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Case Studies of Energy Saving and CO_2 Reduction by Cogeneration and Heat Pump Systems

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ABSTRACT

This paper describes two case studies: 1) a cogeneration system of a hospital and 2) a heat pump system installed in an aquarium that uses seawater for latent heat storage. The cogeneration system is an autonomous system that combines the generation of electrical, heating, and cooling energies in a hospital. Cogeneration systems can provide simultaneous heating and cooling. No technical obstacles were identified for implementing the cogeneration system. The average ratio between electric and thermal loads in the hospital was suitable for the cogeneration system operation. An analysis performed for a non-optimized cogeneration system predicted large potential for energy savings and CO_2 reduction. The heat pump system using a low-temperature unutilized heat source is introduced on a heat source load responsive heat pump system, which combines a load variation responsive heat pump utilizing seawater with a latent heat-storage system (ice and water slurry), using nighttime electric power to level the electric power load. The experimental coefficient of performance (COP) of the proposed heat exchanger from the heat pump system, assisted by using seawater as latent heat storage for cooling, is discussed in detail.

Keywords: Cogeneration System; Heat Pump System; Energy Saving; CO_2 Reduction; Hospital; Aquarium

1. Introduction

Following the crisis of the Great Eastern Japan Earthquake and the nuclear power plant accidents on March 11, 2011, the future energy balance flow for Japan was quantitatively estimated. Cogeneration systems and heat pump systems are especially becoming increasingly important technologies after the nuclear power plant accidents. This paper describes two case studies of energy systems: 1) a cogeneration system of a hospital; and 2) a heat pump system installed in an aquarium that uses seawater as latent heat storage. These systems have several advantages, including lower consumption of primary energy, reductions in the levels of air pollution, and less expenditure. Simultaneous production of heating, cooling, and power provides higher overall system efficiency. Depending on the conditions, these combined systems can be the most economical solution for a building. The requirement is that the system should be located where there is high consumption of electrical, heating, and cooling energy throughout the year. A hospital is a perfect example of the type of consumer with those conditions. This system might not be profitable during a certain period of the year because of the relative costs of gas and electricity. Therefore, it is important to make a detailed analysis of any planned system and examine the various possible operating regimes [1-3].

The basis of a cogeneration system is its electrical, heating, and cooling device. However, different kinds of cogeneration systems are distinguished by the types of driving units and cooling devices that make up the systems. The driving unit of a cogeneration module can be a steam turbine, a gas turbine, a reciprocating engine, or a fuel cell. The cooling energy from a cogeneration system is mainly produced with either a turbo-chiller or an absorption chiller; the choice depends on the required output power and the operating regime [4-7]. This work examines the technical viability of the systems to determine the better choice for an operating pattern for a cogeneration system supplying energy to a hospital, starting from an analysis of energy consumption data available for the hospital; no obstacles were identified in the technical feasibility of the cogeneration [8].

On the other hand, to reduce the emissions of carbon dioxide that contributes to global warming, the effective use of energy, such as the efficient use of various types of waste heat and renewable energy, should be promoted. A heat pump system can produce more heat energy than the energy that is used to run the heat pump system. Therefore, a heat pump system is considered to be one representation of a machine system that can efficiently use energy, and a load leveling air-conditioning system that uses unutilized energies at high levels [9-13].

This paper also discusses a heat pump system installed in an aquarium that uses seawater as latent heat storage [14]. To maintain indoor temperatures, such as using air conditioner to maintain the indoor conditions at a constant temperature and a constant relative humidity and to cool the water supply to the fish tanks in the aquarium, heat from seawater is collected as the heat source for the heat pump system. The pump system using low-temperature unutilized heat sources is introduced on a heat source load responsive heat pump system, which combines a load variation responsive heat pump utilizing seawater with a latent heat-storage system (ice and water slurry), using nighttime electric power serving as electric power load leveling. The experimental coefficient of performance (COP) of the proposed heat pump with the latent heat-storage cooling system is discussed in detail.

2. Cogeneration System in a Hospital

It is very important to determine the optimal patterns for the driving units of a cogeneration system in a hospital. However, it has been very difficult to solve this problem under the actual conditions. Therefore, establishing the optimal controls to accommodate the changing energy demands of a hospital have never been technically accomplished because of the following reasons: 1) the monthly energy consumption of a hospital is affected by seasonal changes of energy demands throughout the year, 2) the daily energy consumption is affected by changes during weekdays or holidays, and 3) the hourly energy consumption is affected by differences in daytime or nighttime energy usage. This study will add to the challenges of obtaining a new solution. The cogeneration system is conceived as an autonomous system that combines the generation of electrical, heating, and cooling energy in the hospital. The gas engine generators of the adopted cogeneration units have higher efficiency (40.7%) than other conventional driving units; they are Miller cycle gas engines, which use a novel technology that drives cogeneration systems to efficiently produce electrical and heat energy. The average ratio between the electric and thermal loads in the hospital is suitable for the cogeneration system operation [1,2,5]. A case study performed for a non-optimized cogeneration system predicted large potential for energy savings and CO_2 reduction [15-18].

2.1. Energy Demand in the Hospital

The hospital examined in this study belongs to the Shimane University Faculty of Medicine in Japan. The hospital is an eight-story building and was completed in 1977; therefore, its facilities are superannuated. The area that is heated and air-conditioned is 42,203 m^2, and there are 616 beds. Despite this quantitative analysis of energy consumption, a qualitative analysis is needed to assess whether a cogeneration system can meet the energy demand. 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; and a turbo-chiller, 400 RT), as shown in **Figure 1**. Power is usually purchased from the electric utility. Mainly, all-air systems have been adopted using air-treatment units that allow the adjustment of temperature and humidity; a typical temperature range for the heat exchanger in such units is 70˚C - 85˚C.

The typical daily consumption in 2005, shown in **Figure 2**, for electrical, heating, and cooling loads, is nearly constant only for the summer, autumn, and winter, because the typical day energy consumption profiles in the spring is almost same that as the autumn. The typical hourly consumption profiles in 2005, shown in **Figure 3**, for heating and cooling are quite regular, with a small increase during the morning or afternoon, depending on whether it is a weekday or a holiday. The hourly electric load profile is characterized by regular power requests during the day with a leap in demand for the lighting system and the elevators. Obviously, certain electric loads require a very high level of supply security; therefore, dedicated engines or inverter groups are usually provided for energy supply in case of power-grid failures.

2.2. Description of the Cogeneration System

This study sights at the possibility of installing a cogeneration system in a hospital, *i.e.*, the simultaneous generation of heating, cooling, and electrical energy. **Figure 4** shows the concept of an autonomous system for the combined generation of electrical, heating, and cooling energy. The driving cogeneration units are two high-efficiency Miller cycle (40.7%) gas engines (GE-1 and GE-2).

