ECONOMIC AND ENVIRONMENTAL EVALUATION OF CO_2 HEAT PUMP SYSTEMS TO SUPPLY HOT WATER FOR A HOSPITAL

Shu YOSHIDA, Energy Use Research and Development Center,
The Kansai Electric Power Co., Inc., Osaka, Japan
Keisuke HOSHINO, Graduate Student, Graduate School of Fundamental Science and Engineering, Waseda University, Tokyo, Japan
Koichi ITO, Yoshiharu AMANO and Takumi HASHIZUME, Professors,
Research Institute for Science and Engineering, Waseda University, Tokyo, Japan

Abstract: An electrically driven heat pump using CO_2 as the refrigerant is developed to supply hot water with a high coefficient of performance [COP] for use in buildings such as hospitals, hotels, and so on. In addition, these COP values of conventional heat pumps which use alternative chlorofluorocarbon gases have also risen step by step in recent years.

This study compares several alternative heat pump and hot water tank systems as well as a gas-fired boiler system from economic, energy saving and environmental points of view based on a mathematical optimization method. A hospital is taken as the objective of this study, and the energy demand for hot water supply is estimated hourly and monthly through one year. As there are alternative modes for the system's operation, a mathematical optimization method is applied at this stage for responding to changing energy demands in a timely manner. The economic evaluation of the systems is done by applying the annualized costs method.

Our results show that there exists an economically optimal combination of heat pumps and hot water tank of proper capacity. It is also seen that systems adopting heat pumps have advantages over gas systems from the economic, energy saving and environmental points of view.

Key Words: economic comparison, heat pump systems, gas system, optimal operation

1 INTRODUCTION

With the rise of living standards, the energy consumption for hot water supply has become relatively high in buildings such as hospitals, hotels, and so on. In order to raise the energy efficiency in this sector, an electrically driven heat pump (HP) which uses CO_2 as the refrigerant was developed and has recently been attracting attention in Japan because of its high coefficient of performance (COP). In addition, COP values of conventional electrically driven HPs which use alternative chlorofluorocarbon gases are also rising steadily, reflecting technology improvements in recent years. For practical applications of these HPs for hot water supply, it is very important to plan the system combined with the proper numbers of HPs and a hot water storage tank (HWT) of proper capacity to meet the energy demands.

The purpose of this study is to compare several of the alternative HP systems mentioned above together with a gas-fired boiler system from the economic, energy saving and environmental points of view. A hospital with a total floor area of 20,000 m^2 is taken as the object of this study, and the energy demand for hot water supply is estimated hourly and monthly throughout one year. Several alternative systems will be compared, with different combinations of numbers of HPs and HWTs with various capacities. As there are alternative modes of operation for these systems, a mathematical optimization method will be applied at this stage for adjusting the energy demand for hot water supply for each day. By applying the annualized costs method (Witte et al., 1998), the economic evaluation will compare the

annual total costs of the different systems. In addition to this economic evaluation of the alternative systems, an energy saving evaluation and an environmental evaluation will also be done briefly.

2 ALTERNATIVE HOT WATER SUPPLY SYSTEMS

Three types of hot water supply systems are compared as shown in Fig. 1.

2.1 CO_2 Heat Pump System (System A)

The first system is an electrically driven CO_2 HP with one HWT (System A) as shown in Fig. 1(a). In this system, cold water is supplied directly to the HP. This water is warmed by the HP, and the hot water is supplied to the HWT through a one-way pipe, labeled ① in Fig. 1(a). With this HP, it is possible to change the temperature of the hot water supplied by changing the operational mode, but details will be explained later. When the temperature of the hot water in the HWT falls below the setting point, due to heat loss from the tank, the hot water in the HWT is returned to the HP, warmed once again, and returned to the HWT, as shown by ② in Fig. 1(a) (temperature preserving operation). This HWT is an open type tank, and the volume of hot water stored can be varied over time. The capacity of this HWT is V m^3, but due to structural constraints with this type of tank, it isn't possible to completely fill the tank with hot water. In other words, there is dead space in this tank, and the effective storage ratio of the

