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Saving energy in a hospital utilizing CCHP technology

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ABSTRACT

This paper describes a study that starts with an analysis of typical energy demand profiles in a hospital setting followed by a case study of a combined cooling, heating, and power (CCHP) generation system. CCHP is an autonomous system that combines the generation of electrical, heating, and cooling energy. The driving units are two high-efficiency gas engines that produce electrical and heat energy. A gas engine meets the high electrical and heating energy demand requirements - a natural gas-fueled reciprocating engine generates 735 kW of power. In our case, the electrical energy was used only in the hospitals. Purchasing power from the public network covers deficits in the required electricity. Generated steam drives three steam-fired absorption chillers and provides heat for individual consumers; thus, the system provides simultaneous heating and cooling. Implementing the CCHP system did not identify any technical obstacles. The hourly energy demands during several seasons throughout the year determined the typical patterns for CCHP driving units. The average ratio between electric and thermal loads in the hospital is suitable for operating the CCHP system. An analysis performed for an improved CCHP system predicted a large potential for energy savings and CO_2 reduction.

1. Introduction

Combined cooling, heating, and power (CCHP) generation is becoming an increasingly important technology. It affords several advantages such as low consumption of primary energy, reductions in the levels of air pollution, and less expenditure. Simultaneous production of heating, cooling, and power provides high overall system efficiency. Depending on the conditions, this combined system can be the most economical solution for a building if the system is located where there is a high consumption of electrical, heating, and cooling energy throughout the year. A hospital is a perfect example reflecting such consumption conditions. The system might prove unprofitable during a certain period of the year because of the relative costs of gas and electrici-

ty; thus, it is necessary to make a detailed analysis of any planned system and examine various possible operating regimes (Bizzarri et al. [1], Szklo et al. [2]).

The CCHP system is based on the electrical, heating, and cooling device. The type of driving unit and cooling device distinguish different kinds of CCHP systems. A CCHP driving unit module can be a steam turbine, a gas turbine, a reciprocating engine, or a fuel cell. A turbo or absorption chiller generally produces the cooling energy from a CCHP system-the choice depends on the required output power and operating regime (Santoyo et al. [3], Bilgen [4]). Fig.1 shows the actual CHP/CCHP installation data for commercial use in Japan at the end of March 2006

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[5]. Fig.1 (a) indicates the distribution of the total number of sites (4,638) to various facilities in the buildings, with hospitals representing 16% of the sites. Fig.1 (b) indicates the distribution of the total capacity (1,646 MW) to various building facilities, with hospitals accounting for 16% of the capacity. It is important to determine the optimum patterns for the driving units of CCHP in a hospital; however, it has been proven difficult to solve this problem under actual conditions. The optimum control for following the variable energy demands of a hospital has never been accomplished technically because of the number of variables in a hospital: the monthly energy consumption changes seasonally, the daily energy consumption differs between weekdays and holidays, and the hourly energy consumption differs between day and night. company (ESCO) project, described in Appendix 3, starting from an analysis of available hospital energy-consumption da-

ta. The technical feasibility study did not identify any obstacles (Okamoto [6]). This study attempts to provide a new solution. This work examines the technical viability and the effectiveness of a driving pattern for a hospital CCHP system under an energy service CCHP is conceived as an autonomous system for the combined generation of electrical, heating, and cooling energy in the hospital. The Miller cycle gas-engine generators of the adopted CCHP units have higher efficiency (40.7%) than other conventional driving units. These use a novel technology that efficiently drives the production of electrical and heat energy in CCHP systems. The average ratio between the electric and thermal loads in the hospital is suitable for operating the CCHP system (Bizzarri *et al*. [1], Szklo *et al*.[2], Santoyo *et al*.[3]). A case study performed for an improved CCHP system predicted a large potential for energy savings and CO_2 reduction.
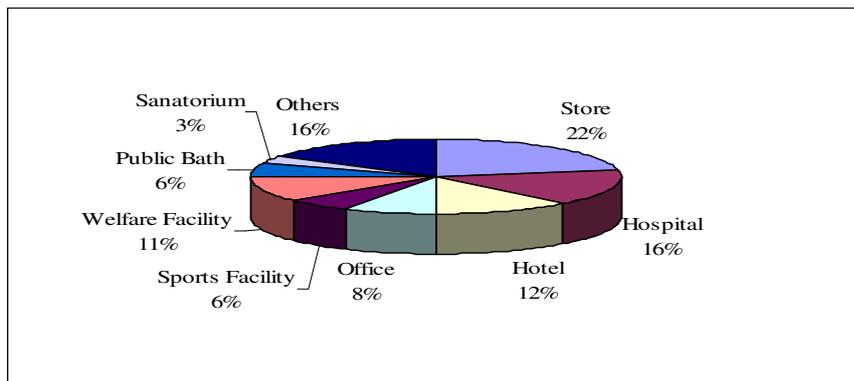
(a) Ratio of Sites (Total Number of Sites: 4,638)
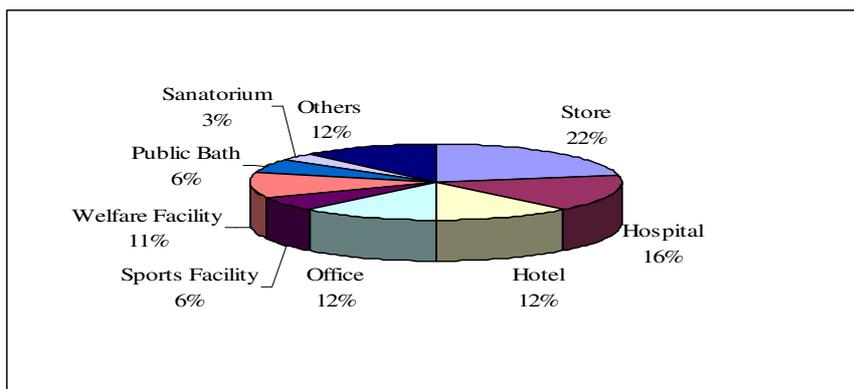
(b) Ratio of Capacity (Total Capacity: 1,646 MW)