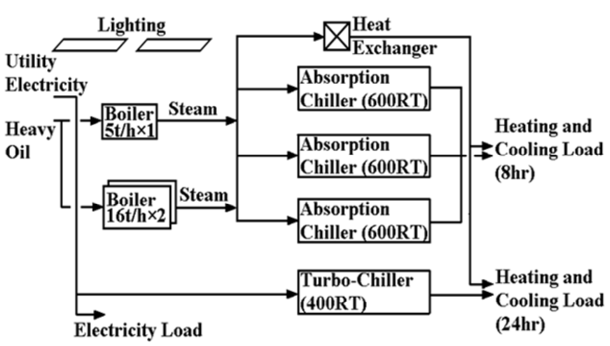
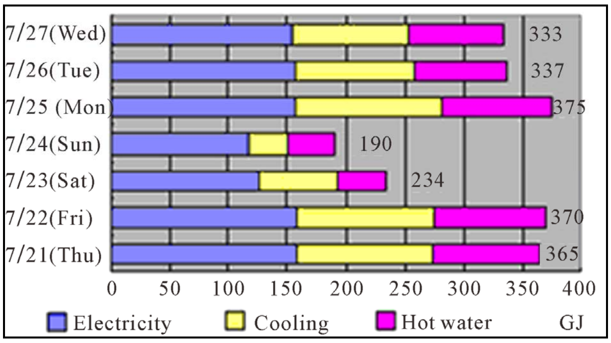


Figure 1. The conventional hospital system.



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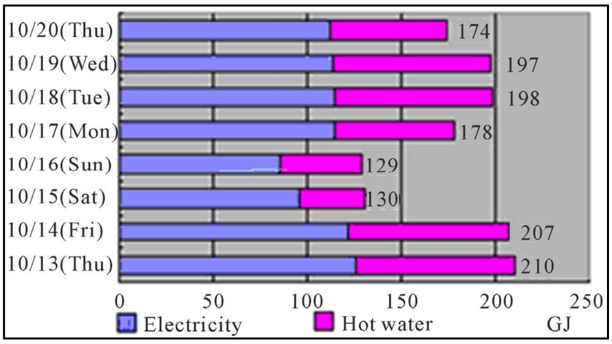

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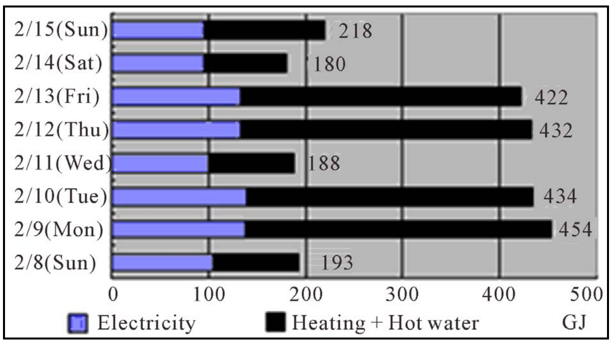

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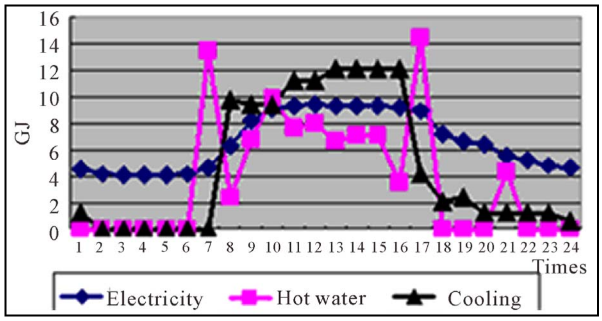
Figure 2. Daily energy consumption of the hospital. (a) Consumption during a typical week in summer; (b) Consumption during a typical week in autumn; (c) Consumption during a typical week in winter.

A gas engine is used as a driving unit because of the high demand for electrical and heating energy. The natural gas-fueled reciprocating engine generates 735 kW. **Table 1** shows the energy consumption of the conventional system and the cogeneration system throughout the year. For our study, electrical energy will be used only in the hospital. Electricity can also be purchased from the public network to cover a deficit, as shown in **Table 1**. **Table 1** shows the consumption of electricity from the public utility by the conventional system and the amount of natural gas consumed by the cogeneration system. Generated steam drives three steam-fired absorption chillers of the same conventional type (600 RT × 3) and use the present storage (1000 m^3), which is delivered to individual heat consumers, as shown in **Figure 4**, which shows the amount of generated steam throughout the year. An additional peak-time waste heat boiler provides additional heat during the winter period. This system can provide simultaneous heating and cooling, as shown in **Figure 4**. **Figure 5** shows the heating load during the winter and the cooling load during the summer of 2009. It is necessary to install an additional absorption chiller



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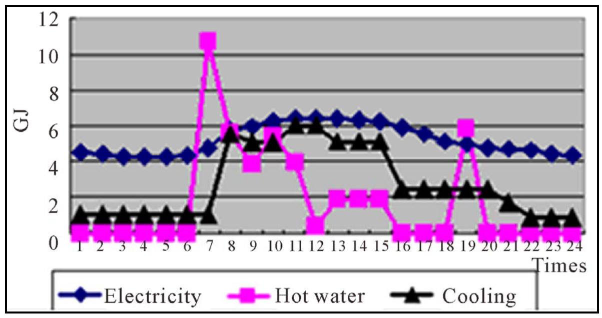

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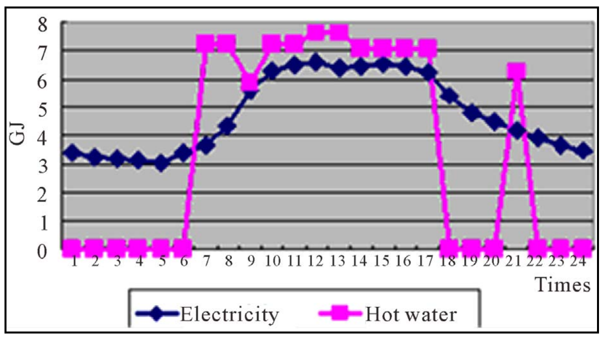

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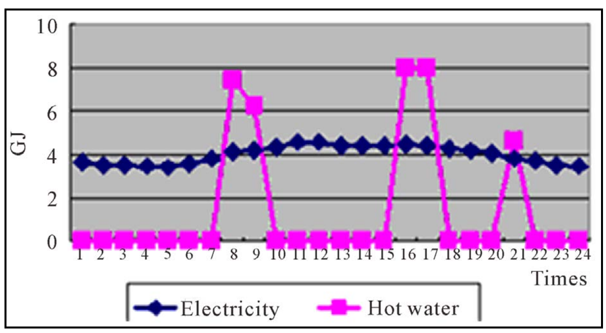

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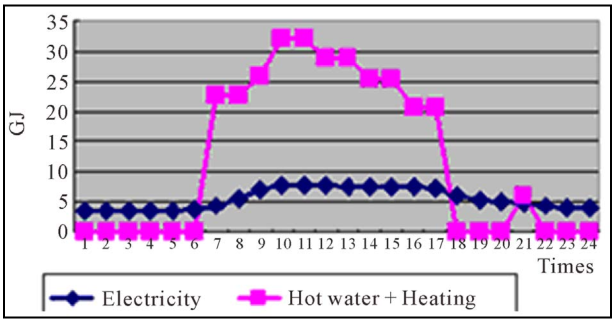