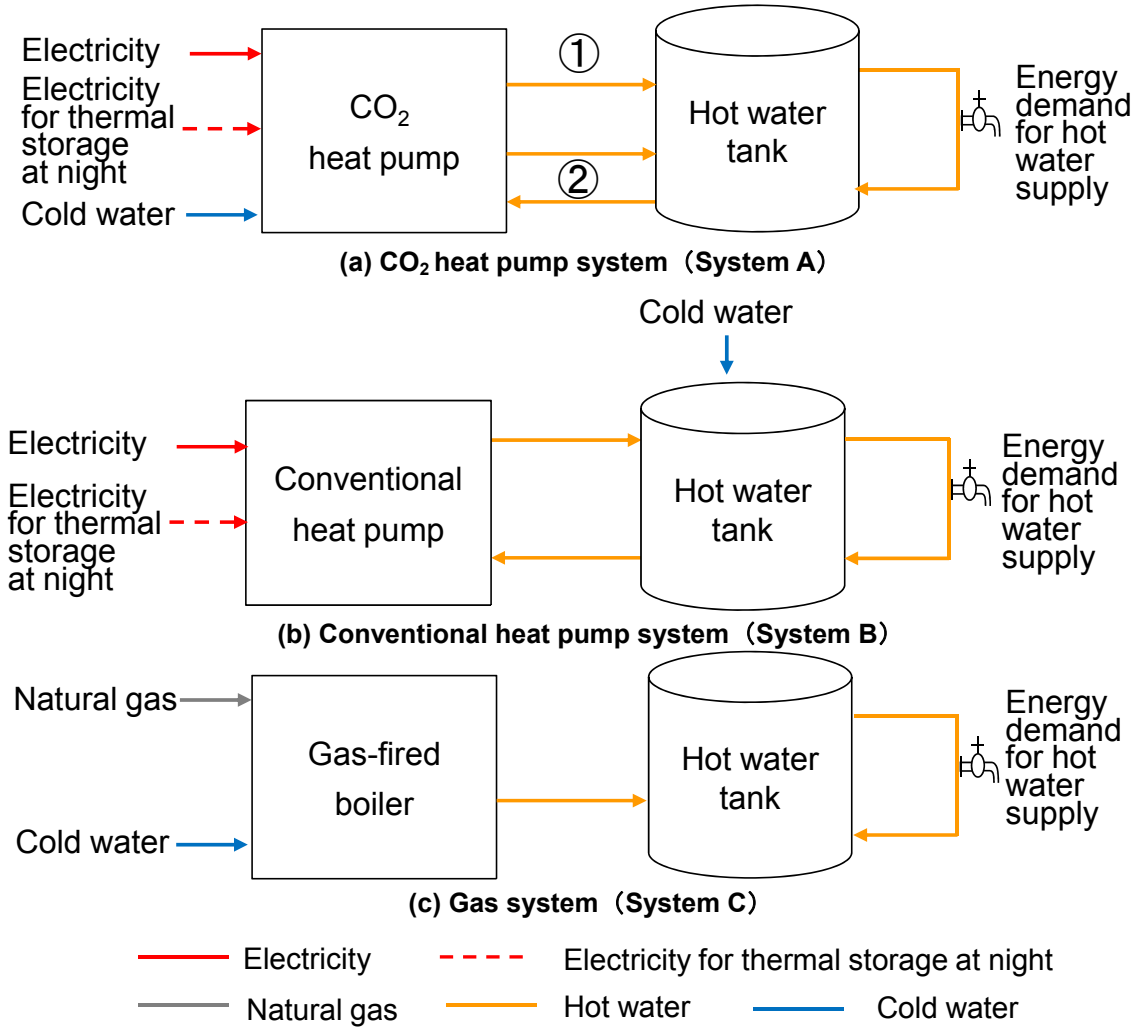


Figure 1: Alternative hot water supply systems

HWT is introduced to express this factor. In this system, there are a number, N, of HPs, all with equal capacities. This system's construction is also the same for System B.

2.2 Conventional Heat Pump System (System B)

The second system (System B) studied is a conventional electrically driven HP using an alternative chlorofluorocarbon gas as the refrigerant with a HWT as shown in Fig. 1(b). As shown in this figure, the cold water is supplied into the HWT, and is warmed by the HP through a circulatory flow between the HP and HWT. In this system, an open type HWT is assumed to be installed.

2.3 Gas Hot Water Supply System (System C)

The last alternative system (System C) uses gas-fired boilers with a HWT as shown in Fig. 1(c). In this system, the cold water is supplied to gas-fired boilers with equal capacities, and the hot water is supplied to HWT, but there is no feedback path such as there are in Systems A and B. This HWT is a closed-type tank, and the hot water storage capacity doesn't vary over time. The effective storage ratio of this HWT is taken as 100%.

3 SYSTEM EVALUATIONS BY OPTIMIZATION METHOD

3.1 Framework of Systems Evaluation

First of all, the energy required for hot water supply is estimated for the object hospital through one year. In other words, this energy demand is estimated at each 24-hour sampling period on representative days of each month as well as on the peak demand day.

Then, as alternative systems which can supply the hot water requested above, many combinations of number of HPs and capacity of HWT are investigated in this study. In the following numerical study, from a practical engineering standpoint, both the CO_2 HP and the conventional HP with proper capacities are selected, and it is assumed that there are no alternatives concerning the HP units themselves.

Next, for each candidate system, it becomes necessary to determine the system's operational policy for varying the energy demand over one year. In this place, a mathematical optimization method is applied. The details will be explained below in Section 3.2.

After determining the system's operational policy, it becomes possible to calculate the annual input energy cost for each system. Then, based on the annualized costs method, the economic evaluation of each system is performed, as explained in Section 3.3.

Lastly, by calculating the annual total amounts of primary energy consumption and CO_2 emission, the energy saving evaluation and the environmental evaluation are compared with alternative systems.

