SIMULATION STUDY ON A NET-ZERO ENERGY HOUSE WITH SOLAR AIR COLLECTORS

Takafumi Kusunoki[1], Mitsuhiro Udagawa[1], Kanade Hirayanagi[1], Yasuyo Matoba[1]

Hyunwoo Roh[2] and Makoto Satoh[3]

[1] Kogakuin University, Tokyo(Japan), [2] OM SOLAR Inc., Ltd., Shizuoka(Japan),

[3] Satoh Energy Research, Ltd., Tokyo(Japan)

1. Introduction

All fresh air solar heating systems are prevailing in Japan. While air collector systems are free from freezing in cold weather and the heated air can be used directly for space heating, in the all fresh air heating system the solar collector inlet temperature is the outdoor air temperature and usually lowers than the room air temperature. However, considering the two stage solar collectors composed of a pre-heat collector and a glazed collector, the inlet air temperature of the glazed collector is similar to the room air temperature by the pre-heat collector. The air duct system is simplified because it is not necessary to provide the return air path. This system is possible to provide both solar heat and power when the photovoltaic (PV) modules are put on the pre-heat collector. In this study, the possibility of a net-zero energy house using the solar air heating system with the optimal control methods is examined using the simulation program EESLISM (Udagawa, Satoh, 1985).

2. The solar air heating system

The solar air heating system takes advantage of the building integrated heating system. The air is drawn from the eaves and heated by the solar heat absorbed by the roof. The heated air flows into the room through the underfloor space. Therefore, it is possible to reduce the heating load in winter. Whereas an air conditioner circulates the air of the room, the solar air heating system always introduces the fresh air and it keeps the comfortable indoor air quality. In addition, the heating air can cover some of the hot water heating load by exchange the heat with water before used for space heating. As the solar air heating system can not cover all of the space and hot water heating load, the auxiliary heating system is necessary. The cooling is usually needed using the room air conditioners. The power generation by PV panels is essential to achieve a net zero energy house. The net zero energy house is expected using the PV modules and the glass covered air collector. In this study, the simulation model for the OM solar system known as the air heating system is considered. The OM solar system is an all fresh air solar heating system using the roof integrated collector. It has been used since 1987 in Japan.

3. Simulation model

Three simulation buildings were assumed as shown in Figs. 1-A and 1-B and Fig. 2 (Udagawa, Satoh, 1999). The total floor area of each house is 125 m^2.

Fig. 2 is a modified single family house model derived from the standard model (Udagawa, Satoh, 1999). The original model did not introduce the solar air heating system. The shed roof was assumed in this study for preparing enough area for the solar collectors and PV modules. The room air conditioners are assumed to heating and cooling of LD, MB, CBS and CBN. In addition to the original model the DHW system with the heat storage tank volume of 370 litters heated by a heat pump unit was assumed.

Fig. 1-A is a solar house based on the house in Fig.2. The glass covered solar collector of 30 m^2 is mounted on the roof. The pre-heat collector of 31 m^2 is mounted before the glass covered collector. It is expected that the inlet air temperature of the glass covered collector is similar to the room air temperature in winter by the

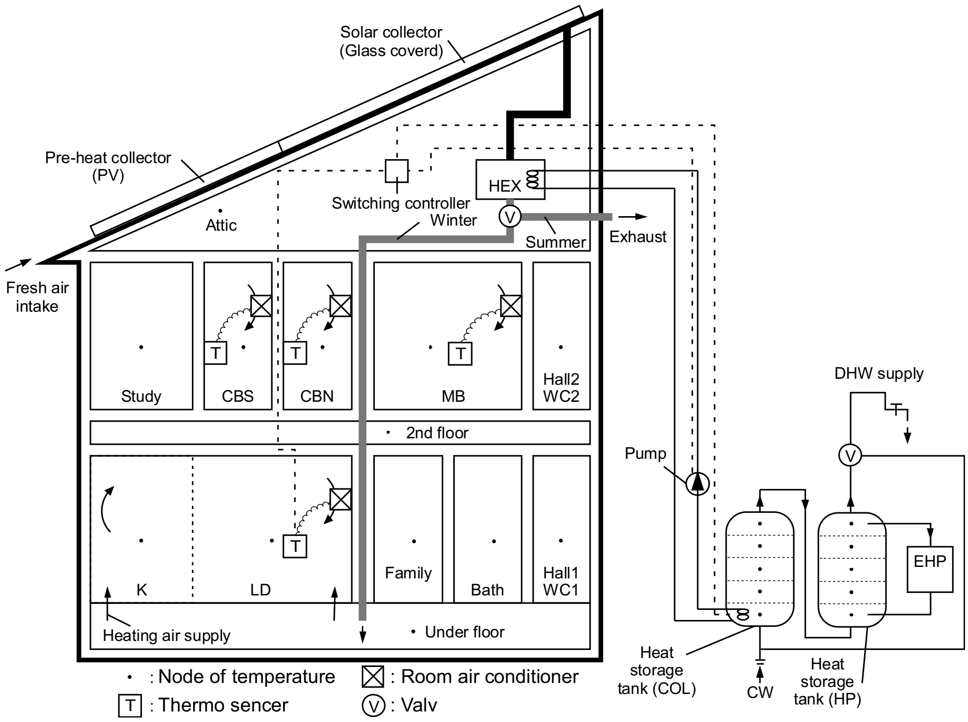

Fig. 1-A: solar heating system model (shed roof)