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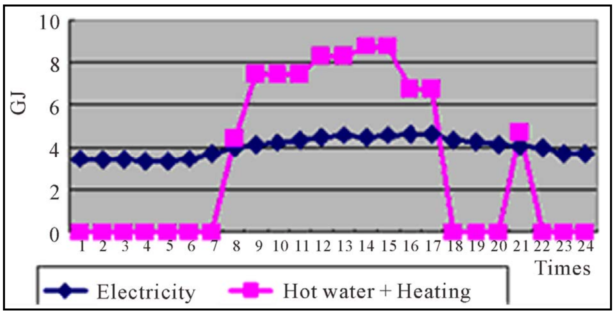


(f)

Figure 3. Hourly energy consumption of the hospital. (a) Consumption during a typical weekday in summer; (b) Consumption during a typical holiday in summer; (c) Consumption during a typical weekday in autumn; (d) Consumption during a typical holiday in autumn; (e) Consumption during a typical weekday in winter; (f) Consumption during a typical holiday in winter.

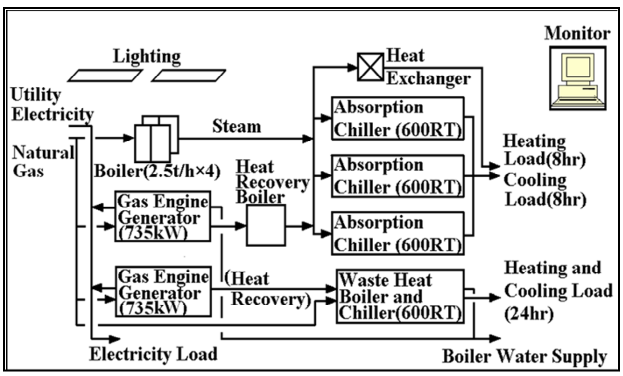
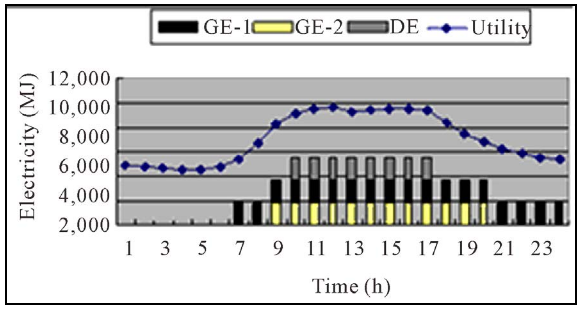


Figure 4. The cogeneration system of the hospital.

to increase the reliability of the cooling energy supply.

The typical patterns for the driving units of the cogeneration are indicated in **Figure 5**, and these patterns are based on the hourly energy demands during several seasons and on weekdays or holidays, as shown in **Figure 3**. The planned patterns for electricity in several seasons are shown in **Figure 5**. The choice of patterns for generated electricity, indicated in **Figures 5(a)** and **(b)**, are based on the hourly heating load and cooling loads for a summer weekday and holiday, respectively. The deficit in electricity is supplied by an emergency diesel



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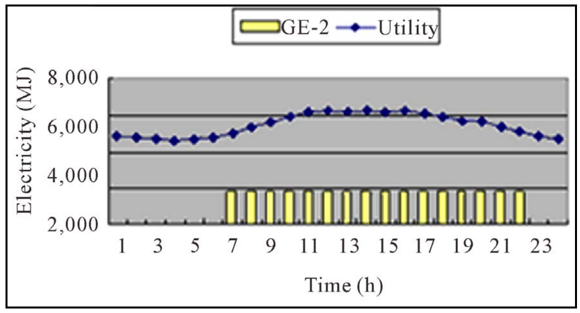

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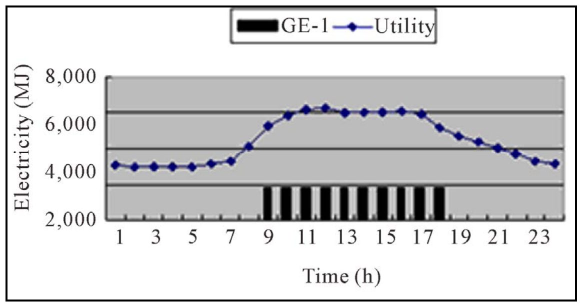

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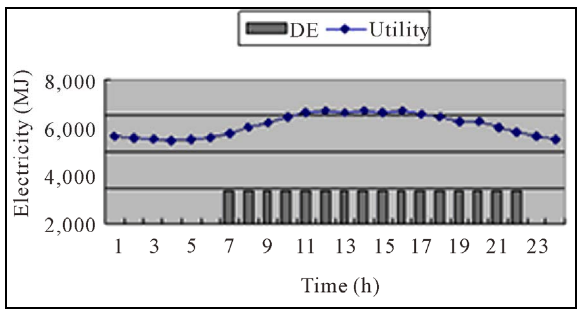

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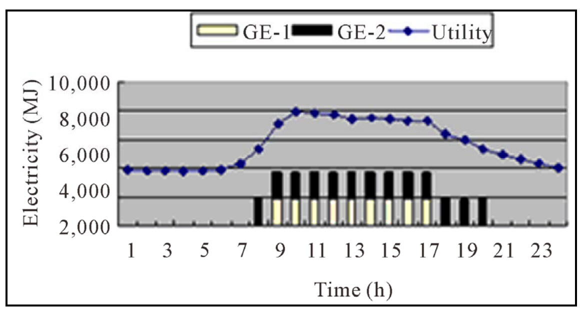

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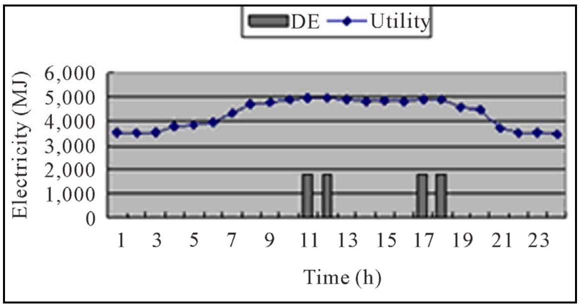

(f)

Figure 5. Energy consumption of the cogeneration system. (a) Energy use pattern during a typical summer weekday; (b) Energy use pattern during a typical summer holiday; (c) Energy use pattern during a typical autumn weekday; (d) Energy use pattern during a typical autumn holiday; (e) Energy use pattern during a typical winter weekday; (f) Energy use pattern during a typical winter holiday.

generator (DE). The patterns in autumn, indicated in **Figures 5(c)** and **(d)**, depend on the temporal hot water requirements for weekdays and holidays, as shown in **Figures 3(c)** and **(d)**, respectively. The patterns in winter indicated in **Figures 5(e)** and **(f)** are based on the hourly heating load (hot water and heating) on weekdays and holidays, as shown in **Figures 3(e)** and **(f)**, respectively. Normally, the heat energy needs in winter are too high to use as the basis of the maximum amount of heating energy required when planning a cogeneration system. The requirements for electrical, heating, and cooling energy vary within certain limits. These are the energy consumption estimates for the cogeneration system described in **Table 1**. We chose a cogeneration module on the basis of a peak cooling load. For cooling purposes, we chose three absorption chillers; one of them having cooling power of 600 RT.

