Doctor of Engineering Thesis

Performance Analysis and Optimization of Biogas-Fuelled Cogeneration Systems in Sewage Treatment Plants

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Contents

Nomenclature

A	Heat transfer area, m^2
C	Heat capacity, kW/K
CA	Carbon content by mass in fuel, $kg_{\text{-C}}/kg_{\text{-fuel}}$
COP	Coefficient of performance, -
Co	Cost, yen
CR	Heat capacity ratio of the exhaust heat exchanger, -
c_p	Specific heat under constant pressure, kJ/kgK
E	Energy, kW
$FESI$	Fuel energy saving index, -
h	Enthalpy, kJ/kg
I	Equipment capacity, kg/h
K	Overall heat transfer coefficiency, kW/m^2K
k	Ratio of heat capacity, -
LHV	Lower heating value, MJ/m^3 or MJ/kg
m	Mass or volume fuel rate, m^3/s or kg/s
m'	Mass of crushed ice used in methane hydrate, g
P	Pressure, Pa
PB	Payback amount, yen
PBP	Payback period, year
P_e	Electrical power, kW
Q	Heat, kW
r	Pressure ratio or exhaust heat and electricity generated ratio of the C
T	Absolute temperature, K
TS	Solid concentration of sludge, -
t	Temperature, °C
$Unit$	Unit, -
v	Volume of gas absorbed by hydrate, $m^3_{\text{-gas}}/kg_{\text{-ice}}$
v'	Volume of gas absorbed by hydrate in experiment, $cm^3_{\text{-gas}}/25g_{\text{-ice}}$
W	Electrical power, -
ρ	Density, kg/m^3
η	Efficiency, -
ω	Revolution speed, rpm
α	Capacity ratio of absorption heat exchanger, -
μ	Correction factor of heat medium flow rate of the AHE, -
ε	Temperature exchange efficiency, -
φ	Atom or molecule mass content in fuel or exhaust gas, -

Subscript

a	Working fluid of micro gas turbine
a.b	Administration building
air	Air
amb	Ambient
an	Annual
BER	Biogas energy recovery
b or boiler	Boiler
b.p	Biogas produced
b.l	Loss at boiler
biogas	Biogas
C	Compressor
c	Cooling mode
c.f	Cold fluid
CGS	Cogeneration system
CO_2	Carbon dioxide
co&ab	Condenser and absorber
conv.	Conventional system
d	Demand
e.b	Extra biogas
e.m	Extra methane biogas
ehr	Exhaust heat recovery
ele	Electrical power
exe, e	Exhaust gas
FL	Full load
f	Flare
fuel	Fuel
g	Heat input of heat medium of absorption heat exchanger
g.c	Gas compressor
g.s	CO_2 separator
grid	Electrical power grid
H	High temperature heat source
h	Heating mode
h.d	Heat demand
h.f	Hot fluid
heat	Heat
hmfr	Heat medium flow ratio of absorption heat exchanger
HP	Heat pump
i	Inlet or inner side
install	Install
i.c	Ice crusher
i.m	Ice maker
l	Low temperature heat source
m	Maintenance

max	Maximum
mech	Mechanical
min	Minimum
MGT	Micro gas turbine
MH	Methane hydrate
net1	Net energy1(Excluding mechanical work)
net2	Net energy2(Including mechanical work)
o	Outlet or outer side
p.p	Power plant
p.p.l	Loss at power plant
PL	Partial load
PSA	Pressure swing absorption method
R	Recuperator
r.b	Remaining biogas
r. g. d	Refrigerated gas dryer
r.h.d	Remaining heat demand
red	Reduction of electrical power or biogas
ref	Refrigerator
s	Sludge or Ideal temperature in cycle
S.C	Rated heating capacity of absorption heat exchanger
S.G	Rated heat input in heat medium of absorption heat exchanger
S.H	Rated cooling capacity of absorption heat exchanger
s.h	Sludge heating
s.i	Influent sludge
T	Turbine
t.l	Heat loss from digester tank
total or *t*	Total
tr	Total energy recovery
u.b	Unutilized biogas
used	Utilized heat or electrical power
unused	Unutilized heat or electrical power
w	Hot water
w.t	Wastewater treatment

Abbreviation

AHE	Absorption heat exchanger
CGS	Cogeneration system
EHE	Exhaust heat exchanger
FC	Fuel cell
GE	Gas engine
HP	Heat pump
MGT	Micro gas turbine
MH	Methane hydrate

Abstract

In terms of securing energy resources and reducing environmental problems, the utilization of biomass has been studied. Biomass is known as renewable energy which can supply more stable energy than other renewable energy types such as wind and solar energy. Thus, its application has become more important in the recent years. Abundant biogas has been produced by anaerobic digestion of sewage sludge, one of waste type biomass in sewage treatment plants. Thus, its utilization potential is very high. The installation of efficeint power plant systems in sewage treatment plants is indispensable for the efficient utilization of biogas. In this study, micro gas turbines (MGTs) were used as the prime movers of Cogeneration Systems (CGSs). MGTs have low emissions and maintenance requirements and can also use fuel with low heating value. The performance and the optimized configuration method of the system was investigated in this study.