Fig.1: Actual CHP/CCHP installation data
for commercial use at the end of March 2006 [5]

2. Energy demand in a hospital

The energy demand in hospitals can vary widely from year to year depending on the number of patients and facilities. Most hospitals are growing more rapidly than the economy as a whole, and an accurate forecast of energy demand requires a significant effort. The large differences in the energy demands among hospitals require a feasibility study for each case with *ad hoc* considerations. This work proposes some guidelines for the application of CCHP in hospitals beginning with a statistical distribution of available energy-consumption data. Hospital energy demand correlates with many factors, including heat loss by infiltration and the loss through windows and roofs, and thus related to the heated or air-conditioned surfaces and volume. The hospital examined in this study belongs to the Shimane University Faculty of Medicine in Japan. The hospital is an eight-story building completed in 1977; therefore, its facilities are obsolete. The area that is heated and air conditioned is 42,203 m² and there are 616 sick beds. Despite this quantitative analysis of energy consumption, determining whether a CCHP system can meet the energy demand requires qualitative analysis. The hospital has a central system for hot or warm water production (heavy oil fueled boilers; 16 t/h × 2 and 5 t/h × 1) and cooling (three absorption chillers, 600 RT; turbo chiller, 400 RT) as shown in Fig.2. Typically, the electric utility provides the power. The hospital primarily uses all-air systems with air-treatment units that allow adjustment of temperature and humidity; a typical temperature range for the heat exchanger in such units is 70–85°C.

Figures 3 and 4 show the annual and monthly energy consumption profiles for the hospital, respectively. The bars in Fig. 3 represent the electric consumption for feeding an absorption chiller covering the entire cooling demand and the lighting system, the hot water and sterilization demand, cooling, and the heating consumption. The monthly electric consumption, shown in Fig. 4, is regular because the electric load corresponds to fairly constant activities year-long.

Fig.5 compares the heat ratio of the university hospital with the averaged heat ratio of other hospitals in Japan [7]. The Energy Conservation Center of Japan (ECCJ) defines heat ratio as the ratio of heating and cooling demand to the annual energy consumption [7]. The heat ratio of the university hospital is 0.32, which is lower than the 0.4 average for other hospitals in Japan. Appendix 1 gives the definition of the heat ratio. A case study predicts a large potential for energy savings. The daily consumption in 2005, shown in Fig.6, for electrical, heating, and cooling loads, is nearly constant for summer, autumn, and winter. The daily consumption on 2/11(Wed) in Fig.6 (c) is relatively low, because it happened to be a holiday. The typical hourly consumption profiles for heating and cooling in 2005, shown in Fig.7, are quite regular, with a small increase during the mornings or afternoons depending on whether it is a weekday or a holiday. The hourly electric load profile represents regular power requests during the day, with a demand leap for the lighting system and the elevators. Obviously, certain electric loads require a very high supply safety; hence, dedicated engines or inverter groups provide energy in case of power grid failures.
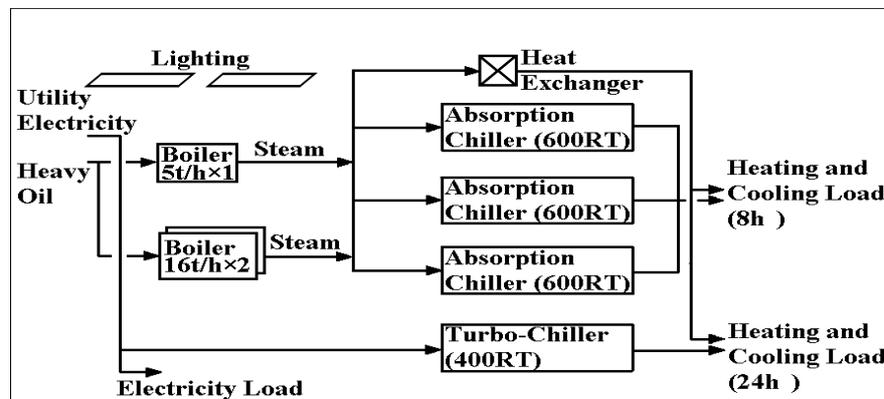