2.3. Energy Saving and CO_2 Reduction of the Cogeneration System Installed in a Hospital

When retrofitting a conventional plant, as shown in **Figure 1**, with cogeneration technology, the existing components and equipment must be integrated with the new ones. This section examines a typical hospital energy system and how it would be integrated with the required system. **Figure 4** shows the new components or major changes that include two gas engine generators and a heat-recovery boiler. When the conventional system is converted to a cogeneration system, the existing boilers and chillers can be used as auxiliary systems. The same piping used for the existing centralized all-air system for heating and cooling can be used.

To confirm all these considerations, a brief analysis was performed for the hospital with the obtained monthly electricity, heavy oil, and natural gas consumption indicated in **Table 1**. This analysis is much more general; the purpose of this section is to show the enormous potential for energy saving with a cogeneration system in the hospital, where interesting results might be achieved even by a non-optimized plant design and operation. The calculations for cogeneration system are performed using two gas engines with a heat-recovery boiler and three absorption chillers; it strictly follows the sum of electrical demand for direct users and for feeding the absorption chiller.

The energy-saving ratio was calculated by:

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

The energy provided by a conventional system and cogeneration system is described in **Table 1**. Here T represents the total energy consumption of the conventional system, and C represents the energy consumption of the cogeneration using electricity from a public utility. T is the sum of the fuel consumption in the local energy system and in a power plant that supplies electricity. The energy rates used in **Table 1** are explained in **Appendix**. The energy-saving ratio calculated by simulation is 16.5% in the feasibility study [19]. Because both the total energy consumption of the conventional systems in the feasibility study [19] and the verification study are the same, the actual energy consumption of the cogeneration system are overestimated in the verification study. The prime reason to adopt a cogeneration system cannot be entirely based on the hourly consumption profiles for heating and cooling with a small increase during the morning or afternoon depending on whether it is a weekday or holiday.

The CO_2 reduction ratio is calculated by:

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

The CO_2 emitted by the conventional system and the cogeneration system is described in **Table 1**. X represents the total amount of CO_2 from the conventional system, and Y represents the amount of CO_2 from cogeneration with natural gas and electricity from public utilities. X is the sum of the CO_2 amount emitted from the utility electricity and the heavy oil plant. The detailed emission rates in **Table 1** are given in **Appendix**. The amounts of CO_2 emitted from the cogeneration system driven by natural gas are much smaller than those from the conventional system, because much of CO_2 amount from the conventional system is emitted from the heavy oil plant.

3. The Heat Pump System in the Aquarium

Before Energy consumption tests were ran in the aquarium for two years. Overall performance characteristics that were of particular interest were the integrated COP along with other instantaneous comparisons of power,

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Table 1. Energy consumption and CO_2 emissions of the conventional system and the cogeneration system.

Month	Conventional System			Cogeneration System	
	Electricity (kWh)	Heavy Oil (L)	Natural Gas (m^3)	Electricity (kWh)	Natural Gas (m^3)
April	1,291,580	93,358	7034	825,840	160,104
May	1,306,100	50,258	7034	906,660	104,189
June	1,458,060	97,087	7034	946,320	145,528
July	1,657,000	154,286	7034	994,260	249,380
August	1,661,820	166,932	7034	1,004,520	225,876
September	1,504,160	114,955	7034	975,600	177,445
October	1,367,580	59,345	7034	972,240	111,506
November	1,321,180	110,781	7034	963,060	138,195
December	1,423,180	171,110	7034	958,260	202,818
January	1,489,120	212,179	7034	998,400	204,811
February	1,344,760	186,068	7034	888,600	173,531
March	1,449,840	176,325	7034	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
CO_2 (kg)	9,587,281	4,316,174	199,625	6,317,243	4,873,092
Total (MJ)		235,972,309		206,878,423	
CO_2 (kg)		14,103,079		11,190,335	
	Energy Saving Ratio (%)			12.3	
	CO_2 Reduction Ratio (%)			20.7	

refrigerant flow rate, and temperatures [20]. This heat pump system has two operational modes. The first mode is a cooling mode that uses ice with water slurry, which is the typical mode during the summer. In this mode, the ice is produced using the heat pump connected with the latent heat-storage system. The second mode is the winter mode, in which the circulating water is heated by the heat pump connected with the heat exchanger system to collect heat from the seawater and the ambient air. Energy-saving effects and carbon dioxide-reducing effects of the heat pump system are estimated from the test results.

The objective of this study is to compare the actual operating characteristics and efficiency of a seawater-source heat pump using an ice-storage system to the predicted evaluation of the two assumed conventional systems. That is, an air-source heat pump without ice storage and an oil-fired absorption refrigerating system. The desired outcome would be to show that the seawater-source heat pump significantly uses less electricity than the air-source heat pump and the oil-fired system. Additionally, the CO_2 emissions for the seawater-source heat pump favorably compare as they might be less than those for the other conventional assumed systems described.

3.1. System Description

Shimane Aquarium (AQUAS) is located in an area facing the Japanese Sea (in the Shimane Prefecture, Japan). The building has two stories and a cellar with a total floor area of 10,293 m^2, and the volume of the fish tank is 3000 m^3. The primary cooling loads at the aquarium are air conditioning for building, cooling of the ventilation air for the fish tank, and cooling and heating of the water in the fish tank. The system selected is one that combines two seawater-source heat pumps, WSHP001 and 002 (cw: 650 kW, hw: 732 kW) and a heat recovery type of air-source heat pump, AWSHP003 (cw: 510 kW, hw: 697 kW). Seawater-source heat pumps transfer heat to and from the seawater by means of circulated water and a heat exchanger. An air-source heat pump uses the outdoor air for heat absorption and rejection. This pump is more common because of its lower initial cost and ease of installation, but seawater-source heat pump is more energy efficient. The heat pump tested in this work transfers heat to the outdoor air and to the sea. It maintains some of the initial cost advantages of the air-source heat pump and some of the performance advantages of the seawater-source heat pump.

The systems provide water cooling using off-peak power. The primary heat source is the heat collected from the seawater and stored in the ice-storage tank, IS (ts: 4500 kWh × 2). The heat produced by the heat pump at night is stored in the ice-storage tank. **Figure 6** shows a diagram of the heat pump system in a summer mode (charging the ice storage). In general, the increased efficiency of the seawater-source heat pump is gained by two mechanisms. First, water is a much better heat transfer fluid than air, so heat is moved much more efficiently. Second, the seawater allows the heat pump to extract heat from water that is usually warmer than the outside air during the winter and cooler than the outside air during the summer. This allows a more efficient heat pump operation. The seawater-source heat pump usually provides warmer supply air temperatures during the winter and cooler supply air temperature during summer, which increases comfort levels.

