SYSTEM PERFORMANCE OF HVAC IN A LOW ENERGY HOUSE IN THE COLD REGION OF JAPAN

Sayaka TAKEDA-KINDAICHI, Assistant Professor, The University of Tokyo, Tokyo, Japan
(Formerly Assistant Professor, Hokkaido University, Sapporo, Japan)
Katsunori NAGANO, Professor, Hokkaido University, Sapporo, Japan
Takao KATSURA, Director, Fujiwara Environmental Science Institute Ltd., Sapporo, Japan
Shogo HORI, Graduate Student, Hokkaido University, Sapporo, Japan
Kazuo SHIBATA, President, Nissin Techno Incorporated, Sapporo, Japan

Abstract: This study describes a field test on a low energy house built in the cold region of Japan. The floor area is about 200 m^2. The building envelope consists of high insulated walls and windows and a floor with high heat capacity. Totally the Q-value and C-value are 0.96 $W/(m^2 \cdot K)$ and 0.4 cm^2/m^2 respectively.

For heating and cooling, a ground source heat pump unit made in Japan is installed. Continuous heating operation indicates that the supply temperature for floor heating can be mostly kept low between 30ºC and 35ºC throughout the season. The daily average heating output is 3.0 kW, where higher COP can be achieved due to the partial load operation. We can also observe a high seasonal performance. The system COP including the pumping power reaches 4.45. Besides it, acceptable thermal environment is brought about at an air changing rate of 0.5 hr^{-1}. The room temperature is kept stable above 20ºC all day. The vertical temperatures also show uniform distributions.

From the monthly electric consumption, the largest consumption is showed in January due to the heating operation. The power production by the solar photovoltaic (PV) system nearly reaches the consumption in the summer season. The total amount of the annual electric consumption consists of 37% of heating, 10% of DHW and 53% of ventilation, lighting and the rest. The real consumption, that is, the difference between the production and consumption, is observed at 24 kWh/m^2, which is equivalent to 236 MJ/m^2 in the primary energy amount. Totally 48% of the electric power demand can be covered by the PV system.

Keywords: ***low energy houses, HVAC systems, ground source heat pump systems, COP, SCOP, annual energy balance.***

1 INTRODUCTION

Originally, “how to keep off the summer heat” has been the most important issue to be considered in the design of conventional residential buildings for most area of Japan. Many openings on the outer walls can provide natural ventilation through the room space in summer. However, it also means that such construction tends to cause cold and uncomfortable thermal environment in winter. In order to achieve healthy and acceptable environment for habitants throughout the year, improvement of insulation and air tightness of building envelopes have been a fundamental and necessary design concept at present.

The levels of insulation and air tightness for residential buildings of Japan are regulated in a notification so-called the Next-Generation Energy Conservation Standard. For instance, residential buildings should be designed not to exceed a heat loss coefficient (Q-value) of 1.6 $W/(m^2 \cdot K)$ and an equivalent clearance area (C-value) of 2.0 cm^2/m^2 in the coldest region of Japan. The insulation levels can be modified for passive solar houses in the standard. It also refers to the need of proper ventilation more than 0.5 times per hour basically.

The heat load can be certainly decreased in well insulated and airtight buildings. In terms of the air conditioning system, such low energy houses require the sufficient efficiency even for the partial heat load. The use of heat pumps has been recognized to be a solution for further energy savings in low energy houses. In particular, hydraulic floor heating systems using heat pumps may allow lower supply temperature due to larger radiation area and then bring higher efficiencies of heat pumps.

This study describes a field monitoring on a low energy house built in the cold region of Japan. The building envelope consists of high insulated walls and a floor with high heat capacity. A large window area made by Low-E triple glasses filled with Argon gas is mainly faced on the south direction. Totally the Q-value and C-value are 0.96 W/(m^2·K) and 0.4 cm^2/m^2 respectively and quite lower than the standard. For heating and cooling, single U tubes are installed into two boreholes and connected to a ground source heat pump (GSHP) unit made in Japan. The heat from the GSHP is radiated by floor heating in the room space. The variation of supply water temperature needed by the user is observed through the measurement in the heating period. The system performance and indoor thermal environment are also discussed. Moreover, the monthly electric consumption and production by the solar photovoltaic (PV) system are compared and finally the annual energy balance is evaluated.

