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Evaluation on the viability of combined heat and power with different distributed generation technologies for various bindings in Japan

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***Abstract*—**This paper has examined the energy consumption characteristics in six different buildings including apartments, offices, commercial buildings, hospitals, hotels and educational facilities. Then 5-hectare (50000m^2) development site for respective building's type has been assumed as case study to evaluate the introduction effect of Combined Heat and Power (CHP). All kinds of CHP systems with different distributed generation technologies including Gas Turbine (GT), Gas Engine (GE), Diesel Engine (DE), Solid Oxide Fuel Cell (SOFC) and Polymer Electrolyte Fuel Cell (PEFC), have been simulated by using HEATMAP, CHP system analysis software. And their primary energy utilization efficiency, energy saving ratio and CO_2 reduction ratio have evaluated and compared respectively.

The results can be summarized as follows: Various buildings have their special heat to power ratio characteristics. Matching the heat to power ratio demanded from an individual building with that supplied from a CHP system is very important. It is necessary to select a reasonable distributed generation technologies according to the load characteristics of various buildings. Distributed generation technologies with high energy generating efficiency and low heat to power ratio, like SOFC and PEFC is more reasonable selection for Building Combined Heat and Power (BCHP). CHP system is an attractive option for hotels, hospitals and apartments in Japan. The users can achieve high energy saving and environmental benefit by introducing a CHP systems. In others buildings, especially like commercial buildings and offices, the introduction of CHP system is unreasonable.

***Keywords*—**Combined heat and power, Distributed generation technologies, Heat-to-Power ratio, Energy saving ratio, CO_2 reduction ratio

I. Introduction

In recent years as a supplement for conventional large-scale power generation system, distributed generation technologies has got more comprehensive attention. During the last 20 years, in Japan, as a main kind of distributed generation technologies, Combined Heat and Power (CHP) has been developed rapidly and the number of CHP systems has increased from 67 in 1986 to 7,359 in 2007, and the total generating capacity has increased from 200kW in 1986 to 8,786 MW as of March 2007[1]. However, at present it provides only a small portion of nation's energy, about 1.2% of the total primary energy supply. But active efforts are being made to promote it with Kyoto Protocol being implemented in February 16.2005.The government's target for 2010 is to increase the share of CHP to approximately 3% in total energy supply [2]. Therefore, it can be expected that CHP should have larger potential market in Japan. And according to a survey, CHP systems have mainly been installed in the industrial and commercial buildings. However, the energy consumption for buildings in Japan accounted for more than 26.4% of total primary energy [3]. Based on this, Building Combined Heat and Power (BCHP) is expected to pay an important role in energy supply for various buildings.

According to a survey [4], in Japan, various distributed generation technologies for CHP, including Gas Turbine (GT), Gas Engine (GE), Diesel Engine (DE), Solid Oxide Fuel Cell (SOFC) and Polymer Electrolyte Fuel Cell (PEFC), and so on, have been used widely in various buildings. Due to each distributed generating technology being special running characteristics, it is very important to how to select a reasonable distributed generation technology according to the load characteristics for various buildings.

This paper has assessed the energy consumption for six different buildings including apartments, offices, commercial buildings, hospitals, hotels and educational facilities in Japan. And their characteristics of heat-to-power ratio have been discussed. The viability of five CHP system with different distributed generation technologies for various buildings has been examined by comparing their primary energy utilization efficiency with that in the conventional system. Various cases have been evaluated regarding energy saving and environmental effect by using computer software, HEATMAP.

II. Study Objective and Load Assessment

A. Study objective

In this paper, a 5-hectare development site is located in Kitakyushu, the south of Japan on the northern tip of Kyushu. It is a city with a typical maritime climate. Annual average temperature is about 17 , the hottest month occurs generally in August with monthly average temperature approximately

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30 and the coldest month is in January with monthly average temperature about 7 .

