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Feasibility Study on Using Combined Heat and Power Energy Systems for Various Buildings in Japan

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This paper examined the energy consumption characteristics in six different buildings including apartments, offices, commercial buildings, hospitals, hotels and education facilities. Then 5-hectare (50,000m^2) development site for respective building's type was assumed as case study to evaluate the viability of Combined Heat and Power (CHP) energy systems. A CHP system was selected according to their characteristics for each type building. And HEATMAP, a district energy system analysis software, was used to evaluate each system's energy saving, environmental effect and economic efficiency. The results can be summarized as follows: in hotels and hospitals at the proposed site, the CHP system is an attractive option in Japan. In others buildings, especially commerce buildings and offices, the introduction of CHP system is unreasonable.

Keywords: *Combined heat and power, Various buildings, Energy saving ratio, CO_2 reduction ratio, Payback times*
コージェネレション、用途別建物、省エネ率、CO_2削減率、単純回数年数

1. INTRODUCTION

Combined heat and power (CHP) is an efficient approach to generating electricity and thermal energy from a single fuel source. By recycling this waste heat, it can achieve the primary energy efficiencies of about 70%, a dramatic improvement over the average 35% efficiency of conventional fossil-fuelled power plants. Higher efficiencies reduce air emissions of carbon dioxide and sulphur dioxide. In Japan, during the last 20 years, CHP has been developed rapidly. The number of CHP systems grew from 67 in 1986 to 6,139 in 2005, and the total generation capacity grew from 200kW in 1986 to 7,994MW as of March 2005[1]. CHP systems contributed to 3% of the total electricity in Japan [2]. And it can be expected that CHP will play a more important role in electricity supply with Kyoto Protocol implemented in February 16, 2005. Also, according to a survey [3], in Japan, CHP systems were used widely in various buildings and their generating electricity capacity ranged several ten to several thousands kilowatt. They usually achieved from 60% to 80% overall energy utilization efficiency with from 20% to 34.5% generating electricity efficiency and from 19.5% to 50% exhaust heat utilization efficiency. And various buildings had obvious different energy utilization efficiency because of their different energy consumption characteristics.

This paper examined the energy consumption characteristics for six different buildings including apartments, offices, commercial buildings, hospitals, hotels and education facilities. Then 5-hectare (50,000m^2) development site for respective building's type was assumed as case studies to evaluate the introduction effect of CHP system. A rational CHP system was selected according to their characteristics for each type building. And each system was evaluated and compared regarding energy utilization efficiency, energy-saving and environmental effect and economic efficiency by using CHP system analysis software, HEATMAP.

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2. STUDY OBJECTIVE AND LOAD ASSESSMENT

2.1 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 30℃ and the coldest month is in January with monthly average temperature about 7℃.

2.2 Load assessment

In this study, the annual load demand for heating, cooling, hot water and electricity for various types were calculated according to Ojima's annual energy unit [4] and were shown in Figure 1. For example, the hotel has the largest annual load, about 3,421MJ/m^2 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 peak and annual load for various buildings were assessed and were summarized in the Table 1.

As we know, the heat to power ratio is defined as the rate of the 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 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, since 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 was calculated by the hourly heat and power demand and their characteristics were analyzed. Figure 2 ((a) - (f)) shows the characteristics of the heat to power ratios for various buildings. Analysis of the