In the initial stage, the effect of ambient temperature on the basic component of the biogas-fuelled CGS, the energy balance of the anaerobic digestion and performance of the MGT-CGS was clarified. On the basis of this result, improvement of the performance of the biogas-fuelled CGS in a cold region that has high and varies heat demand throughout the year was investigated. In this case, the CGS alone cannot cover the total heat demand and hence other auxiliary equipment including a boiler, a heat pump and a gas storage system were also considered. It was found that performance can be improved when the boiler was replaced by the heat pump, and all biogas produced and exhaust heat recovered by the CGS can be efficiently used when the gas storage system was also installed with the CGS. In the second stage, focused was given to the optimized configuration method of the CGS that can utilize all biogas produced efficiently regardless of the region and ambient temperature conditions. It was clarified that in terms of energy utilization efficiency, the most efficient CGS can be obtained when the exhaust heat index of the CGS, exhaust heat recovery efficiency η_{ehr} is approximately equal to the energy index of the plant, ratio of annual

average of heat demand $Q_{h.d}$ to the biogas energy produced $Q_{b.p}$, ($Q_{h.d}$ / $Q_{b.p}$).

On the other hand, MGTs are classified as gas turbines that have electrical power output capacity of 30-300kW, and depending on the output capacity, their electrical power output efficiency at full load and partial load are different. Thus, in the third stage, the suitable size (electrical power output capacity) of an MGT-CGS depending on the scale of the sewage treatment plant (biogas energy produced) and its optimization was investigated. It was found that the most efficient MGT-CGS can be obtained when the fuel energy input of the MGT-CGS at full load is approximately equal to the biogas energy produced of the plant. Finally, it can be summarized that this study successfully clarifies in detail the most efficient configuration of cogenerations based biogas-fuelled power plants and, this study can also give valuable guide regarding the method of the performance optimization of a biogas-fuelled CGS.

Chapter 1

Introduction

The utilization of renewable energy, especially biomass that can supply energy stably is very important to tackle energy source depletion and environmental problems. However, since biomass are scattered in a wide area with low energy density, large amount of cost and energy are required to collect before it can be utilized. On the other hand, waste type of biomass such as sewage sludge and livestock is readily collected at a single site, and its utilization is therefore comparatively easier. Especially, in sewage treatment plants, sewage sludge has been converted to biogas, easily utilizable fuel by anaerobic digestion during the sludge treatment. Furthermore, heat for the anaerobic digestion and space heating, as well electrical power for operating various pumps and compressors for wastewater treatment are also needed in the plant. In this study, in order to efficiently utilize biogas produced and cover these heat and electrical power demand simultaneously, we had focused on the utilization of biogas by distributed cogeneration systems (CGSs). Thus, all biogas produced in the plant can be efficiently utilized, and electrical power and heat losses can also be minimized by the concept of "local production for local consumption". Due to unforeseen circumstances Japan was severely hit by the Great East Japan Earthquake on March 11th 2011, and severe accident also occurred at Fukushima Nuclear No. 1 Power Plant. This accident was not only caused blackout and electrical power shortage in the Tohoku area, but also in the capital area. Rising of the public concern and criticism regarding nuclear power plant after the nuclear accident is still fresh in our minds. Thus, technology on efficient utilization waste type biomass by distributed CGSs became more essential. In this study, in order to increase the application of biogas-fuelled CGSs in sewage treatment plants and to utilize efficiently all biogas produced in the plants, performance of a biogas-fuelled CGS and its performance optimization method were investigated.