B. Load assessment

In this study, the annual load demand for heating, cooling, hot water and electricity for various types are calculated according to Ojima's annual energy unit [4]. For example, the hotel has about 3,421MJ/m^2 annual load, including heating, cooling, hot water and electricity being respectively, 496MJ/m^2, 271MJ/m^2, 1,296 MJ/m^2 and 1,358 MJ/m^2. And according to the data available [5], the daily, hourly and monthly percentage can be gained. Therefore, the hourly, maximum, minimum and annual loads for various buildings are assessed and were summarized in the Table 1. The minimum electricity for hotels, apartments, educational facilities, offices, hospitals and commercial buildings are 919kW, 228kW, 102kW, 196kW, 473kW and 407kW respectively.

As we know, the heat to power ratio is a key factor influencing the introducing effect of CHP. It is defined as the

Table 1 Maximum, minimum and annual load for various buildings

Type	Load	Heating	Cooling	Hot water	Electricity
Hotels	Max(kW)	3072	2080	4320	3634
	Min(kW)	0	0	940	919
	Annual(GJ)	24786	13565	64791	67910
Apartments	Max(kW)	1734	506	2081	1117
	Min(kW)	0	0	0	228
	Annual(GJ)	6213	1019	11210	17134
Education facilities	Max(kW)	3853	1064	761	1439
	Min(kW)	0	0	0	102
	Annual(GJ)	10385	3183	754	16492
Offices	Max(kW)	4076	3278	212	2648
	Min(kW)	0	0	0	196
	Annual(GJ)	11798	13065	1776	38276
hospitals	Max(kW)	6062	4036	5490	3439
	Min(kW)	0	0	0	473
	Annual(GJ)	23802	9818	50388	47235
Commerce buildings	Max(kW)	2387	3239	914	8015
	Min(kW)	0	0	0	407
	Annual(GJ)	7258	15240	5401	104019