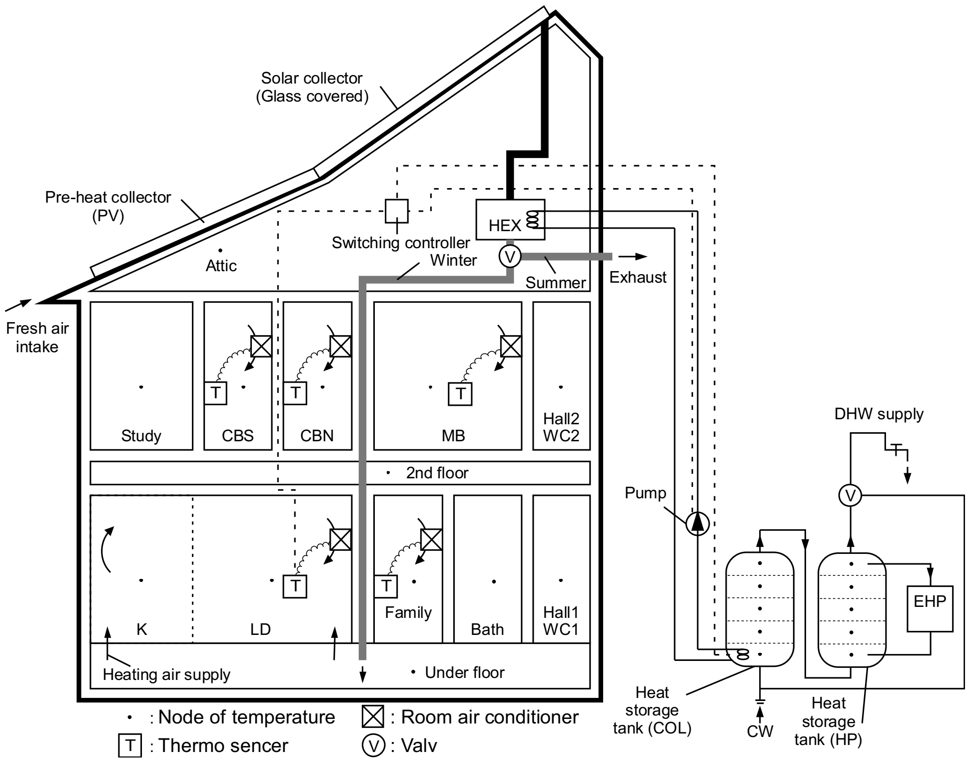

Fig. 1- B: Solar heating system model (steep tilt angle of the glass covered collector)

pre-heat collector. The PV module is combined with the pre-heat collectors. The generate electricity by the PV module is necessary to achieve the Net Zero Energy. This PVT collector improves the efficiency of the PV modules by the cooling effect of the air flow under the PV modules. The warmed air heats the DHW (Domestic hot water) by the heat exchanger in the supply duct. After the heat exchange the warmed air is exhausted to the outside in summer and intermediate season. In case of the warmed air temperature is higher than the underfloor temperature, the air flow into the Living and Kitchen through the underfloor space. Two

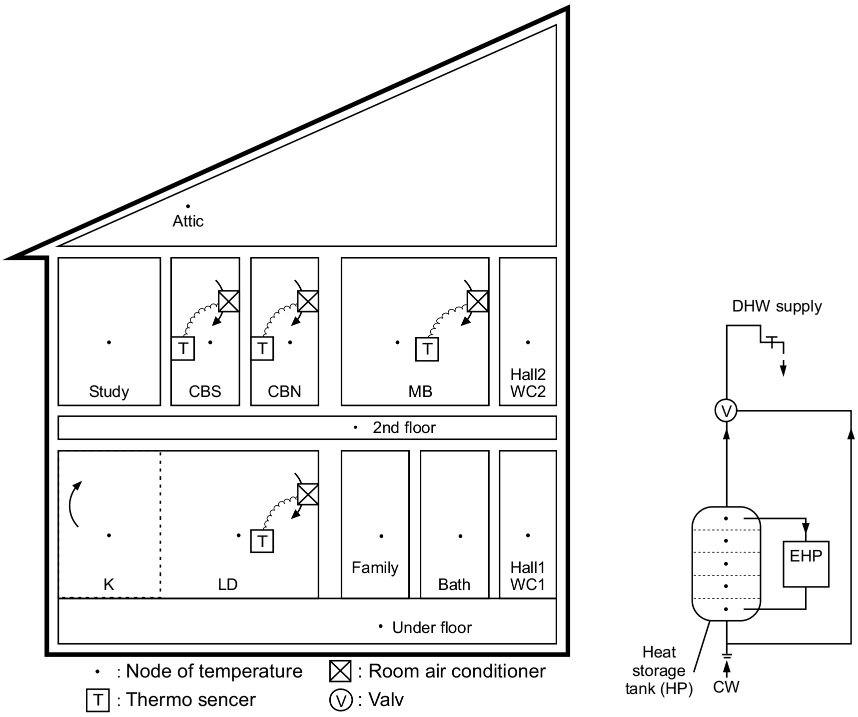

Fig. 2: Base case model

Tab. 1: Simulation case

			Case1-N Case1-D	Case2-N Case2-D	Case3-N Case3-D	Base case-N Base case-D
Simulation model			Fig.1-A	Fig.1-B	Fig.1-A	Fig.2
Solar system	Glass covered collector	Area	30m^2			-
		Tilted angle	26.6 degrees	35.0 degrees	26.6 degrees	-
		Azimuth	due south			-
	Pre-heat collector (PV module)	Area	31m^2			-
		Tilted angle	26.6 degrees			-
		Azimuth	due south			-
	PV modules	Capacity	(High efficiency PV) 5.5 kW (31m^2)			-
Building	Window		Low-emission double pane (6+A12+6)			
	Insulation		Phenol foam (wall:150mm ,floor:150mm, ceiling:200mm)			
Air conditioning	Operating time		Living (6:01-13:00, 16:01-23:00) Main bedroom (0:01-7:00, 22:01-24:00) CBS, CBN (0:01-7:00, 20:01-24:00)			
	Set pint temperature	Summer	20.0 degrees C (Operative temperatures)			
		Winter	28.0 degrees C (Operative temperatures)			
	APF *		6.0			
Heat pump unit	Thermal capability		4.5 kW			
	APF *		3.0			
Heat storage tank	Volume		370 litter (heating by heat pump unit)			
			200 litter (heating by solar energy)			-
	Inslation		Glass wool		Vacuum inslation	Glass wool
Heat exchanger	Air to water	Efficiency	50 %			-
	Tank integrated		30 %			
Heat collection fan	Electricity use		150 W			-
Pump	Electricity use		35 W			-