3.2 Determination of System's Operational Policy by Optimization Method

First of all, it is necessary to formulate the characteristics of each piece of equipment (i.e., HP and gas-fired boiler) included in Systems A~C by mathematical equations. In this study, all input-output relationships of each piece of equipment are approximated by line segments. By introducing 0-1 integer variables together with continuous ones, it becomes possible to formulate them adequately, but the detailed explanation is omitted here (Ducrocq et al., 1985; Ito et al., 1997). The COP values of the HPs depend on the temperatures of the ambient air, the input cold water, and the supplied hot water (T_a, T_w, and T_s, respectively). Next, the heat balance relationship of HWT is expressed as

$$\frac{Q(k+1)-Q(k)}{\Delta t} = Q^{in}(k) - Q^{out}(k) - Q^{loss}(k), \qquad (1)$$

where k is the sampling hour (k=0,1,⋯,24), Q is the amount of heat stored in the HWT, Q^{in}, Q^{out}, and Q^{loss} are the heat input into, heat output from, and heat loss from the HWT, respectively, and Δt (=1 hour) is the sampling time interval. In the heat loss Q^{loss}, the loss from pipes is also added only for the simplicity of the mathematical formulation. The system's operational policy is determined for each day by assuming that both amounts of heat stored in the HWT at the beginning and at the end of the day are equal to each others, i.e.,

$$Q(0)=Q(24)\ . \tag{2}$$

Moreover, to avoid shortages in the hot water supply caused by unexpected demand increases, the minimum volume of hot water storage in HWT ($\underline{V}$) is imposed here by

$$V(k) > \underline{V}\ (k=0,1,\cdots,24)\ . \tag{3}$$

In this place, $\underline{V}$ is converted to a heat amount by assuming that T_s=65°C and T_w=8°C, respectively. In addition to these relationships concerning the characteristics of each piece of equipment, energy balance ones are considered together with supply and demand ones, and all these ones are considered as constraints in the optimization problem.

The objective function adopted here to determine the system's operational policy is the input energy cost for each day. The unknown variables of the proposed optimization problem are those related to the operation of each piece of equipment, such as on-off status and the operational load of the HP or boiler.

As a result, the problem of determining the system's operational policy is formulated as a mixed-integer linear programming one. This problem is solved numerically using the GAMS/CPLEX solver (Brooke et al., 1998), which is a general method combining the branch and bound algorithm with the simplex one.

3.3 Economic, Energy Saving, and Environmental Evaluation of Each System

In order to evaluate each system from the long-term economic viewpoint, the annualized costs method is adopted in this paper. Namely, the annual total cost defined by

$$J = J_p + J_e + J_m \tag{4}$$

is calculated for each system, where J_p, J_e and J_m are the annual capital, the annual input energy, and the annual maintenance costs, respectively. Expressing P as the total initial equipment cost of each system, the annual capital cost J_p is calculated as

$$J_p = RP\ , \tag{5}$$

where R is the recovery factor of capital cost calculated by

$$R = \frac{r(1+r)^{\kappa}}{(1+r)^{\kappa}-1}\ . \tag{6}$$

In this equation, κ is the lifetime of the equipment and r is the interest rate, though the salvage value of each piece of equipment is simply neglected in this study.

Next, the annual input energy cost, J_e in Eq. (4), can be obtained by summing up the daily optimal costs, calculated by the optimization method explained in Section 3.2, through one year. In addition, it is assumed here that the annual maintenance cost, J_m in Eq. (4), can be calculated by summing up all maintenance costs for each piece of equipment by multiplying the unit cost of maintenance with the respective equipment capacity.

Lastly, the energy saving evaluation and the environmental evaluation are done by

calculating the annual total amounts of the primary energy consumption and the CO_2 emissions respectively, which reflect the optimal operational policy of each system, as explained in Section 3.2.

4 NUMERICAL ANALYSYS FOR A HOSPITAL

4.1 Energy Demand for Hot Water Supply

For a hospital with total floor area of 20,000 m^2, the energy demand for hot water supply is estimated as shown in Fig. 2 based on the actual measured data, though it is simplified as the demand for each 24-hour sampling time on representative days of each month together with the peak demand day in February, respectively.