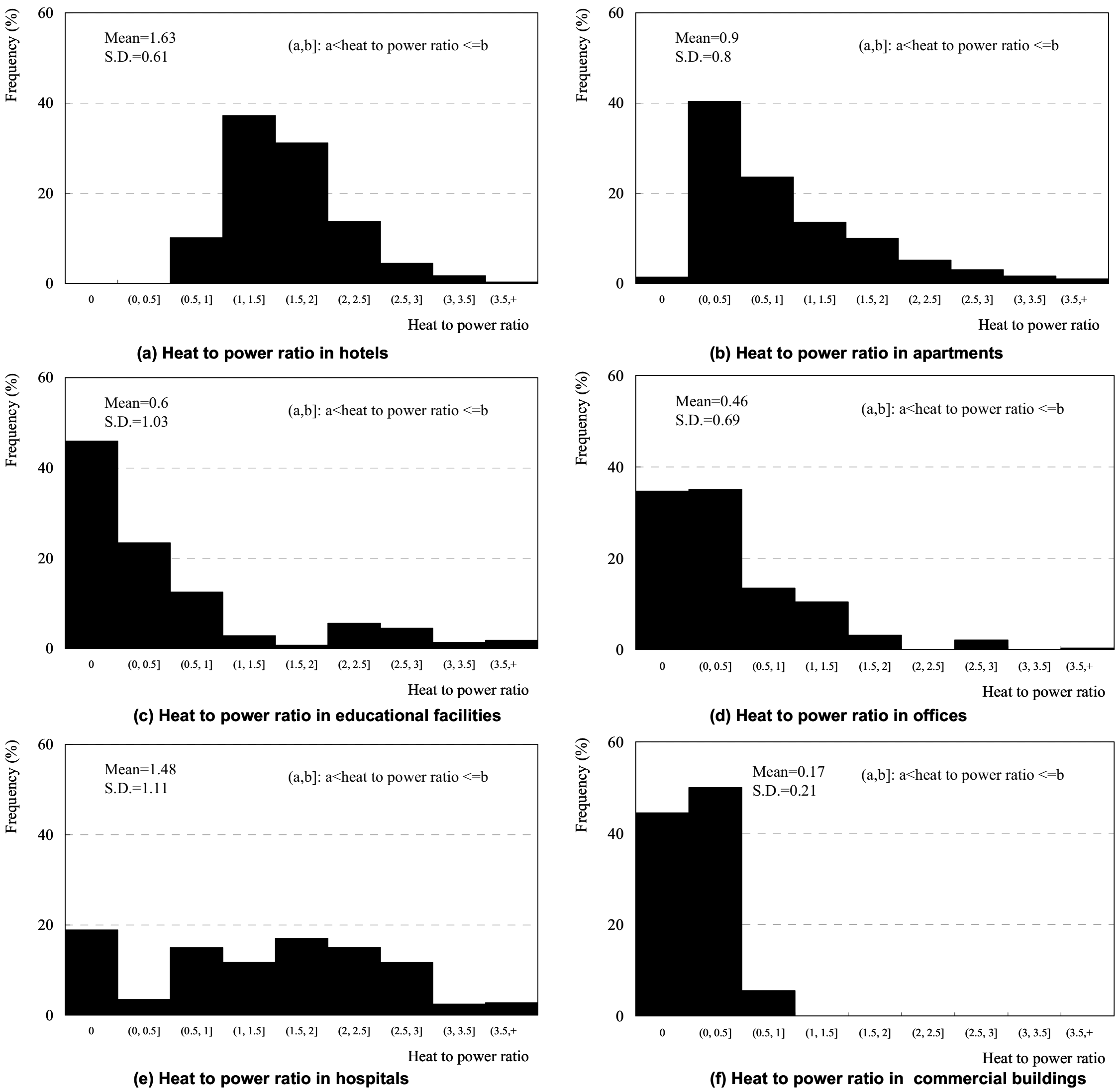

Fig.1: The characteristic of heat to power ratio for various buildings

rate of useful thermal energy production (or demand) to that of electrical energy production (or demand). For a CHP project, matching the heat to power ratio demanded from an individual building (and /or local network) with that supplied from a CHP system is very important. The more closely a CHP unit can match the instantaneous supply of heat and electricity with the instantaneous demand for heat and electricity, the more fuel efficient it will be. In the case of power generation technologies, because fuel is the dominant source of marginal running costs, higher fuel efficiency is concomitant with lower marginal costs. Higher fuel efficiency also results in lower emissions. On the demand side, the heat and power demanded in a home or office varies rapidly and sporadically over a large range. However, on the supply side, the heat and power supply remains relative stable due to the constant electricity generation and heat recovery efficiency of CHP system. Therefore, matching the heat to power ratio between demand and supply is a formidable task.

In this paper, the hourly heat to power ratio for various buildings is calculated by the hourly thermal and power energy demand and their characteristics have been analyzed. Fig.1 (a f) shows the characteristics of heat to power ratios for various buildings. Analysis of the heat to power ratio profiles displays the following characteristics: The heat to power ratio for various buildings fluctuates with the wide range from 0 to 5, and various buildings have different heat to power ratio characteristics. Considering the mean of heat to power ratios, hotels have the maximum value with 1.63, followed by hospitals with 1.48, apartments with 0.9, and educational facilities with 0.6, offices with 0.46, and commercial buildings with the lowest - only 0.17. Hotels and apartments have similar heat to power characteristics. Their heat to power ratios mainly center at more than 0 and less than 2.5, which shares of the 95% of the total frequency. For educational facilities, offices and commercial buildings, mostly heat to power ratio are less than 0.5. Hospital's heat to power ratio disperses at the total range.

III. The Relationship between Heat to Power Ratio of User and Energy Saving Ratio of CHP

As described in the former section, heat to power ratio is a decisive factor influencing CHP systems. In this section, the relationship between the heat to power ratio of the user and the energy saving ratio of CHP systems has been analyzed. In order to compare, an alternative conventional system described in Fig.2 is assumed. In this case, the electricity demand is supplied by the utility electricity company. Room air conditioners are used to supply cooling and heating demands. Gas heaters provide hot water.

CHP system is illustrated in Fig.3.The operating mode of CHP systems is assumed to be electrical tracking. This means that CHP equipments will be operated to satisfy electric loads.

