DEVELOPMENT OF MULTI-SOURCE AND MULTI-USE HEAT PUMP SYSTEM

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Abstract: A heat pump system is expected to reduce more energy than traditional systems. However, it is difficult for a conventional heat pump system to reduce further energy. Therefore, to achieve higher efficiency than conventional systems, Multi-Source and Multi-Use Heat Pump (MMHP) system is proposed.
MMHP system connects multiple heat sources such as solar heat, ground source and air source and multiple heat uses such as cooling, heating, and hot water supply with the water loop. Each heat use side can utilize heat efficiently. In addition, MMHP system has a characteristic of a daily geothermal storage which keeps efficiency and reduces the initial cost to embed heat exchangers.
In this paper, MMHP system was simulated compared with the conventional heat pump system. The results show that the power consumption of MMHP system was reduced by maximum 44 % in summer and 39 % in winter.

Key Words: heat pumps, ground source, multi source, multi use

1 INTRODUCTION

Heat pump systems can achieve a higher efficiency and save more energy than traditional systems and they are introduced to the fields requiring much energy such as cooling, heating and hot water. In conventional heat pump systems, outdoor air is mainly used as the heat source and the heat use is connected to the heat source individually. In this system further energy reduction is too difficult in the years ahead, because the single system is limited to be improved. Then, to achieve high efficiency system, the system using multiple sources and multiple uses is expected.
In Japan, the interest for ground source heat pump systems in addition to air source heat pump system has increased during the last years. However, ground source heat pump systems are spread slowly due to some barriers; firstly the drilling cost is expensive with the complex ground condition in Japan; secondly the efficiency of heat pump systems gradually becomes less efficient with time and ground source will be not available unless the heat extraction and injection from the ground is balanced as suggested by Li X et al. (2006).
On the other hand, in cold regions like Europe, ground source heat pump systems are widely spread, and some studies show the system using solar as the heat source with ground source connected to heating and how water supply in order to operate with high efficiency (e.g. Kjellsson E et al. (2006)).But this system don't focus on the heat source temperature which is important for a heat pump system and only few studies show that a heat pump system is developed in terms of the heat source temperature. Furthermore, without considering the heat source temperature, it is very difficult to reduce more energy in the future.

Therefore, in this paper, to reduce more energy, Multi-Source and Multi-Use heat pump (MMHP) system was proposed. In this system, multiple heat sources such as solar heat, ground source, and air source are utilized and multiple heat uses such as cooling, heating, domestic hot water supply, freezing are used in light of the heat source temperature. They are connected to each other with the water loop, so that each use side can utilize heat efficiently. The geothermal characteristic which enables heat source temperature stable with daily cycle was simulated and the effect of MMHP system was showed with the feasibility study.

2 SYSTEM SUMMARY

2.1 The concept of MMHP

MMHP developed in this paper is shown in Figure 1. This system includes various equipments as the heat use, such as horizontal ground heat exchangers using ground heat, outside equipments using air and solar, and water circulation loops connecting to each other. The circulation water temperature is stably kept by all heat source equipments which can keep heat balance into the ground and surrounding ground temperatures, so this system needs no antifreeze.
For example in houses, cooling, heating, hot water supply, and freezing are used as the heat use, and heat is used efficiently because each use has the distributed heat pump using circulation water and heat is recollected with the water loops if the exhaust heat exists. Additionally as for hot water supply, it is possible to use instantaneous water heater without a storage tank.