Ice-storage technology has been shown to be effective in reducing the operating cost of cooling equipment during the summer time. By operating the refrigeration equipment during off-peak hours to recharge the ice storage and by discharging the storage during on-peak hours, a significant fraction of the on-peak electrical demand and energy consumption is shifted to off-peak periods. Cost savings are realized because utility rates favor leveled energy consumption patterns. The variable rates reflect the high cost of providing energy during relatively short on-peak periods. Therefore, they constitute an incentive to reduce or avoid operation of the cooling plant during peak periods by using cold storage. The large difference between on- and off-peak energy and peak consumption rates should make cold-storage systems economically feasible.

3.2. Loads of the Building throughout the Year

Figure 7 shows the ambient air temperature, the ambient air humidity, and the seawater temperature throughout the year. The maximum temperature in August was 35.9˚C, and the mean temperature was 28.3˚C. Relative humidity ranged from about 70% at night to 95% during the day in August. **Figure 8** shows the daily loads of the cooling air conditioning for the space above the fish tank, cooling water, and heating water for the fish tank, and the air conditioning for the building during the period from March 27, 2000 to March 10, 2001. The air-conditioning load for the building during the summer exceeded the predicted loads, but loads in the winter were about 70% of the predicted loads. The loads to provide cooling water and cooling air conditioning for the fish tank have been stable and constant since May, 2001. The loads to provide cooling water for the fish tank could be generated only during the summer time, but the loads of heating water for the fish tank could be produced only during the winter.

The primary cooling loads at the aquarium cool the water in the fish tank and cool ventilation air in the building. **Figure 9** shows the typical building cooling requirements on a typical summer day between August 14 and August 20, 2000. The loads to provide cool air conditioning were nearly constant every day. The loads to provide cool ventilation air in the building and cool water in the fish tank were greatest in the afternoon because of hotter outside air. The outside air temperatures increased and, combined with solar gains, lighting, and a large audience energy gains, the cooling loads increased during the day. The relationship between cooling air-conditioning and cooling water loads is an important consideration regarding the type of heat pump system to install in the aquarium because the heat pump produces cooling water for the aquarium from seawater-source heat and air-source heat.

Winter days tend to be warm in Shimane Prefecture. For example, **Figure 10** shows the use of aquarium heating and airconditioning on a typical winter day between January 15 and January 21, 2001. These data are from operator records for these periods. On these days, the plant provided maximum heating using air to warm each individual building's system. By reducing the amount of outside air used in the building, the heat needed is also reduced, while the amount of heating (heat recovery) is increased. When minimum outside air is used, the major heat is utilized (after initial building warm-up) for air-conditioning. On an average winter day, large heating (heat recovery) loads could be generated from heating water for the fish tank.

3.3. Energy Usage

Figure 11 compares the daily electrical consumption of the three heat pumps from March 27, 2000 until February 26, 2001. During the first two months after the kilowatt-hour meters were installed, the AWSHP003 used about 22% of the electricity that the building used. Average energy usage for those months was 3900 kWh per day for the AWSHP003. This included both heating and cooling modes of operation with the transition from heating to cooling occurring in April. The electrical requirements of the AWSHP003 relatively remained constant throughout the year. AWSHP003 was running throughout the day. The load factor of this heat pump was 50% during the period of cooling and air conditioning in the summer time, and the load factor was about 60% during the period of heating in the winter.

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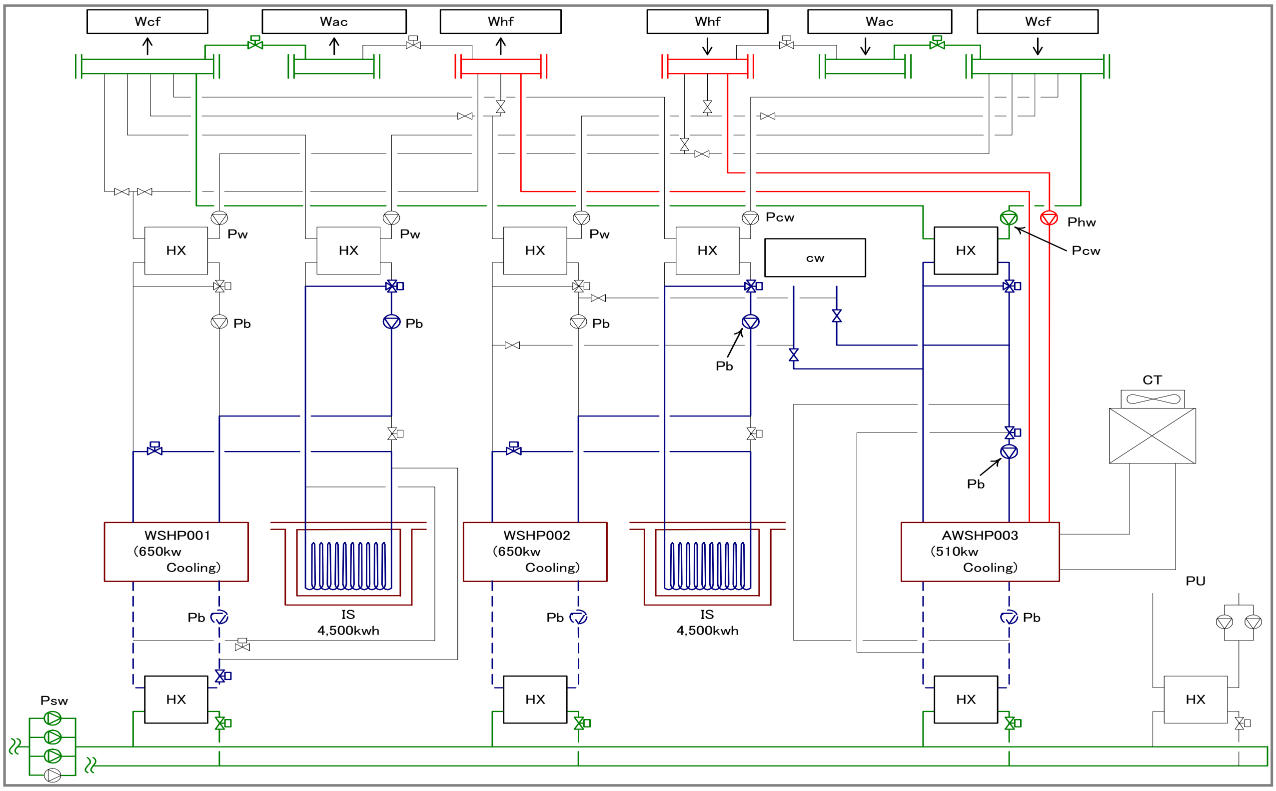

Figure 6. Diagram of the heat pump system in the aquarium (summer mode: charging the ice storage).