* APF (Annual Performance Factor)

heat storage tanks are prepared for the solar houses shown in Figs. 1-A and 1-B. One tank volume is 200 litters heated by the solar energy using the heat exchanger. And the other tank volume is 370 litters heated by the heat pump unit for auxiliary heating. Each heat storage tank is connected in series.

Fig. 1-B is provided with the steep tilted angle of the glass covered collector. It is expected to increase the heat collection in winter.

Tab. 2: Simulation case for DHW and heat pump unit

		Case1-N Case2-N Case3-N Base case-N	Case1-D Case2-D Case3-D Base case-D
Operating time of Heat pump unit		Midnight (23:01-7:00)	Daytime (15:01-20:00)
Set pint temperature	Summer	80.0 degrees C	70.0 degrees C
	Winter	60.0 degrees C	50.0 degrees C
	Intermediate	70.0 degrees C	60.0 degrees C
DHW supply temperature		42 degrees C	

4. Simulation method

Tab. 1 shows the simulation cases. The envelope configuration for each model is as shown in Tab. 1. They are composed of high-performance thermal insulation in order to achieve a net zero energy.

The occupants of the house were assumed a family of four. The occupant schedule is shown in Table A-1 in the appendix (Higuchi et al., 2011). The household appliance schedule is shown in Table A-2 and the lighting schedule is shown in Table A-3 (Higuchi et al., 2011). Tables 2, 3 are in the appendix. The schedules were switched for weekdays and holidays.

The set point air temperatures of the air conditioners are 20 degrees C in winter and 28 degrees C in summer controlled with the operative temperatures as shown in Tab.1. The air conditioners were not use in intermediate seasons.

The heat pump capacity is assumed to be 4.5 kW. The set point temperature of the heat pump outlet is different for operation time as shown in Tab.1. Larger heat loss of the heat storage tank is considered in the case of midnight operation of the heat pump. Therefore, the set point temperature is higher than the daytime operation case. The DHW supply temperature is 42 degrees C in each case. Figure A-1 in the appendix shows the DHW use. The DHW uses depend on the seasons, which are 441 litter/day in winter, 330 litter/day in summer, and 370 litter/day in spring and fall. The electricity supply for the fan is 150W. The electricity supply for the pump is 35W. The simulation tool EESLISM was used. The weather data of Tokyo was used. The standard weather data prepared as the Expanded AMeDAS Weather Data (AIJ, 2005) and the supplied city water temperature data prepared by the Solar System Development Association in Japan were used in this simulation. The time increment of the simulation is 1 hour.

5. Simulation results

Fig. 3 shows the weather data in the winter and the summer. The horizontal solar radiation is small on 6th January. It increases from the next day. The outdoor air temperature is lower than 10 degrees C during all days. The outdoor air temperature is always above 0 degree C. The summer days shown in Fig. 3 are all clear days. The maximum of the outdoor air temperature is 35 degrees C on 5th August.

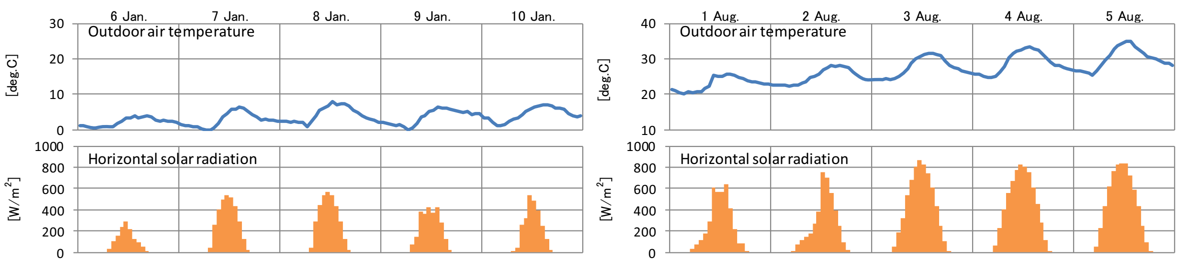

Fig. 3: The weather data (Tokyo)