1.1. Energy crisis

Recently, humankind is facing twin energy related problems, depletion of fossil fuel source and environmental disruption causes by too much consumption of fossil fuel. International Energy Agency (IEA) reported that under the current energy consumption rate, the reserves of petroleum, natural gas and coal will be lasted only about 42, 64 and 164 years, respectively [1]. Moreover, global population is increasing and the problems will be more severe. Fig. 1.1 shows the estimated incremental of global energy demand on the basis of current energy utilization situation [2]. As shown in the figure, petroleum, coal and natural gas are still the main global energy sources. Since 1980, energy demand has been increasing with an annual incremental rate of 1.6%. Moreover, compared to the 1980 it is estimated that the amount of energy demand will be doubled in 2030. The increase rate in energy demand divided by sector is shown in Fig. 1.2. It shows that approximately half of the increment is from electrical power generation [1]. Thus, in order to meet future energy demand and maintain the environmental aspects at the same time, the utilization of renewable energy such as biomass, wind and solar with high efficiency is important, especially in the electric power generation sector.

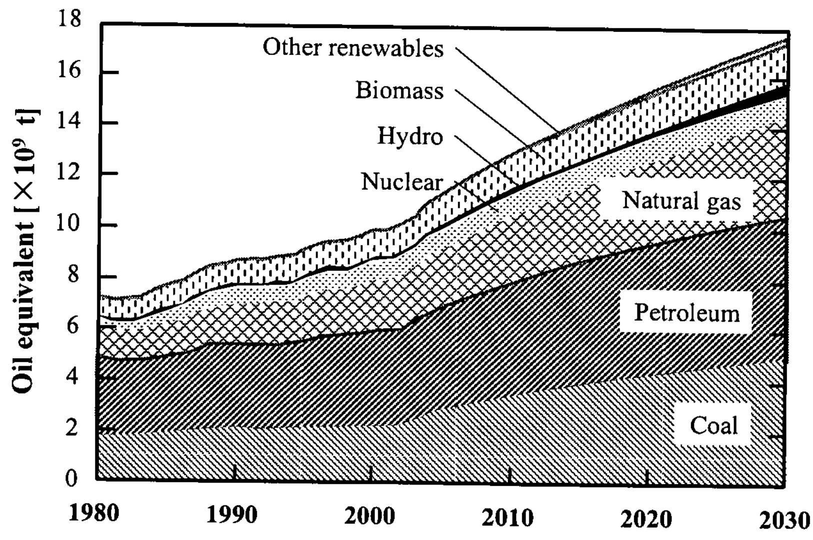


Fig. 1.1 Global energy demand increase

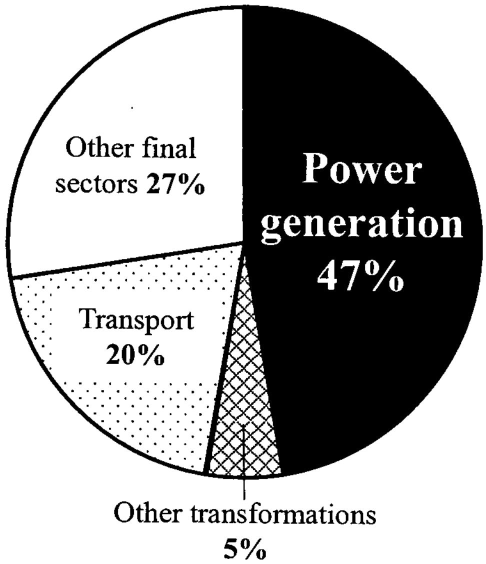


Fig. 1.2 Increase rate for every energy sector from 2004 to 2030

1.2. Biomass and Cogeneration System

Biomass is all energy sources that are derived from organic compound from living matter excluding fossil fuels. Plants receive light from the sun as its energy source, and they form hydrocarbon bond from water and carbon dioxide. This organic chemical energy derived from photosynthesis is the origin of biomass. As shown in Fig. 1.3, approximately 173 PW of sunlight radiation that receives by earth and a portion will be decreased by reflection and absorption in the atmosphere, and approximately 82 PW will finally fall on the earth's surface. The net production of biomass by this photosynthesis is approximately 170 Gt (dry-weight) in a single year which is equivalent to 100 TW. This amount is approximately equal to 7-10 times of energy consumed by humankind. However, besides the 'biomass flow' by sun radiation stated-above, there are also 2Tt of 'biomass stock' on the earth. Thus, biomass must be used in the range of 'biomass flow'. If biomass are used by considering the amount of 'biomass stock', biomass will be renewable and sustainable energy source [3]. Besides the abundant amount, biomass also has other advantages compared to the other renewable energy sources. Biomass is comparatively not easily influenced by environment and energy can be therefore supplied stably [4]. Moreover, although carbon dioxide will be produced if biomass is burned, carbon dioxide produced will be re-used to grow plants, and biomass is therefore carbon-neutral energy. These are the characteristics that made a great expectation to the utilization of biomass.