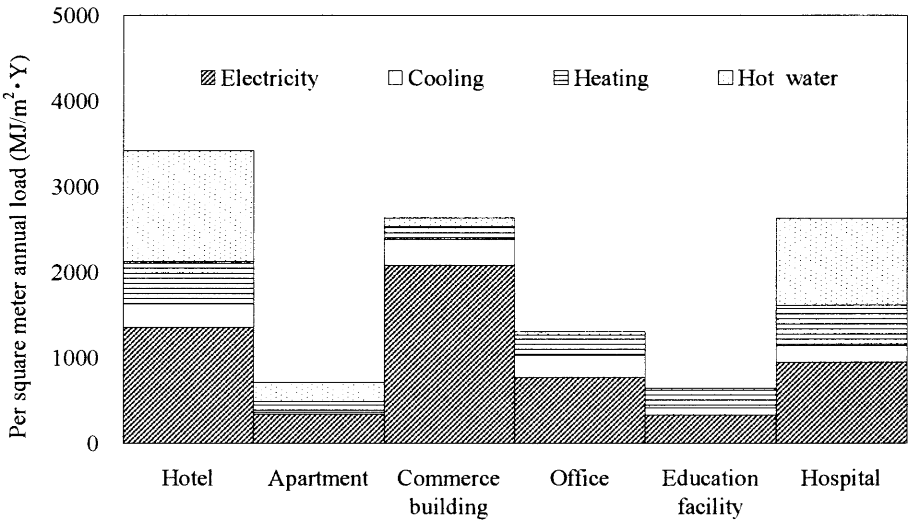
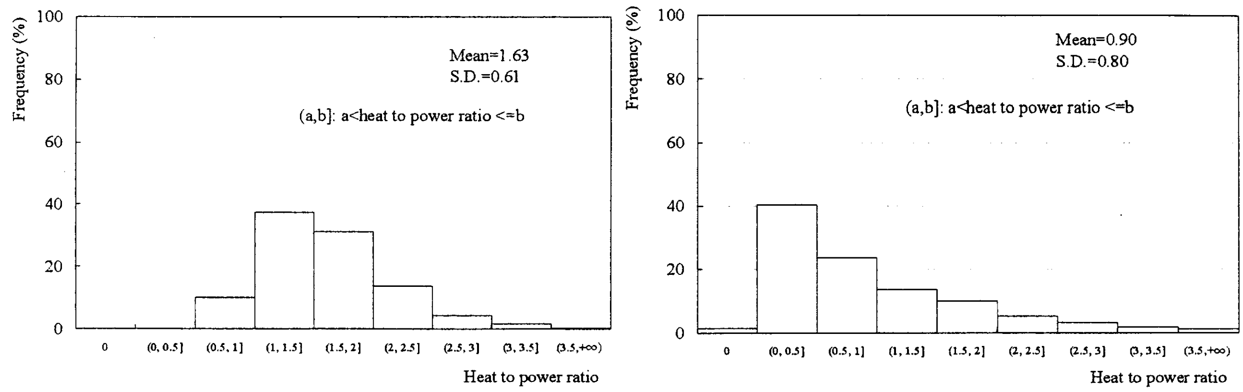


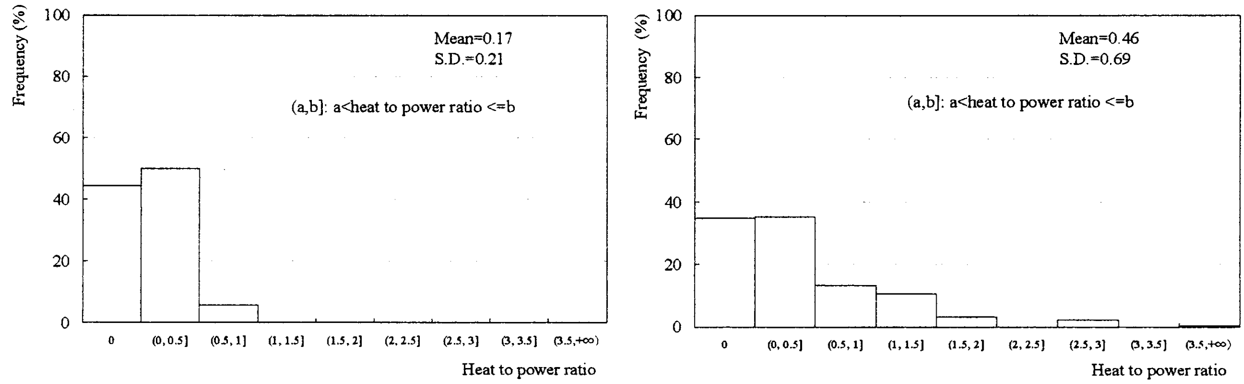
Fig. 1: Per Square meter annual load for various buildings