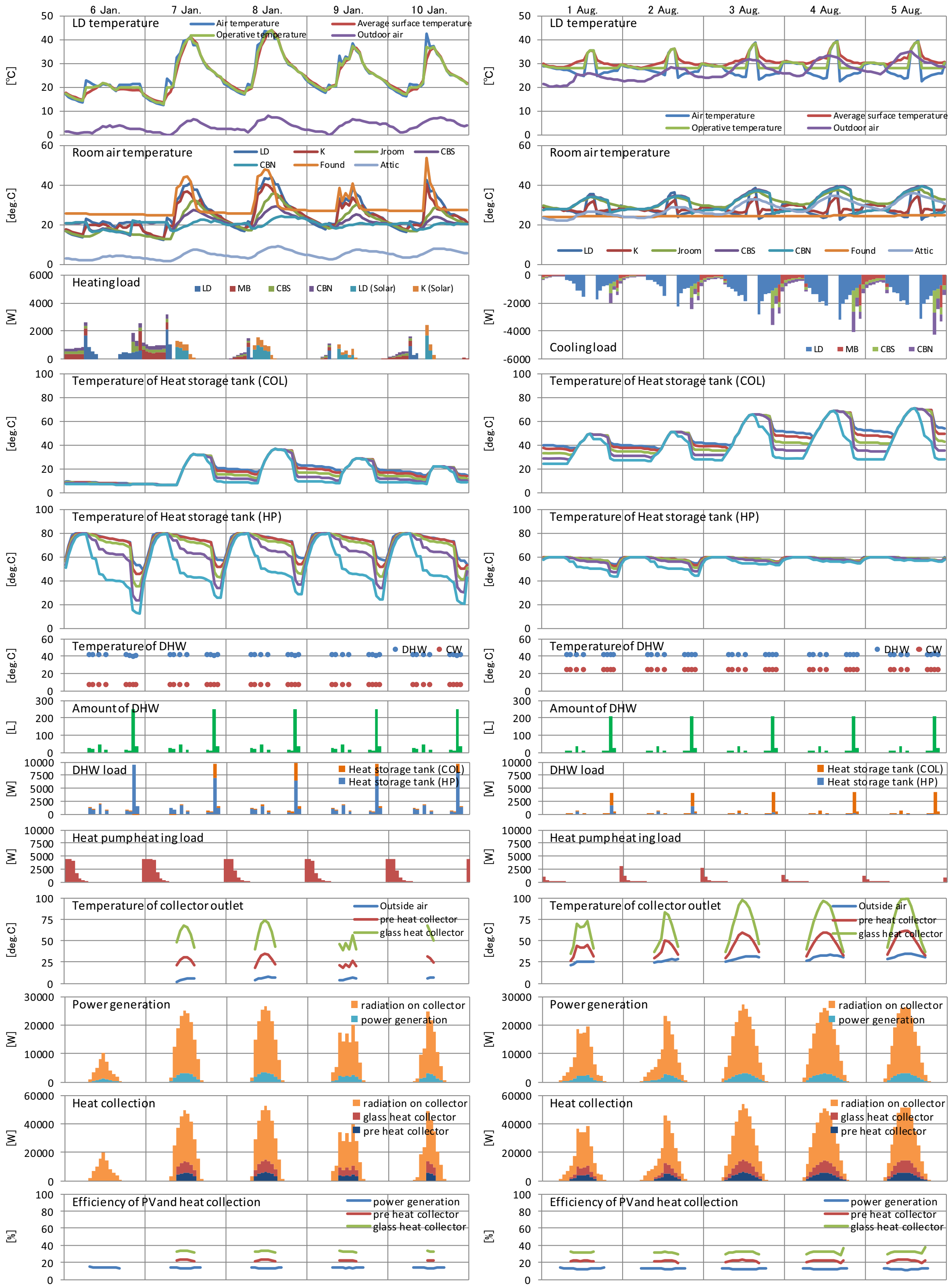

Fig. 4: Simulation results in Case1-N

Fig. 4 shows the simulation results in Case1-N (HP operated during midnight). The solar heating system operates from 7th to 10th, January. The solar heat supply is used for the DHW heating and the space heating. The of the pre-heat collector outlet temperature is 25 degrees C and the glass covered collector outlet temperature is 75 degrees C in winter. The temperature of the glass covered collector inlet is 20 degrees C

