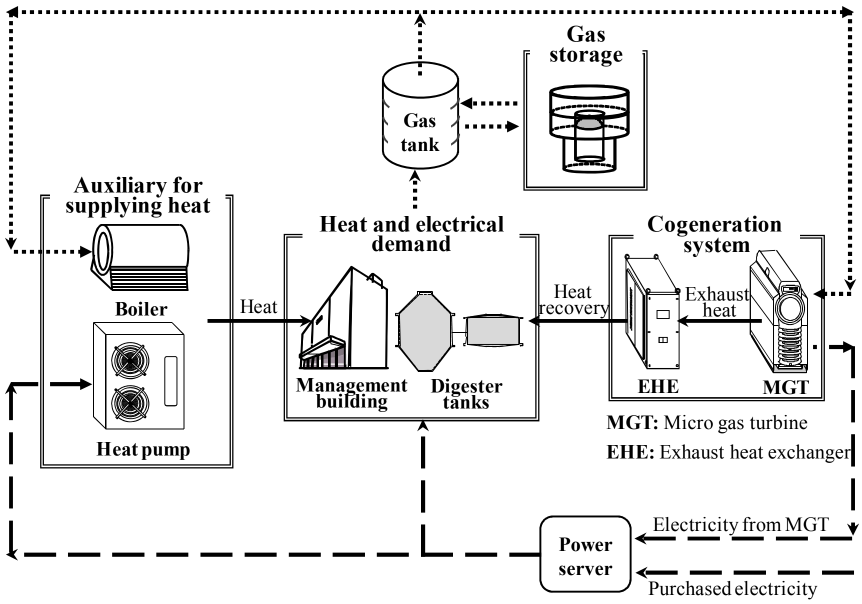

Fig. 2. Overall system of the biogas CGS in the facility.

Table 4. Components for all arrangements and theirs CGS units.

	Components	CGS units
(A1) CGS and boiler	CGS, boiler	0 ~11
(A2) CGS, boiler and gas storage a. Storage medium is ice from water b. Storage medium is ice from snow	CGS, boiler, gas storage	4~8
(A3) CGS and HP a. Ambient air as heat source of HP b. Wastewater as heat source of HP	CGS, HP	7~11
(A4) CGS, HP and gas storage	CGS, HP, gas storage	5~11

The gas storage method considered here is a methane hydrate (MH) storage method that has the possibility of energy saving storage and it is also suitable for a cold region [(22)~(23)].

Two cases were investigated for A2: the MH with crushed ice from water and with crushed ice from snow. This is explained in detail in section 2.3. Two other cases were also investigated for A3. Since wastewater with a high temperature is available for the STP, besides the case of ambient air being used as the heat source of the HP, the case of wastewater being used as the heat source was also investigated.

2.3 Energy utilization in the facility

The heat energy of biogas that produced $Q_{b.p}$ can be expressed as equation (5) and the exhaust heat recovered by all of the CGS units Q_{CGS} can be expressed as equation (6):

$$Q_{b.p} = m_{b.p} \cdot LHV, \tag{5}$$

$$Q_{CGS} = Q_{ehr} \cdot Unit, \tag{6}$$

where $m_{b.p}$ is the biogas production rate [m^3/s], LHV is the lower heating value of the biogas [kJ/m^3], Q_{ehr} is the exhaust heat recovered by one unit of the CGS [kW], and $Unit$ is the number of the CGS units [-]. After traces of water and hydrogen sulfide have been eliminated from the bulk biogas, it is finally composed of approximately 60%-v methane and 40%-v carbon dioxide, and therefore Q_{LHV} is assumed to be 21 500 kJ/m^3.

Since heat demand in a cold region is high, the CGS in all arrangements can only cover a part of the heat demand and the remaining heat demand is covered by the boiler or the HP. The remaining heat demand $Q_{r.h.d}$ can be expressed as the following equation:

$$Q_{r.h.d} = Q_{h.d} - Q_{CGS}. \tag{7}$$

When the boiler was used to cover the remaining heat demand, the balance between the remaining heat demand $Q_{r.h.d}$ and the remaining biogas $Q_{r.b}$ was calculated, and finally unutilized biogas $Q_{u.b}$ was calculated by the following equation:

$$Q_{u.b} = \eta_b \cdot Q_{r.b} - Q_{r.h.d}, \tag{8}$$

where η_b is the boiler efficiency [%], which was assumed to be 85%[24].