The energy saving ratio of CHP is defined as the percent of energy saved and can be calculated by comparing with a conventional energy supply system:

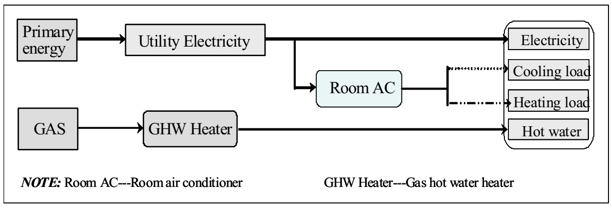

Fig. 2 Energy supply plan of conventional system

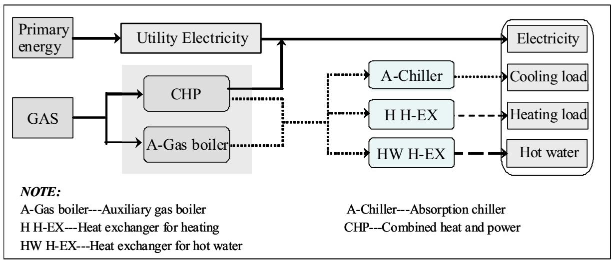

Fig. 3 Energy supply plan of CHP system

$$\eta_{\Delta E}^{CHP} = \frac{Q_E^{Conv} - Q_E^{CHP}}{Q_E^{Conv}} \tag{1}$$

Considering electrical tracking, when the demand side heat to power ratio ≤ the supply side CHP's ratio $\sigma \le \sigma_{CHP}$,

$$\begin{aligned}\eta_{\Delta E}^{CHP} &= \frac{Q_E^{Conv} - Q_E^{CHP}}{Q_E^{Conv}} \\ &= \frac{(E/\eta_{Conv}^P + E\sigma/\eta_{Conv}^H) - E/\eta_{CHP}^P}{(E/\eta_{Conv}^P + E\sigma/\eta_{Conv}^H)} \\ &= \frac{(1/\eta_{Conv}^P + \sigma/\eta_{Conv}^H) - 1/\eta_{CHP}^P}{(1/\eta_{Conv}^P + \sigma/\eta_{Conv}^H)}\end{aligned} \tag{2}$$

When $\sigma \ge \sigma_{CHP}$,

$$\begin{aligned}\eta_{\Delta E}^{CHP} &= \frac{Q_E^{Conv} - Q_E^{CHP}}{Q_E^{Conv}} \\ &= \frac{\left(E/\eta_{Conv}^P + E\sigma/\eta_{Conv}^H\right) - \left(E/\eta_{CHP}^P + \left(E\sigma - E/\eta_{CHP}^P \ \eta_{CHP}^H\right)/\eta_{Conv}^H\right)}{\left(E/\eta_{Conv}^P + E\sigma/\eta_{Conv}^H\right)} \\ &= \frac{\left(1/\eta_{Conv}^P + \sigma/\eta_{Conv}^H\right) - \left(1/\eta_{CHP}^P + \left(\sigma - 1/\eta_{CHP}^P \ \eta_{CHP}^H\right)/\eta_{Conv}^H\right)}{\left(1/\eta_{Conv}^P + \sigma/\eta_{Conv}^H\right)}\end{aligned} \tag{3}$$

Where,

$\eta_{\Delta E}^{CHP}$: Energy saving ratio of CHP system;

Q_E^{Conv} : Total primary energy input in the conventional energy supply system, MJ;

Q_E^{CHP} : Total primary energy input in the CHP energy supply system, MJ;

E : Electricity load demand, MJ;

η_{Conv}^P : Electricity generation efficiency on the conventional energy supply system;

η_{Conv}^H : Thermal efficiency of the boiler on the conventional energy supply system;

σ : The heat to power ratio on the demand side;

σ_{CHP} : The heat to power ratio on the supply side;

η_{CHP}^P : Electricity generation efficiency CHP system;

η_{CHP}^H : Thermal recovery efficiency of CHP system;