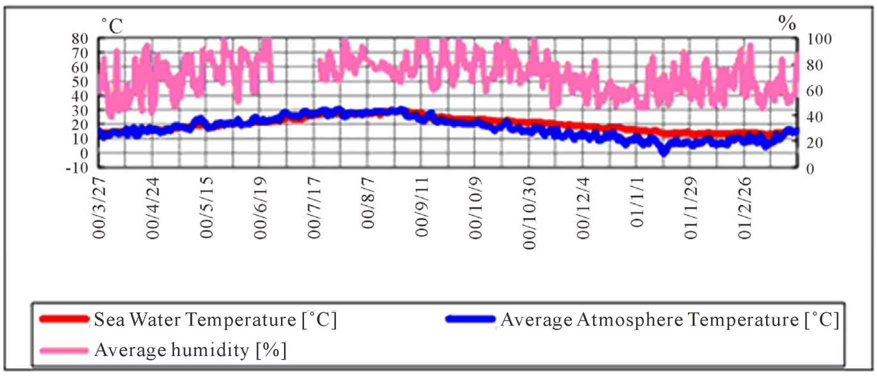

Figure 7. Seawater temperature, air temperature and humidity.

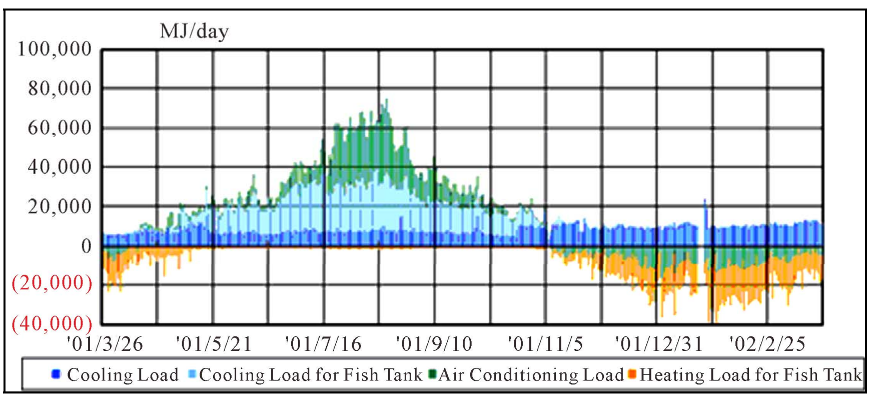

Figure 8. Daily loads of the building during the year.

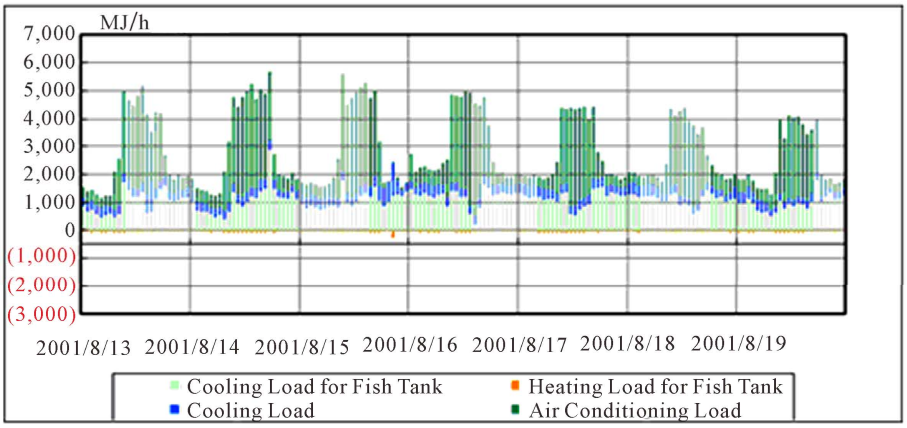

Figure 9. Hourly loads of the building during the summer.

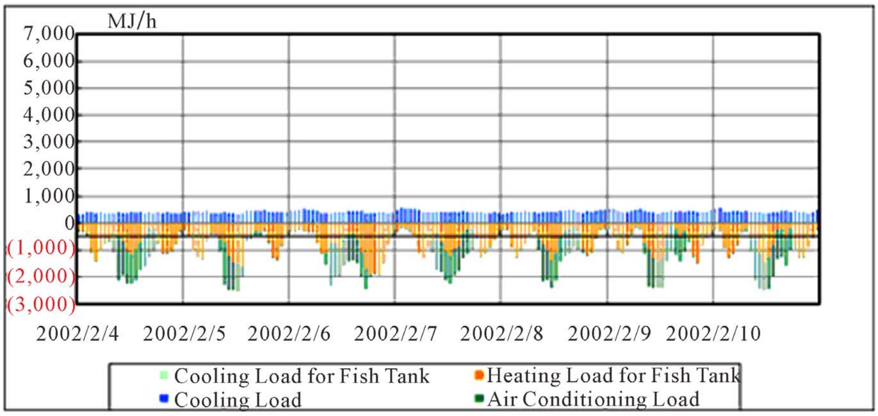

Figure 10. Hourly loads of the building during the winter.

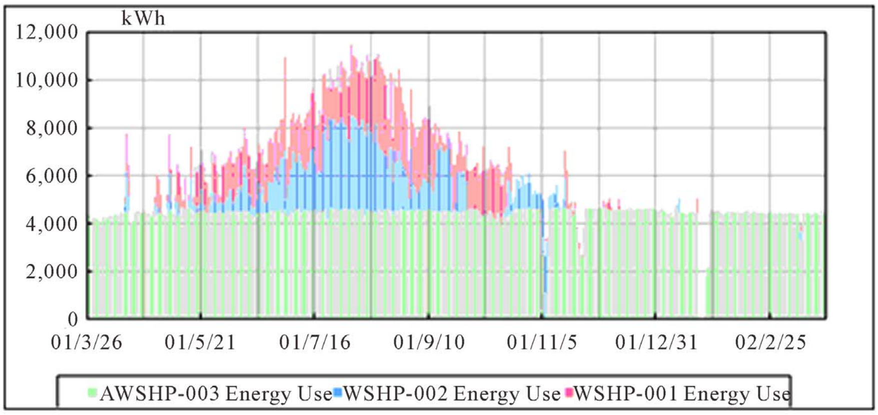

Figure 11. Daily electrical consumption of three heat pumps.

The WSHP001 and WSHP002 relatively used more energy during the summer than during the winter. Overall, during the period from April 15 to November 21, 2000, the WSHP001 and WSHP002 used about 80% of the energy that the AWSHP003 used. The electrical energy usage of both WSHP001 and WSHP002 peaked during the period from August 14 to August 20 because of the heavy air-conditioning load of the building. Both WSHP001 and WSHP002 supplied only the cooling energy for the air conditioning of the building and the cooling water for the fish tank during the summer time. With more data from the winter months, it was expected that the energy usage of the WSHP001 and 002 would approach about zero.WSHP001 and WSHP002 were not used for heating in the winter, except during the maintenance period of AWSHP003.

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Figure 12 shows the typical energy consumption of the WSHP001 and WSHP002 for the period after the kilowatt-hour meters were installed in March 2000. Periodic readings began after August 14, and weekly readings were conducted until August 20, 2000. Both of the WSHP001 and WSHP002 fully ran after the initial building opening in the morning, stopped operations during the period from 1:00 p.m. to 4:00 p.m. in the afternoon, and ran again with the ice-storage tanks according to the loads from 4:00 p.m. Summer days tended to produce more energy from cooling than was needed, and the ice-storage tanks ran at night to produce ice and water slurry to charge the ice-storage tank. Cooling heat was picked up by the ice-storage system, resulting in warmer chilled water return. This warmer chilled water return was stored in the ice-storage tank. Viewed as a heat source for the building, this increase in ice and slurry water temperature was (potential) heat storage.