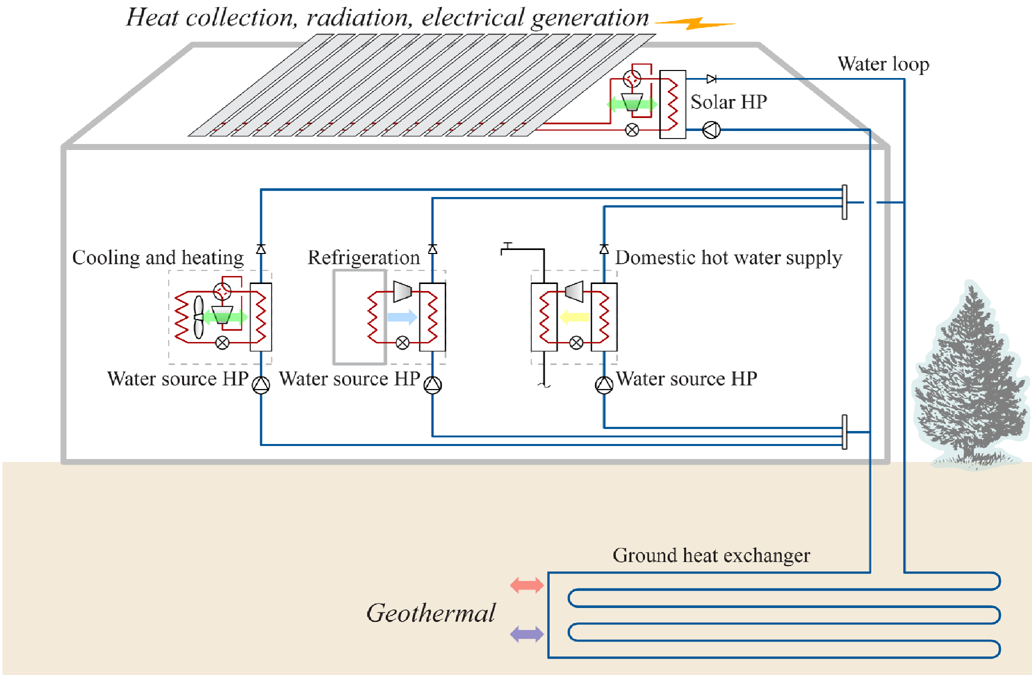
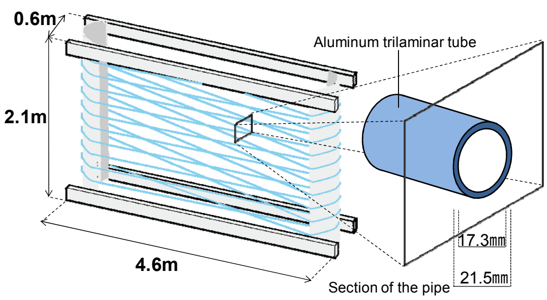


Figure 1. Concept of MMHP system

2.2 Ground source heat pump system

In the conventional ground source heat pump (GSHP) system with the seasonal thermal storage, the initial cost is expensive because the heat exchangers are embedded deeply and need large area in order not to be thermally affected each other. On the other hand, in MMHP system, the feature is the daily thermal storage with a high dense horizontal ground heat exchanger which enables the reduction of the initial cost.
For example, in winter, the heat in heating is extracted from the ground, and the ground temperature is tried to be restored by the surrounding ground. However, as a consequence the ground temperature and the efficiency of the heat pump decreases gradually. Then in MMHP system, ground temperature is daily restored to its original value with the artificial heat supply using outside equipments which is called active recovery (AR) to replenish with natural recovery. In this case, it is important to avoid injecting the heat to the ground excessively. Consequently ground temperature and the efficiency of heat pump keep stable every day.
Figure 2 shows the new ground heat exchanger. In MMHP system, a high dense horizontal ground heat exchanger was developed. Heat exchangers need less soil volume than usual due to the daily thermal storage. If this heat exchanger is buried at shallow depth between 2 m and 4 m with the general-purpose machine such as a backhoe as shown Figure 3, the drilling cost which becomes a barrier in Japan will be much cheaper than GSHP system.



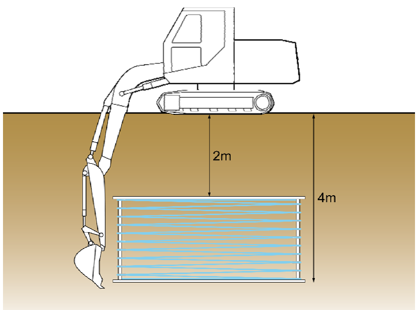


Figure 2. A high dense horizontal ground heat exchanger

Figure 3. Drilling image

2.3 Outside equipments for AR

If air source heat pump is used for AR, it is expected that it is downsized and the cost will be cheap. However, it is difficult to operate it efficiently in MMHP system. So the Photovoltaic Sol-Air heat pump (PVSAHP) as shown in Figures 4 and 5 was developed. In PVSAHP, solar energy is utilized heat and electric generation on the surface of the panel and air source is utilized with the fins attached on the back of the panel.
For example, in summer, PVSAHP cools the circulation water with nocturnal radiation at night, and the ground gets cooled and recovered via circulation water.