2 SYSTEM SPECIFICATION

2.1 Physical properties of the building envelope

Figure 1 shows an external appearance of the measured low energy house. The house is built in the *Naganuma* town, which is located at lat. 43ºN and long. 141ºE and 40 km southeast from *Sapporo*. It has a concrete basement and adopts a wooden construction method for the living space. The total floor area is 200 m^2. Usually two people are living there.

Table 1 indicates the physical properties of the building envelope. The thicknesses of the thermal insulation are 240 mm at the ceiling and 186 mm at the outer walls. At the floor, foamed polystyrene boards with 50 mm thick are installed under the floor slab, which is about 300 mm thick. Cross linking polyethylene pipes with 13A are buried in the slab for floor heating. 28 mm plywood is laid on the concrete slab and then is covered with 15 mm wooden flooring as the top layer. The total window area is 83 m^2, in which of 63% are faced in the south direction. Passive solar gain is expected in winter. The window area mainly consists of low-E triple glasses filled with Argon gas. The heat transfer coefficient including the wooded flame is about 1.3 W/(m^2·K) on average.

Q value is then calculated as 0.96 W/(m^2·K), including heat loss by ventilation at 0.5 hr^{-1}. C value is also measured at 0.42 cm^2/m^2 by an air tightness test.



Figure 1: External appearance

Table 1; Physical properties of the building

	Insulation	Area [m²]				
Ceiling	240 mm	132				
Outer walls	186 mm	E	W	S	N	Total
		47	38	55	94	234
Floor	50 mm (with concrete slab of 300 mm)	200 (Base: 23, First: 132, Second: 45)				
Windows	Low-E Triple filled with Argon gas (1.3 W/(m²K))	E	W	S	N	Total
		6	9	53	14	82

Q value	0.96 W/(m²K)
C value	0.42 cm²/m²

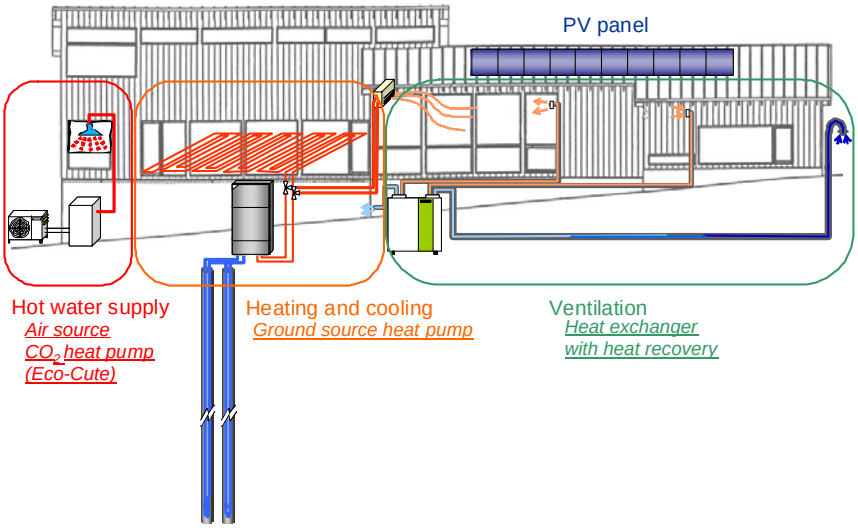


Figure 2: System configuration

2.2 HVAC system

2.2.1 Heating and cooling

Figure 2 shows a system configuration of the low energy house. A ground source heat pump (GSHP) system is applied for heating and cooling. Two boreholes were drilled at intervals of five meters. Each length is about 100 m and single U tube was inserted inside each one. The water level was measured at -14.7 m from the ground level and the water temperature was at 10.8ºC. The geological layer mainly consists of mud stone under the water level. The effective thermal conductivity of the ground is evaluated as 1.4 W/(m^2·K) by a thermal response test.