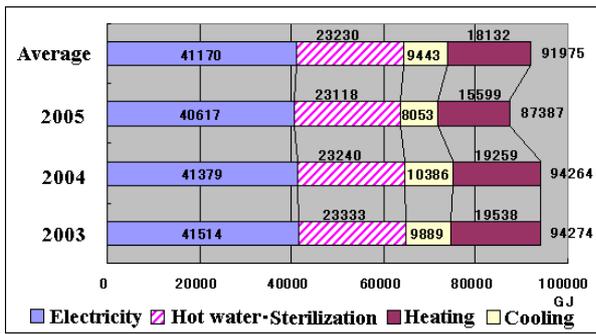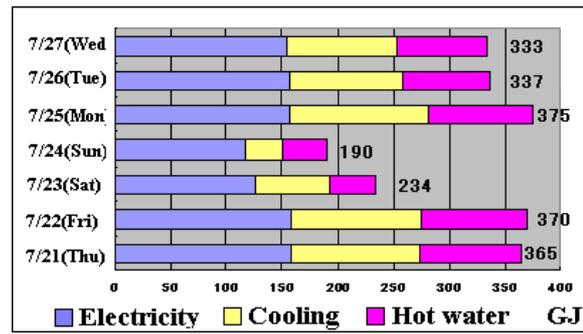
Fig.2: Conventional hospital system

Fig.3: Annual hospital energy consumption
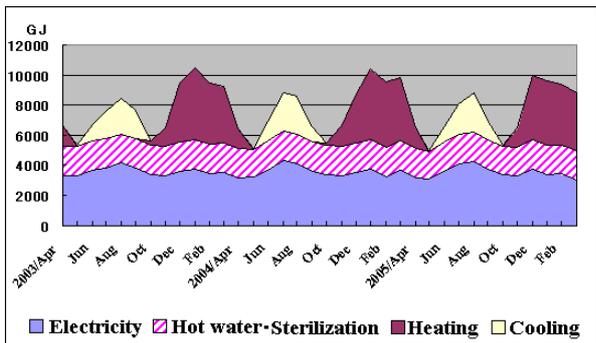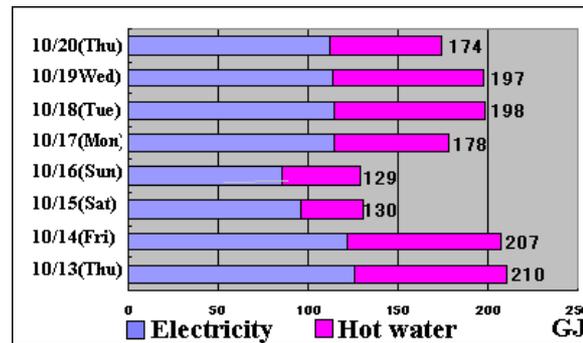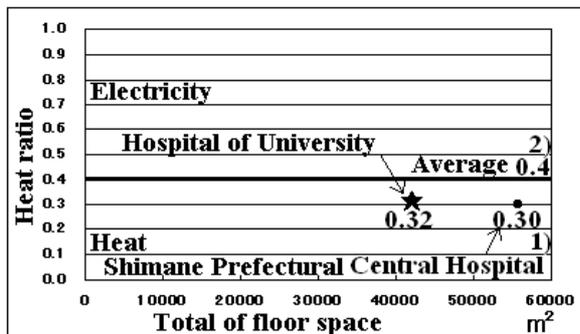

(a) A week in summer

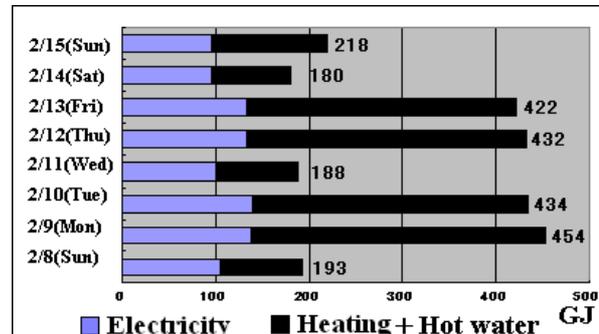Fig.4: Monthly hospital energy consumption

(b) A week in autumn

Source 1): Shimane Prefectural Central Hospital [8]
Source 2): ECCJ; Energy Conservation Center, Japan [7]

Fig. 5: Comparison of heat ratios [7]