The heat pump operating at night removed energy from the seawater and produced cooling water, which was stored in the ice-storage tank. The ice and water slurry were used during the next day with the largest loads early in the afternoon. The ice-storage system provided a match in time between cooling availability and the time when heat was needed. By operating the refrigeration equipment during off-peak hours to recharge the ice storage and discharge the storage during on-peak hours, a significant fraction of the on-peak electrical demand and energy consumption were shifted to off-peak periods (see **Figure 13**). It also provided the means to recover and produce cooling at the lowest possible cost by using off-peak electrical energy.

3.4. Energy Efficiency

The summer mode was most efficient for two reasons. The owner received the full benefit of air conditioning the building and cooling water for the fish tank at the same time. In addition, the cold water from the ice-storage tanks maintained the condensing temperature, which in turn reduced the work performed by the heat pumps. When operating in the winter mode, the AWSHP003 obtained its heat from outdoor air and accrued air-conditioning benefits. However, the cold water benefit still occurred. We found from the monitoring data that the COP was relatively high, averaging 3.4 during the summer time. When operating in the summer mode with ice storage, the COP of WSHP001 was 2.6, and the COP of WSHP002 was 3.0 for the output for each unit of electrical energy used (see **Figure 14**). This was the best use of resources and was quite remarkable, considering that it operated in this mode 60% of the time on a year-round basis.

In winter, when the unit was mainly operating in the winter mode, the COP was quite low. The COP was even lower for AWSHP003 than WSHP001 and WSHP002, even though it was working throughout the year. By checking the daily results, we found that the load running was often performed for most of the running time to allow a very low COP. Another reason for the decreased COP of AWSHP003 was due to the heat-recovery running mode, even though the heating loads were almost zero.

The performance of the heat pumps with the ice-storage system was compared with those two other systems (assumed systems), which were installed in the aquarium where heating and cooling were supplied with combinations of the air-source heat pump system without ice storage and the oil-fired absorption refrigerating system. Energy consumption by the WSHP001 and WSHP002 was19% less than the consumption by the oil-fired absorption refrigerating system (see **Figure 15**).

The seawater-source heat pump system emitted 86 tons of CO_2 in a year. This favorably compared to the emissions of the other alternatives for heating and cooling in the two other systems (assumed results): the emissions of the air-source heat pump system without ice storage were 102 tons of CO_2, and the emissions of the oil-fired absorption refrigerating system were 176 tons of CO_2. The electric heat pump with ice storage emitted two times less CO_2 than did the oil-fired system for heating and cooling (see **Figure 16**). In **Figures 15** and **16**, the oil-fired absorption refrigeration system had a smaller percentage of the energy use in nighttime and daytime, because much of energy consumption depended on the energy use of heavy oil instead of electricity in the oil-fired absorption refrigeration system.

4. Conclusions

This paper described two case studies: a cogeneration system of a hospital and a heat pump system installed in an aquarium that used seawater as latent heat storage. First, this work discussed the technical viability and the pattern of operation suitable for a cogeneration system that supplied energy to the Shimane University Hospital. The analysis started with the energy consumption data available for the hospital; no technical obstacles were identified. The typical patterns for operational units of the cogeneration system were decided by the hourly energy demands during several seasons throughout the year. The average ratio between the electrical and thermal load in the hospital was suitable for the operation of a cogeneration system. A case study performed for a non-optimized cogeneration system predicted large potential for energy savings and CO_2 reduction. These will be precisely analyzed in future study.

The second case study examined a seawater-source heat pump system installed in a newly built aquarium in Shimane Prefecture, Japan, which provided simultaneous

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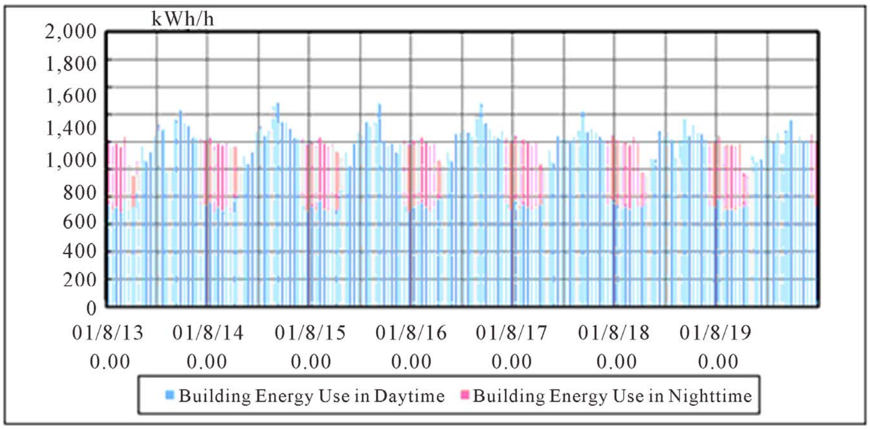

Figure 12. Hourly energy consumption of the building during the summer.

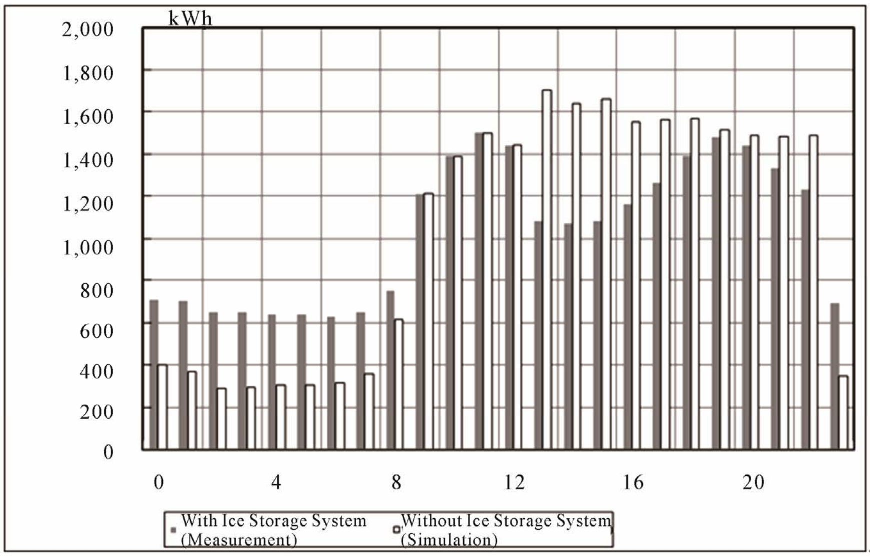

Figure 13. Shift of peak loads.