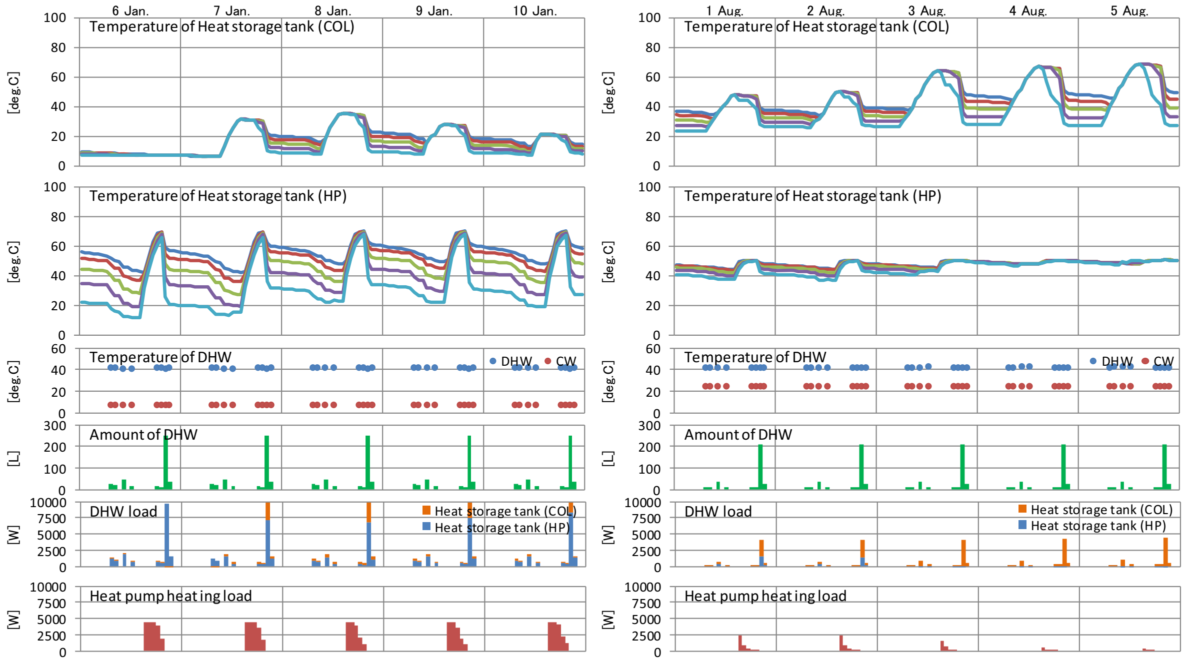

Fig. 5: Simulation results in Case1-D

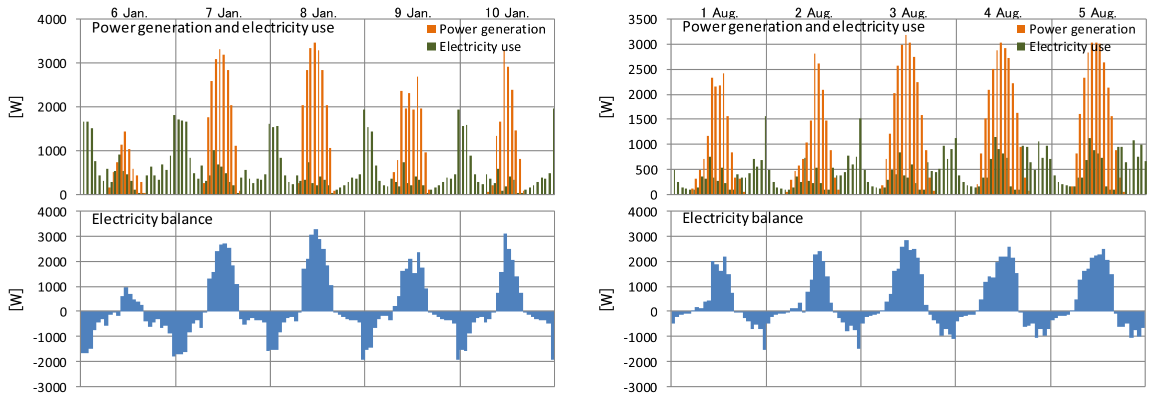

Fig. 6: Simulation results of power generation and electricity use in Case1-N

higher than the outdoor air temperature by the effect of the pre-heat collector. The annual collector efficiencies are 24 % for the pre-heat collector and 34 % for the glass covered collector, respectively. The annual PV power generation efficiency is 14 %.

The air temperature of LD exceeds 40 degrees C when operated the solar heating system from 7th to 10th, January. The solar heat supply exceeds 2300W on 10th, January. The air conditioner heating load in the morning of 8th to 10th, January is less than 1600W by the solar heat supply. As the solar heating system does not operate on 6th January, the air conditioner heating load exceed is 3200W in the morning on 7th January.

For the DHW system, the water in the heat storage tank is heated from 7 degrees C to 36 degrees C by the solar energy. The heat load by the heat pump unit becomes smaller because the water heated by the solar heat flew into the second heat storage tank. The solar heat supply covered 30 % of the DHW heating load.

In summer, the solar heat is used for only the DHW heating. The pre-heat collector outlet temperature of is 55 degrees C and the glass covered collector outlet temperature is close to 100 degrees C in summer as shown in Fig. 4. The maximum cooling load is 4300W for the midnight operation. The water temperature of the solar heat tank on the clean day is heated to 70 degrees C. The heat pump load is small.

Fig. 5 shows the simulation results in Case1-D (HP operated during daytime). The room temperature and air conditioner load in Case1-D are the same to Case1-N in each season. While the set point temperature of the

