Feasibility Study on Using Combined Heat and Power Energy Systems for a Science and Technology Complex in Japan

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ABSTRACT

Kitakyushu Science and Research Park (KSRP) in Japan aims to build a community, designed to host educational and research institutes from advanced science and technology as well as provide a comfortable living environment for employees and students. The total area of development is approximately 335 ha. It will be carried out in three stages. The second-stage, a Greenfield site, will occupy 135.5 ha area, including 37.3 ha for the university and related facilities, a 42.3 ha housing development area, 8.2 ha of roadside facilities, 23.4 ha of roads, and 6.6 ha of green space. In this paper, we assess the opportunity for using combined heat and power (CHP) energy systems in a large research institutional complex or campus. The viability of the using CHP, where electricity and heat are produced from the same fuel source, was analyzed for four different options for energy supply systems. Various scenarios were evaluated and compared regarding energy utilization efficiency, energy saving and environmental effects, and economic efficiency. The results of the investigation are summarized as follows:

- The primary energy utilization efficiencies for CHP and district heating and cooling (DHC) systems at the proposed site ranged from about 45% to 52%. These efficiencies were greater than the corresponding conventional energy supply system with generation of heat and power in separate processes.
- Scenario 4, which uses CHP for all buildings except for detached housing, had the shortest payback at about 4.3 years, about 1 year less than Scenario 2, the DHC system.
- Despite having slightly lower primary energy utilization and environmental efficiency, Scenario 4 achieved better economical effects than Scenario 3. Economically, Scenario 4 had a significant reduction in payback time compared with Scenario 3.

Introduction

Combined heat and power (CHP), is a well known highly efficient approach to generating electricity and thermal energy from a single fuel source. Producing electricity and heat from the same energy source means that lower fuel consumption takes place, the energy is generated at a lower cost, and energy is produced in a more environmentally friendly way. All these reasons have made the use of CHP plants more attractive worldwide. In the future, CHP will inevitably replace separate power and heating industries. In Japan, which depends on imports for most of its primary energy supply, CHP has grown more important and is widely expected to expand in order to increase the primary energy efficiency of electricity production and reduce the environmental impact. During the last 20 years, CHP has developed rapidly. The number of CHP systems in Japan has increased from 67 in 1986 to 6,139 in 2005, and the total generation capacity has increased from 200 kW in 1986 to 7,994 MW as of March 2005 (Japan Cogeneration Center, 2005). CHP will play a more important role in energy supply due to the implementation of the Kyoto Protocol in February 2005. According to the statistical data from the Japan Cogeneration Center, CHP systems have mainly been installed in the industrial and commercial sectors. However, the energy consumption for dwellings in Japan accounts for 26.4% of total primary energy (Ruan et al, 2005). Therefore, it can be expected that CHP systems for buildings (BCHP) should have a large potential market in Japan.

This paper examines the viability of BCHP in a development complex by analysis of a scenario study in Kitakyushu, Japan. A multidisciplinary team comprising researchers, a local architectural and engineering practice and the development office for KSRP examined how urban design could enhance the opportunities for more sustainable development. An integrated approach was taken for the development area in order to assess the potential for energy systems and environmental solutions. The load for heating, cooling and electricity was assessed and the characteristics of the heat-to-power ratio discussed. The viability of BCHP was examined by analysis of various options. Various scenarios were evaluated and compared regarding energy utilization efficiency, saving energy, environmental effect and economic efficiency.

Study Objective and Load Assessment

Study Objective

The KSRP aims to build a community designed to host educational and research institutes from advanced science and technology and to provide a comfortable living environment for employees and students. The total area of development is approximately 335 ha and will be carried out by dividing the whole land readjustment project into three stages. The first-stage project reached 121 ha and was carried out by The Urban Renaissance Agency from 1995 to 2005. To reduce the environmental load, some environmentally friendly distributed energy systems have been installed, such as new energy supply systems including photovoltaic (PV), fuel cells and gas engines. In stage two, some new distributed energy technologies were considered to reduce the environmental load. The second-stage will occupy a 135.5 ha area, including 37.3 ha of university and related facilities, 42.3 ha of housing development zone, 8.2 ha of roadside facilities, 23.4 ha of roads, 6.6 ha of park and green space, and so on. The building facility comprises 5,232 m^2 of detached houses (DH), 43,840 m^2 of apartments (APT), 2,280 m^2 of commercial buildings, 21,562 m^2 of offices, a 41,480m^2 of educational facilities, and 7,250m^2 for a hospital.