Table 1: Peak and annual load for various buildings

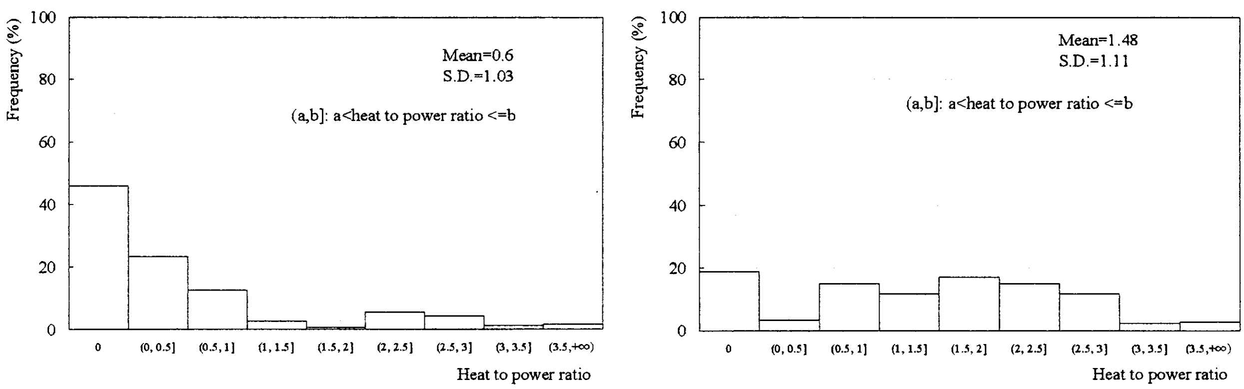
Type	Load	Heating	Cooling	Hot water	Electricity
Hotel	Peak(kW)	3,072	2,080	4,320	3,634
	Annual(GJ/Year)	24,786	13,565	64,791	67,910
Apertment	Peak(kW)	1,734	506	2,081	1,117
	Annual(GJ/Year)	6,213	1,019	11,210	17,134
Commerce building	Peak(kW)	2,387	3,239	914	8,015
	Annual(GJ/Year)	7,258	15,240	5,401	104,019
Office	Peak(kW)	4,076	3,278	212	2,648
	Annual(GJ/Year)	11,798	13,065	1,776	38,276
Education facility	Peak(kW)	3,853	1,064	761	1,439
	Annual(GJ/Year)	10,385	3,183	754	16,492
Hosptial	Peak(kW)	6,062	4,036	5,490	3,439
	Annual(GJ/Year)	23,802	9,818	50,388	47,235



(a) Heat to power ratio in hotels **(b) Heat to power ratio in apartments**



(c) Heat to power ratio in commercial buildings **(d) Heat to power ratio in office**



(e) Heat to power ratio in educational facilities **(f) Heat to power ratio in hospitals**

Fig. 2 The characteristic of heat to power ratio for various buildings

heat to power ratio profiles obtained displays the following characteristics: The heat to power ratio for various buildings fluctuates over the wide range from 0 to 5, and various buildings have different heat to power ratio characteristics. Considering heat to power ratios of more than 0.5, hotels have the maximum value with 100%, followed by hospitals with 79%, apartments with 59%, and educational facilities with 31%, offices with 30%, and commercial buildings with the lowest - only 6%.

3. THE RELATIONSHIP BETWEEN HEAT TO POWER RATIO AND ENERGY SAVING RATIO OF CHP

As described in the former section, the heat to power ratio is a key factor influencing the effect of CHP systems. In this section, the relationship between the heat to power ratio and the energy saving ratio was analyzed. The operating mode of CHP systems was assumed to be electrical tracking. This means that CHP equipment will be operated to satisfy electric loads. The energy saving ratio of CHP is defined as the percent of energy saved, as compared with a conventional energy supply system:

$$\eta_{\Delta E}^{CHP} = \frac{Q_E^{Conv} - Q_E^{CHP}}{Q_E^{Conv}} \quad (1)$$

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

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

Considered with electrical tracking, when $\sigma \ge \sigma_{CHP}$,

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

Where,

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

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

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

E :Electricity load demand, KJ/Year;

η_{Conv}^{P} :Electricity generation efficiency on the conventional energy supply system; it is assumed as 0.35;

η_{Conv}^{H} :Thermal efficiency of the boiler on the conventional energy supply system; it is assumed as 0.8;

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; it is assumed as 0.287 based on running data of an existing CHP system at KSRP;

η_{CHP}^{H} :Thermal recovery efficiency of CHP system; it is assumed as 0.477 based on running data of an existing CHP system at KSRP.