According to the survey [7]-[9], COP and efficiencies for various equipments are listed in the Table 2. Using the above assumed values for CHP efficiencies and the equation (3), one can calculate the relationship between the heat to power ratio and the energy saving ratio as illustrated in Fig. 4. From the figure, it can be concluded that all profiles have the same tendency, energy saving ratios for various distributed generation technologies increase to their peak values firstly, then decrease with the rise heat to power ratio. SOFC has the maximum peak energy saving ratio with 39.1%, followed by PEFC with 36.9%, GE with 29.4%, DE with 28.6% and GT with 14.2%, corresponding, the heat to power ratio required being at 1, 1.4, 1.7, 0.9 and 2 respectively. That is to say, a kind of different distributed generation technologies are generally fit for some kind of building. For example, for hotels, compare with other distributed generation technologies, PEFC and SOFC should have higher energy saving ratio. It is the reason that the heat to power ratio for hotels centered at the range with [1, 1.5], where the peak of energy saving ratio for PEFC and SOFC occurs right at the heat to power ratio required with 1.4 and 1.

IV. Case Studies and Simulation Method

Based on the heat to power ratio characteristics of various buildings and the relationship between heat to power ratios and energy saving ratios, five kinds of CHP systems with various distributed generation technologies are introduced to provide the energy demand for various type buildings including hotels, apartments, educational facilities, offices, commercial buildings and hospitals. Because electricity from the CHP system can not to be sold in Japan, the capacity of CHP system is assumed to only satisfy the minimum the electricity demand. Therefore, the electricity generating capacity of the CHP systems for hotels, apartments, educational facilities, offices, hospitals and commercial buildings are 900kW, 200kW, 400kW, 196kW, 100kW and 450kW, respectively according to the Table 1. Deficits of electricity are provided by the utility electricity company. Heat load, including heating load and hot water, is supplied mainly by heat exchangers, which utilize the recovered heat from the CHP system. An absorption chiller, which recovers the waste heat from the electricity generating cycle, is used to provide the cooling load. An auxiliary gas boiler is used to supply the deficits of thermal energy.

Also, in this paper, the following assumptions are used: The CHP system is operated in electrical tracking mode. Performance of the generator under part-load conditions is same as at full electricity generating capacity. When the amount of electricity generated by the CHP system cannot satisfy the demand of users, the utility electricity company supplies the deficit. Similarly, an auxiliary gas boiler is used to supply deficits of thermal energy. Surplus thermal energy expelled directly into atmosphere.

HEATMAP [6], district energy system analysis software for steam, hot water and chilled-water system, was used to simulate the systems presented in this paper. It is a Microsoft Windows®-based software tool developed by Washington State University. It is an easy-to-use software program that was specifically developed to help plan, analyze, and operate district heating and cooling systems such as cities, towns, universities and industrial parks. It provides comprehensive computerized simulations of district heating and cooling systems, allowing users to analyze the performance of existing networks as well as model proposed systems, expansions and upgrade. HEATMAP comprises fours main parts: load assessment, equipment, operating simulation and pipeline calculations. A load table with the loads of 8,760 hours for electricity, cooling, heating and hot water can be imported to HEATMAP directly. Then equipment items and their capacities and characteristics were selected according to the load characteristic. After inputting these details, simulations were undertaken. Finally, overall evaluation results regarding energy efficiency, environmental and economical effects can be obtained.

Table 2 COP and Efficiency for various equipments

Equipments		COP/Efficiency
Utility electricity	Generating electricity	0.35
Room air conditioner	For cooling	3.22
	For heating	2.83
Gas hot water heater		0.8
Auxiliary gas boiler		0.8
Absorption chiller		1.2
GE	Generating electricity	0.287
	Heat recovery	0.477
GT	Generating electricity	0.22
	Heat recovery	0.43
DE	Generating electricity	0.35
	Heat recovery	0.32
SOFC	Generating electricity	0.4
	Heat recovery	0.4
PEFC	Generating electricity	0.34
	Heat recovery	0.49