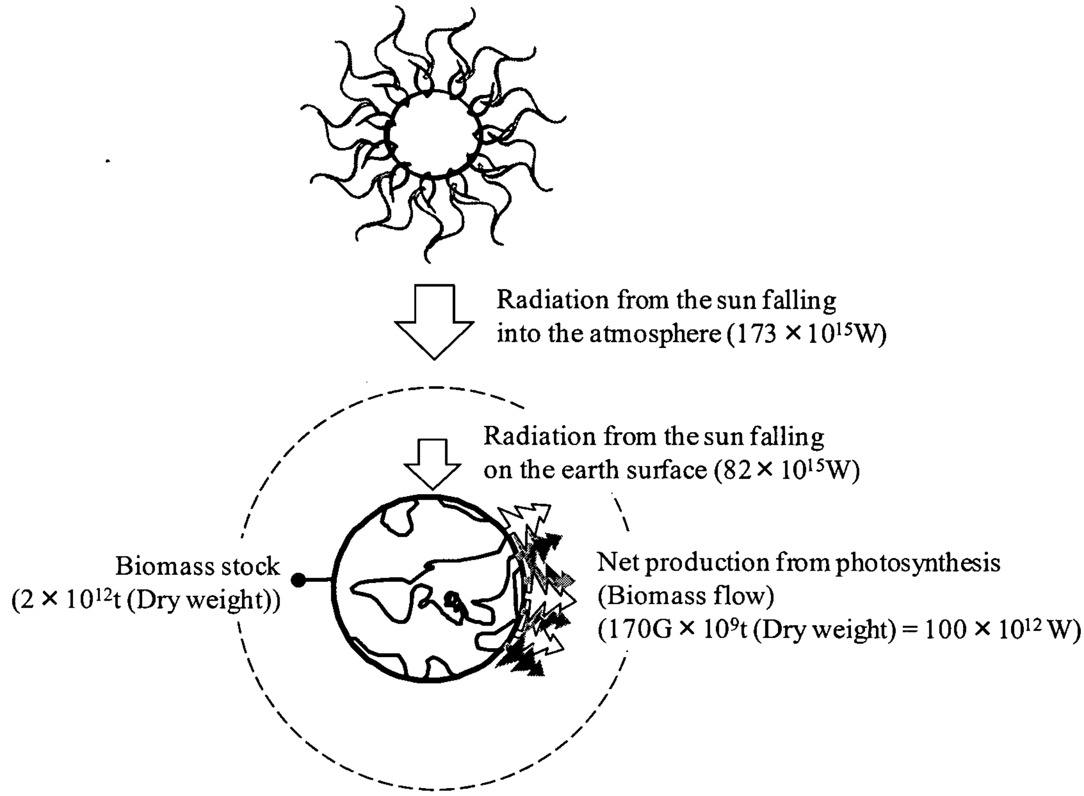


Fig. 1.3 Biomass on the earth

In Japan, Biomass Nippon Strategy was established in December 2002 with tackling global warming and establishing recycle-oriented society are its main objectives [4]-[5]. On the other hand, the measures outlined in the European Union Biomass Action Plan also will increase biomass (solid biomass, biogas, biofuels and renewable municipal waste) utilization. It is expected that biomass consumption will reach approximately 150 Mtoe by 2010 [6].

However, biomass has a characteristic that its abundant amount is scattered in a wide range with low energy density [4], [7]-[9]. Thus, considering there will be a great amount of cost and energy required to collect biomass in a single site, distributed generation system of biomass is preferred. By the concept of 'local production for local consumption', biomass energy can be used as the electrical power and heat at the site by application of a high efficiency technology, cogeneration system (CGS). In addition, this renewable energy distributed power generation is also one of the key factors for widespreading of the future electrical power network, smart grid.