Using the above assumed values for CHP efficiencies, one can calculate the relationship between the heat to power ratio and the energy saving ratio as illustrated in Figure 3. From the profiles in Figure 3 it can be concluded that:

(1) Only when heat to power ratio is more than 0.5 can energy savings be achieved;

(2) Energy saving ratios increase to a maximum value of 29.4%, then decrease with further rises of the heat to power ratio.

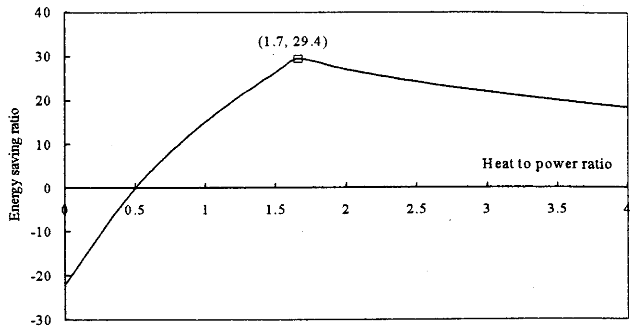


Fig.3 The relationship between heat to power ratio and energy saving ratio of CHP

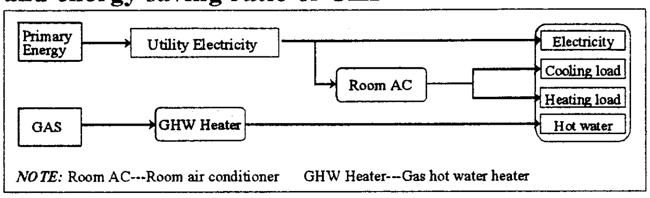


Fig. 4 Energy supply plan of conventional system

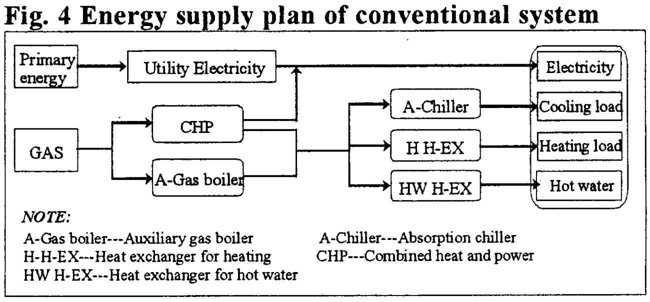


Fig. 5 Energy supply plan of CHP system

Table 2 COP/Efficiency for various equipments

Equipments		COP/efficiency
Utility electricity	Generating electricity	0.35
	Transport and distribution	0.9
Room air conditioner	For cooling	3.22
	For heating	2.83
Gas hot water heater		0.78
Auxiliary gas boiler		0.8
Absorption chiller	For cooling	1
	For heating	0.8
CHP system	Generating electricity	0.287
	Heat recovery	0.477

4. CASE STUDIES

Based on the heat to power ratio characteristics of various buildings and the relationship between heat to power ratios and energy saving ratios, six energy supply systems were modeled in this paper. In order to compare, an alternative conventional system described in Figure 4 was 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 was illustrated in Figure 5. In this case, the CHP system provides part of the electricity load. The CHP capacity required is 25% of the peak electrical load, which is the average value for CHP systems in Japan [3] Therefore, in the hotel, the CHP capacity is taken to be 900kW (the peak demand is about 3,600kW). Deficit of electricity is 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 were used:

(1) The CHP system is operated in electrical tracking mode.

(2) Performance of the generator under part-load conditions is same as at full electricity generating capacity.

(3) 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.

(4) Table 2 specifies COP or efficiency for various kinds of equipment.

5. SIMULATION METHOD

HEATMAP [6], a 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 are selected according to the load characteristic. After inputting these details, simulations are undertaken. Finally, overall evaluation results regarding energy efficiency, environmental and economical effects can be obtained.