(c) A week in winter

Fig. 6: Daily hospital energy consumption

3. Technical potential of CCHP in a hospital

3.1 Description of the CCHP system in hospital

The Shimane University Hospital is a large consumer of electrical, heating, and cooling energy. For this reason, installing a system for the simultaneous generation of electric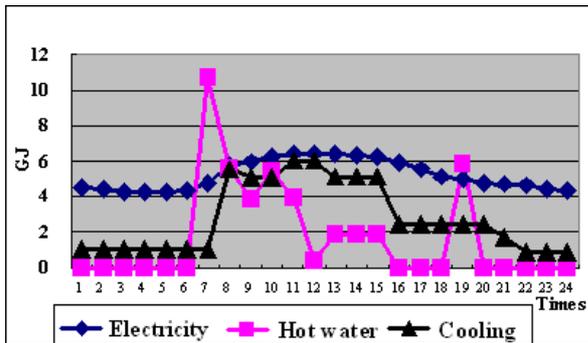al, heating, and cooling energy would be ideal to reduce the initial investment and operating costs and meet ecological requirements. Several studies performed on the design of cogeneration systems in hospitals (Bizzarri *et al*. [9]) have demonstrated different technical possibilities and have tried to
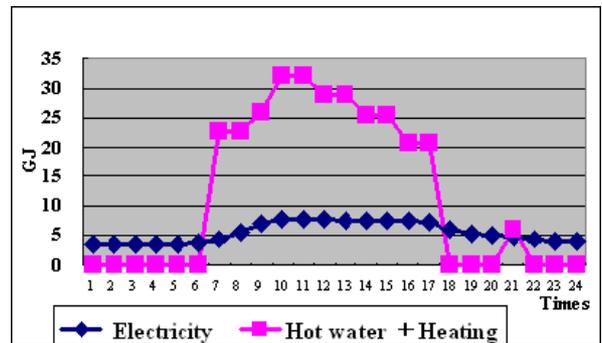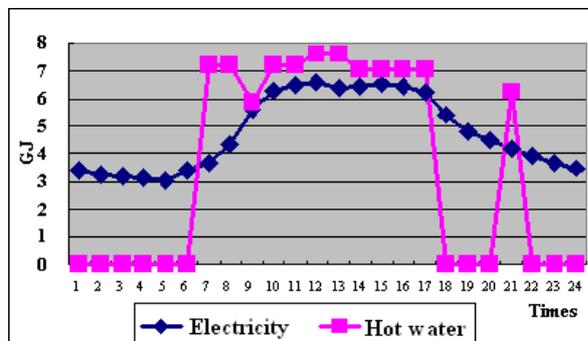
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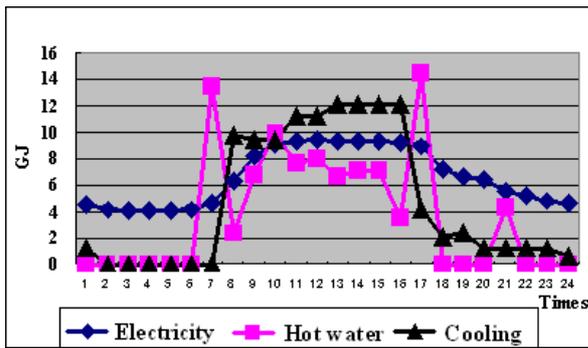
(a) Typical weekday in summer
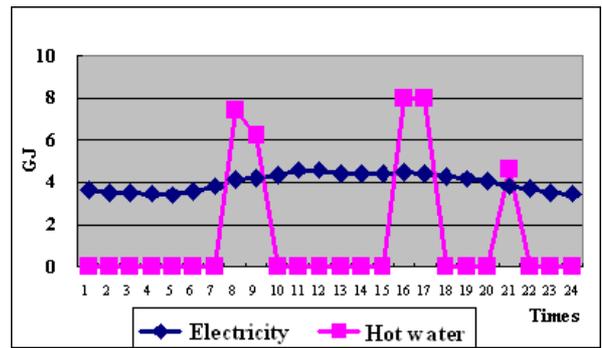
(d) Typical holiday in autumn

(b) Typical holiday in summer

(e) Typical weekday in winter

(c) Typical weekday in autumn
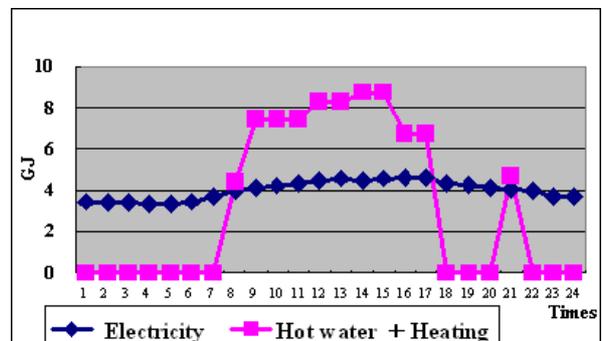
(f) Typical holiday in winter

Fig.7: Hourly hospital energy consumption

identify economic benefits. This paper faces the design challenge of improving the CCHP system needed for load fluctuations (Bizzarri *et al*. [9]). The actual needs for electric, heating, and cooling energy determine the best gas engines and chillers. We have tried to find the ideal system for year-long operation.