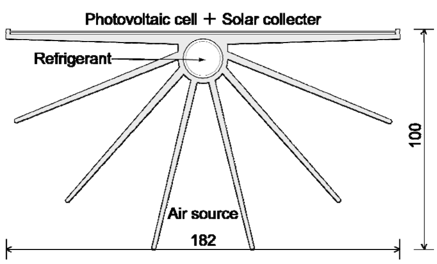


Figure 4. Photovoltaic Sol-Air heat pump (PVSAHP)

Figure 5 The section of PVSAHP panel

3 THE CHARACTERISTIC ANALYSIS OF GEOTHRMAL IN MMHP

A numerical simulation was conducted to predict the change of ground and circulation water temperatures in cooling, heating and AR mode of MMHP system with daily thermal storage. In this analysis, a numerical model which was developed by Nam Y et al. (2008) was used.

3.1 Analysis model and conditions

In the model shown in Figure 6, a middle layer of ten layers making up the heat exchanger unit was extracted and two 4000 mm coil pipes were analyzed in 10000 mm × 8000 mm × 200 mm area.
Table 1 shows the conditions of the calculation. The initial ground temperature was provided with 16^{o}C which is average ground temperature in Tokyo. The heat exchange capability is 1.5kW per one unit.
In this analysis, the simulation period was set to one week based on the MMHP system with daily thermal storage compared to the conventional ground source heat pump system with seasonal thermal storage. The temperature of circulation water was calculated in cooling and heating, and AR mode. The amount of heat into the ground with AR was one third of that in cooling and heating mode.

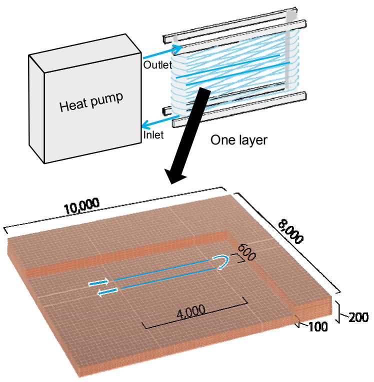


Figure 6. Analysis model

Table 1. Calculation conditions

Initial temperature (°C)		16	
Heat exchange capability (kW)		1.5	
Mesh conditions		Soil	Coil
	Hydraulic conductivity (10^{-4}m/s)	3.0	0
	Porosity (-)	0.3	0
	Heat capacity (10^{6}J/m^{3} ·K)	2.70	2.38
	Heat conductivity (w/m ·K)	2.40	0.41

Analysis results

Figure 7 shows the daily average temperature of the circulation water in MMHP system and GSHP system in heating and AR mode. Without AR, the inlet water temperature in GSHP system notably decreased day by day. On the other hand, with AR, the inlet water temperature difference in MMHP keeps stable within 1 ^{o}C.
The daily average temperature of the circulation water in MMHP in cooling and AR mode is presented in Figure 8. As in the case of heating, with AR, the temperature increased very little.

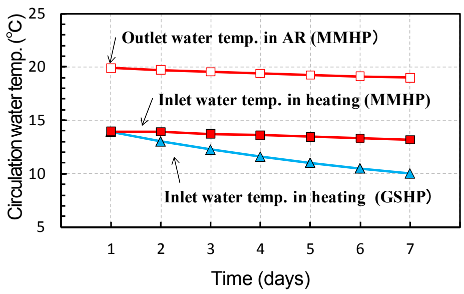


Figure 7. Temperature in heating and AR mode

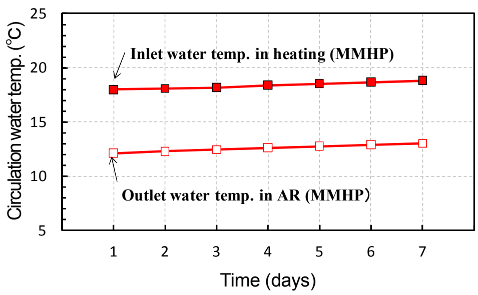


Figure 8. Temperature in cooling and AR mode

4 FEASIBILITY STUDY

The effect of MMHP system was simulated compared to the conventional heat pump (CVHP) system on Japanese house. Power consumption and electric power charge of MMHP system and CHP system were analyzed.

4.1 Analysis model

The modeled Japanese house was in Tokyo and the total floor area was 300 m^2. A family of six lives in the house.
Figure 9 shows the detail of CVHP and MMHP. In CVHP system, cooling, heating and domestic hot water system (DHW) use air source heat pumps, and DHW has a storage tank. On the other hand, in MMHP system, cooling, heating and DHW use ground source heat pumps, and air source heat pump system or PVSAHP with 10 m^2 panels as AR equipments were used to recovery the ground temperature. All heat pump systems and the ground heat exchanger were connected to each other with the water loop, so the heat was used efficiently.