For A2, in which the boiler and the gas storage system were used together with the CGS, the remaining biogas in summer was carried over to winter and was used as fuel of the boiler to cover the remaining heat demand. In this case, in order to determine whether the biogas stored can sufficiently cover the remaining heat demand or not, the energy balance of the remaining biogas and the remaining heat demand in the four years of the analysis period was calculated by the following equation:

$$Q_{u.b} = \frac{1}{4}\sum_{i=1}^{n}\left(\eta_b \cdot Q_{r.b_i} - Q_{r.h.d_i}\right), \tag{9}$$

where the unutilized biogas $Q_{u.b}$ must be larger than 0 kW. The storage method considered here was an MH storage method, and experimental studies on the feasibility of MH storage have been carried out in the laboratory [22], [25]. In practice, there are various methods for the formation of MH, including formation of MH by water and gas in a porous medium, formation of MH by stirring gas and water, and formation of MH by spraying water droplets into gas [26]~[29]. As a means for utilizing snow, which is abundantly available in a cold region, the possibility of formation of MH by gas and crushed ice has been investigated in our laboratory. The total power required for MH storage Pe_{MH} including the power of ice maker $Pe_{i.m}$, ice crusher $Pe_{i.c}$, gas compressor $Pe_{g.c}$, and refrigerator Pe_{re} was calculated on the basis of experimental results and specifications of equipment to produce MH [22], [25]. Pe_{MH} can be expressed as the following equation:

$$Pe_{MH} = Pe_{i.m} + Pe_{i.c} + Pe_{g.c} + Pe_{re}, \quad (10)$$

where $Pe_{i.m}$ was not calculated when snow was assumed to be used as the storage medium. In the calculation, the rate of MH formation is assumed to be 67% on the basis of experimental results [22], [25].

When the HP is used to cover the remaining heat demand instead of the boiler in A3 and A4, the electrical power required for the input of the HP Pe_{HP} was calculated by equation (11):

$$Pe_{HP} = \frac{Q_{r.h.d}}{COP}, \quad (11)$$

where COP is the coefficient of performance of the HP [-]. COP of the HP is usually 50~60% of the COP of the reversed Carnot cycle [30]. However, the efficiency of HPs has recently been increasing because many improvements have been made to components of the HP, including the compressor, motor, heat exchanger, refrigerant and heat insulator. Therefore, COP of the HP is assumed to be 65% of COP of the reversed Carnot cycle [31]~[35]. COP can be calculated by the following equation:

$$COP = \frac{T_h}{T_h - T_c} \times 0.65, \quad (12)$$

where T_h is the temperature of the higher heat source [K] and T_c is the temperature of the lower heat source [K]. It was found that at ambient temperature of -9~23°C, COP of the HP was in the range of 2.4~3.5. In addition, since the temperature of wastewater is higher than the ambient temperature, the wastewater has the potential to be utilized as a heat source for the HP. Thus, two cases were investigated for A3: ambient temperature as the heat source of the HP (A3. a) and wastewater as the heat source of the HP (A3. b).

In order to evaluate the effectiveness of the proposed arrangements, all CGS arrangements were compared to a conventional system in which only a boiler was used to cover the total heat demand of the facility and the remaining biogas was incinerated. The reduction of electrical power demand Pe_{red}, compared to the conventional system $Pe_{conv.}$, can be calculated by the following equation:

$$Pe_{red} = Pe_{conv.} - \left(Pe_{CGS} - Pe_{MH} - Pe_{HP}\right), \quad (13)$$

where Pe_{CGS} is the electrical power generated from the CGS [kW].

It is also important to investigate how efficiently the proposed systems can utilize all biogas produced in the facility. Besides the electrical power reduction, biogas energy recovery efficiency was also calculated. The energy recovery efficiency of biogas indicates both the electrical power and heat energy that can finally be recovered from biogas by the proposed systems. It can be expressed as the following equation:

$$\eta_{b.e.r} = \frac{Pe_{red} + \left(Q_{CGS} + Q_b + Q_{HP} - Q_{u.ehr}\right)}{Q_{b.p}}. \quad (14)$$

3. Results and discussion

3.1 Relationship between heat demand and energy of biogas produced

The relationship between heat demand and energy of biogas produced is shown in Fig. 3.