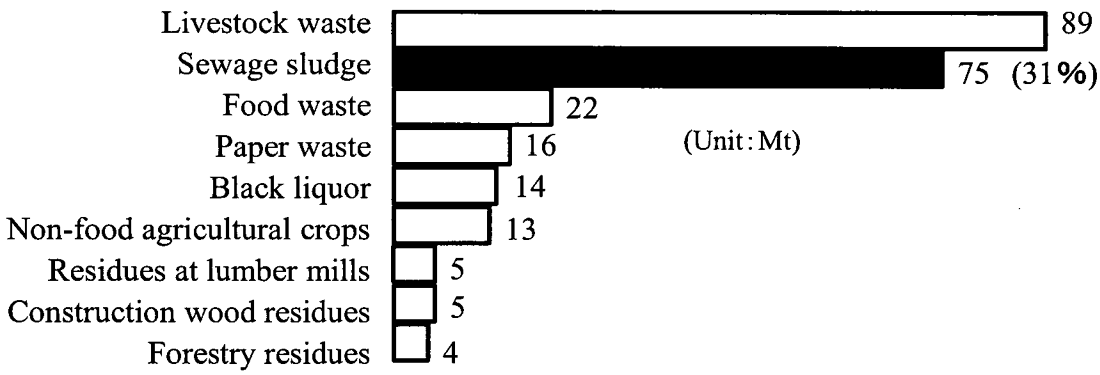
Current ongoing energy policy in Japan has objectives to achieve energy self-sufficiency rate and zero-emission generation. There is a target to increase energy self-sufficient rate from 18% to 40% by 2030. Thus, there is an objective to increase nuclear power generation that costs less and zero-emission from 26% to 53% in electrical power generation sector [10]. However, unfortunately Japan was severely hit by the Great East Japan Earthquake on March 11th 2011, and another major catastrophe was also occurred at Fukushima Nuclear No.1 Power Plant. The area of blackout and electrical power shortage is not only limited in the Tohoku area but also in capital area. Rising of the public concern and criticism regarding nuclear power plant after the nuclear accident is still fresh in our minds. Thus, technology for efficient utilization waste type biomass by distributed CGS became more important.

1.3. Current status of biogas-fuelled cogeneration systems in sewage treatment plants

As shown in Table 1.1, waste type biomass such as livestock waste, sludge waste, food waste are readily collected in one site, and they are comparatively easy to be used compared to other types of biomass, and therefore its potential to be utilized is high [4] -[11]. In sewage treatment plants, wastewater from the city is treated in order to conserve the better water environment, and treated clean water is re-used or released to the river. In addition, in order to stabilize, reduce and detoxify the remained sewage sludge, it is converted to by-product, biogas by anaerobic digestion, and therefore sewage sludge is already converted to fuel that can be easily used [12]-[13]. A portion of biogas produced in the plant is burned in a boiler to cover heat demand on the plant. However, since the main work of the administrative staffs in the plant is regarding the management of the quality of water not the efficient utilization of biogas, a large amount of remaining biogas is usually not used but incinerated [6], [14].

Besides the heating demand for anaerobic digestion, heat also required for hot-water supply and space heating of administration buildings, and electrical power also required to operate various pumps and compressor for the wastewater treatment process. Thus, all biogas produced can be efficiently utilized and cover heat electrical power demand of the plant at the same time by a biogas-fuelled cogeneration system (CGS). Therefore, focus has been given to the CGS, a system that can efficiently produce electrical power and heat simultaneously by a single fuel source. As shown in Fig. 1.4, there are approximately 1900 sewage treatment plants in Japan, but only approximately 300 (16% of the total) of the plants equipped with anaerobic digestion, and approximately only 30 plants (2% of the total) can use CGS [12], [14]. The same situation was also found in the US, in which there are approximately 16042 of sewage treatment plants, but only 3452 (22% of the total) of the plants equipped with anaerobic digestion and only 266 plants (2% of the total) can use CGS [21]. Thus, 98% of the all facilities are still not utilizing biogas, and biogas is therefore an abundant untapped source that has very high potential to be utilized.

Table 1.1 Annual production rate of waste type biomass



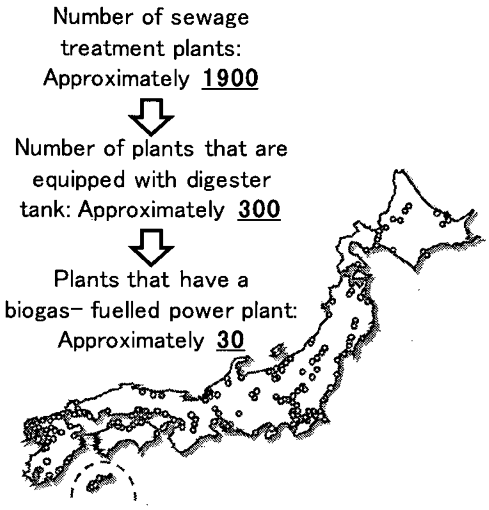


Fig. 1.4 Current status of biogas-fuelled CGS in Japan

Table 1.2 shows the details of places and the scale of biogas-fuelled power plants in sewage treatment plants in Japan [3], [12], [14]-[19]. There are shown from Hokkaido, the northern part to Okinawa, the southern part of Japan. As shown in the table, there are approximately 30 plants that equipped with biogas-fuelled power plants in Japan. Moreover, if biogas production amount of every plant is examined, almost 90% of those plants have annual biogas production of more than 1 500 000 m^3. This indicates that biogas-fuelled CGSs are usually installed in comparatively large-scale plants, and installation progress of biogas-fuelled CGSs is slow for middle- and small-scale plants that produce biogas less than 1 500 000 m^3 [17].