3 cases were simulated. In MMHP system, air source heat pump was used as an AR equipment without PVSAHP (case 1). SAHP was used as an AR equipment without PV (case 2). And with PV, PVSAHP was used as an AR equipment (case 3).
The typical summer and winter days were tested in this feasibility study.

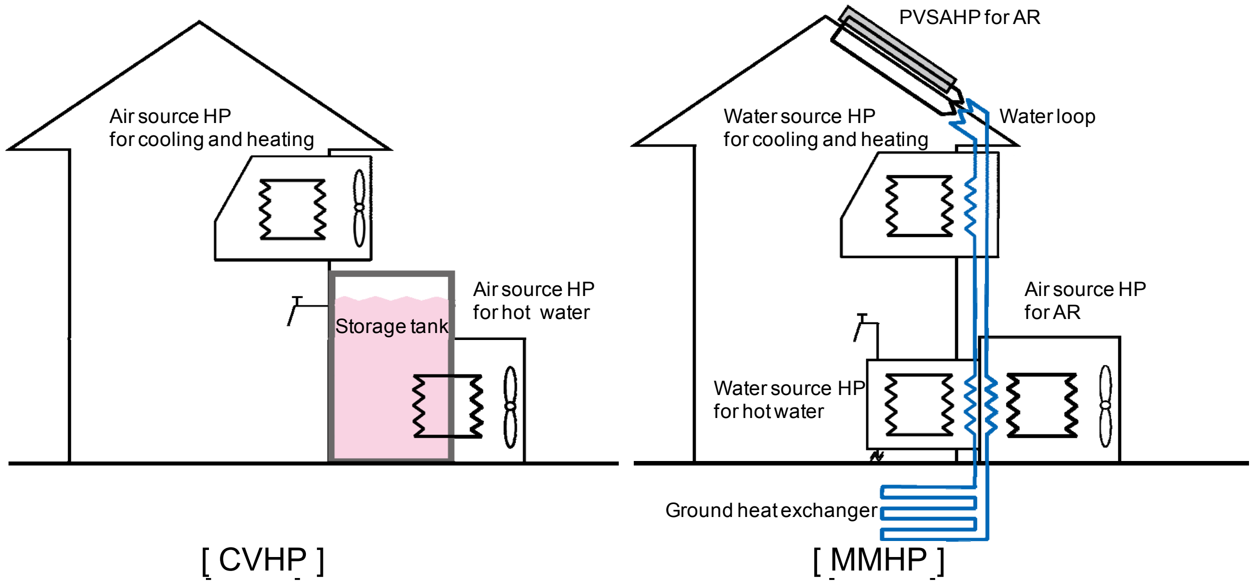


Figure 9. System diagram of the conventional heat pump (CHP) system and MMHP system

4.2 Cooling, heating, hot water and AR loads

The cooling and heating loads have been obtained in the TRNSYS modeling environment developed by Klein et al. (2007). The hot water load was calculated based on Japanese typical style.
The loads of cooling, heating, hot water and AR (case 1) were shown in Figures 10~13. In MMHP system, the AR was operated late at night in summer, because outdoor temperature was cooler than daytime (case1) and additionally, nocturnal radiation can be utilized (case 2 and 3). In winter, the AR was operated at daytime, since the outdoor temperature is warm (case1) and additionally, solar energy was utilized (case2 and 3). On the other hand, in THP system, DHW was operated late at night for load leveling.