It is clearly shown that heat demand greatly fluctuated throughout the year in the range of 340~910 kW, while biogas production energy only fluctuated in the range of 850~1233 kW. The conventional system could cover the total heat demand throughout the year, but a large amount of biogas was incinerated, especially in summer. For the case of the CGS, since heat recovery of the MGT-CGS used here is around 45%, the CGS could not cover total heat demand, especially in winter. Thus, a CGS in a cold region must be arranged to conform to the energy balance of heat demand and biogas production.

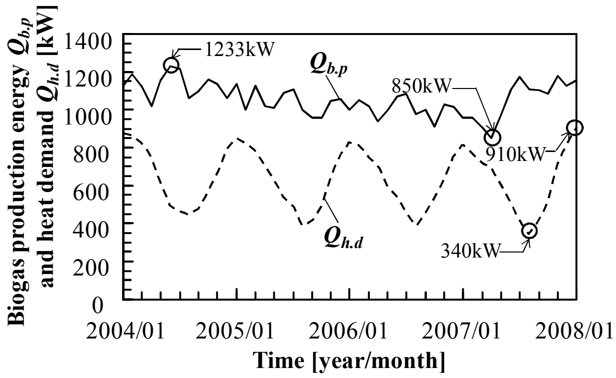

Fig. 3. Relation of biogas production and heat demand.

3.2 Energy balance in the facility

Results of energy balance in the facility for A1, A2, A3 and A4 are shown in Fig. 4(a), (b), (c) and (d), respectively. The heat demand $Q_{h.d}$ and exhaust heat recovered by the CGS Q_{CGS} are shown at the top of each figure. Thus, the shaded area shown in each figure indicates the remaining heat demand $Q_{r.h.d}$ that could not be covered by the CGS. The remaining heat demand $Q_{r.h.d}$ is also shown at the bottom of each figure together with the heat value of remaining biogas $Q_{r.b}$.

For A1, Q_{CGS} varies throughout the year in the range of 0~609 kW. Q_{CGS} exceeds $Q_{h.d}$ in summer but only covers a small amount of $Q_{h.d}$ in winter. Meanwhile, $Q_{r.h.d}$ and $Q_{r.b}$ also fluctuated throughout the year with a large amount found in winter but a small amount in summer. It was also shown that $Q_{r.b}$ is higher than $Q_{r.h.d}$ throughout the year. Although $Q_{r.h.d}$ is high in winter, if $Q_{r.b}$ is burnt in the boiler, it could cover the total heat demand.

Similar results are shown for A2, but A2 had a smaller variation than A1 in Q_{CGS} and the CGS could cover at least 169 kW of $Q_{h.d}$. The Q_{CGS} also did not exceed $Q_{h.d}$ in summer. At the bottom of the figure, it is shown that $Q_{r.h.d}$ is higher than $Q_{r.b}$ in winter, whereas $Q_{r.b}$ is higher than $Q_{r.h.d}$ in summer. Thus, if $Q_{r.b}$ in summer is carried over to winter and burnt in the boiler, it can cover the total heat demand. In the case of A1, approximately 129 000 m^3 of biogas must be stored in summer and this is 8% of the total annual biogas production. However, this percentage may depend on the variation of heat demand between summer and winter and the performance of anaerobic digestion plants. A biogas storage system by hydrate formation is also investigated by Marumoto et al. and Contana et al. [(36)~(37)].

For A3, since biogas is only supplied to the CGS, Q_{CGS} varies in a small range of 370~609 kW throughout the year. It is also shown that Q_{CGS} exceeds $Q_{h.d}$ in summer and that Q_{CGS} is lower than $Q_{h.d}$ in winter. Since all biogas produced is used by the CGS, $Q_{r.b}$ is almost 0 kW throughout the year. Meanwhile, $Q_{r.h.d}$ varies throughout the year in the range of 0~438 kW. However, if electrical power produced by the CGS is used as an input of the HP, it can cover the total heat demand. The MEGA Q, recently developed a large-scale HP system by Daikin Co. can meet $Q_{r.h.d}$ throughout the year. It is series linking capable HP, and therefore it can cover heat demand throughout the year in a range from 35kW to more than 400 kW [38]. Sarah et al. also reported that large-scale heat pumps were recently installed in a university and office building [39].