Load Assessment

Kitakyushu is located in the south of Japan on the northern tip of Kyushu and faces the Sea of Japan. It is a city with a typical maritime climate. Annual average temperature is about 17 degree Celsius. The hottest month occurs generally in August with a monthly average temperature of about 30 degree Celsius and the coldest month is in January, with a monthly average temperature about 7 degree Celsius. From a paper (Ojima lab 1995), it was possible to assess the unit load per square meter for heating, cooling, hot water, and electricity for various building types in different months. For example, heating load, hot water and electricity for a DH are respectively 31.22 MJ/m^2, 15.38 MJ/m^2 and 20.06 MJ/m^2 in January. The percentage of every day in every month and the percentage of every hour in every day can be gained according to the paper (Nishita 1997). Therefore, various hourly load demands of 8,760 hours, hourly peak load and annual total load for various buildings were assessed. Table 1 provides the summary for the annual and peak load demand for various buildings.

Table 1. Peak and Annual Demand for Heat and Electricity for Various Buildings

TYPE	AREA(m^2)	LOAD	HEATING	COOLING	HOT WATER	ELECTRICITY
DH	5232	Peak(W/m^2)	37	9	24	17
		Annual(kWh/m^2)	32	4	40	67
APT	43840	Peak(W/m^2)	35	10	42	22
		Annual(kWh/m^2)	35	6	62	95
COMMERCE BUILDING	2280	Peak(W/m^2)	48	65	18	160
		Annual(kWh/m^2)	40	85	30	578
OFFICE	21562	Peak(W/m^2)	82	66	4	53
		Annual(kWh/m^2)	66	73	10	213
EDUCATION FACILITY	41480	Peak(W/m^2)	77	21	15	29
		Annual(kWh/m^2)	58	18	4	92
HOSPITAL	7250	Peak(W/m^2)	121	81	110	69
		Annual(kWh/m^2)	132	55	280	262

The heat-to-power ratio is defined as the ratio 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. 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 relatively stable due to the constant electricity generation and heat recovery efficiency of CHP systems. Therefore, matching the heat-to-power ratio between demand and supply is a formidable task.

In CHP systems, although there are others factors that influence the optimal energy supply, such as the load timing, the peak-to-base (discussed in Ruan, 2005), and the hourly heat-to-power ratio are decisive factors for a CHP system without a storage system including electrical and thermal energy. Therefore, in this paper, the hourly heat-to-power ratio for various buildings has been calculated by the hourly heat and power demand and their characteristics have been analyzed. Figure 1 (Figure 1-1~ Figure 1-8) shows the characteristics of heat-to-power ratios for various buildings. Analysis of the heat-to-power ratio profiles obtained displayed the following characteristics:

- The heat-to-power ratio for various single buildings fluctuates over the wider range of 0 to 5. Various buildings have different heat-to-power ratio characteristics. Considering heat-to-power ratios of more than 0.5, hospitals have the maximum value with 79%, followed by apartments with 59%, detached houses with 62%, and educational facilities with 31%, offices with 30%, and commercial buildings with the lowest-only 6%.
- Heat-to-power ratios greater than 0.5 are more frequent in complex facilities (Figure 1-7 & Figure 1-8) than in single buildings, except hospitals.
- Comparing Figure 1-7 with Figure 1-8, it can be concluded that detached housing has little influence on the heat-to-power ratio in a complex facility because of the very low floor area, only accounting for 4% of the total floor area.