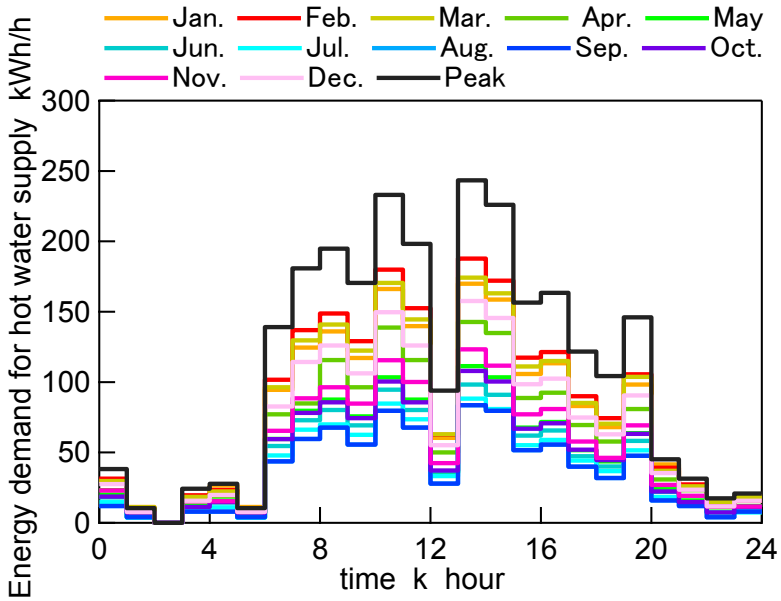


Figure 2: Energy demand for hot water supply

4.2 Performance Characteristics of Heat Pumps

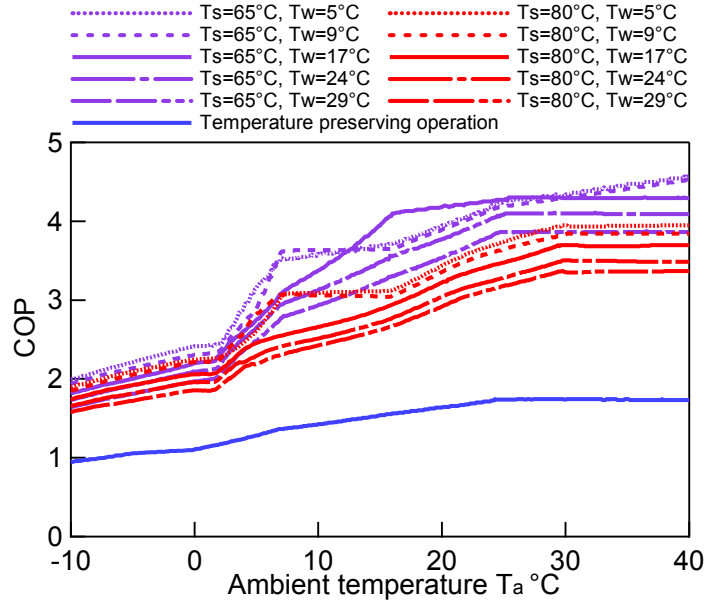
The performance characteristics of the CO_2 HP and the conventional HP are shown in Figs. 3 and 4, respectively. In Fig. 3(a), the value of COP is shown, which depends on the temperatures T_a, T_w, and T_s. In this figure, the value of COP for the temperature preserving operational mode is also shown, where it is assumed that it depends only on T_a, and doesn't depend on either T_w or T_s. The reason for this is that the warmed water circulates only between the CO_2 HP and the HWT as shown in Fig. 1(a) ②, and the temperatures of the water input to the HP and output from the HP are nearly equal to each other. Reflecting this fact, the COP value at this operational mode is very low as shown in Fig. 3(a).

Figure 3(b) shows the value of the heat output of hot water supplied from the CO_2 HP together with the electricity input consumed by the HP. These values also depend on T_a, T_w, and T_s, excluding the temperature preserving operational mode.

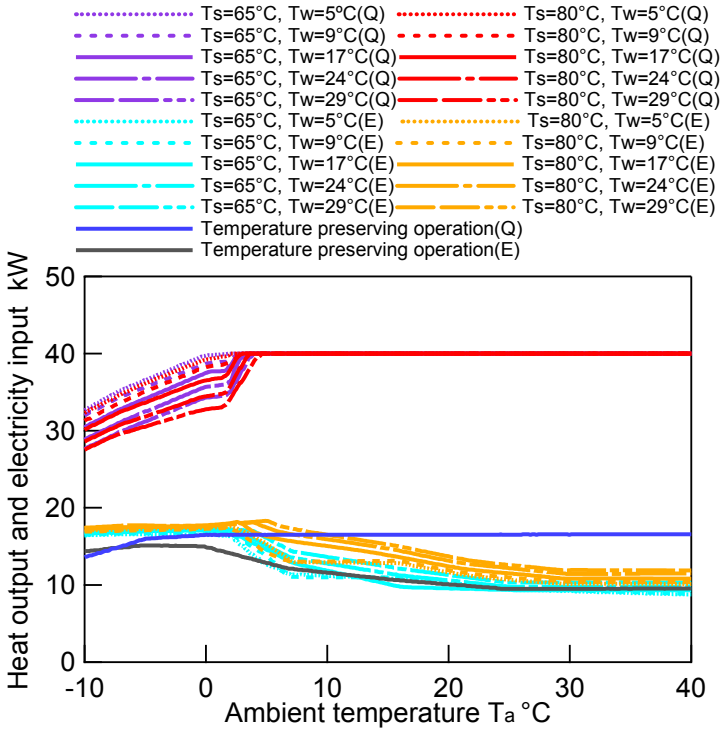
As explained in Section 2.1, it is possible to change the temperature, T_s, of the hot water supplied by the CO_2 HP by changing its operational mode; i.e., T_s=65°C or 80°C. In addition to the temperature preserving operational mode, the above temperature, T_s, is determined by the method proposed in Section 3.2.

Next, the performance characteristics of the conventional HP are shown in Fig. 4: (a) shows

the COP value, and (b) shows the value of the heat output together with the electricity input of the HP selected here. These values depend only on T_a, and not on either T_w or T_s because of its circulatory warming operation, as shown in Fig. 1(b). In System B, there are no alternative operational modes such as those in System A.