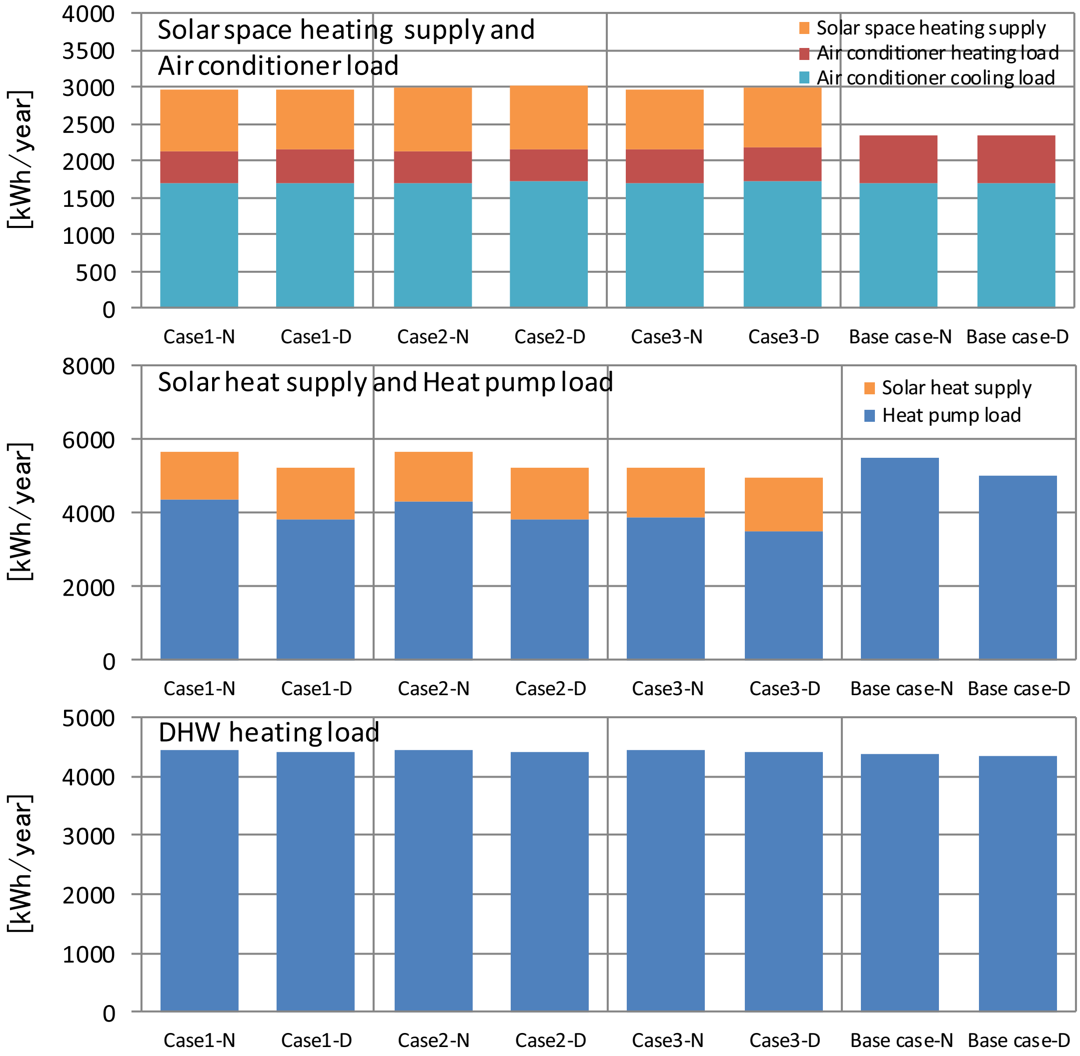

Fig. 7: Simulation results of annual energy use

heat pump outlet is 10 degrees C lower than that of Case1-N, the temperature of DHW of the set point temperature 42 degrees C. The heat loss of the heat storage tank is small because the time is short from the operation of the heat pump unit to the DHW use. The heating load of the heat pump unit is almost nothing on 4 and 5 Aug. The heating load of the heat pump unit in Case1-D is smaller than that of Case1-N.

Fig. 6 shows the simulation results of the PV power generation and the electricity use in Case1-N. The maximum power generation is 3477W in winter. The peak electricity use is 1950W when the heat pump operation starts. Therefore, the daily electricity balance is minus in winter which means the generated power is supplied to the grid. During the night 1950W of electricity is supplied from the grid at the maximum.

The maximum power generation is 3198W in summer. The peak electricity used 1500W when the heat pump operation starts. The electricity use is covered by the PV generation in summer.

The annual heating load by the air conditioners and the solar heat supplied for the rooms shows in Fig 7. The heating load is 653 kWh/year in Base case without the solar air heating system. The total heat supply to the rooms is larger than that of Base case, because in Cases1-3 large amount of solar energy are supplied. The heating load of the air conditioner is reduced to 70 %. The steeped tilted angle of the glass covered collector is used in Case2, the solar heat supply is slightly larger than the other case. The steep tilted angle is not effective for the reduction of the heating load.

The solar heat supply, the heat pump load and the annual DHW heating load are shown in Fig7. The solar

Tab. 3: Simulation results of annual performance (Secondary energy)

[kWh/year]	Case1		Case2		Case3		Base case	
	Case1-N	Case1-D	Case2-N	Case2-D	Case3-N	Case3-D	Base case-N	Base case-D
Household appliance and Lighting	2048	2048	2048	2048	2048	2048	2048	2048
Heating load	74	74	72	71	75	74	109	109
Cooling load	284	282	282	283	283	282	281	282
Air collector fan	318	318	316	316	318	318	-	-
DHW heat pump	1439	1262	1435	1258	1278	1149	1839	1673
Pump of DHW	69	69	68	68	69	69	-	-
Total (Electricity)	4232	4053	4222	4045	4071	3941	4278	4113
Gas cooker	945	945	945	945	945	945	945	945
Total	5177	4998	5167	4990	5016	4886	5223	5058
PV generation	5087	5087	5088	5088	5087	5087	-	-
Amount of energy reduction	-90	89	-78	98	71	201	-	-