6. RESULTS AND DISCUSSION

6.1 Primary energy utilization efficiency and energy saving ratio

In general, primary energy utilization efficiency is an important index evaluating actual CHP project. 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, KJ/Year;

$Q_{Pow}^{Utility}$:Electric energy by the utility, KJ/Year;

Q_H^{CHP} :Thermal energy supplied by the CHP system, KJ/Year;

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

In this paper, primary energy utilization efficiency for various buildings were calculated and demonstrated in Figure 6. From the profiles of primary energy utilization efficiency, it was concluded that CHP system in hospitals achieved 61.2% primary energy utilization efficiency, a considerable improvement of 8.9% higher than the conventional energy supply system. Next, in hotels, primary energy utilization of CHP system is 60.5%, 10.2% higher than that of the conventional energy supply system. Similarly, in apartments, primary energy utilization efficiency increased 5.5% by introducing the CHP system. Commerce buildings and education facilities has almost same primary energy utilization efficiencies in the two energy supply systems. In office, CHP system has lower primary energy utilization efficiency than conventional system.

Energy saving ratios as defined by Equation 1 for various buildings were calculated and illustrated in Figure 7, and shown that the hotel and the hospital achieved more than 12% energy saving ratio because they had higher primary energy utilization efficiency than the conventional energy supply system. Similarly, office had -14.5% energy saving ratio. This means that in the office, introduction of CHP system is unreasonable.

6.2 CO_2 reduction ratio

Environmental impact is an important factor, which cannot be neglected in any project. CO_2 emissions were calculated and CO_2 reduction ratio is defined as follows:

$$\eta_{\Delta CO_2}^{CHP} = \frac{EX_{CO_2}^{Conv} - EX_{CO_2}^{CHP}}{EX_{CO_2}^{Conv}} = \frac{\left(ex_{CO_2}^{Gas} \times G^{Conv} + ex_{CO_2}^{Pow} \times P_{Utility}^{Conv}\right) - \left(ex_{CO_2}^{Gas} \times G^{CHP} + ex_{CO_2}^{Pow} \times P_{Utility}^{CHP}\right)}{\left(ex_{CO_2}^{Gas} \times G^{Conv} + ex_{CO_2}^{Pow} \times P_{Utility}^{Conv}\right)} \qquad (5)$$

Where,

$\eta_{CO_2}^{CHP}$:CO_2 reduction ratio of CHP system;

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

$EX_{CO_2}^{CHP}$:CO_2 emissions of the CHP system, kg/Year;

$ex_{CO_2}^{Gas}$:Unit of CO_2 emissions per cube meter natural gas; it equals to 2.36kg/m^3;

$ex_{CO_2}^{Pow}$:Unit of CO_2 emission for per kWh electricity; it equals to 0.65kg/kWh;

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

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

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

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

According to the equation 5 and energy consumptions of the various buildings, CO_2 reduction ratios were calculated and shown in Figure 8. This shows that the hotel had the highest CO_2 reduction ratio with 17.3%, followed by hospital with 16.4%, apartment with 13.0%, office with 6.38%, education facility with 4.9% and commerce building with only 0.7%.