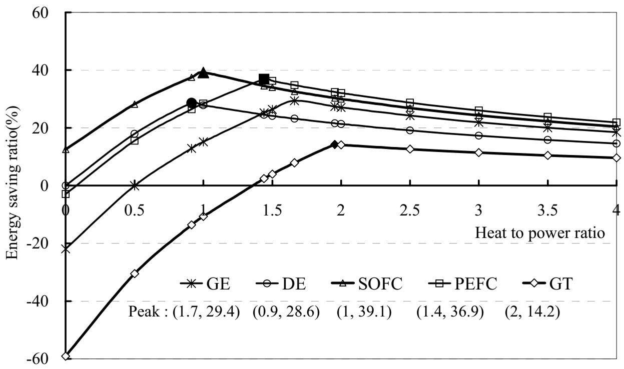

Fig. 4: The relationship between heat to power ratio of the user and energy saving ratio of CHP

V. Results and Discussion

In general, primary energy utilization efficiency is an important index evaluating CHP projects. It is the rate of the amount of useful utilization energy to primary input energy. And it can be defined as follows:

$$\eta_E^{CHP} = \frac{Q_{Pow}^{CHP} + Q_{Pow}^{Utility} + Q_H^{CHP} + Q_H^{Boiler}}{Q_E^{Conv}} \quad (4)$$

Where

η_E^{CHP} : Primary energy utilization efficiency;

Q_{Pow}^{CHP} : Electric energy supplied by the CHP system, MJ;

$Q_{Pow}^{Utility}$: Electric energy supplied by the utility, MJ;

Q_H^{CHP} : Thermal energy supplied by the CHP system, MJ;

Q_H^{Boiler} : Thermal energy supplied by the auxiliary gas boiler, MJ;

In this paper, primary energy utilization efficiency for various buildings are calculated and demonstrated in fig. 5. From the charts, it is concluded that CHP systems in hotels achieved high primary energy utilization efficiency with 61%, about 6% higher than conventional energy supply system; Especially, PEFC has 63% primary energy utilization efficiency, a considerable improvement of 8% than conventional energy supply system. Next, in apartments, primary energy utilization of CHP system is 54%, 3% higher than that of the conventional energy supply system. Similarly, in hospitals, primary energy utilization efficiency increased 2% by introducing the CHP system. Offices and educational facilities have almost same primary energy utilization efficiencies, about 48%, which is a little improvement or more lower than the conventional energy supply system. In commercial buildings, CHP system has lower primary energy utilization efficiency than the conventional system. It is reason that hotels, apartments and hospitals have high heat to power ratio, their average value is 1.03, 0.9 and 1.48 respectively. However, offices, educational facilities and commercial buildings have low heat to power ratio, especially, for commercial building, this value only is 0.17. This implies that the thermal energy from CHP systems can not be fully utilized. In addition, the distributed generation technologies have generally lower electricity generating efficiency than the conventional energy supply.

Energy saving ratios as defined by equation 1 for various buildings are calculated and illustrated in Fig. 6, and shows that hotels achieve about 4-13% energy saving ratio because they have higher primary energy utilization efficiency than conventional energy supply system. In apartments and hospitals, CHP systems expect for GT achieved generally plus energy saving ratios. This is because that GT has too high heat to power ratio (supply side), reaching to 2; while the mostly heat to power ratio of apartments and hospitals (demand side) is less than 2. This make the mostly thermal energy from CHP system can not be utilized. For educational facilities, offices and commercial buildings, because they have lots of heat to power ratio with 0, which implies that in mostly time, they have not thermal energy demand. This makes lots of thermal energy from CHP system can not be utilized. Therefore, they have minus energy saving ratio. This means that in the offices and