Figure 1. The Characteristic of Heat-to-Power Ratios for Various Buildings

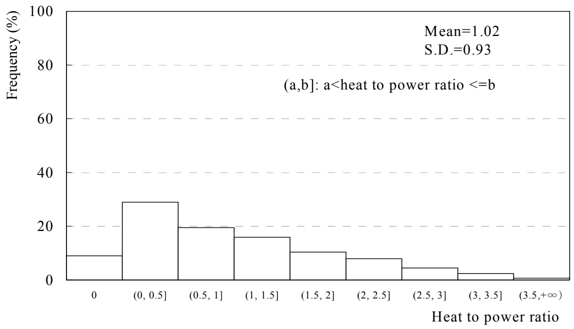


Figure 1-1: Heat-to-power ratio in detached houses

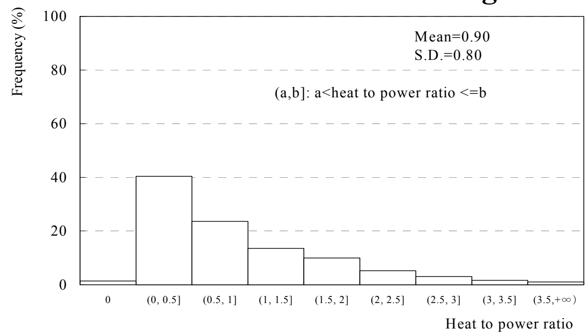


Figure 1-2: Heat-to-power ratio in apartments

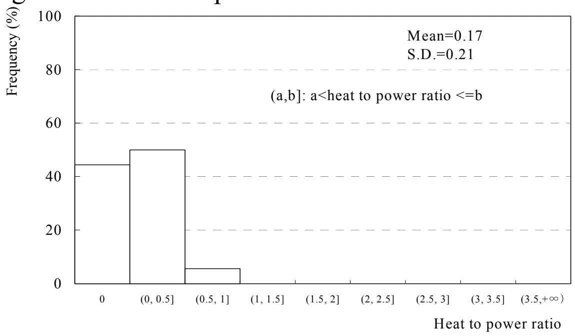


Figure 1-3: Heat-to-power ratio in commercial buildings

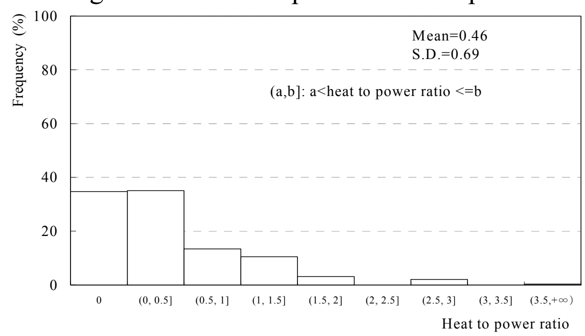


Figure 1-4: Heat-to-power ratio in offices

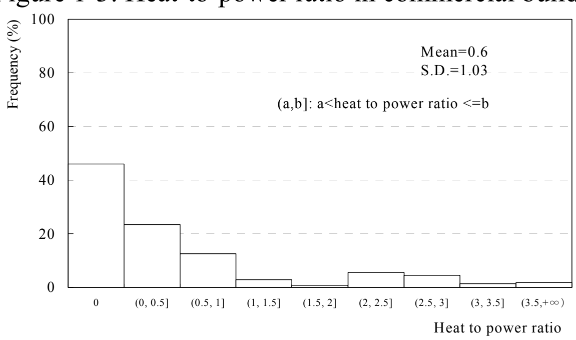


Figure 1-5: Heat-to-power ratio in educational facilities

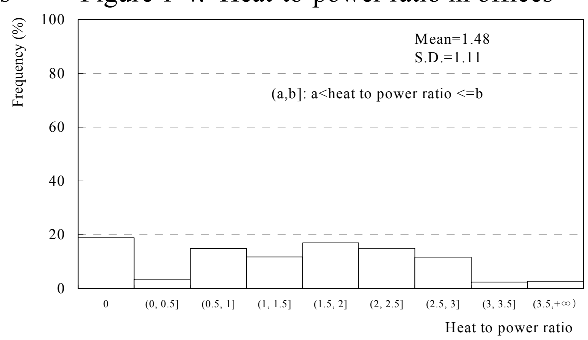


Figure 1-6: Heat-to-power ratio in hospitals

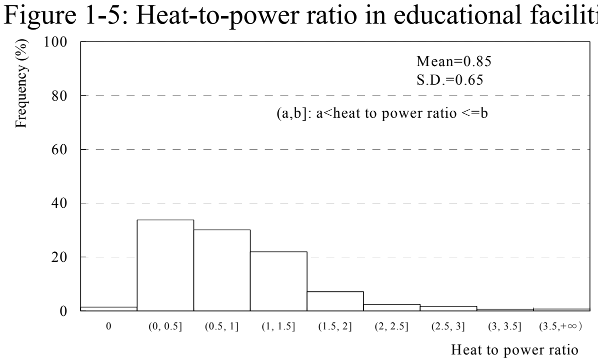


Figure 1-7: Heat-to-power ratio in complex facilities

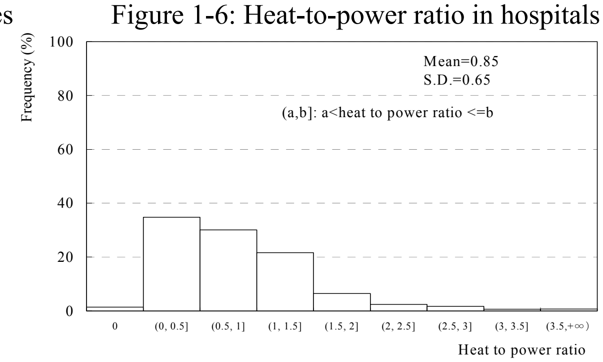


Figure 1-8: Heat-to-power ratio in complex facilities

The Relationship between Heat-to-Power Ratio and Energy Saving Ratio

As described in the former section, heat-to-power ratio is a key factor influencing the efficiency of CHP systems. In this section, the relationship between the heat-to-power ratio and the energy saving ratio will be analyzed. 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, as compared with a conventional energy supply system. It can be defined as follows:

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

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

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

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

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

Where,

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

Q_E^{Conv} = Total primary energy input in the conventional energy supply system;

Q_E^{CHP} = Total primary energy input in the CHP energy supply system;

E = Electricity load demand;

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. It can be calculated by using the ratio of the thermal recovery efficiency to the electricity generation efficiency.