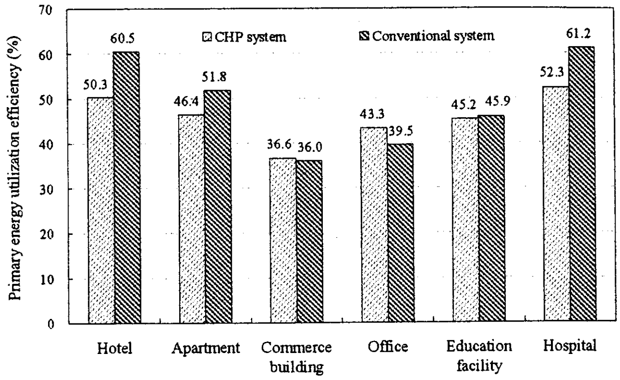


Fig. 6 Primary energy utilization efficiencies for various buildings

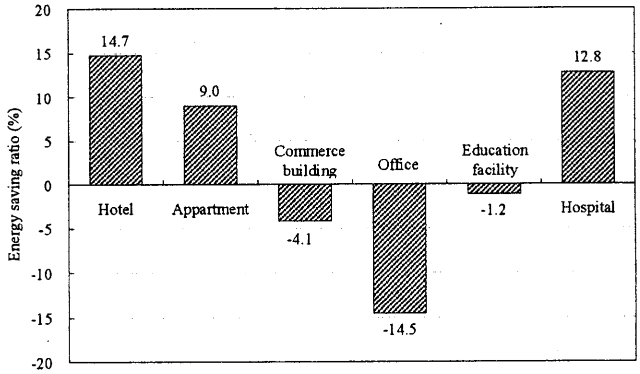


Fig.7 Energy saving ratios for various buildings utilization efficiency

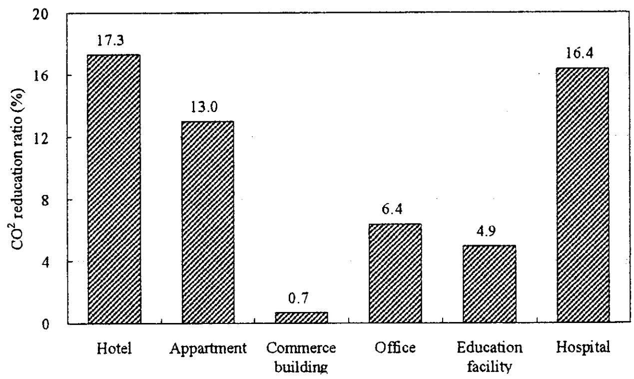


Fig. 8 CO_2 reduction ratios for various buildings

6.3 Payback times

Financial cost is a key criterion in any investment decision. In Japan, profitability is the most cited reason for adopting CHP [7]. In this paper, initial investment and running costs for various options were calculated and payback time in years is defined as follows:

$$Y_{payback\ times} = \frac{C_{Initial}^{CHP} - C_{Initial}^{Conv}}{C_{Running}^{Conv} - C_{Running}^{CHP}} \qquad (6)$$

Where,

$C_{Initial}^{CHP}$:Initial investment of CHP system, ¥;

$C_{Initial}^{Conv}$:Initial investment of the conventional energy supply system, ¥;

$C_{Running}^{CHP}$:Running cost of CHP system, ¥/Year;

$C_{Running}^{Conv}$:Running cost of the conventional energy supply system, ¥/Year;

$$C_{Initial}^{CHP} = C_{Initial}^{Unit} + C_{Initial}^{Boiler} + C_{Initial}^{ABS} + C_{Initial}^{FC} + C_{Initial}^{Pipe} = 25\times a_1 + 800\times a_2 + 14.5\times a_3 + 6\times a_4 + 40\times a_{51} + 10\times a_{52} \quad (7)$$

Where,

$C_{Initial}^{Unit}$:CHP equipment's investment, including CHP unit and electric substation, × 10^4¥/Year;

$C_{Initial}^{Boiler}$: Gas boiler investment, × 10^4¥/Year;

$C_{Initial}^{ABS}$: Absorption-chiller investment, including unit and cooling tower, × 10^4¥/Year;

$C_{Initial}^{FC}$:Fan coil investment, × 10^4¥/Year;

$C_{Initial}^{Pipe}$:Pipeline investment, including main and branch line, × 10^4¥/Year;

a_1 :The capacity of CHP unit, kW;

a_2 :The capacity of auxiliary gas boiler, tons/hr;

a_3 :The capacity of absorption-chiller, RT;

a_4 :The number of fan coils; each independent room uses one fan coil, Unit;

a_{51} :The length of main line, m;

a_{52} :The length of branch line, m;

$$C_{Initial}^{Conv} = C_{Initial}^{RC} + C_{Initial}^{Heater} = 10\times b_1 + 15\times b_2 \quad (8)$$

Where,

$C_{Initial}^{RC}$:Room air conditioner investment, 10^4¥;

$C_{Initial}^{Heater}$:Gas heater investment, 10^4¥;

b_1 :The number of room air conditioners, each independent room uses one room air conditioner;

b_2 :The number of gas hot-water heaters, each unit uses one room gas heater;

$$C_{Running}^{Conv} = C_{Running}^{Convgas} + C_{Running}^{Convpow} = \sum_{i=1}^{N}\sum_{j=1}^{12} Q_{ij}^{Convgas} C_{ij} + \sum_{i=1}^{N}\sum_{j=1}^{12}\left(Q_{ij}^{Convpow} E_{ij} + 1{,}134 + 302\right) \quad (9)$$

Where,

$C_{Running}^{Convgas}$:Investment of natural gas, ¥/Year;

$C_{Running}^{Convpow}$: Investment of utility electricity, ¥/Year;