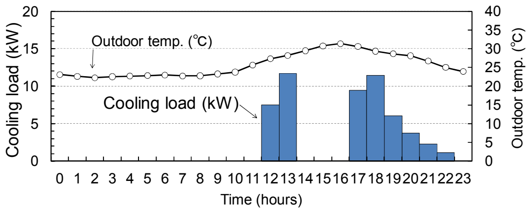


Figure 10. Cooling load in summer

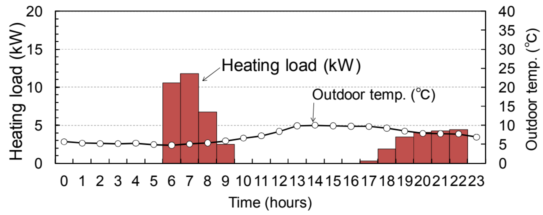


Figure 11. Heating load in winter

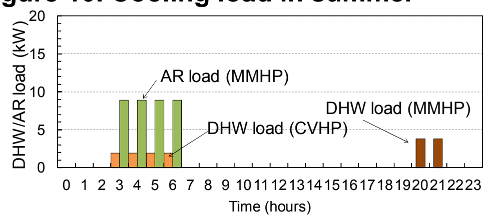


Figure 12. DHW and AR loads in summer

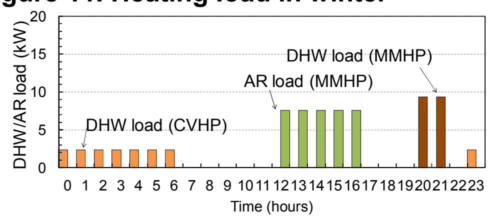


Figure 13. DHW and AR loads in winter

4.3 Setting coefficient of performance (COP)

Each COP was calculated based on Carnot's cycle with relation given by

$$COP = \alpha \frac{T_1}{T_1 - T_2} \qquad (1)$$

where α is the rate of Carnot's cycle and 0.6 in this paper, T_1 and T_2 are condensing or evaporating temperature.
The calculation conditions about condensing and evaporating temperatures (case 1) were shown in Table 2. Heat source temperatures of circulation water were set from the results of the numerical simulation. Each COP in MMHP was higher than that in CVHP.

Table 2. Calculation conditions

Operation	Description	Summer		Winter	
		MMHP	CVHP	MMHP	CVHP
Cooling or heating	Heat source temp. (℃)	20	28	12	7.2
	Condensing temp. (℃)	27	43	42.5	42.5
	Evaporating temp. (℃)	5.5	5.5	5.0	-11.3
	COP (-)	7.8	3.7	5.0	3.5
DHW	Heat source temp. (℃)	20	21.2	12	5.4
	Condensing temp. (℃)	37.8	50.3	29.2	40.7
	Evaporating temp. (℃)	12.5	2.7	5.0	-13.1
	COP (-)	7.4	4.1	7.5	3.5
AR	Heat source temp. (℃)	21.2	—	9.6	—
	Condensing temp. (℃)	43.7	—	21	—
	Evaporating temp. (℃)	11.0	—	-8.9	—
	COP (-)	5.2	—	5.9	—

4.4 Results

Power consumptions and electric power charges in MMHP system and CVHP system were calculated.
Figures 14 and 15 show the summer results. In Figure 14 a), the power consumptions of cooling and DHW were reduced by about 50 % compared to CVHP system. However, the power consumption of AR was 7.1 kWh. Consequently, the total reduction of power consumptions in MMHP system was 6 % (case1). Therefore, using SAHP system which is operated more efficiently than air source heat pump as AR, the power consumption of AR were reduced by 30 % compared to case1. The total power consumptions were reduced by 21 % (case2) in Figure 14 b). Furthermore, with PVSAHP, the total power consumptions in MMHP system were reduced by 44 % compared to CVHP system in Figure 14 c). As for electric power charges, without PV, they were reduced by about 30 % (case1 and 2), and using PV, they were reduced by 88% (case3) in Figure 15.
Figures 16 and 17 show the winter results. In Figure 16 a), the total reduction of power consumptions in MMHP system was only 1 %. The one of some causes about this lower rate of reduction than in summer was what exhaust heat can’t be utilized. Then, with SAHP which uses the solar heat, the electric power consumption of AR was reduced one-third compared to air source heat pump as AR, so the total power consumptions were reduced by 23 % (case2) in Figure 16 b). Additionally, with PVSAHP, the total power consumptions were reduced by 39 % compared to the THP (case3) in Figure 16 c).As for electric power charges, with PVSAHP as AR, they were reduced by 70 % compared to CVHP system in Figure 17 c).