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;

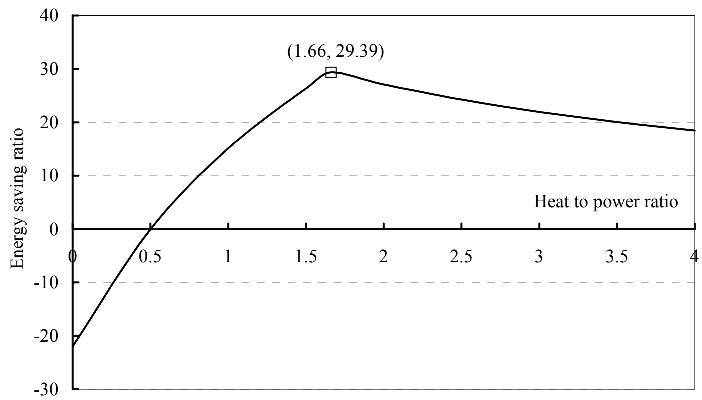
η_{CHP}^{H} = Thermal recovery efficiency of CHP system; it is assumed as 0.477 based on running data of an existing solid oxide fuel cell (SOFC) CHP system at KSRP.

From the above equations 2 and 3, it can be found that in a CHP system, when CHP system equipment is decided and it is assumed that the equipment's efficiencies under the part-load conditions is same as one at full electricity generating capacity, the energy saving ratio is influenced by the heat-to-power ratio on the demand side. Using the above assumed values for the thermal recovery efficiency and the electricity generation efficiency of a fuel cell, one can calculate the relationship between the heat-to-power ratio and the energy saving ratio for the fuel cell CHP system as illustrated in Figure 2. From the profiles it can be concluded that:

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

- Energy saving ratios increase to a maximum value of 29.39% with 1.66 of σ_{CHP} , then decrease with further rises of the heat-to-power ratio. It can be expressed that, the recovered thermal energy from a CHP system cannot be fully utilized by the user when σ is less than 1.66. On the contrary, when σ is more than 1.66, the recovered thermal energy cannot satisfy user demand. Therefore, an auxiliary gas boiler must be operated to supply deficits of thermal energy, which reduces the energy saving ratio.

Figure 2. The Relationship between Heat-to-Power Ratio and Energy Saving Ratio



Scenario Studies

Based on the heat-to-power ratio characteristics of various buildings and the relationship between heat-to-power ratio and energy saving ratios, four energy supply systems were modeled in this paper. The details of the fours scenarios are listed in Table 2.

Scenario 1 is a conventional system (described in Figure 3) and it is a baseline. In this scenario, the electricity load demand is supplied by the utility electricity company. Room air conditioners are used to supply cooling and heating demands. Gas heaters provide hot water.

Scenario 2 is assumed to use a DHC system as illustrated in Figure 4. In this Scenario, the electricity demand for all buildings is supplied by the utility electricity company. Gas boilers provide heating and hot-water load. Absorption chillers are used to provide the cooling load.

Scenario 3 is assumed to use a CHP system as illustrated in Figure 5. In this Scenario, the CHP system provides part of the electricity load for all buildings, including apartments, detached houses, commercial buildings, offices, hospitals and educational facilities. 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. Deficits of electricity are provided by the utility company. A gas boiler is used to supply the deficits of thermal energy.

Scenario 4 is also assumed to also use a CHP system as illustrated in Figure 5. However, in this Scenario, detached houses use the conventional energy system, not the CHP system, for the following reasons. First, detached housing has little influence on the overall load characteristics (compare Figure 1-7 with Figure 1-8). Second, the introduction of a CHP system for detached houses will obviously increase the hot-water pipeline investment. Also, in this paper, the following assumptions have been used:

Figure 3. Energy Supply Plan of Conventional System

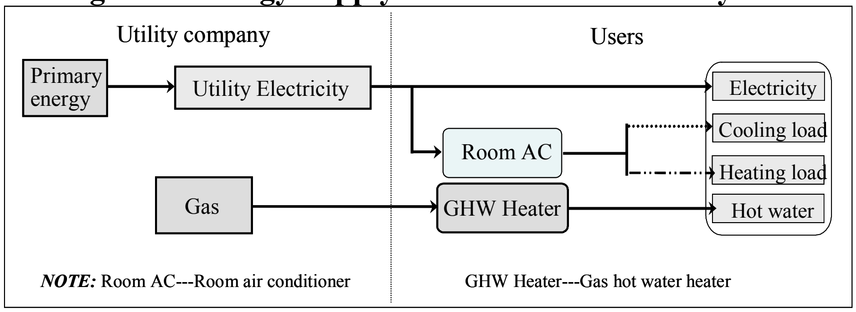


Figure 4. Energy Supply Plan of DHC System

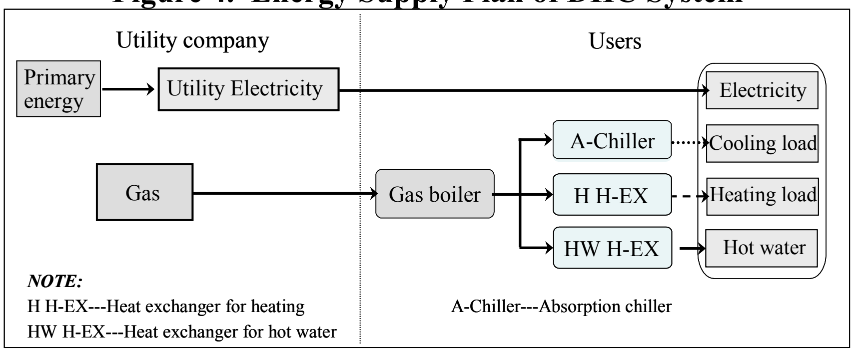


Figure 5. Energy Supply Plan of CHP System

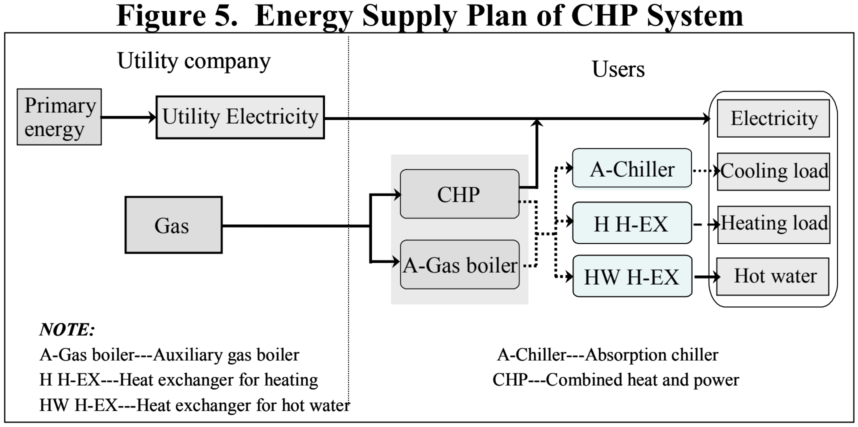


Table 2. Details for Various Scenarios

Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	
Building	All buildings	All buildings	All buildings	DH	All buildings except for DH
System mode	Room AC	DHC	CHP	Room AC	CHP
Sketch figure of system	Figure 3	Figure 4	Figure 5	Figure 3	Figure 5
Annual heating load (MWh/Year)/ Peak heating load (kW)	6,673/6,651	6,673/6,651	6,673/6,651	167/192	6,506/6,459
Annual cooling load (MWh/Year)/ Peak cooling load (kW)	3,198/2,931	3,198/2,931	3,198/2,931	20/49	3,177/2,882
Annual hot water load (MWh/Year)/ Peak hot water load (kW)	5,433/2,046	5,433/2,046	5,433/2,046	208/124	5,225/1,922
Annual electricity load (MWh/Year)/ Peak electricity load (kW)	16,344/3,281	16,344/3,281	16,344/3,281	350/89	15,994/3,192

NOTE: ***Room AC :*** air-conditioner; ***DHC:*** district heating and cooling; ***CHP:*** combined heat and power; ***DH:*** detached house

- The CHP capacity required for Scenario 3 and Scenario 4 is 25% of the peak electrical load, which is the average value for CHP systems in Japan (Ruan et al. 2005). Therefore, the CHP capacity is taken to be 800 kW (the peak demand is about 3,200 kW).
- Performance of the generator under the part-load conditions is the same as one operating at full electricity generating capacity.
- When the amount of electricity generated by the CHP system cannot satisfy the user, the utility electricity company supplies the deficit. Similarly, an auxiliary gas boiler is used to supply deficits of thermal energy. When the thermal energy recovered form CHP system exceeds the thermal energy demand of the user, the surplus energy is expelled directly into the atmosphere.
- Table 3 specifies coefficient of performance (COP) or efficiency for various kinds of equipment.