The heat pump unit adopted in the house has an inverter controlled rotary compressor. It means the heat output varies according to the revolution of the compressor. Each plot in the Figure 3 shows the measured partial load efficiency of the heat pump for the heating operation. Here, coefficient of performance (COP) of a heat pump is determined by a division of a heating output (Q_2) by a power consumption for the compressor. For instance, it has a maximum heating output of 10 kW at an inlet temperature in the primary side (T_{1in}) of 0ºC and an outlet temperature in the secondary side (T_{2out}) of 35ºC. COP is observed at 3.7 in the conditions, whereas COP is varied according to Q_2 and can be increased to 4.5 at a heating output of 4 kW. The figure also reveals lines approximated by a multi-regression analysis. The function is useful for a performance prediction for a longer term.

The heat produced by the heat pump is distributed to the room space through floor heating. Cooling is also possible through fan coil units in summer. The heat pump provides a constant supply temperature T_{2out}, which is set by the user depending on the heating load.

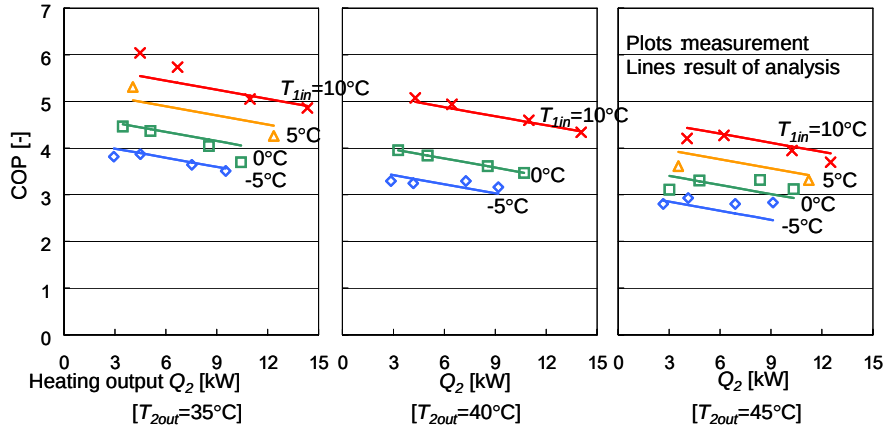


Figure 3: Partial load efficiency of the GSHP (Data from SUNPOT Co., Ltd.)

Solutions of ethylene glycol and propylene glycol are used as heating media in the primary and secondary sides of the heat pump. Each volume density is 30% and 20% respectively.

2.2.2 Ventilation

First, outside air for the ventilation is preheated in a heat tube, which is buried below 1.55 m in the ground and is about 50 m long. Ribbed PVC pipes with a diameter of 150 mm or 200 mm are used for the heat tube. In order to prevent the problem of condensed water during the summer season, the laid heat tube slopes slightly and condensed water can be drained from the lowest point.

Next, a mechanical ventilation unit with heat recovery is applied. The unit has a temperature exchanging efficiency of 90%.

2.2.3 Hot water supply

A heat pump water heater so called "*Eco cute*" developed for the cold region has been adopted. It is a kind of air source heat pumps and CO_2 is used for a refrigerant in it. The hot water produced in the heat pump is stored in a tank of 460 L.

2.2.4 Others

The building also has an equipment of the solar photovoltaic (PV) power generation system. Polly crystalline PV modules integrated with a metal roofing material are installed as shown in Figure 1. The total generating capacity under an intensity of solar radiation of 1000 W/m^2 is 6.8 kW.