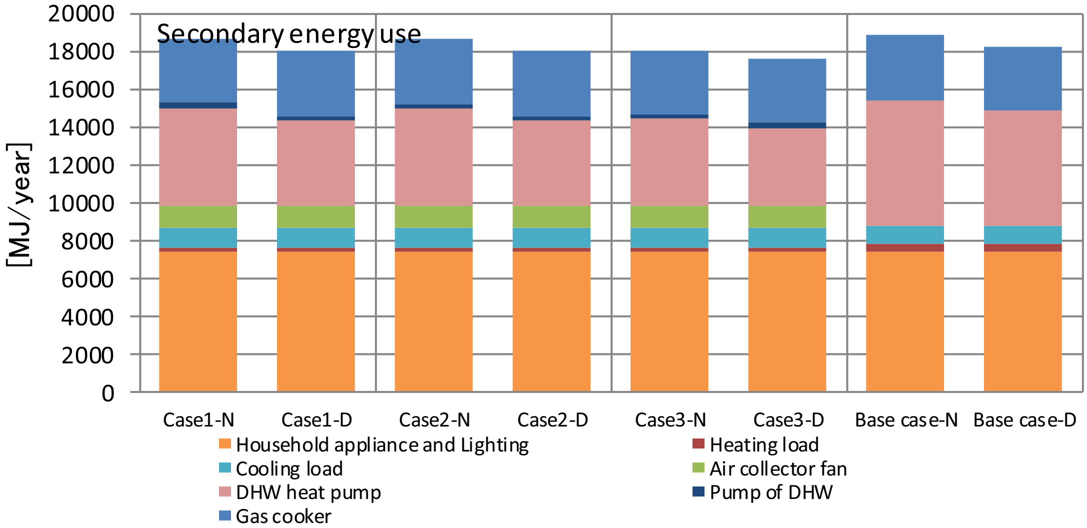

Fig. 8: Secondary energy use

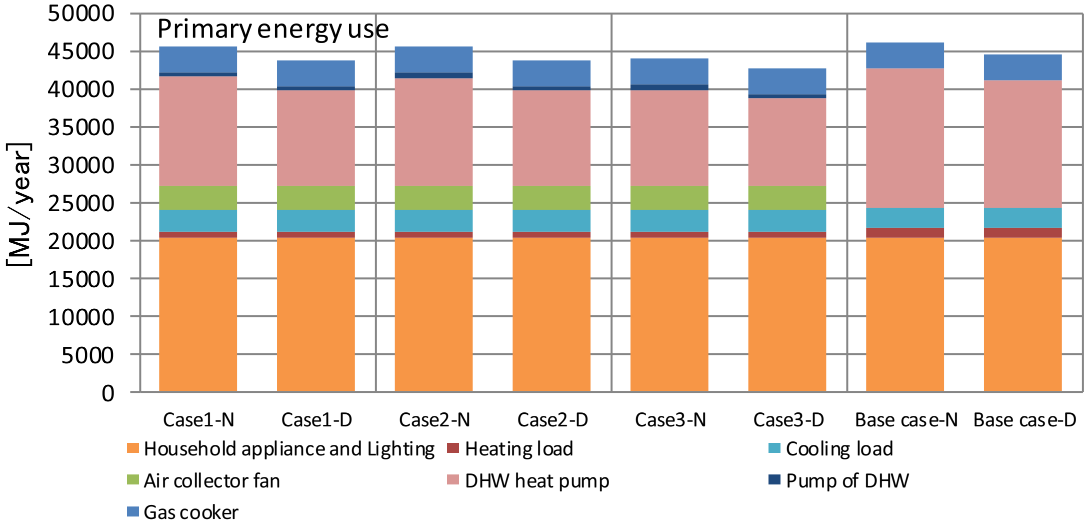

Fig. 9: Primary energy use

energy covers 20 to 30 % of the DHW heating load. The heating load of the heat pump unit operating during the daytime is smaller than that operated during the midnight in each case. In Case 2, the solar heating supply

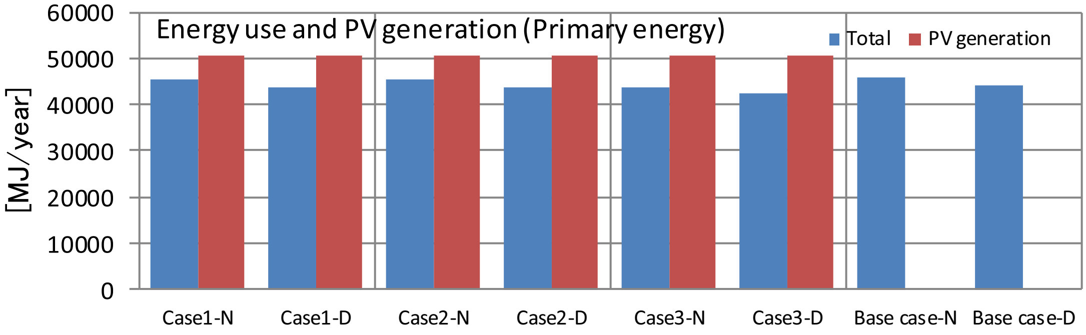

Fig. 10: Energy use and PV generation (Primary energy)

was larger in winter, but that is smaller in summer by the steep tilted angle of the glass covered collector. Therefore, the reduction of the annual energy use by the steep tilted angle for the DHW heating load is small. The DHW heating load is sensitive to the heat loss of the heat storage tanks. In Case 3 because of the improvement of the insulation of the heat storage tank, the heat loss is low. Therefore, it contributed to achieve the net zero energy, even if using the low cost midnight electricity. In Case 3-D, the reduction was the highest in the all Cases. The heat pump heating load is reduced to 60 % comparing to Base case.

Tab. 3 and Fig. 8 show the annual secondary energy use. Fig. 9 shows the annual primary energy use. Fig. 10 shows the annual power generation and the electricity energy use. The APF (Annual Performance Factor) of the air conditioners is assumed to be 6.0 for both in heating and cooling and that of the heat pump unit is assumed to be 3.0. The energy use of the gas cooker is assumed to be 945.0 kWh/year (Higuchi et al., 2011). The energy conversion factor of the electricity is assumed to be 9.97 MJ/kWh. As the results, Case1-D, Case2-N, Case3-D and Case3-N achieve the net zero energy in the secondary energy use. And, the all cases achieve the net zero energy in the primary energy.

6. Conclusion

The simulation study was carried out to examine the possibility of the net zero energy house with the air heat collecting system. For the auxiliary heat source of the DHW heating, the heat pump unit was assumed.

Providing 30 m^2 of the glazed solar collector and 31 m^2 of pre-heat collector with the 5.5 kW of the high performance PV modules, the all cases achieve the net zero energy in the primary energy.

The simulation results showed that the heat pump operate during daytime can reduce the electricity energy use than that operate during the midnight, because the reduced heat loss of the heat storage tank. However, it found that the annual electricity energy use is almost the same to the other cases operated the heat pump unit during midnight by improvement insulation of the heat storage tank.

The effect of the tilted angle of the glazed collector was small, nevertheless the larger solar heat collection in winter.

7. References

Takafumi Kusunoki and Mitsuhiro Udagawa, 2010, Simulation Study for the Advanced Solar Hot Water Heating Systems, Proceedings of ISES EuroSun2010.

Takafumi Kusunoki and Mitsuhiro Udagawa, 2008, Study of Heat Load in Simulation of Solar Hot Water Heating Systems, Proceedings of ISES EuroSun2008.