Similar results are shown for A4, but unlike A3, Q_{CGS} does not exceed $Q_{h.d}$ in summer. A similar amount of $Q_{r.h.d}$ is also shown, but if an HP is used, the total heat demand could be covered. Meanwhile, $Q_{r.b}$ showed a negative value in winter. This means that biogas supplied to the CGS exceeds the biogas produced. However, if a gas storage system is installed, remaining biogas can be carried over to winter and this arrangement makes it possible. In this case, 7% of total annual biogas production, 105 000 m^3 of biogas must be stored in summer.

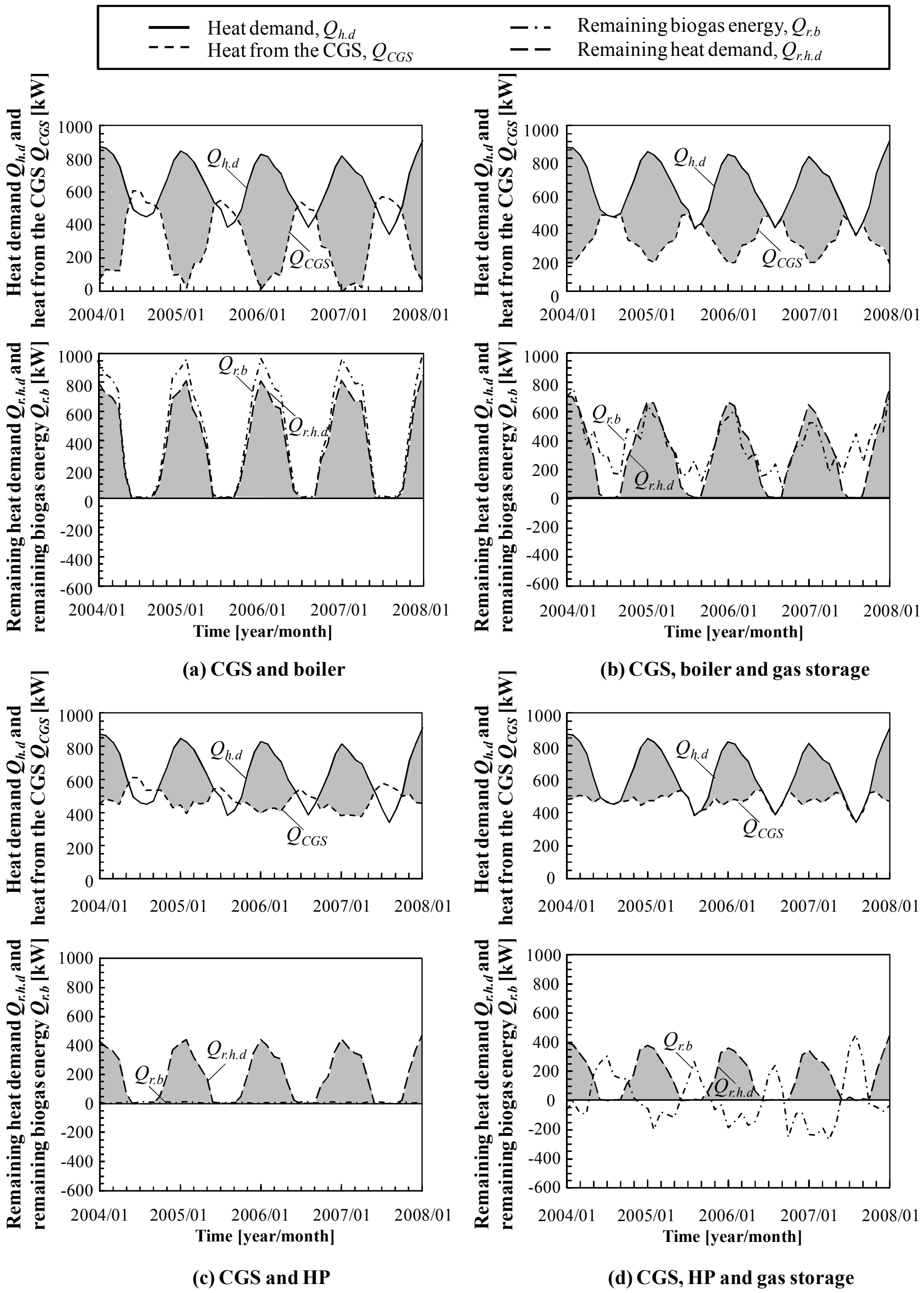

Fig. 4. Energy balance in the facility for all arrangements.