This study looks at the possibility of installing a CCHP system for the simultaneous generation of heating, cooling, and electrical energy. Fig.8 shows the concept of an autonomous system for the combined generation of electrical, heating, and cooling energy in a hospital. The driving CCHP units are two high-efficiency Miller cycle (40.7%) gas engines (GE-1 and GE-2). The mechanism of the Miller cycle engine cylinder is as

follows. Before compression, the volume of the Miller cycle is reduced compared with that of a conventional engine by opening the inlet valve and discharging some of the mixed air in the cylinder. However, the expansion ratio is the same as that in a conventional engine. In other words, it produces the same amount of energy, but

improves the engine efficiency by reducing the energy used during compression [10].

A gas engine serves as a driving unit because of the high demand for electrical and heating energy. The natural gas-fueled reciprocating engine generates 735 kW of power. Table 1 shows the energy consumption of the conventional
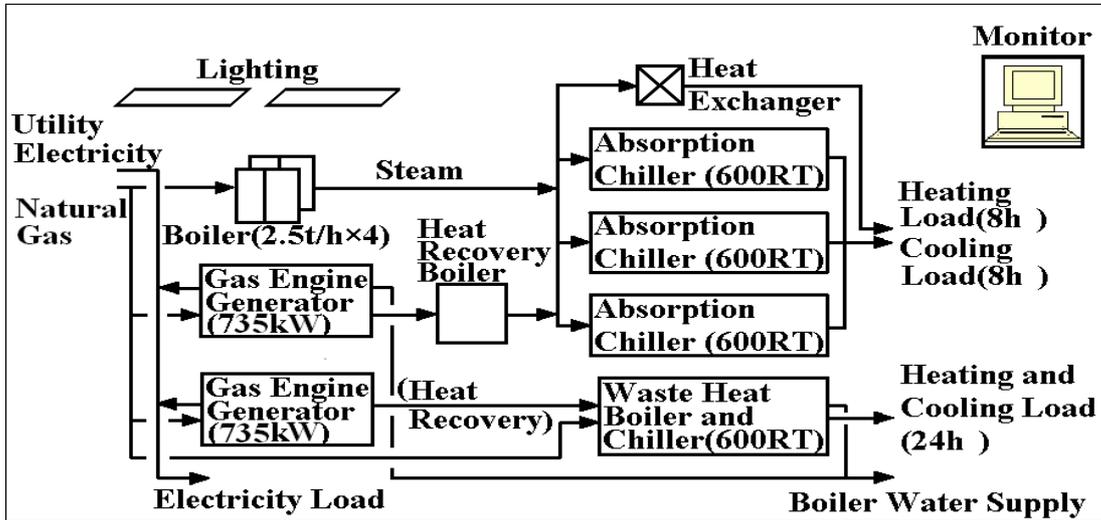
Fig.8: CCHP system for a hospital

Table 1. Energy and CO_2 content of conventional and CCHP systems

| Month	Conventional System			CCHP	
	Electricity (kWh)	Heavy Oil (L)	Natural Gas (m^3)	Electricity (kWh)	Natural Gas (m^3)
April	1,291,580	93,358	7,034	825,840	160,104
May	1,306,100	50,258	7,034	906,660	104,189
June	1,458,060	97,087	7,034	946,320	145,528
July	1,657,000	154,286	7,034	994,260	249,380
August	1,661,820	166,932	7,034	1,004,520	225,876
September	1,504,160	114,955	7,034	975,600	177,445
October	1,367,580	59,345	7,034	972,240	111,506
November	1,321,180	110,781	7,034	963,060	138,195
December	1,423,180	171,110	7,034	958,260	202,818
January	1,489,120	212,179	7,034	998,400	204,811
February	1,344,760	186,068	7,034	888,600	173,531
March	1,449,840	176,325	7,034	948,660	167,121
Total	17,274,380	1,592,684	84,408	11,382,420	2,060,504
Total (MJ)	169,807,155	62,273,944	3,891,209	111,889,189	94,989,234
CO2 (kg)	9,587,281	4,316,174	199,625	6,317,243	4,873,092
Total (MJ)	235,972,309			206,878,423	
CO2 (kg)	14,103,079			11,190,335	
Energy Saving Ratio (%)	12.3				
CO2 Reduction Ratio (%)	20.7				

system and CCHP throughout the year. In our case, only the hospital uses the electricity and purchases from the public network to cover the deficit, as shown in Table 1. Table 1 shows the utility electricity from a conventional system and the amount of natural gas consumed by CCHP. Generated steam drives three conventional steam-fired absorption chillers (600 RT × 3) and the storage of the original system (1,000 m³), which is delivered to individual heat consumers, as shown in Fig. 8.