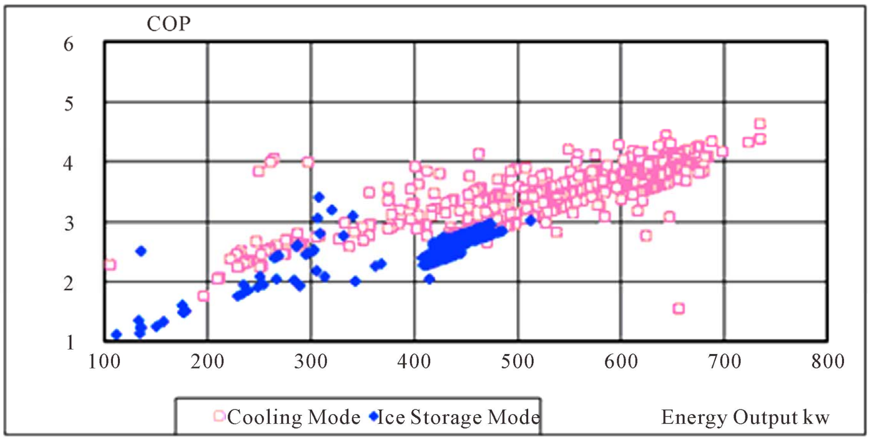

Figure 14. The COP of WSHP001.

heating and cooling. A COP of the WSHP001 system at running conditions was 3.4 for cooling and 2.8 for ice storage. By operating the refrigeration equipment during off-peak hours to recharge the ice storage and by discharging the storage during on-peak hours, a significant fraction of the on-peak electrical demand and energy

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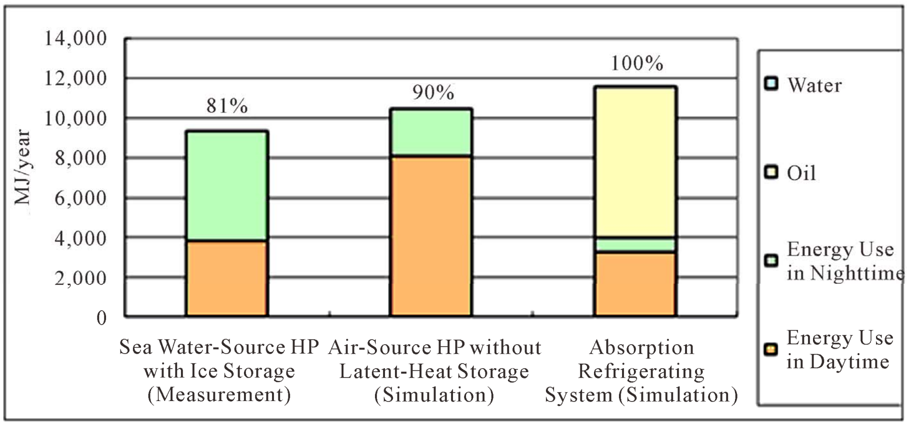

Figure 15. Reduction of energy consumption of WSHP001 and WSHP002.

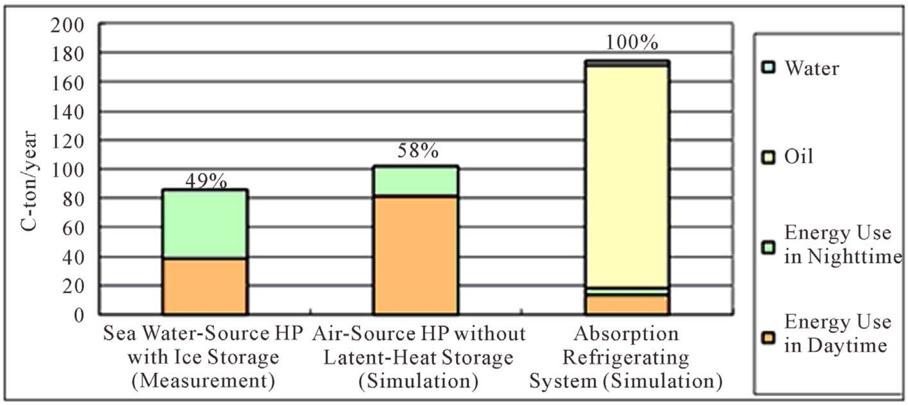

Figure 16. Reduction of CO_2 emissions of WSHP001 and WSHP002.

consumption were shifted to off-peak periods. Then, this case study was compared to two other assumed systems in which heating and cooling was supplied by a conventional air-source heat pump and a conventional oil-fired refrigerant. The energy consumption of the seawater-source heat pump for heating and cooling was 19% lower than the energy consumption of the oil-fired absorption refrigerating system. In addition, the CO_2 emissions for heating and cooling were favorably compared because the emissions of heat pump system were two times less than those for the oil-fired system.

5. Acknowledgements

The author gratefully acknowledges the contributions of the staff of the Shimane University Hospital. The concept of a specially designed seawater-source heat pump with ice-storage system was formerly introduced by The Chugoku Electric Power Co., Inc. I want to thank Mr. M. Koyama and Mr. T. Kuriyama of Nikken Sekkei Ltd. for their guidance in planning the present study. I also want to thank the staff of The Aquarium (AQUAS) in Shimane Prefecture for assisting with the project. The work was sponsored by The Chugoku Electric Power Co., Inc.

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Nomenclature

AWSHP003: seawater- and air-source heat pump 003
C: generated electricity, heating, and cooling energy by a cogeneration system
COP: coefficient of performance
CT: cooling tower
h, hr: hour
HX: heat exchanger
IS: ice-storage tank
P: pump
PU: power unit
RT: ton of refrigeration
t: ton
T: total energy consumption of conventional system
WSHP001: seawater-source heat pump 001
WSHP002: seawater-source heat pump 002
X: total amount of CO_2 from a conventional system
Y: amount of CO_2 from a cogeneration system

Subscripts

ac: air conditioning
b: brine
cf: cooling for fish tank
cw: cooling water
hf: heating for fish tank
hw: heating water
sw: seawater
ts: thermal energy storage
w: cooling and heating water

Appendix

The results in **Table 1** are as follows. The electricity provided by the public utility is the primary energy, and it is included in the analysis to accommodate its large consumption. It will be analyzed separately in future study.
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 cogeneration system generator = 0.41

$$\begin{aligned}
T &= \text{Electricity} + \text{Heavy Oil} + \text{Natural Gas} \\
&= 17,274,380(\text{kWh}) + 1,592,684(\text{L}) + 84,408(\text{m}^3) \\
&= 169,807,155(\text{MJ}) + 62,273,944(\text{MJ}) + 3,891,209(\text{MJ}) \\
&= 235,972,309(\text{MJ})
\end{aligned}$$

$$\begin{aligned}
C &= \text{Electricity} + \text{Natural Gas} \\
&= 11,382,420(\text{kWh}) + 2,060,504(\text{m}^3) \\
&= 111,889,189(\text{MJ}) + 94,989,234(\text{MJ}) \\
&= 206,878,423(\text{MJ})
\end{aligned}$$

$$\therefore \frac{T-C}{T} \times 100(\%) = \frac{235,972,309 - 206,878,423}{235,972,309} \times 100(\%) = 12.3(\%)$$