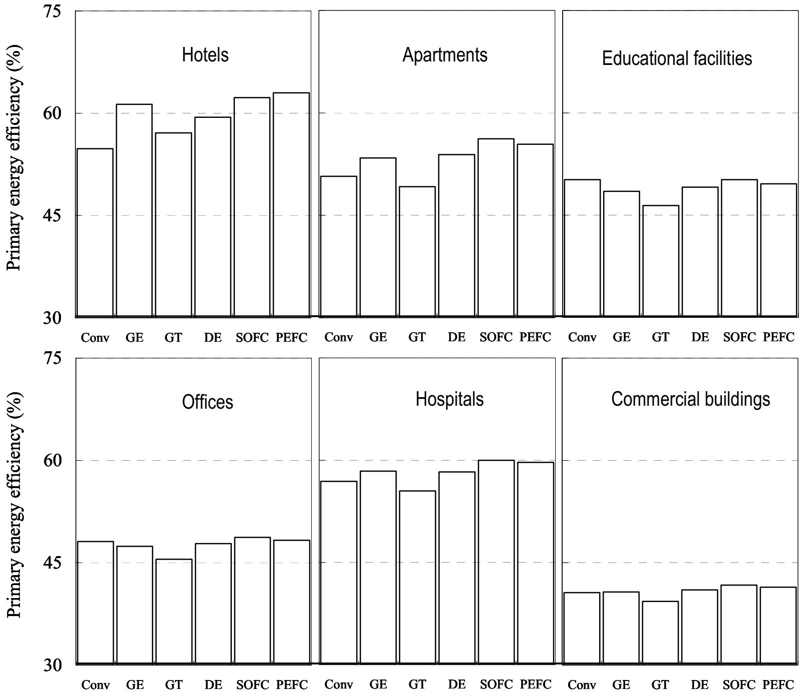

Figure 5 Primary energy utilization efficiencies for various buildings

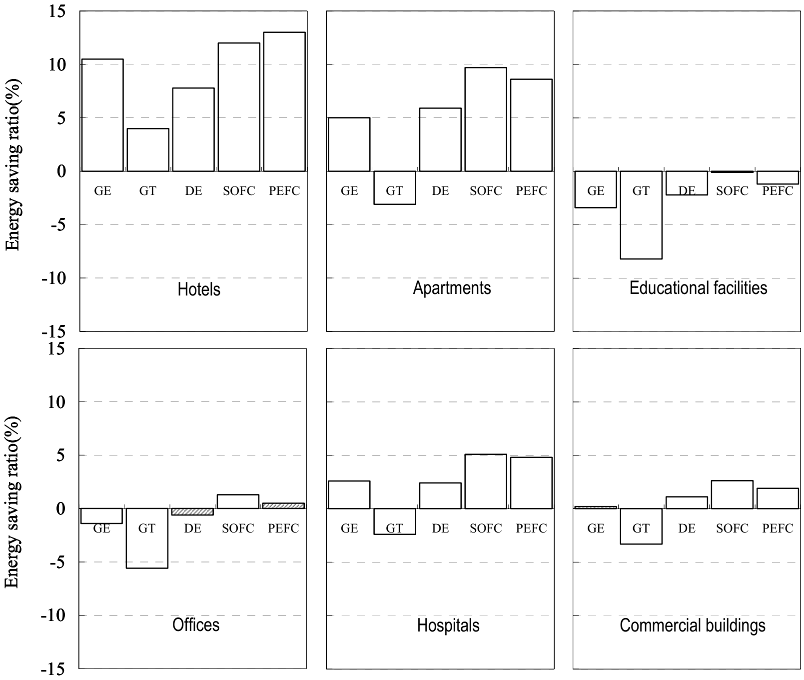

Figure 6 Energy saving ratios for various buildings utilization efficiency

commercial buildings, the introduction of CHP system is unreasonable.

Environmental impact is an important factor cannot be neglected in any project and the CO_2 emissions are calculated and CO_2 reduction ratio is defined as follows:

$$\eta_{\Delta CO2}^{CHP} = \frac{EX_{CO2}^{Conv} - EX_{CO2}^{CHP}}{EX_{CO2}^{Conv}} = \frac{(ex_{CO2}^{Gas} \times G^{Conv} + ex_{CO2}^{Pow} \times P_{Utility}^{Conv}) - (ex_{CO2}^{Gas} \times G^{CHP} + ex_{CO2}^{Pow} \times P_{Utility}^{CHP})}{(ex_{CO2}^{Gas} \times G^{Conv} + ex_{CO2}^{Pow} \times P_{Utility}^{Conv})} \quad (5)$$