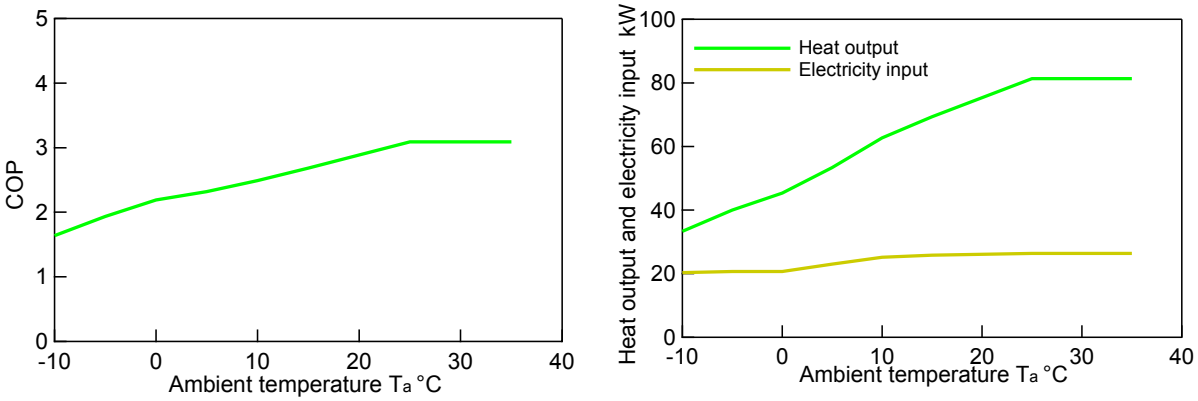


(a) COP



(b) Heat output and electricity input

Figure 3: Characteristics of CO_2 HP



(a) COP **(b) Heat output and electricity input**

Figure 4: Characteristics of conventional HP

4.3 Miscellaneous Input Data and Energy Rates

In Table 1, other miscellaneous input data are shown related to the capacities, thermal characteristics, and costs of the equipment included in Systems A~C, together with those necessary for the energy saving and the environmental evaluation processes. However, detailed data related to T_w and T_a are omitted here.

Table 2 shows the rates of purchased electricity and natural gas applied in the Kansai area, Japan.

Lastly, in the economical evaluation of each system, the lifetime of all equipment, κ, is set as 15 years, and the interest rate is set as r=3 %/year; i.e., the recovery factor of capital cost is R=0.08377.

Table 1: Miscellaneous input data

Type of system	System A	System B	System C
Equipment capacity of HP and boiler	40.0 kW/unit	59.5 kW/unit	291.0 kW/unit
Number of HPs and boilers (N)	4~6	4~6	2
Capacity of HWT (V)	2~50 m^3		10 m^3
Minimum volume of hot water storage required ($\underline{V}$)	$\underline{V}(0)$=0 m^3 , $\underline{V}(1)$=3.66 m^3, $\underline{V}(2)$=7.32 m^3		—
Thermal efficiency of boiler	—		0.823
Ratio of heat loss from HWT	0.38 %/h		
Ratio of heat loss from pipes	20.0 %/day		
Effective storage ratio of HWT	75 %		100 %
Equipment costs of HP and boiler	4,190×10^3 yen/unit		2,163×10^3 yen/unit
Equipment cost of HWT	290.0×10^3 yen/m^3 + 1,226×10^3 yen		957.6 ×10^3 yen/m^3
Unit cost of maintenance	1,422 yen/kW		706 yen/kW
Primary energy conversion unit	9.76 MJ/kWh		45.0 MJ/Nm^3
CO_2 emission unit	0.299 kg-CO_2/kWh		2.29 kg-CO_2/Nm^3

Table2: Rates of purchased electricity and natural gas

Utility	Energy charge	Demand charge	Customer charge
Electricity	(Jul.~Sep.) 11.23 yen/kWh (Other months) 10.21 yen/kWh	1,685.25 yen/(kWh・month)	—
Electricity for thermal storage at night	(22:00~8:00) 5.94 yen /kWh	—	—
Natural gas	(May~Dec.) 94.54 yen/m^3 (Other months) 83.28 yen/m^3	1,077.30 yen /(m^3/h・month)	22,730 yen/month

5 NUMERICAL RESULTS AND DISCUSSIONS

5.1 Optimal Systems of Each Type by Changing Total Number of Equipment

In Fig. 5 and Table 3, the optimal annual costs of the alternative systems are shown for different values of the total number, N, of HPs and boilers, respectively. In Table 3, the amounts of annual primary energy consumption and annual CO_2 emissions are also shown for the respective systems.

In Fig. 5, for example, the abbreviation System-A-N(4)-V(10) denotes System A with the total number of pieces of equipment equal to 4, and the capacity of the HWT (V) equal to 10 m^3. As shown in these results, the optimal system which minimizes the annual total cost is System-A-N(4)-V(10), and the worst one is System-C-N(2)-V(10). From an economic viewpoint, System A is a little superior to System B, but the difference is not so large. Increasing the number of HPs increases the annual total cost progressively for both Systems A and B. In Fig. 6, the optimal operation of Systems A and B in January are shown for each optimal system shown in Fig. 5. In addition, for these systems, changes of both COP and unit cost of heat for each HP are shown in Fig. 7. As shown in Fig. 7(b), the unit cost of System B is relatively high at daytime compared with the value at nighttime because of the rates of purchased electricity shown in Table 2. Therefore, the conventional HP operates fully at nighttime, and the hot water