Fig.8 shows the generated steam throughout the year. A peak-time waste heat boiler provides additional heat during winter. This system provides simultaneous heating and cooling as shown in Fig. 8. Fig.9 shows the heating load during the winter and the cooling load during the summer in 2009. Increasing the reliability of the cooling energy supply requires installation of an additional absorption chiller.

Fig.9 shows typical patterns for the CCHP driving units based on the hourly energy demands
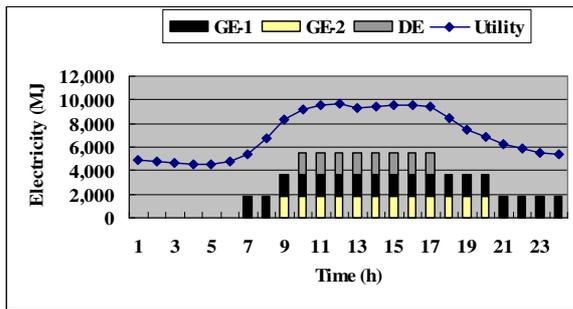
(a) Typical pattern for driving units on a summer weekday
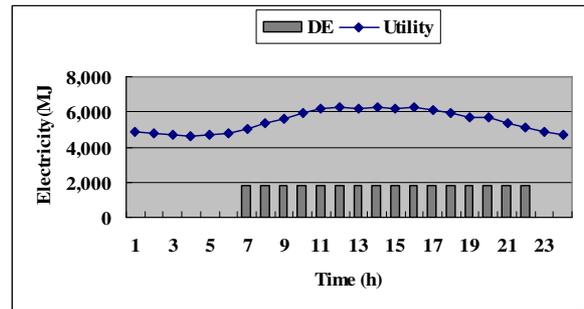
(d) Typical pattern for driving units on an autumn holiday
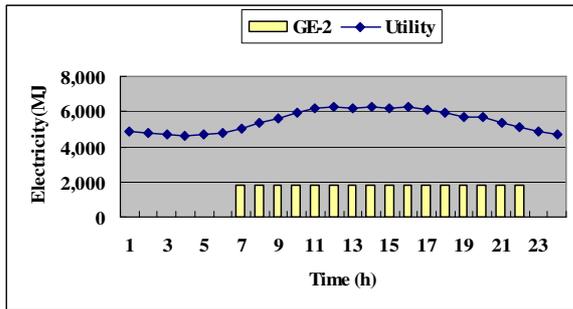
(b) Typical pattern for driving units on a summer holiday

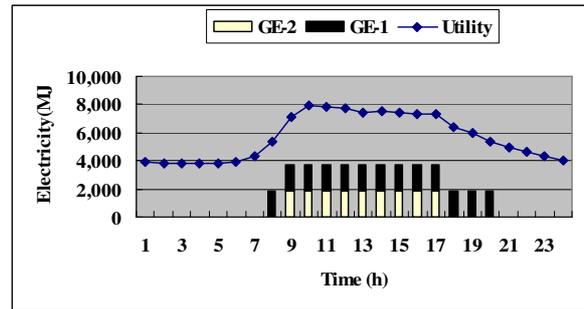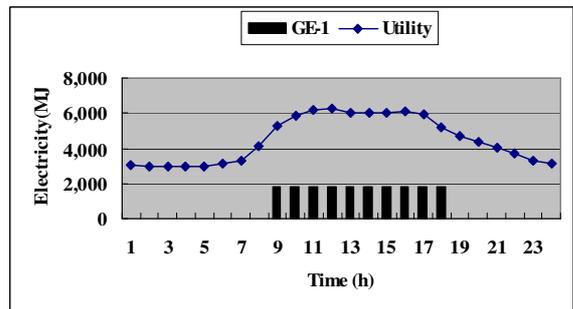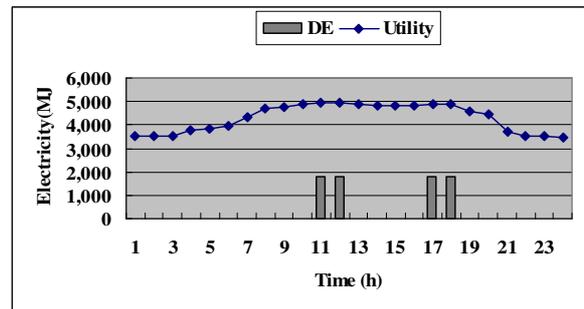(e) Typical pattern for driving units on a winter weekday

(c) Typical pattern for driving units on an autumn weekday

(f) Typical pattern for driving units on a winter holiday

Fig.9: Energy content of planned cogeneration system

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during several seasons and on weekdays and holidays shown in Fig.7. The choice of patterns for generated electricity indicated in Figs. 9(a) and 9(b) meet the hourly heating load and cooling loads on summer weekdays and holidays, respectively.