Table 3. COP or Efficiency for Various Equipments

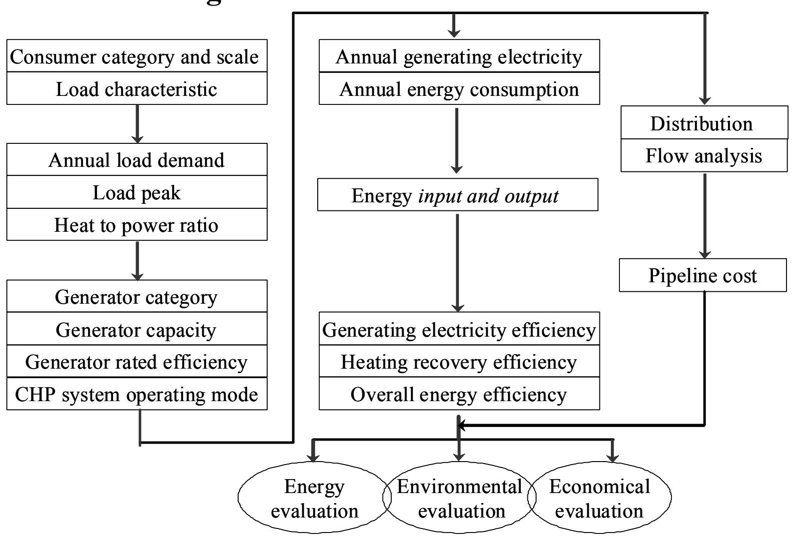
Equipments		Efficiency	COP
Utility electricity	Generating electricity	0.35	−
	Transport and distribution	0.9	−
CHP system	Generating electricity	0.287	−
	Heat recovery	0.477	−
Gas hot water heater		0.78	−
Auxiliary gas boiler		0.8	−
Room air conditioner	For cooling	−	3.22
	For heating	−	2.83
Absorption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

Simulation Method

HEATMAP (Ruan & Gao, 2005), 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.

Figure 6 is shows the HEATMAP structure, which comprises the following fours main parts: load assessment, equipments, operating simulation and pipeline calculation. First, HEATMAP provides a model for estimating consumer energy load by using DOE2's building simulation analysis program or directly accepting a user furnished annual building energy load of 8760 hours. Second, HEATMAP then optimizes the equipment and operating strategy of a production plant or system according to the load demand and optimizes the pipeline network by hydraulic and thermal analyses. Finally, it estimates system costs and helps to plan wise market strategies and assess environmental benefits. In this paper, load tables with the loads of 8760 hours for various scenarios were imported into HEATMAP directly. Then equipment items and their capacities and characteristics were selected according to their load characteristics. After inputting these details, simulations were undertaken. Finally, overall evaluation results regarding energy efficiency, environment and economical effect can be obtained according to the simulation for various scenarios

Figure 6. HEATMAP Structure

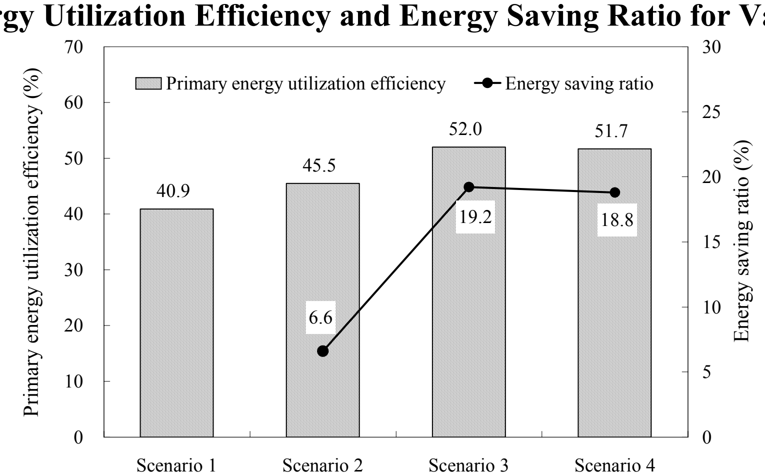


Simulation Results and Discussion

Primary Energy Utilization Efficiency and Energy Saving Ratio

In general, primary energy utilization efficiency is an important index for evaluating actual projects. Primary energy utilization efficiency is defined as the rate of the amount of useful utilization energy to primary input energy. In this paper, the primary energy utilization efficiency and the energy saving ratio for the four scenarios were calculated and demonstrated in Figure 7.

Figure 7. Energy Utilization Efficiency and Energy Saving Ratio for Various Scenarios



From the profiles of primary energy utilization efficiency, it was concluded that Scenario 3 has the highest primary energy utilization at 52.0%, approximately 11.1% higher than Scenario 1, the conventional energy supply system. Scenario 2 achieved 45.5% primary energy utilization efficiency, 4.6% higher than Scenario 1. Scenario 4 is very similar to Scenario 3. Correspondingly, Scenario 3 and Scenario 4 achieved approximately a 19% energy saving ratio.