3 HEAT LOAD CALCULATION

3.1 Conditions for calculation

Firstly, the heat load of the low energy house is calculated by using a software named *SMASH*. The actual size, direction and physical properties of the building and the other operating method are given for the calculation. The weather data of *Sapporo* is used for the outdoor condition. The heating operation is continuous all the day, in which room temperature is set at 22ºC. The cooling one is intermittent at a set temperature of 26ºC.

3.2 Results and discussion

Figure 4 shows variations of the hourly heating load and cooling load on the upper side. It also reveals the frequency of appearance of the heating load on the lower side.

Totally 6,316 kWh of heat is needed for space heating in a season. The peak load reaches 5.5 kW but such higher heat load accounts for only a few percents. 97% of the heating load is less than 4 kW. The result suggests possibilities of the use of lower supply temperatures and then

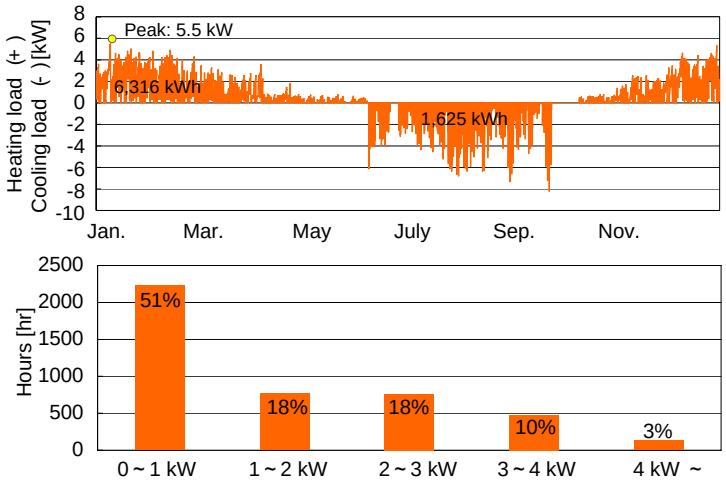


Figure 4: Variations of heating/cooling load (upper) and frequency of appearance of the heating load (lower)

improvement of COP even in the cold region of Japan.

4 RESULTS AND DISCUSSION ON THE FIELD MONITORING

4.1 Temperature variations

The measurement was mainly conducted in the winter season from 2006 to 2007. Figure 5 indicates seasonal variations of temperatures and daily average heating output from the heat pump. The temperatures are the daily average ones during operation.

It was a relatively mild weather condition during the winter season. The outdoor air temperature is -6.8ºC at the minimum. The supply temperature to the floor heating T_{2out} is changed by the user depending on the thermal comfort or the weather forecast. The highest one is shown around 40ºC for a few days in the beginning. But it almost ranges between 30ºC and 35ºC except for them.

In the primary side, it can be seen that the return temperature from the ground T_{1in} is mostly kept higher than the outdoor air temperature. It means the advantage of the use of the ground as a heat source of heat pumps. Also, the temperature shows a relatively stable variation around 0ºC although it decreases to -3ºC at the lowest when the set value of T_{2out} is changed. It suggests that there is little fall of the temperature throughout the season in spite of the continuous heat extraction from the ground.

The figure also indicates a variation of room temperature, which is measured at a ventilating opening for exhaust in the room. It is found that the temperature can be nearly kept above 20ºC concerning the daily average one. Detailed room temperatures measured in the room space on January 17th in 2007 are shown in Figure 6. T_{2out} is set at 30ºC in the day. The vertical distributions of the room temperatures are kept uniformly in every period of time. The lowest distribution is seen in the early morning, when the outdoor air temperature is -4.1ºC. However the room temperatures can be almost 20ºC even in the severe condition. Therefore, sufficient thermal environment can be obtained even though the supply temperature is quite low around 30ºC in such a building which has a high performance of thermal insulation. On the other hand, the room temperature is increased to 28ºC due to the solar heat gain in the daytime. Such overshooting would be improved by heat storage to an additional storage device for instance.