Besides cost, impurity content in biogas and biogas production amount are among the reasons why the installation of biogas-fuelled power plants has been not widespreading. Generally, installation of a biogas-fuelled power plant requires high initial cost. Moreover, life-time of engine components, NOx removal catalyst of a gas engine, a prime mover that usually used for the power plant is also short, and this causes further increase in installation, as well operation and maintenance cost. This is because the formation of silica when siloxane, one of biogas impurity contents is burned inside the engine. This is one of the reasons of the delay of the installation of biogas-fuelled power plants before it was

Table 1.2 Current status of biogas-fuelled power plants in Japan

Name of the plants			Condition of the biogas-fuelled power plants			
			Prime mover	**Generating capacity [kW]**	**Biogas production amount [$\times 10^4 m^3/y$]**	**Electrical power demand reduction rate [%]**
1	Hokkaido	Kitami STP	**Gas turbine**	6×30	**156**	12
2	Hokkaido	Hakodate STP (Nanbu)	Gas engine	1×500	217	21
3	Hokkaido	Ebetsu STP	Gas engine	1×250	166	28
4	Hokkaido	Asahikawa STP	Gas engine	1×700	254	13
5	Hokkaido	Tomakomai STP (Nishi-Cho)	Gas engine	3×80	268	-
6	Aomori	Hachinohe STP (Toubu)	Gas engine	3×170	-	-
7	Iwate	Kitakamikawajyouryuu STP (Tounan)	Gas engine	1×590	410	9
8	Yamagata	Yamagata STP	Gas engine	1×178	**147**	18
			Fuel cell	2×100		41
9	Niigata	Nagaoka STP (Chuo)	-	-	-	-
10	Ibaraki	Hitachi-shi Ikenokawa STP	Gas engine	1×500	**74**	18
11	Ibaraki	Ishi STP	Gas engine	280	-	-
12	Gunma	Isesaki STP	**Gas turbine**	1×30	**42**	16
13	Tokyo	Odai STP	Gas engine	3×680	528	19
14	Tokyo	Morigasaki STP	Gas engine	1×3 200	1 202	16
15	Kanagawa	Yokohama STP (Hokubu)	Gas engine	4×920 1×1100	1 649	69
			Fuel cell	1×200		5
16	Kanagawa	Yokohama STP (Nanbu)	Gas engine	2×1200	1 351	43
17	Ishikawa	Daishoujikawa STP	**Gas turbine**	2×30	**17**	13
18	Kyoto	Rakunan STP	Gas engine	1×990	-	-
19	Osaka	Nakahama STP	Gas engine	2×600	318	28
20	Osaka	Harada STP	Gas engine	1×400	712	6
21	Osaka	Ebie STP	Fuel cell	1×200	357	3
22	Hiroshima	Hiroshima STP (Nanbu)	Gas engine	1×200	599	4
			Gas engine	1×450		9
23	Yamaguchi	Bofu-shi Bofu STP	Gas engine	2×200	**64**	4
24	Fukuoka	Nichimei STP	Gas engine	2×200 6×25	511	1
25	Fukuoka	Fukuoka STP (Chubu)	Gas engine	1×500	178	5
26	Kumamoto	Kumamoto STP (Hokubu)	Fuel cell	4×100	180	50
27	Miyazaki	Miyazaki STP	Gas engine	1×250	183	22
28	Miyazaki	Myoda STP	Gas engine	1×250	**65**	20
29	Saga	Saga-shi STP	Gas engine	16×25	**110**	-
30	Okinawa	Naha STP	Gas engine	3×270	465	34
31	Okinawa	Nago STP	Gas engine	2×25	-	12