CO_2 Reduction Ratio

Environmental impact is an important factor that cannot be neglected in any project. Compared with a centralized plant, decentralized combustion systems have fewer pollutants, including CO_2, NO_X and SO_X. In this paper, the CO_2 reduction ratio is selected as an index to evaluate the environmental effect of a CHP system and it is defined as follows:

$$\eta_{\Delta CO2}^{CHP} = \frac{EX_{CO2}^{Conv} - EX_{CO2}^{CHP}}{EX_{CO2}^{Conv}} = \frac{(ex_{CO2}^{Gas} \times G^{Conv} + ex_{CO2}^{Pow} \times P_{Utility}^{Conv}) - (ex_{CO2}^{Gas} \times G^{CHP} + ex_{CO2}^{Pow} \times P_{Utility}^{CHP})}{(ex_{CO2}^{Gas} \times G^{Conv} + ex_{CO2}^{Pow} \times P_{Utility}^{Conv})} \quad (4)$$

Where,

η_{CO2}^{CHP} = CO_2 reduction ratio of CHP or DHC system;

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

EX_{CO2}^{CHP} = CO_2 emissions of the CHP or DHC system, kg;

ex_{CO2}^{Gas} = CO_2 emissions per cubic meter of natural gas, 2.36kg/m^3;

ex_{CO2}^{Pow} = CO_2 emissions per kWh electricity, 0.65kg/kWh, which is an average emission value of the utility electricity in Japan;

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

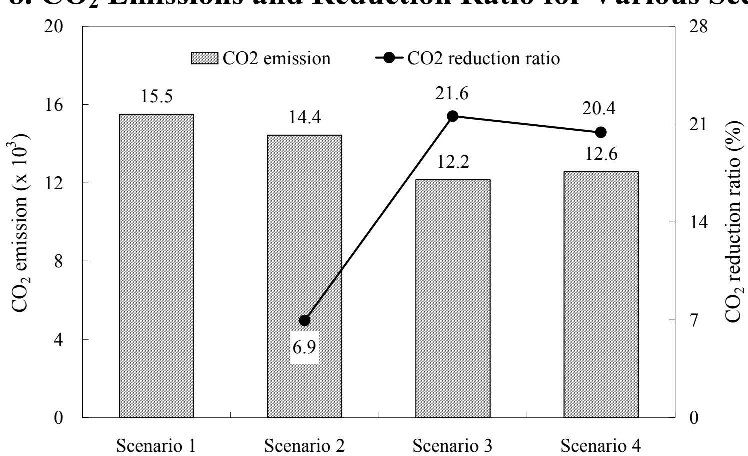
G^{CHP} = Consumption of natural gas in the CHP or DHC system, m^3;

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

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

According to equation 4, and energy consumptions of the various energy supply system, CO_2 emissions and reduction ratios for various scenarios were calculated and are shown in Figure 8. Compared with Scenario 1, Scenario 3 reduced 3,300 tons CO_2 every year, followed by Scenario 4 with 2,900 tons, Scenario 2 with 1,100 tons. Correspondingly, their CO_2 reduction ratios are 21.6%, 20.4%, and 6.9%.

Figure 8. CO_2 Emissions and Reduction Ratio for Various Scenarios



Payback Times

Financial cost is a key criterion in any investment decision. In Japan, profitability is the most cited reason for adopting CHP (Bonilla, 2002). In this paper, initial investment and running costs for various options are calculated and payback times are defined as follows:

$$Y_{payback\ year} = \frac{C_{Initial}^{CHP} - C_{Initial}^{Conv}}{C_{Running}^{Conv} - C_{Running}^{CHP}} \quad (5)$$

Where,

$C_{Initial}^{CHP}$ = Initial investment of CHP or DHC system, in yen ¥;

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

$C_{Running}^{CHP}$ = Running cost of CHP or DHC system, ¥/year;

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

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

Where,

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

$C_{Initial}^{Boiler}$ = Gas boiler investment, 10^4¥;

$C_{Initial}^{ABS}$ = Absorption-chiller investment, including absorption-chiller and cooling tower, 10^4¥;

$C_{Initial}^{FC}$ = Fan coil investment, 10^4¥;

$C_{Initial}^{Pipe}$ = Pipeline investment, including main and branch line, 10^4¥;

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;

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

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

$$C_{Initial}^{Conv} = C_{Initial}^{RC} + C_{Initial}^{Heater} = 10 \times b_1 + 15 \times b_2 \quad (7)$$

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;

$$C_{Running}^{Conv} = C_{Running}^{Convgas} + C_{Running}^{Convpow} = \sum_{i=1}^{N} \sum_{j=1}^{12} Q_{ij}^{Convgas} C_{ij} + \sum_{i=1}^{N} \sum_{j=1}^{12} (Q_{ij}^{Convpow} E_{ij} + 1{,}134 + 302.4) \quad (8)$$

Where,

$C_{Running}^{Convgas}$ = The investment of natural gas, in ¥;