$Q_{ij}^{Convgas}$: The consumption volume of natural gas for unit i in mouth j, m^3/month;

C_{ij} :The price type of natural gas for unit i in mouth j; it refers to Table 3;

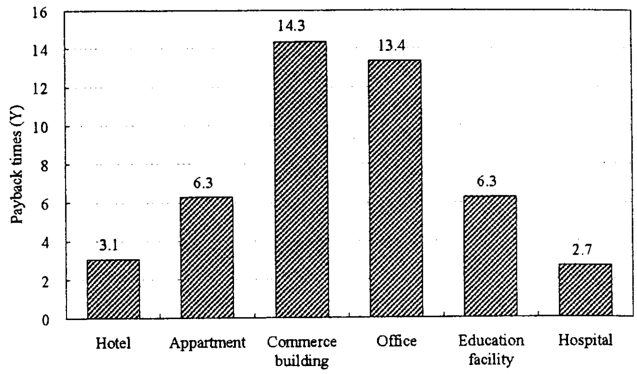


Fig. 9 Payback times for various buildings

Table 3 Price of Natural Gas from Saibu Gas Company

Price rank	Volume (m^3)	Initial fee (Yen/month)	Price (Yen/m^3)
A	0~15	872	200
B	15~30	1,092	185
C	30~100	1,460	171
D	more than	1,710	168

Table 4 Price of Utility Electricity

Price rank	Consumption (kWh)	Price (Yen/ kWh)
A	0~120	16
B	120~300	21
C	more than	23

$Q_{ij}^{Convpow}$:The consumption amount of utility electricity for unit i in mouth j, kWh;

E_{ij} :The price type of utility for unit i in mouth j, m^3; it refers to Table 4;

N :The number of housing units;

$$C_{Running}^{CHP} = C_{Running}^{CHPgas} + C_{Running}^{CHPUtility} + C_{Maintenance}^{CHP} = \left(12\times d_0 + 840\times d_1 + 1.1\times d_2 + 41.9\times d_3\right) + \left(1200\times d_4 + 15.1\times d_5 + 13.7\times d_6\right) + 2\times d_7 \quad (10)$$

Where,

$C_{Running}^{CHPgas}$:Investment of natural gas, ¥/Year;

$C_{Running}^{CHPpow}$:Investment of utility electricity, ¥/Year;

$C_{Maintenance}^{CHP}$:Maintenance of CHP system, ¥/Year;

d_0 :The fundamental investment in every month; equals to 105,000¥/Month;

d_1 :Total consumption of natural gas, m^3;

d_2 :The peak volume of natural gas, m^3;

d_3 :The total consumption of natural gas in January, February, March and December, m^3;

d_4 :Peak volume of utility electricity, kW;

d_5 :The total consumption of utility electricity in July, August and September, kWh;

d_6 :The total consumption of utility electricity in other seasons, kWh;

d_7 :The total amount of generating electricity, kWh;

Initial and operating costs for various buildings were used to calculate the payback times shown in Figure 9. These show that the hospital and hotel had the shorter payback times, less than 3 years. Payback times in apartments and education facilities are more than 6 years. Commerce buildings and offices spent the terrible about 14 years to return the CHP's investment.

7. CONCLUSIONS

This study simulated the performances of CHP systems in 5-hectare (50,000m^{2}) development site for respective building's type in Kitakyushu of Japan. The results of the investigation can be summarized as follows:

(1)The hotels and hospitals at the proposed site achieved approximately 60% primary energy utilization efficiencies, more than 12% energy saving ratio and above 16% CO_2 reduction ratio and spent only less than 3 years return to the investment of CHP system.

(2)Compared with the conventional system, despite having a slightly higher or lower energy saving ratio and some certain degree higher CO_2 reduction ratio, the CHP systems of apartments and education facilities had the payback times of more than 6 years.

(3)For CHP systems in commerce buildings and offices at the proposed site, the primary energy utilization efficiencies were low. And energy inputs were bigger than that for the corresponding conventional energy supply system with generation of heat and power in separate processes. Furthermore, the user will spend more than 13 years return the investment.

In summary, at the proposed site, in hotels and hospitals, the CHP system is an attractive option in Japan. In others buildings, especially commerce buildings and offices, the introduction of CHP system is unreasonable.

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