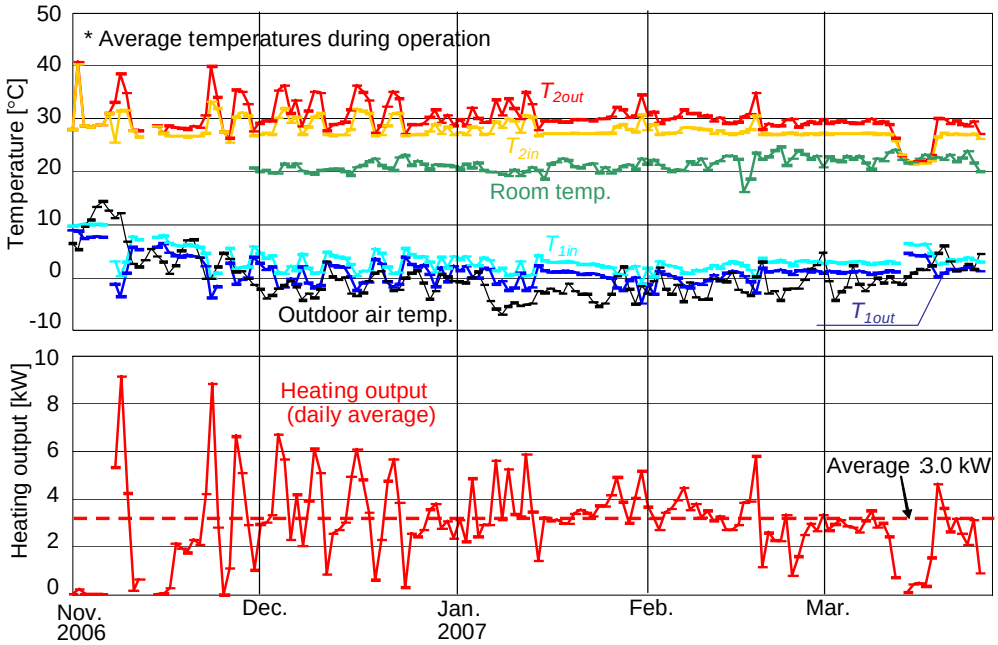


Figure 5: Seasonal variations of temperatures (upper) and daily average heating output (lower)

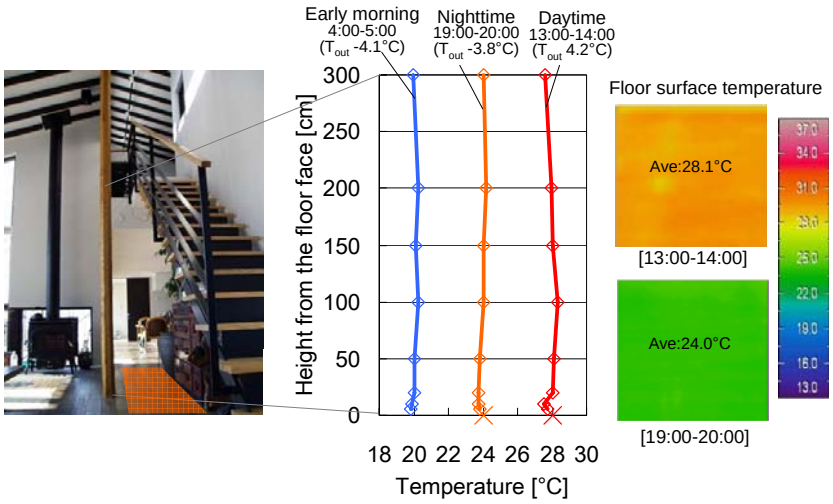


Figure 6: Vertical distributions of room temperature and floor surface temperatures measured by an infrared camera

4.2 Performance of the GSHP system

The daily average heating output ranges from nearly 0 to 9 kW as shown in Figure 5. The lower ones from 2 kW to 6 kW can be seen with higher frequency compared to the higher one above 6 kW. The seasonal average one is calculated as 3.0 kW, which is about one third of the heating capacity of the heat pump mentioned before. Such partial load operation can lead to improvement of the performance.