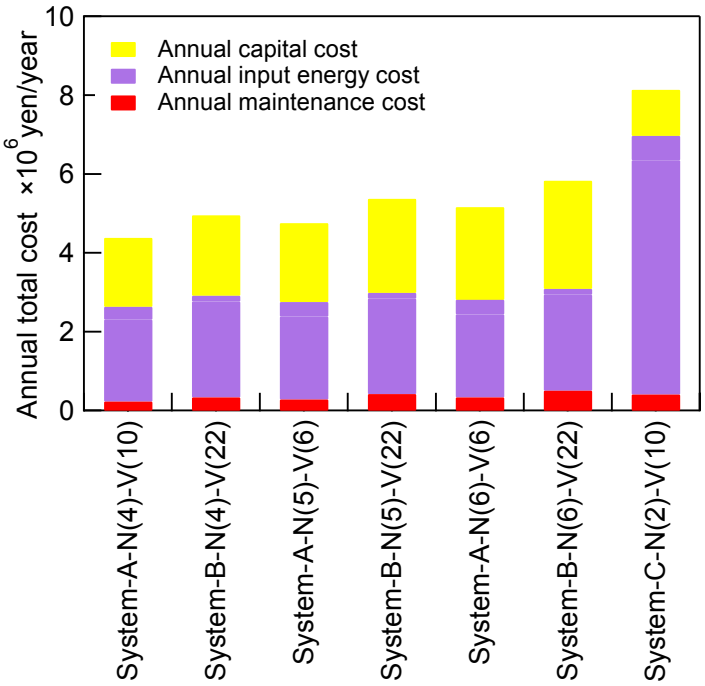


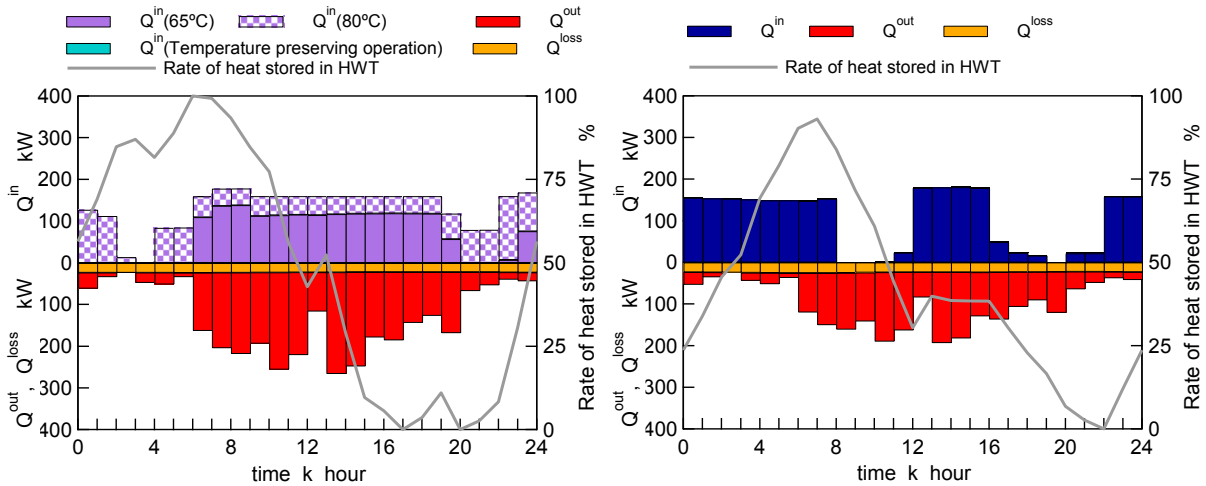
Figure 5: Optimal annual total cost of each system

produced is stored in the HWT for the useage during the daytime as shown in Fig. 6(b). On the other hand, the COP value of the CO_2 HP rises in the daytime due to the rise of ambient temperature as shown in Fig. 7(a). As a result, the unit cost of heat becomes relatively low as shown in Fig. 7(b), and the CO_2 HP of System A operates in the daytime as shown in Fig. 6(a). It is also notable that in Fig. 6(a), the HP of System A is mainly operated in the T_s=80°C mode to cover the storage capacity of the HWT.

In Table 3, the annual primary energy consumption is shown for each optimal system. From the energy saving viewpoint, System A is the best, because the COP value of the CO_2 HP is very high, as shown in Fig. 7(a). Though the energy saving ratio of System B is better than that of System C, it is not so high compared with that of System A. Next, as shown in Table 3, the amount of annual CO_2 emission of System C is very high compared with those of Systems A and B. The CO_2 emission value of System A is lower than that of System B, and these values decrease for both systems with the rise in the number of HPs. The reason for this is as follows: if there are more HPs within the system, it becomes possible to select a better combination for the system's operational policy, and thus decrease the amount of CO_2 emission.