Where,

η_{CO2}^{CHP} : CO_2 reduction ratio of CHP system;

EX_{CO2}^{Conv} : CO_2 emissions of the conventional energy supply system, kg;

EX_{CO2}^{CHP} : CO_2 emissions of the CHP system, kg;

ex_{CO2}^{Gas} : Unit of CO_2 emissions per cube meter natural gas; it equals to 2.37kg/m^3;

ex_{CO2}^{Pow} : Unit of CO_2 emission for per kWh electricity; it equals to 0.38kg/kWh;

G^{Conv} : Consumption amount of natural gas in the conventional energy supply system, m^3;

G^{CHP} : Consumption amount of natural gas in the CHP system, m^3;

$P_{Utility}^{Conv}$: Utility electric power used in the conventional energy supply system, kWh;

$P_{Utility}^{CHP}$: Utility electric power used in the CHP system, kWh;

According to the equation 5 and energy consumptions of the various buildings, CO_2 reduction ratios were calculated and shown in Fig.7. This shows that hotels had the highest CO_2 reduction ratio with 29.7%, followed by apartments with 25.1%, hospitals with 21.7%, educational facilities with 18.2%, offices with 16 % and commercial buildings with only 10%.

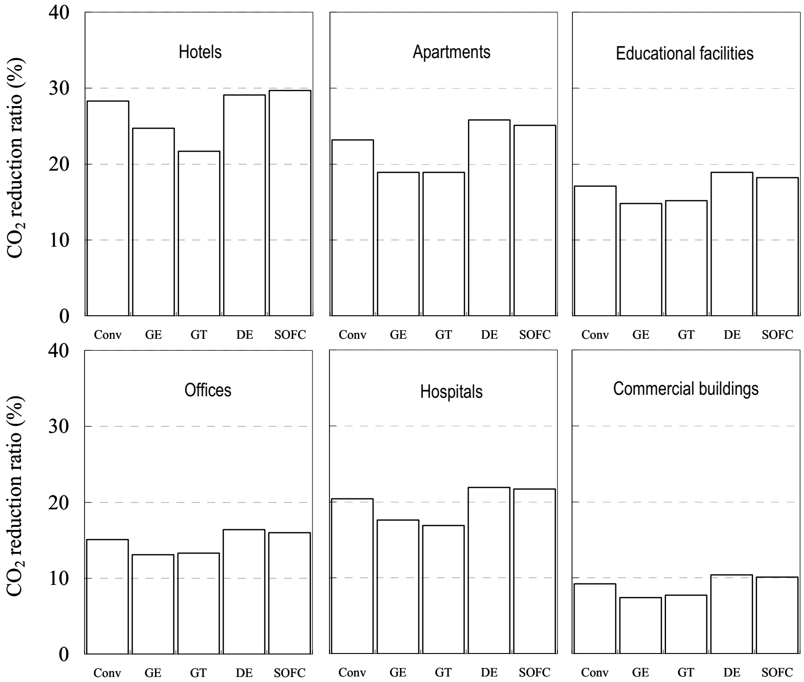

Figure 7 CO2 reduction ratios for various buildings

VI. Conclusion

This study simulated the performances of CHP systems with various distributed generation technologies for different type buildings in Japan. The results of the investigation can be summarized as follows:

1) Various buildings have their special heat to power ratio characteristics. Matching the heat to power ratio demanded from an individual building with that supplied from a CHP system is very important. It is necessary to select a reasonable distributed generation technologies according to the load characteristics of various buildings.

2) Distributed generation technologies with high energy generating efficiency and low heat to power ratio, like SOFC and PEFC is more reasonable selection for BCHP.

3) CHP system is an attractive option for hotels, hospitals and apartments at the proposed site. The users can achieve high energy saving and environmental benefit by introducing a reasonable CHP systems. In others buildings, especially commerce buildings and offices, the introduction of CHP system is unreasonable.

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