Figure 7 shows the monthly integrated heating output and the monthly average COP and $SCOP_1$. The seasonal heat balance of the GSHP system is also indicated in Figure 8. $SCOP_1$ is an index to show a system performance of the GSHP, in which the power consumption from the circulation pump in the primary side is added to the one in the COP.

The monthly heating output is varied depending upon the outdoor air temperature. The maximum one is 2,591 kWh and is observed in January. Supposing that the system is operated every day for 24 hours in the period, the daily average heating output is calculated as 3.5 kW, where the heat pump can work with higher efficiency due to the partial load operation even in the coldest season. The monthly average COP is shown within a range from 4.66 to 5.72. Totally in the season, the electrical power consumption is 2,455 kWh, the heating output is 12,624 kWh and then average COP is calculated as 5.14. This high performance seems to be due to the following three reasons.

1) Primary temperature condition: The temperatures in the primary side can be mostly kept higher than 0ºC since the system has enough length of the boreholes of 200 m.
2) Secondary temperature condition: The supply temperature can be set quite low around 30ºC even in the coldest period since the low energy house is well insulated and has a large area of radiation through floor heating.
3) Partial load operation: The heat pump can be operated in the partial load range. It results in the higher COP as shown in Figure 3.

The seasonal $SCOP_1$ reaches 4.45. The high system performance may be brought by the use of the adequate circulation pumps. It should be noted that excess designs of the circulation system may cause decrease the system performance.

Figure 8 also shows comparisons of CO_2 emissions in different heat source systems. The thermal efficiencies in the boiler systems are assumed 0.85. It can be seen that the GSHP system provides a CO_2 reduction effect of 58% compared to the oil boiler system in the estimation.

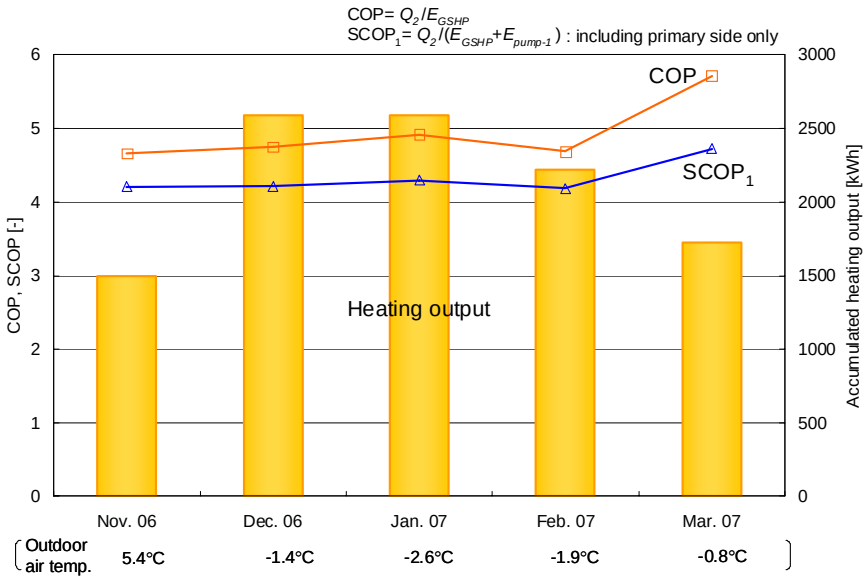


Figure 7: Monthly integrated heating output and monthly average COP and $SCOP_1$ of the GSHP system