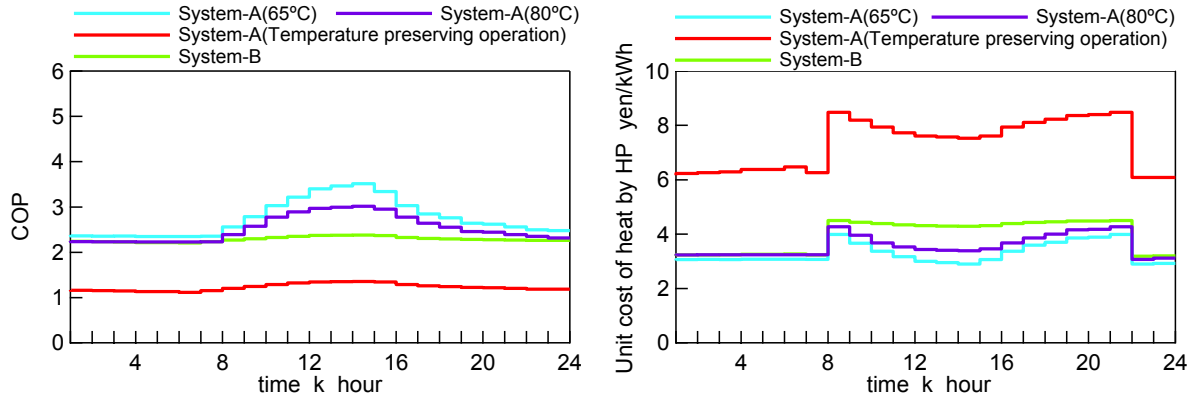
Table 3: Detailed results of alternative optimal systems

System		A	B	A	B	A	B	C
Numbers of HP and boiler (N)		4	4	5	5	6	6	2
Capacity of HWT (V)	m^3	10.0	22.0	6.0	22.0	6.0	22.0	10.0
Annual total cost	$\times 10^6$ yen/year	4.385	4.956	4.758	5.376	5.165	5.809	7.483
Annual capital cost	$\times 10^6$ yen/year	1.750	2.041	2.003	2.392	2.354	2.743	1.165
Annual input energy cost	$\times 10^6$ yen/year	2.408	2.576	2.470	2.561	2.469	2.558	5.908
Annual maintenance cost	$\times 10^6$ yen/year	0.228	0.338	0.284	0.423	0.341	0.508	0.411
Annual primary energy consumption	$\times 10^6$ MWh/year	2.292	2.928	2.269	2.928	2.269	2.924	3.031
Annual CO_2 emission	t-CO_2/year	70.22	89.69	69.51	89.70	69.50	89.59	154.24



(a) System-A-N(4)-V(10) (Jan.) **(b) System-B-N(4)-V(22) (Jan.)**

Figure 6: Optimal operation of Systems A and B

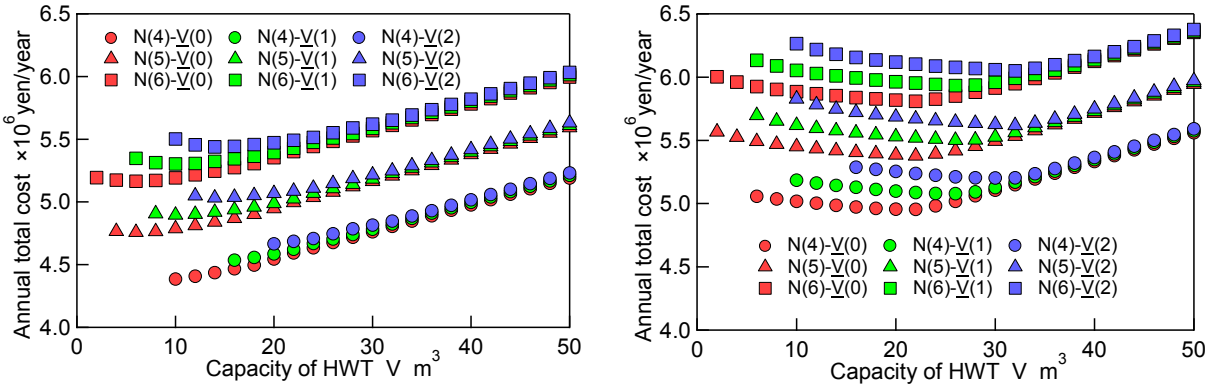


(a) COP (Jan.) **(b) Unit cost of heat by HP(Jan.)**

Figure 7: COP and unit cost of heat by HP

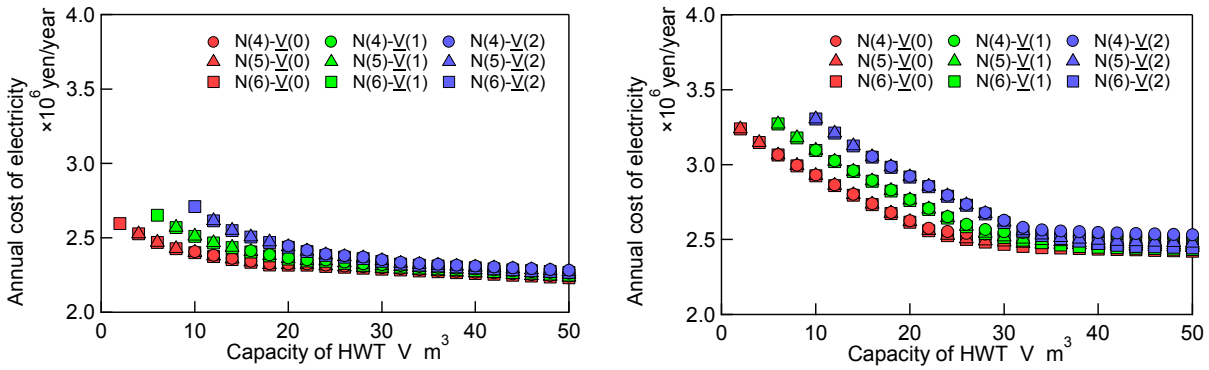
5.2 Effect of Capacity of HWT and Minimum Volume of Hot Water Storage