Takafumi Kusunoki and Mitsuhiro Udagawa, 2010, Evaluation of Auxiliary System in Solar DHW Heationg –Solar heating with heat pump-, Proceedings of JSES/JWEA Joint Conference 2010, pp.47-50. (In Japanese)

Takafumi Kusunoki and Mitsuhiro Udagawa, 2008, Detailed Results of the Solar DHW Heating System Simulation, Proceedings of JSES/JWEA Joint Conference, pp.237-240. (In Japanese)

Takafumi Kusunoki and Mitsuhiro Udagawa, 2007, Effect of Hot Water Heating Load in Solar DHW Heating System, Proceedings of JSES/JWEA Joint Conference, pp.217-220. (In Japanese)

Mitsuhiro Udagawa, and Makoto Satoh, 1999, Energy Simulation of Residential Houses using EESLISM, Proceedings of Building Simulation, pp.91-98. (In Japanese)

Mitsuhiro Udagawa, A proposed standard model house for the heat load simulation, 1985, Proceedings of 15th AIJ symposium on Heat, pp.23-33.

Yoshiki Higuchi, Mitsuhiro Udagawa and Makoto Satoh, 2011, Verification of the Zero Energy House in a Dense Housing Area, vol.37 Journal of JSES, pp.31-39. (In Japanese)

AIJ (Architectural Institute of Japan), 2005, Expended AMeDAS Weather Data. (In Japanese)

Appendix

Table A-1: Occupant schedule of the model house

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
LD								1	4	1	1	1	1	1	1			3	3	3	3	2	2	1
MB	2	2	2	2	2	2	2	1																1
CBN	1	1	1	1	1	1	1	1														1	1	1
CBS	1	1	1	1	1	1	1	1														1	1	1

Table A-2: Household appliances schedule

WEEKDAY	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Daily total	
LD	183.3	37.8	37.8	37.8	37.8	37.8	37.8	37.8	115.1	99.2	70.9	57.8	37.8	138.7	102.0	37.8	37.8	70.9	84.6	97.7	207.0	135.0	97.6	146.0	1983.4	Wh
K								17.4						17.4						34.8					69.6	Wh
Family	53.6								53.6	15.5													107.3		230.0	Wh
MB											275.1														275.1	Wh
CBN	7.5																							22.5	30.0	Wh
CBS	7.5																							22.5	30.0	Wh
Total	251.9	37.8	37.8	37.8	37.8	37.8	37.8	55.2	168.7	114.7	346.0	57.8	37.8	156.1	102.0	37.8	37.8	70.9	84.6	132.4	207.0	135.0	204.9	191.0	2618.0	Wh

WEEKDND HOLIDAY	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Daily total	
LD	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	189.6	97.7	311.0	247.5	189.6	57.8	37.8	37.8	138.7	172.2	207.0	138.7	97.7	97.7	146.0	2506.5	Wh
K										17.4				17.4					34.8						69.6	Wh
Family	53.6								53.6	69.0									53.6				53.6		283.4	Wh
MB											412.5														412.5	Wh
CBN																						30.0	30.0	30.0	90.0	Wh
CBS																						30.0	30.0	30.0	90.0	Wh
Total	91.4	37.8	37.8	37.8	37.8	37.8	37.8	37.8	91.4	276.0	510.2	311.0	247.5	207.0	57.8	37.8	37.8	138.7	260.6	207.0	138.7	157.7	211.3	206.0	3452.0	Wh

Table A-3 Lighting schedule

WEEKDAY	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Daily total	
LD	35.1							22.6	70.0	52.5	115.0	17.5		67.5	52.5			35.1	70.0	70.0	70.0	70.0	70.0	70.0	887.5	Wh
K									27.5												10.0	50.1			87.6	Wh
Family	4.8							4.8	9.5	4.0	8.7	4.8			4.8			1.6	1.6	3.2	4.8	3.6	16.6	15.4	87.9	Wh
Hall	7.1							7.1	14.3	7.1	14.3	7.1			7.1							7.1	28.5	28.5	128.3	Wh
Bath																						3.4	6.8	10.1	20.3	Wh
MB											35.0														35.0	Wh
CBN	70.0										35.0											52.5	17.5	70.0	245.0	Wh
CBS	70.0										35.0											52.5	17.5	70.0	245.0	Wh
Total	186.9	0.0	0.0	0.0	0.0	0.0	0.0	34.4	121.2	63.6	242.9	29.3	0.0	67.5	64.4	0.0	0.0	36.6	71.6	73.1	84.8	239.1	156.9	264.1	1736.5	Wh

WEEKDND HOLIDAY	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Daily total	
LD										70.0	70.0	70.0	70.0	70.0	40.0			70.0	70.0	70.0	70.0	70.0	70.0	70.0	879.9	Wh
K										50.1	67.5			32.5					55.0		55.0				260.0	Wh
Family	4.8								13.1	13.1	14.2		1.6	0.0				7.5	8.3	3.2			11.9	15.4	93.0	Wh
Hall	7.1								21.4	21.4	28.5							14.3	7.1				7.1	7.1	114.0	Wh
Bath																		6.8	3.4				6.8	10.1	27.0	Wh
MB											52.5														52.5	Wh
CBN											52.5	70.0	70.0					70.0	70.0	35.0		70.0	17.5	70.0	525.0	Wh
CBS											52.5	70.0	70.0					70.0	70.0	35.0		70.0	17.5	70.0	525.0	Wh
Total	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.4	154.5	337.7	210.0	211.6	102.4	40.0	0.0	0.0	238.5	283.8	143.1	125.0	210.0	130.7	242.7	2476.4	Wh

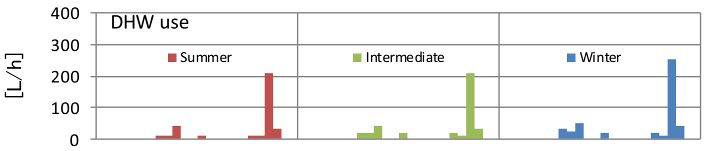

Figure A-1:DHW use