An emergency diesel generator (DE) covers the deficit in electricity. The patterns for autumn, indicated in Figs. 9(c) and 9(d), relate to the hot water demands on weekdays and holidays as shown in Figs. 7(c) and 7(d), respectively. The patterns in winter indicated in Figs. 9(e) and 9(f) relate to the hourly heating load (hot water and heating) on weekdays and holidays shown in Figs. 7(e) and 7(f), respectively.

Normally, the heat-energy needs in winter are too high to use them for planning a CCHP system based on the maximum heating energy required. The requirements for electrical, heating, and cooling energy vary within certain limits. These are the energy consumptions for CCHP described in Table 1. Thus, we chose a CCHP module based on the peak cooling load. For cooling purposes, we chose three absorption chillers, each with a cooling power of 600 RT.

The water temperature in the cooling jacket of reciprocating engines typically exceeds these values and is sufficient for feeding the air-heating system. Depending on the cooling demand levels, installing a double-effect lithium-bromide absorption chiller produces 5–7°C chilled water for the air-treatment units. A double-effect absorption chiller requires superheated feed water at 120–130°C or low-pressure steam (typically 70–90 kPa); only high-temperature heat recovery from exhausts is compatible with the temperature required by the absorption chillers.

3.2 CCHP energy saving and CO$_2$ reduction in Hospitals

Appendix 1 defines the heat ratio. Fig.5 shows that the heat ratio of the university hospital is 0.32, which is lower than the 0.4 average of other hospitals in Japan. Designing a CCHP plant for hospitals requires a modular approach. The CCHP installations in most hospitals over the world consist of several small modules to meet the growing heat demand. A modular approach enhances the reliability of supply, which is a main concern for hospitals. Our experience con-

firms that major opportunities for CCHP technologies exist in large hospitals because of the high capacity required and the regular demand profiles. Installing CCHP technologies in small hospitals usually leads to longer payback periods, which mean static ones.

Retrofitting a conventional plant with CCHP technology, as shown in Fig.2, requires integrating the existing components and equipment with the new ones. This section examines a typical hospital energy system and the required system. Fig.8 shows the new components or major changes for two gas-engine generators and a heat recovery boiler. When converting a conventional system to CCHP technology, the existing boilers and chillers can serve as auxiliary systems, and the new system can use the same piping for the existing centralized all-air system for heating and cooling.

A brief analysis performed for the hospital with the obtained monthly electricity, heavy oil, and natural gas indicated in Table 1 tested all these considerations.

This analysis is general, and the purpose of this section is to show the enormous potential CCHP has for saving energy in a hospital, where an improved plant design and operation achieves interesting results. The calculations are for a CCHP system with a heat recovery boiler, two gas engines, and three absorption chillers; it strictly follows the sum of electrical demand for direct users and for feeding the absorption chiller. These types of studies are usually done in terms of exergy and not energy. One such reference is Norberg *et al.* [11]. However, we believe that these types of studies should be not only done by exergetic analyses but also by energetic ones.

The energy-saving ratio was calculated by:

$$\frac{T-C}{T} \times 100 = 12.3\% . \tag{1}$$

Table 1 gives the energies provided by a conventional system and CCHP, where C represents the energy consumption of CCHP with utility electricity, and T is the sum of the fuel consumption in the local energy system and in the power plant that supplies electricity.

Appendix 2 provides the several energy rates in Table 1. The energy-saving ratio calculated by

the simulation in the feasibility study was 16.5% (Okamoto [6]). As the total energy consumption of a conventional system is the same in the feasibility (Okamoto [6]) and verification studies, the verification study overestimates the actual CCHP energy consumption. The control by the prime mover of CCHP cannot be based on the hourly consumption profiles for heating and cooling with a small increase during mornings or afternoons depending on whether it is a weekday or a holiday.

The CO_2-reduction ratio is calculated by:

$$\frac{X - Y}{X} \times 100 = 20.7\% \ . \tag{2}$$

CO_2 emitted by a conventional system and CCHP is described in Table 1. Here X represents the total amount of CO_2 from the conventional system, and Y represents the amount of CO_2 from the CCHP system. X is the sum of the CO_2 amount emitted from the utility electricity and the heavy oil plant. Appendix 2 gives the detailed emission rates in Table 1. The amount of CO_2 emitted from CCHP driven by natural gas is much smaller than that from a conventional system.

Comparing a CCHP system with a conventional system requires careful evaluation of the unit energy costs. CCHP generally provides a lower electric utilization class and contractual power, implying higher electricity costs. Moreover, the "value" of heat depends on the user characteristics.

Considering, for example, business and commercial use, such a value is simply given by the heat demand times the unit cost of the fuel used in the conventional system; such fuel costs can be the same as for the CCHP plant, or lower, or higher. To account for the user characteristics, the computer program requires a "value" for heat, which must consider the differences in fuel costs and efficiencies between various fuel streams used for CCHP and conventional operations (Bizzarri *et al.* [9]).