* STP: Sewage treatment plant

discovered in a few years ago [19]-[20]. Besides, sewage treatment plants that have a comparatively small amount of biogas production, and on top of this methane content in the biogas is also low, the use of common prime movers that have an electrical power generation capacity of more than a few 100 kW are difficult. A gas engine has complicated structure with frequent maintenance requirement, including water coolant and lubricant is needed, and therefore it is not economically feasible if the electrical power generation capacity of the power plant is small. Thus, although a biogas-fuelled power plant is an effective tool in large-scale plants, it is not widespread in middle- and small-scale plants [20]. In addition, besides the small gas engines with an electrical power generation capacity of less than a few 100 kW, recent attention is given to micro gas turbines (MGTs) and fuel cells [6], [14], [21]-[28]. Fuel cells are the most promising prime mover in terms of efficiency and environment but they still costly and less reliable [29]-[30]. Since MGTs have merits such as less pollution and maintenance requirement, high power density [31]-[33], they will be prime movers that used in biogas utilization besides gas engines from now on. Moreover, since MGTs have comparatively high heat-to-power ratio, they are suitable for the application in sewage treatment plant that needs high heat demand for water and space heating in the administration building, as well for anaerobic digestion.

Comparison of basic specifications and cost for every prime mover is shown in Table 1.3. Since performance and cost of every prime mover that were published by different references is slightly different, data from 4 references are shown in the table [34]-[37]. Table shows that an MGT has slightly lower electrical power efficiency compared to a reciprocating engine, but an MGT has low emission because its combustion temperature is low. On the other hand, excluding reference *B*, other references reported that an MGT has slightly higher installation cost compared to a reciprocating engine. However, in terms of the operation and maintenance cost, reference *C* and *D* reported that an MGT is less expensive compared to a gas engine. Furthermore, Environmental performance of the gas engine and MGT is shown in Table 1.4 [38]. As shown in Table 1.4, an MGT has very low NOx, CO and THC emissions and it has very good environmental performance.

Table 1.3 Comparison of cost and basic specifications of every prime mover

		Reciprocating Engine		MGT	Fuel cell	Photovoltaic	Wind Power	Gas turbine	Steam Turbine	Combined Cyc
		Diesel Engine	Gas Engine							
A										
Power capacity	MW	0.01-5.0		0.03-0.25	0.005-2.0			0.50-50	0.05-50	
Power efficiency(HHV)	%	30-37		23-26	30-46			22-37	15-5	
Overall efficiency(HHV)	%	69-78		61-67	65-72			65-72	80	
Installation cost (power-only)	$/kW	700-1000		1500-2300	2800-4700			600-1400	300-900	
Installation cost (CGS)	$/kW	900-1400		1700-2600	3200-5500			700-1900	300-900	
Maintenance cost	$/kWh	0.008-0.018		0.013-0.020	0.02-0.040			0.004-0.010	<0.004	
NOx Emissions	lb/MWh	0.2-6.0		0.5-1.25	<0.10			0.8-2.4		
B										
Power efficiency(HHV)	%	30		24				30		
Power to weight ratio	kW/t	30		280				150		
Combustion temperature	℃	>2000		840				<1500		
NOx Emissions	ppm	900		9				50		
Installation cost (power-only)※	×10⁴yen/kW	20	25	20	>70	90	30			
C										
Power capacity	MW	0.02-10.0	0.05-5.0	0.03-0.20	0.05-1.0	>1.0		>1.0		
Power efficiency(HHV)	%	36-43	28-42	25-30	35-54	n.a.		21-40		
Package cost (power only)	$/kW	125-300	250-600	350-750	1500-3000	n.a.		300-600		
Installation cost (power-only)	$/kW	350-500	600-1000	600-1100	1900-3500	5000-10000		650-900		
Exhaust heat exchanger cost	$/kW	n.a.	75-150	75-350	incl.	n.a.		100-200		
Maintenance cost	$/kWh	0.005-0.010	0.007-0.015	0.005-0.010	0.005-0.010	0.001-0.004		0.003-0.008		
D										
Power capacity	MW		0.10	0.10	0.20	0.10	0.01			1
Installation cost (power-only)	$/kW		1030	1485		6675	3866			6
Installation cost (CGS)	$/kW		1491	1765	3674					
Maintenance cost	$/kWh		0.018	0.015	0.01	0.005	0.005			0.0

[A] *National Renewable Energy Laboratory, Gas-Fired Distributed Energy Resource Technology Characterizations, 2003, pg. 1-8.*

[B] *K. Ishii, Micro Gas turbine system, Ohm Co., 2002, pp. 146, 169.*

[C] *Distributed Generation Forum, The role of Distributed Generation in Competitive Energy Markets, 1999, pp. 4.*

[D] *The Congress of the United States: Congressional Budget Office, Prospects for Distributed Electricity Generation, 2003, pp. 11.*