The results also show that arrangements A2 and A4, in which a gas storage system is installed, can fully utilize recovered exhaust heat generated by the CGS but that A1 and A3 cannot. The results described above also show that the CGS can replace the conventional system to cover the total heat demand in all proposed arrangements. The CGS can also utilize almost all biogas produced in the plant.

Moreover, unlike conventional system, as a distributed energy system, the CGS converts biogas into electrical power and heat, and these energies are also used to produce new biogas at the plant. It leads to a high efficiency system with minimum losses of heat and electrical power transmission. However, initial cost for the installation may be one of the setbacks for the widespread use of the biogas-fuelled CGS. Since the heat demand also fluctuates throughout the year in a cold region, a control system for the biogas-fuelled CGS is also needed and it also increases the cost for the installation. However, since efficient energy utilization that biogas-fuelled CGS can produce is very important for environment and furthermore the price of fossil fuel is also estimated to be continuously increased, the installation of biogas-fuelled CGS may become more popular in the near future.

3.3 Effectiveness of all arrangements

Unutilized remaining biogas, electrical demand reduction and biogas energy recovery efficiency for all CGS arrangements compared to the conventional system are shown in Fig. 5, Fig. 6 and Fig. 7, respectively. It should be noted that A2.a shows results when ice from water was used as the storage medium and A2.b shows results when ice from snow was used. A3.a shows results when ambient air was used as the heat source of the HP, and A3.b shows results when wastewater was used as the heat source of the HP.

As shown in Fig. 5, all CGS arrangements are more efficient than the conventional system. The conventional system can utilize only 69.7% of biogas produced, whereas all CGS arrangements can utilize almost 100% of the biogas produced.

As shown in Fig. 6 and Fig. 7, compared to the conventional system, A1, the simplest CGS arrangement in which only the CGS and boiler are used, can reduce electrical power demand by 23.2% and recover 73.8% of the energy of biogas produced. However, as shown in section 3.2, this arrangement is inefficient in utilizing recovered exhaust heat and has high fluctuation of CGS units throughout the year.

It is also shown that if the boiler is replaced with the heat pump as in A3, it can further reduce electrical power reduction by 5% and recover an extra 3% of energy of the biogas produced. However, as shown in section 3.2, this arrangement is also inefficient in utilizing recovered exhaust heat.

Exhaust heat can be efficiently utilized if a gas storage system is installed in the system as in A2 and A4. When a boiler is used, compared to the arrangement without gas storage (A1), the arrangement with gas storage (A2.a) can reduce more electrical power. However, since the power required for MH storage is high, the total electrical power demand is almost the same. If snow is used as the storage medium instead of water, another 1% of electrical power can be reduced.

When a heat pump is used, compared to the arrangement without gas storage (A3), the arrangement with gas storage (A4) can further reduce electrical power and recover more energy of the biogas produced. It should be noted that this result is based on the experimental result, and the experimental result until current stage is MH formation ratio of 67%. Thus, if a higher formation ratio can be obtained in the future, more electrical power reduction will be achieved. This concludes that installation of a gas storage system has a potential to increase the efficiency of the CGS system but the overall effectiveness is affected by the performance of the gas storage system.

It was also shown that improvement can be achieved with a CGS arrangement that includes a heat pump (A3) in the facility. If the bulk of wastewater is used as the heat source of the heat pump as in (A3.b), compared to the case of a heat pump using air as the heat source (A3.a), further electrical power reduction of 2% and further recovery of energy of the biogas produced of 1% can be achieved.

As stated above, great improvement in the performance of energy system in the plant can be obtained by only installing the simplest CGS (A1). Further improvement can be obtained if a gas storage system is also installed to the A1 because all biogas produced and recovered exhaust heat can be efficiently used. Moreover, installation of heat pump as an auxiliary heat supplier instead of boiler can also further improve the system performance because more electrical power can be saved by the CGS.