ESCOs generate revenue from fees clients pay from energy savings. ESCOs and their clients enter a performance contract (on a piecework basis) to guarantee energy conservation. Clients pay fees for the comprehensive services provided by ESCOs. Supplemental power costs, defined as the cost of power purchased from the utility on a regular basis and supplemental fuel costs (the cost of fuel required for a conventional boiler and duct burner), were evaluated by ESCOs. The static payback periods derived through cost savings from an efficient CCHP system in the hospital were estimated, including the incremental costs of operating the CCHP system.

In the lower range of electric power supply per maximum demand, the CCHP system capacity is designed for static payback periods of less than five years. The proposed retrofitting situation includes replacement costs. Planning of the hospital CCHP assumed a 15-year contract to guarantee the energy conservation and cost savings provided by ESCOs (Appendix 3).

4. Conclusions

This work discussed the technical viability and improvement of a CCHP system-driving pattern for energy supply in the Shimane University Hospital. The analysis started with the available energy-consumption data for the hospital; no technical obstacles were identified. The hourly energy demand during several seasons throughout the year determined the typical driving patterns.

5. Acknowledgements

Abbreviations

C	electricity, heating, and cooling energy generated by CCHP
CCHP	combined cooling, heating, and power system
GJ	gigajoule
h	hour
RT	ton of refrigeration
t	ton
T	total energy consumption of conventional system

X total amount of CO_2 from conventional system

Y amount of CO_2 from CCHP

Appendix 1

Heat includes both heating and cooling; hence, ECCJ defines the heat ratio as the ratio of heating demand and cooling demand to annual energy consumption by [7].

$$Heat\ ratio = \frac{Heating + Cooling}{Annual\ energy\ consumption} \qquad (3)$$

Fig.5 gives the heat ratio for the University Hospital as 0.32, which agrees with the results obtained in 2008. The thermal energy for hot water sterilization is not included, but will be included in a future study to improve the analysis accuracy.

Appendix 2

In the results in Table 1, utility electricity is the primary energy, and it is included in the analysis to accommodate its large consumption. A future study will analyze it separately.

Dimensions:

1 kWh = 9.83 MJ

Heating value of heavy oil = 39.1 MJ/L

Heating value of natural gas = 46.1 MJ/m^3

Electricity: 0.555 CO_2-kg/kWh

Heavy oil: 2.71 CO_2-kg/L

Natural gas: 2.365 CO_2-kg/m^3

Efficiency of CCHP generator = 0.41

$T = Electricity + Heavy\ Oil + Natural\ Gas$

   $= 17{,}274{,}380\ kWh + 1{,}592{,}684\ L + 84{,}408\ m^3$

   $= 169{,}807{,}155\ MJ + 62{,}273{,}944\ MJ + 3{,}891{,}209\ MJ$

   $= 235{,}972{,}309\ MJ$

$C = Electricity + Natural\ Gas$

   $= 11{,}382{,}420\ kWh + 2{,}060{,}504\ m^3$

   $= 111{,}889{,}189\ MJ + 94{,}989{,}234\ MJ$

   $= 206{,}878{,}423\ MJ$

$$\therefore \ \frac{T-C}{T}\times 100\% = \frac{235{,}972{,}309 - 206{,}878{,}423}{235{,}972{,}309}\times 100\%$$

$$= 12.3\%$$

Appendix 3

An ESCO project is a private energy-saving business activity that offers energy-related services to clients. Companies undertaking ESCO projects are called ESCOs.

For projects operating under a shared saving contract, ESCOs provide comprehensive services for factories, buildings, and other establishments, including audits for energy-saving performance, design, and implementation of conservation measures, maintenance, operation and management of the introduced facilities, and procurement of project funds. ESCOs conserve energy without damaging the environment, while guaranteeing energy savings.

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Biography

Satoru Okamoto is currently a Professor in the Department of Mathematics and Computer Science at Shimane University. He pursued his degree in M.Sc. in 1977 and Ph.D in mechanical engineering in 1980 from Osaka University. Then, he worked as a researcher in the Research & Development Department at Ishikawajima-Harima Heavy Industries Co., Ltd (IHI). At IHI, he worked as a vendor of aircraft engines and gas turbines, and had also designed compressors and fans of jet engines. He was an associate professor in the Department of Mechanical Engineering at Niihama National College of Technology from 1988 to 1994. Meanwhile, in 1994, he joined Professor Donald Rockwell's group at Lehigh University as a visiting research scientist for about one year. During this period, he explored an application of flow visualization and PIV in the field of flow-induced vibrations. He is also a member of AIAA and the Japan Society of Mechanical Engineering. His current research interest lies in advanced thermal and fluids science and technology such as flow-induced vibrations, small-scale energy systems with gas turbines and heat pumps, and experimental fluid dynamics and heat transfer. In addition, he has published over 100 journals and conference papers.