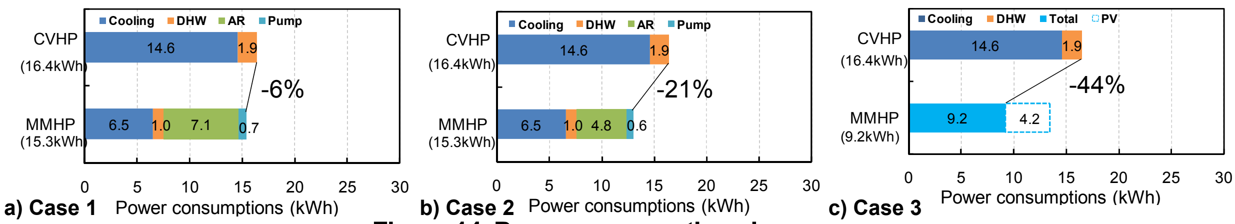


Figure 14. Power consumptions in summer

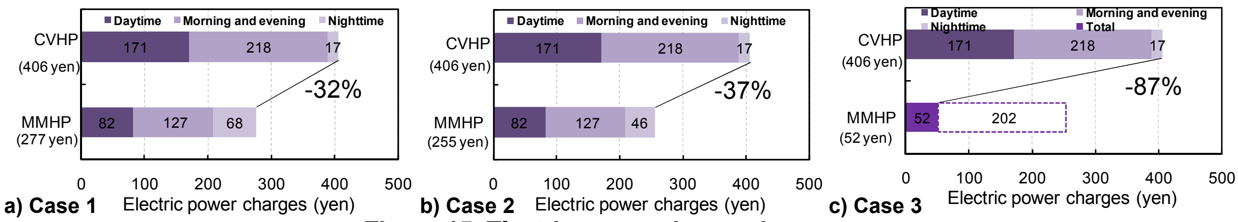


Figure 15. Electric power charges in summer

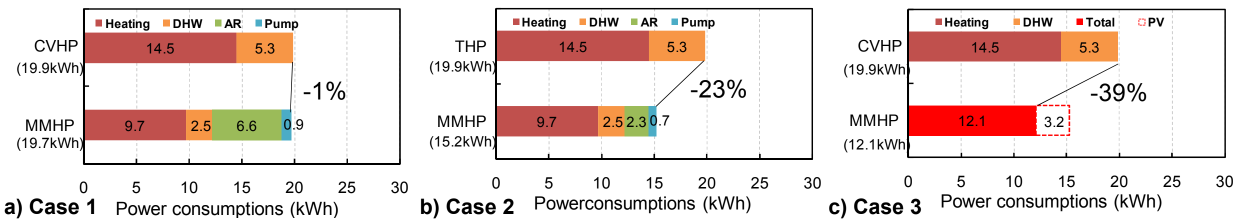


Figure 16. Power consumptions in winter

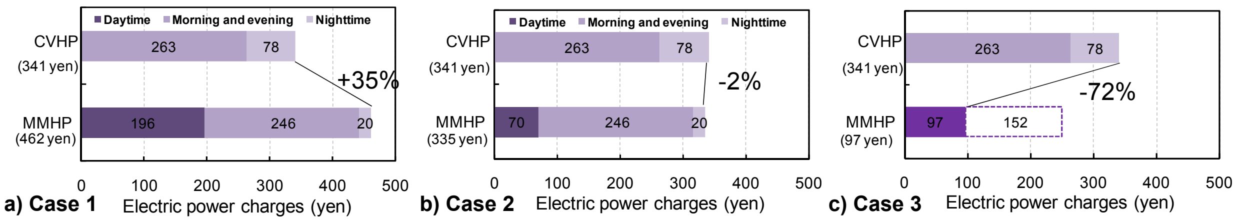


Figure 17. Electric power charges in summer

5 CONCLUSION

In this paper, to achieve higher efficiency than a conventional heat pump system, Multi-Source and Multi-Use heat pump system (MMHP) have been developed. The characteristic of daily geothermal storage was analyzed, and using the results, the feasibility study was calculated. Consequently, with PVSAHP, the Electric power consumptions in summer and winter were reduced by approximately 40% compared to the conventional heat pump system.

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6 REFERENCES

Li X, Chen Z and Zhao J, 2006, "Simulation and experiment on the thermal performance of U-vertical ground coupled heat exchanger", Applied Thermal Engineering 26, pp. 1564–1571

Kjellsson E, Hellström G and Perers B, 2010, "Optimization of systems with the combination of ground-source heat pump and solar collectors in dwellings", Energy 35, pp.2667-2673

Trillat-Berdal V, Souyri B, and Fraisse G, 2006, "Experimental study of a ground-coupled heat pump combined with thermal solar collectors", Energy and Buildings 38, pp. 1477–1484

Nam Y, Ooka R and Hwang S, 2008, "Development of a numerical model to predict heat exchange rates for a ground-source heat pump system", Energy and Buildings 40, pp.2133–2140

Klein SA, Beckman WA, Mitchell JW, et al. 2007, TRNSYS 16 – a transient system simulation program. Madison, USA: Solar Energy