$C_{Running}^{Convpow}$ = The investment of utility electricity, ¥;

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

C_{ij} = The price type of natural gas for unit *i* in mouth *j*; it refers to table 4;

$Q_{ij}^{Convpow}$ = 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 5;

N = The number of housing units;

$$C_{Running}^{CHP} = C_{Running}^{CHPgas} + C_{Running}^{CHPUtility} + C_{Maintenance}^{CHP}$$
$$= (12 \times d_0 + 840 d_1 + 1.13 \times d_2 + 41.919 \times d_3) + (1200 \times d_4 + 15.015 \times d_5 + 13.65 \times d_6) + 2 \times d_7 \quad (9)$$

Where,

$C_{Running}^{CHPgas}$ = The investment of natural gas, ¥;

$C_{Running}^{CHPpow}$ = The investment of utility electricity, ¥;

$C_{Maintence}^{CHP}$ = The maintenance of CHP or DHC system, ¥;

d_0 = The fundamental investment in every month; equals to 105,000;

d_1 = The 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 = The 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;

Table 4. The 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

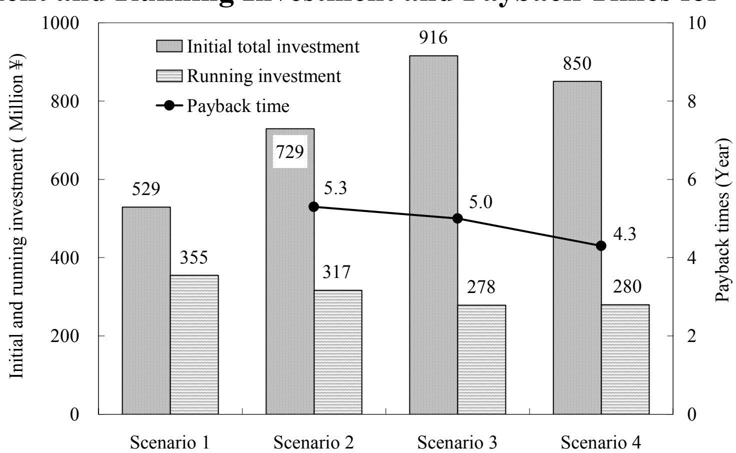
Table 5. The Price of Utility Electricity

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

Costs for the four scenarios can be calculated by using equations 6~9. Payback times were calculated by equation 5 and shown in Figure 9. Figure 9 shows that:

- Compared with the conventional system (Scenario 1), the DHC system increased initial investment by ¥200 million, which resulted from the increased investment for the pipeline and gas boiler. Similarly, two scenarios with CHP systems had a significant increase in the initial investment due to the introduction of the pipeline and CHP equipment.
- The DHC system reduced the running investment of ¥38 million every year more than the conventional system because it spent less investment in selling natural gas. However, it spent more (about ¥100 million) in selling the utility electricity than CHP systems (Scenario 3 and 4), in spite of spending less on maintenance and selling natural gas, which still caused the total running investment to increase to about ¥40 million.
- Compared with Scenario 3, Scenario 4 increased the running investment by about ¥2 million due to selling more of the utility electricity, but it had a significant reduction in the initial investment (about ¥66 million), because of the introduction of CHP systems in the DH increased the pipeline investment by about ¥50 million.
- Scenario 4 has the shortest payback time of 4.3 years, 1 year lower than Scenario 2; the DHC system, and 0.7 year lower than Scenario 3.
- Compared with Scenario 3, Scenario 4 had almost the same energy saving and environmental effects, and it is more economically attractive because it has less initial investment in the pipeline.
- CHP systems achieved not only better economical effects, but also obvious energy saving and environmental effects, compared with the DHC system.

Figure 9. Equipment and Running Investment and Payback Times for Various Scenarios



Conclusions

This study simulated the performances of four options for energy supply systems for a complex development area in Kitakyushu Science and Research Park, Japan. The results of the investigation can be summarized as follows:

- The primary energy utilization efficiencies for CHP and DHC systems at the proposed site ranged from about 45% to 52%. These efficiencies were greater than for the corresponding conventional energy supply system with generation of heat and power in separate processes.

- Of all the options, Scenario 4 had the shortest payback at about 4.3 years, about 1 year less than Scenario 2, the DHC system.
- Despite having slightly lower primary energy utilization efficiency and environmental effects, Scenario 4 achieved better economical results than Scenario 3. Economically, it had a significant reduction in payback time compared with Scenario 3.

In summary Scenario 4, with the CHP system in all buildings expect for the detached houses, is an attractive option for the proposed development complex in Japan. Presently, the market in Japan for BCHP is underdeveloped. However, with the development of technologies for CHP systems and the implementation of policies to encourage their installation, CHP is expected to play a greater role in housing development in the future.

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