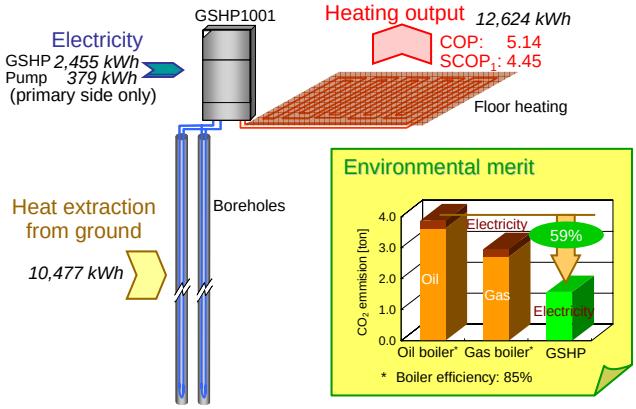


Figure 8: Seasonal heat balance of the GSHP system

4.3 Preheating effect by heat tube

The temperature at the outlet of the heat tube, that is, the one at the inlet of the heat recovering unit was 9.7ºC at the beginning of the heating season. Then it gradually dropped down to 2ºC at the lowest as shown in Figure 9. The average heat extracted from the ground during the heating period was calculated as 220 W, which is equivalent to 4.4 W per unit length of the heat tube. This is used effectively for heating up the supply air and results in 14% reduction of the heating load regarding to the ventilation.

In addition, the authors recognized that the heat tube has a big advantage to avoid the defrost operation of the ventilation unit as the outlet temperature of the heat tube never has dropped below 0ºC.

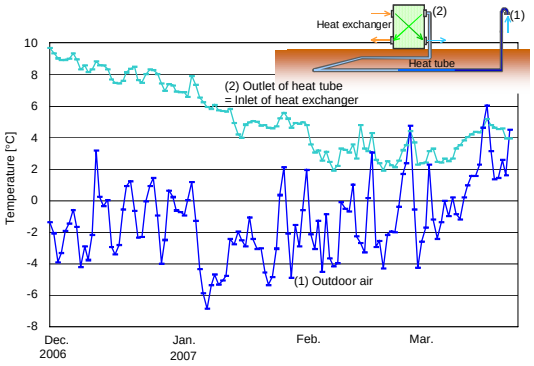


Figure 9: Variation of outlet temperature from the heat tube

4.4 Air changing rate

According to the building management code, a mechanical ventilation equipment which provides a capacity of ventilation rate of 0.5 times per space volume should be installed for residential buildings. In this case, the air volume of the house is about 500 m^3 and the measured centralized supply and exhaust air volumes through the ducts were 231 m^3/h and 224 m^3/h respectively. The measured constant ventilating rate meets the required level when additional local exhaust ventilations are taken into account.

4.5 Annual energy balance

The monthly and annual energy balances in the low energy house are analyzed in Figure 10. The electric consumption consists of the one for heating, hot water supply and the others including ventilation. The production is brought by the power generation by the PV system.

The larger consumption is shown mainly in the winter season due to the heating operation of a heat pump unit. The decrease of the solar power generation in winter seems to be due to snow covering on the roof. On the other hand, the solar power generation nearly reaches or exceed the consumption from May to October.

The total annual consumption is 9,379 kWh and is composed of 37% of heating, 10% of hot water supply and 53% of the rest. On the other hand, the total produced power is 4,534 kWh and the energy self-sufficiency rate, which is shown as the proportion of the production to the consumption, can be 48%. Almost half of the electric power demand can be covered by the PV system. The real consumption for all purposes, which is obtained by calculating the difference between the consumption and production, is 4,845 kWh (24 kWh/m^2). On the other side, it is very obvious that the real electric power consumption for space heating, hot water supply and mechanical ventilation is much less than 20 kWh/m^2. From this point of view, this low energy house reveals the comparable level to that in the requirement of the MINERGIE® standard in Switzerland for instance.

There is a possibility to reduce the real power consumption by development of a solution for the winter snow problem of the PV system. Effective utilization of the exhaust heat from the ventilation or the solar heat brought to the room space by introducing short term thermal storage device will lead to further improvement of the performance of the HVAC system.