※All are shown in dollar except *B*

Table 1.4 Environmental performances of a gas engine and an MGT

		Gas Engine	MGT
NOx	[ppm]	2100	<9
CO	[ppm]	340	<25
THC	[ppm]	150	<9

1.4. Comparison of cost of small cogeneration systems in a sewage treatment plant

It was stated in the previous section that MGTs, gas engine (GEs) and fuel cells (FCs) are the small prime movers for biogas-fuelled CGSs. Herein, analysis results of the cost merit for all CGSs when they are installed in the plant are compared. In general, heat and electrical power output of a conventional system composed of a boiler and a thermal power plant and heat and power output of a CGS was assumed to be equal in order to calculate the cost merit of the installation of a CGS. Then, the installation cost and running cost of a CGS and running cost of a conventional system was compared and evaluation is performed. In this case, fuel cost that occupies the large part of running cost of a CGS must be considered. In general, fuel cost is 80% of the total running cost [39].

On the other hand, a conventional system in a sewage treatment plant is different. In the case of a sewage treatment plant, biogas produced in the plant is used as the fuel. Biogas is usually burned in a boiler to over the total heat demand, but a large amount of remaining biogas is incinerated. Thus, a CGS installed in the plant fulfills a role of the boiler, cover the total heat demand and a portion of electrical power demand, simultaneously. Thus, fuel cost is not considered in running cost of a CGS in the plant, and the merit of the installation of a CGS is the biogas can be converted to electrical power.

Cost merit of a CGS is evaluated by payback period *PBP*, how many years amount of money collected by generating electrical power can cover the amount of money invested for installing the CGS. Important parameters used for the calculation are shown in Table 1.5. Assumptions made are shown below:

Regarding the plant,

- Scale of a plant is described based on its biogas production amount.The model plant used in the calculation was a middle-scale plant that is described in Chapter 2.

Regarding the generation capacity of a CGS,

- Electrical power generation capacity of all CGSs is shown in Table 1.3 (Reference *C*). Appropriate electrical power generation capacity of all CGSs which can utilize all biogas produced was estimated by the relation of biogas produced and electrical power efficiency.

Regarding installation cost of a CGS,

- Despite of using Reference *A* and *C* that show installation cost for a wide range of electrical power capacity, Reference *D* that shows only data for small scale CGS was used for the calculation.
- Besides a prime mover and a heat exchanger, installation cost also includes auxiliary equipment, building construction, land acquisition and preparation. The cost of the CGS itself is usually 55% of the total cost [39]. Total cost of the CGS was estimated by this value.
- There are impurities content including water, H_2S and siloxane in biogas. Since data of the installation cost of biogas pretreatment equipment is difficult to obtain, it was not considered.

Regarding running cost,

- Besides fuel cost that was stated above, running cost also consist of operation and maintenance cost, loan interest and insurance. However, only operation and maintenance cost was considered.
- Electricity rate of Hokuden for office, commercial and factory building was used in the calculation [40].

Table 1.5 Parameters used for the cost calculation

		GE	MGT	FC
Fuel (Biogas production amount)	[kW]	1073	1073	1073
Generation Capacity	[kW]	450	350	500
Electrical power efficiency	[-]	0.40	0.30	0.45
CGS installation cost	[$\times 10^4$yen/kW]	5166	4757	14145
Total installation cost	[$\times 10^4$yen/kW]	9393	8649	25718
Running cost (O&M)	[yen/kWh]	1.39	1.16	0.77
Electricity rate	[yen/kWh]	12.3	12.3	12.3

Electrical power generated by a CGS in a year $Pe_{CGS,an}$ can be calculated by power efficiency of a CGS $\eta_{CGS,ele}$ and amount of biogas produced in a year $Q_{b.p,an}$ as expressed in eq.(1.1).

$$Pe_{CGS,an} = Q_{b.p,an} \cdot \eta_{CGS,ele} \qquad \text{[kWh]} \qquad (1.1)$$

Payback money accumulated in a year PB_{an} can be calculated by cost reduction by the electrical power generated in a year $Co_{Pe,an}$ and operation and maintenance cost of the CGS in a year $Co_{m,an}$ as expressed in eq.(1.2)-(1.3). In addition, Co_{Pe} and Co_m is electricity rate and operation and maintenance cost, respectively.

$$PB_{an} = Co_{Pe,an} - Co_{m,an} \qquad \text{[yen]} \qquad (1.2)$$

$$PB_{an} = Pe_{CGS,an} \cdot Co_{Pe} - Pe_{CGS,an} \cdot Co_m \qquad \text{[yen]} \qquad (1.3)$$

Finally, payback period PBP can be calculated by the following equation.