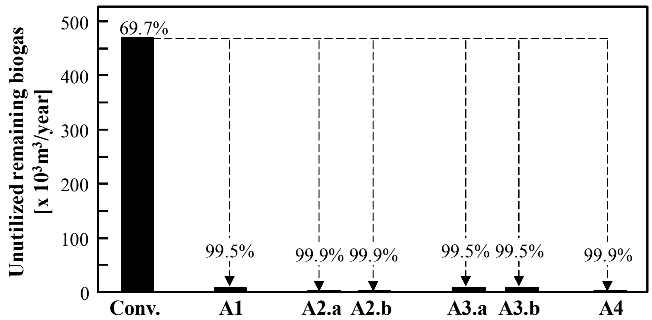

Fig. 5. Annual remaining unutilized biogas for all arrangements.

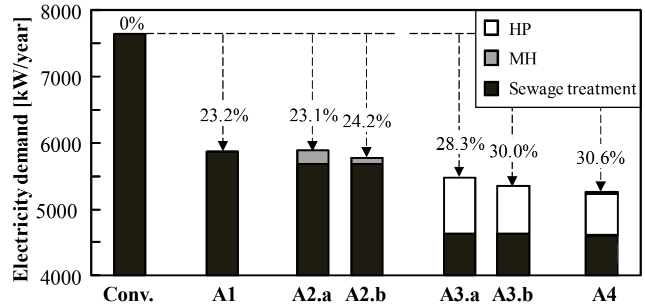

Fig. 6. Annual electricity demand reduction for all arrangements.

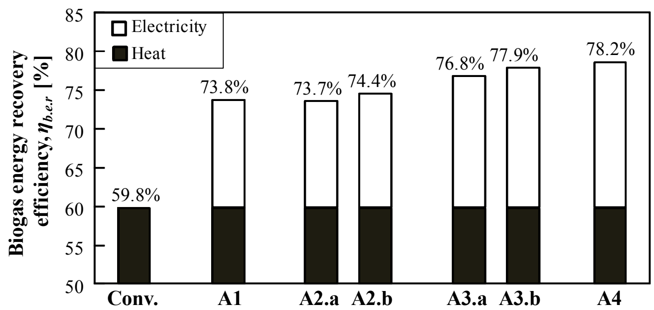

Fig. 7. Annual biogas energy recovery efficiency for all arrangements.

4. Conclusions

In this study, various arrangements of a biogas-fuelled cogeneration system in a sewage treatment plant in a cold region were investigated and the following results were obtained.

1. Biogas production in a sewage treatment plant in a cold region is comparatively

constant, but heat demand fluctuates greatly throughout the year. The heat demand of the facility varies in the range of 340~910 kW throughout the year. Thus, the arrangement of CGS must conform to this energy balance.

2. All proposed CGS arrangements can cover the total heat demand of biogas by only utilizing produced biogas. All CGS arrangements also can utilize almost 100% of the biogas produced, whereas the conventional system can utilize only 69.7% of biogas produced.
3. Great improvement in the performance of energy system in the plant can be obtained by only installing the simplest CGS that uses only a boiler. Compared to the conventional system, the simplest CGS arrangement can reduce electrical power demand by 23.2% and recover 73.8% of the energy of biogas produced. However, this arrangement is inefficient in utilizing recovered exhaust heat, and the CGS units in operation also fluctuate greatly throughout the year, in the range of 0-11 units.
4. Installation of heat pump as an auxiliary heat supplier instead of boiler can also further improve the system performance because more electrical power can be saved by the CGS. It can further reduce electrical power reduction by 5% and recover an extra 3% of the energy of biogas produced. However, this arrangement is also inefficient in utilizing recovered exhaust heat.
5. Further improvement can be obtained if a gas storage system is also installed to the system because excess biogas in summer can be used in winter by storing biogas. Therefore, CGS arrangements that include a gas storage system will enable efficient utilization of biogas and recovered exhaust heat. However, even though installation can use exhaust heat recovery efficiently, the overall effectiveness of the system is also depends on the performance of the gas storage system.
6. Improvement can also be made to the heat pump in the plant. If the bulk of wastewater is used as the heat source of the heat pump, compared to a heat pump that using air as the heat source, further electrical power reduction of 2% and further recovery of energy of the biogas produced of 1% can be achieved.

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