In this section, the effect on the economy of Systems A and B of the capacity of the HWT, V, is studied together with the minimum volume of hot water in the HWT, $\underline{V}$, from Eq. (3). Figure 8 illustrates the effect of changing V on the annual total cost of each system. In this figure, the result of the sensitivity analysis of $\underline{V}$ is also shown for these systems. It is easy to understand that the value of the annual total cost increases with the rise in $\underline{V}$, because the ability of the HWT decreases and the thermal insulation loss increases. It is also notable that, in some cases, the annual total cost decreases and then increases with the increase of V, particularly in System B. To understand these results, the annual cost of electricity is shown in Fig. 9 for each system. The value of this cost decreases with the increase of V, because it becomes possible to utilize cheaper electricity in the nighttime. To check this result, Fig. 10 shows the annual amount of electricity consumption separated into nighttime and daytime values. On the other hand, the annual capital cost of each system increases with the rise of V. As a result, the annual total cost shows the characteristics shown in Fig. 8.



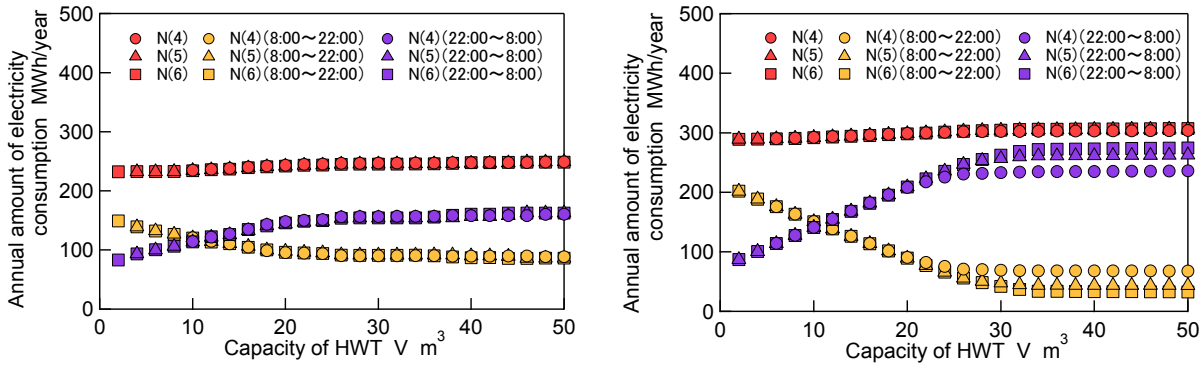
(a) System A **(b) System B**

Figure 8: Anuual total cost by changing the capacity of HWT



(a) System A **(b) System B**

Figure 9: Annual cost of electricity



(a) System-A-V(0) **(b) System-B-V(0)**

Figure 10: Annual amount of electricity consumption

6 CONCLUSIONS

In this paper, CO_2 and conventional heat pumps with hot water storage tanks to supply hot water were compared, together with a gas-fired boiler system, from economic, energy saving and environmental points of view. A mathematical optimization method was applied to determine the system's operational policy, and the annualized costs method was adopted for the economic evaluation of the systems.

A hospital building with a total floor area of 20,000 m^2 was taken as the objective of the numerical study, and the energy demand for hot water supply was estimated over a one year period. Based on the mathematical optimization method mentioned above, many alternative systems were compared by changing the total number of heat pumps, the capacity of the hot water tanks, and the minimum volume of hot water storage required.

The main results obtained are as follows:

(a) From the economic point of view, the CO_2 heat pump system is superior to both the conventional heat pump and gas-fired boiler systems. However, there is only a small difference betweeen the CO_2 and the conventional heat pump systems.

(b) The economically optimal total number of heat pumps is 4 for both the CO_2 and the conventional heat pump systems. There is an optimal capacity of hot water storage tank for each system.

(c) Increasing the total number of heat pumps worsens the economy of the system, but improves both the energy saving and the environmental properties.

(d) When the minimum volume of hot water storage required becomes large, the economy

of each system becomes worse, because the ability of the hot water storage tank decreases and the thermal insulation loss increases.

(e) From the energy saving and the environmental points of view, the ranking of the systems is the same as that explained in (a), but the difference between the CO_2 and the conventinal heat pump systems is somewhat larger.

7 ACKNOWLEDGEMENTS

The authors would like to thank both the Heat Pump and Thermal Storage Technology Center of Japan, and the Research Group for Total Energy Systems Analysis, The Society of Electric Enhancement in Buildings, for their support and cooperation.

8 REFERENCES

Brooke, A., et al., 1998, “GAMS Release 2.50. – A User’s Guide”, GAMS Development Corp.

Witte L.C., Schmidt P.S. and Brown P.R., 1998, “Industrial Energy Management and Utilization”, Hemisphere Publishing, pp. 68-69.

Ito K., Shiba T. and Yokoyama R., 1997, “Optimal capacity planning of thermal storage tank installed into energy supply systems”, *Int. J. Global Energy Issues*, Vol. 9, No. 3, pp. 162-170.

Ducrocq, J.C., 1985, ”Optimal energy management in a complex system with mixed-integer programming”, *RAIRO Automatique-Produtique Informatique Industrielle*, Vol.19, pp. 403-413.