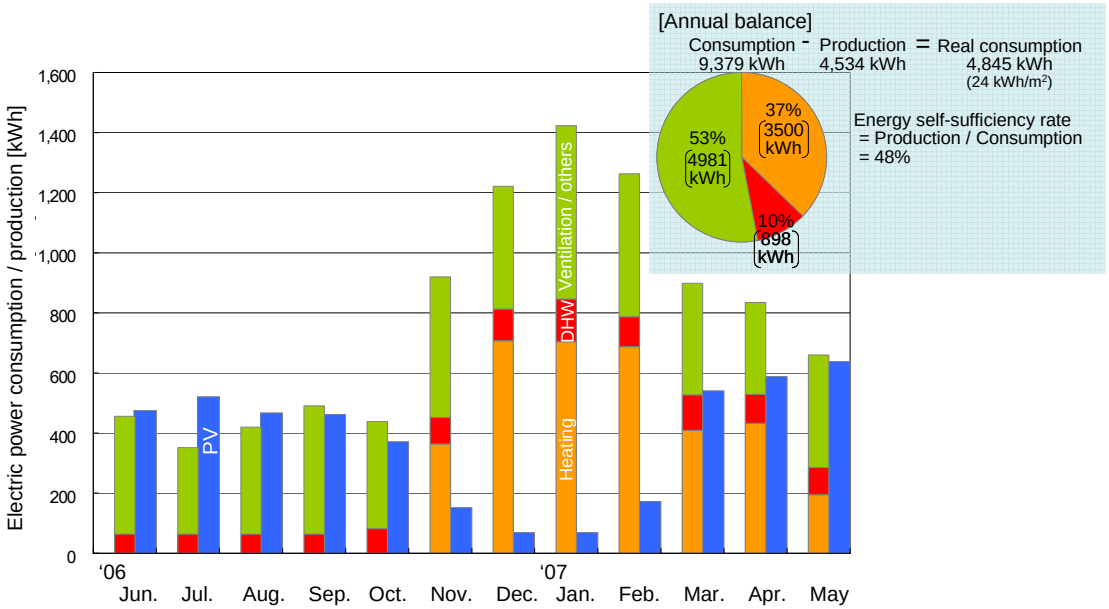


Figure 10: Monthly and annual energy balances in the low energy house

5 CONCLUTIONS

Indoor thermal environment and the performance of the heating system using a ground source heat pump (GSHP) are verified as well as the actual annual energy balance of the target low energy house located in the cold region of Japan. The following summarizes the results reported in this paper.

1. Room temperature can be kept above 20ºC almost all the day even at lower supply temperatures about 30°C. In this case, the daily average heating output from the heat pump is about 3 kW, which resulted in the high efficient operation of the inverter-controlled heat pump in the range of the partial load. Totally the seasonal average SCOP of the heat pump system reaches 4.45. The authors have confirmed that the GSHP system with the inverter-control is a strong solution to achieve better seasonal performance for the space heating purpose.

2. The heat load following ventilation can be drastically reduced by the use of a heat tube with 50 m long and mechanical ventilation units with heat recovery from the exhaust air of the room. The pre-heating effect through the heat tube is estimated as 220 W (4.4 W per unit length of the heat tube) in the winter season on average, which reveals a 14% reduction in the ventilation load for the low energy house. The use of the heat tube also has an advantage in order to prevent the defrosting of the heat exchanger unit even in the coldest season.

3. The total electric power demand for all purposes is 9,379 kWh (47 kWh/m^2) in a year. The real electric power consumption, that is, the difference between the demand and the power generation by the solar photovoltaic system of 4,534 kWh, is calculated as 4,845 kWh (24 kWh/m^2). Totally almost half of energy demand can be covered by the solar system in this low energy house.

6 ACKNOWLEDGEMENTS

This work is supported by *Nippon Steel Engineering Co., Ltd.*, *Hokkaido Electric Power Co., Inc.* and *Sunpot Co., Ltd.* as part of activities of the laboratory of Ground Thermal Energy System in Hokkaido University of Japan (2004-2007). Fruitful discussions with Prof. Tadahiko Ibamoto and Prof. Shigeaki Narita at the laboratory are greatly appreciated here.

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