Low-energy house integrated with heat pump system in Japan

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Due to its high energy efficiency, ground source heat pump (GSHP) systems have been applied in many zero or near-zero energy buildings, which use renewable power generated on-site to offset partially, or completely, the energy consumed in the building on an annual basis. How does the GSHP system perform in these buildings? How much does it contribute to reaching the goal of zero or near-zero energy? In this article, the real performance of a near-zero energy home and its GSHP system will be presented.

Background to low-energy houses in Japan

The Japanese climate [1]

Japan consists of five main islands: Hokkaido, Honshu, Shikoku, Kyushu, Okinawa and other smaller islands. The country extends from the sub-frigid zones in the north to the subtropics in the south, with average annual temperatures varying from 6.4 °C in Wakkanai-city (Hokkaido) to 22.4 °C in Naha-city (Okinawa) as shown in Figure 1. Corresponding temperatures for Sapporo, Sendai, Tokyo, Osaka, Kagoshima are 8.2, 11.9, 15.6, 16.3 and 17.6 °C respectively. Therefore, the number of heating degree-days ΣQ_{h14-10} varies widely from 3218 in Asahikawa to 0 in Naha. Values in Sapporo, Sendai, Tokyo, Osaka and Kagoshima are 2638, 1594, 900, 850 and 515 respectively. On the other hand, cooling degree-days ΣQ_{c24-24} vary from 0 in Asahikawa to 424 in Naha. In Sapporo, Sendai, Tokyo, Osaka and Kagoshima they are 0, 10, 130, 250 and 515 degree-days respectively. Climate conditions in Hokkaido island are similar those of northern European cities and Canadian cities and Chicago in USA.

The average daily insolation does not differ much among cities: in Sapporo, Sendai, Tokyo, Osaka and Kagoshima, it is 12.0 to 13.3 MJ/m^2/day. This suggested that typical passive solar techniques for heating can be effective even in the northern part of Japan.

1.2 Energy consumption in the dwelling sector in Japan [2], [3]

Japan's total primary energy supply and final energy consumption in a year 2006 were 23.8 x 10^{18}J and 16.0 x 10^{18}J, respectively. This is the world's 5th largest consumption. The fraction of energy consumption in both the commercial building sector and the residential sector occupies 32.3 %. Japan has signed the Kyoto protocol and a 6% reduction of CO_2 emission has to be achieved by the end of 2012 compared to that in 1990. However, CO_2 emission levels are still increasing. Especially, increasing energy consumption in both the commercial building and the residential sector has been over 30% compared to 1990. A reason for this trend is increased cooling and heating demand and use of electricity for multiple number of household equipment, and increased total floor area in commercial buildings.

The Japanese government has taken a variety of policies to reduce energy consumption in these sectors. They can be classified into two categories. One targets energy conservation and the other one is related to use of renewable energy. Enhanced thermal insulation of the buildings and use of energy efficient equipments are primary measures. For residences, so-called "Next-Generation Energy Conservation Standard" was established in 1997 and has presented a clear guideline for the required thermal performance of residential building in defined six climatic zones as shown in Figure 1. Table 1 describes representative climatic conditions in winter and summer in each zone, with the required overall heat transfer rate (Q-value) [W/m^2/K] and air leakage equivalent area ratio (C-value) [cm^2/m^2] in accordance with the next-generation energy conservation standard for single-family houses. The required Q-value in Hokkaido is 1.6 W/m^2/K, which is almost the same as that in the US and France, and even slightly higher than that in Germany. In this report, the authors concentrate on the development of low-energy houses in Hokkaido in Japan.

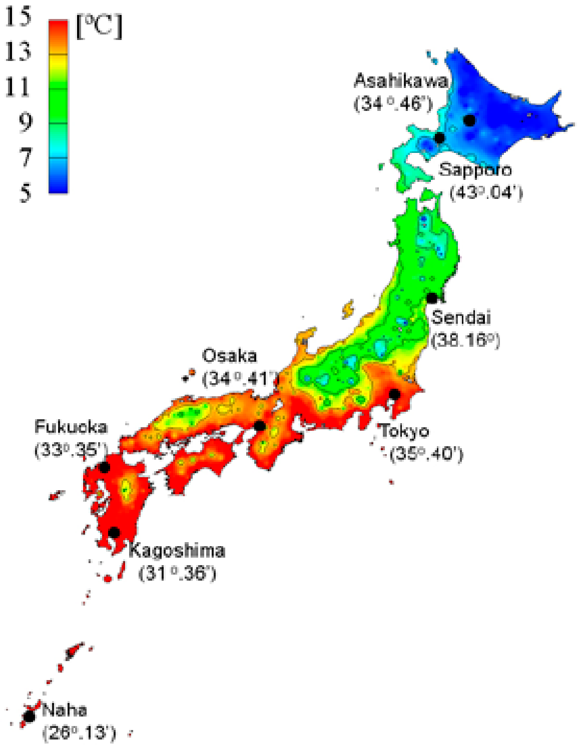


Figure 1 Distribution of annual average air temperature in Japan

Table 1 Climatic features and required building performances

Zone	Color	Climatic feature		Required building performance		
		Summer	Winter	Q-value [W/m²/K]	C-value [cm²/m²]	Annual heating and cooling load [MJ/m²]
I	🟦	Cool	Very cold much snow	1.6	2.0	390
II	🟦	Slightly hot	Cold much snow	2.4	2.0	390
III	🟩	Slightly hot	Slightly cold snow	2.7	5.0	460
IV	🟨	Hot	Moderate	2.7	5.0	460
V	🟧	Hot	Moderate	2.7	5.0	350
VI	🟥	Hot	Warm	3.7	5.0	290

The first full-scale low-energy experimental house at Hokkaido University [4]

The first full-scale low-energy experimental house was built in March 1997 at Hokkaido University. The author joined this project as a project manager under the leadership of Emeritus Prof. Ochifuji. The exterior appearance is shown in Photo 1. Residential floor area was 128 m2, and total floor area was 192 m2.

Photo 1 Low-energy experimental house at Hokkaido University

Passive system

Typical passive solar techniques were adopted in this house.

(1) High thermal performance and low air leakage: The thermally insulated wooden panel construction method was adopted. Ten inches thick foamed polystyrene beads board was sandwiched in this panel. High-performance windows, with a K-value of 1.38 $W/m^2/K$, were fitted mainly on the southern wall (21 m2). The overall heat loss coefficient was estimated as 0.97 $W/m^2/K$, and measured air leakage equivalent area ratio was 0.81 cm^2/m^2.

(2) High internal heat capacity: The ground floor consisted of a 150 mm thick concrete slab, covered by 100 mm thick cement mortar finish. The first floor consisted of 60 mm mortar concrete covering on the wooden floor, with 450 kg of PCM capsules having a phase change temperature around 20 -21 °C for the second floor construction.

(3) Natural ventilation system with earth tubes: Outside fresh air is supplied to the basement space, which acts as a large plenum chamber, through two 20 m long earth tubes which preheat or pre-cool the air passing through them. Natural ventilation through the ventilation shaft was powered by chimney effect of the ventilation tower at the centre of the house. In addition to above, small fans were installed in the side wall of the ventilation shaft in order to distribute fresh air to rooms in each floor.

Active system

A GSHP system and two types of active solar systems were installed as shown in Figure 2.

(1) Heating system; Low-temperature floor heating system heated by a small ground heat source heat pump unit with three buffer tanks of each 310 l volume. A heat pump was specially developed for this project. Compressor capacity was 1.0 kW, with R-134A refrigerant. COP at 0 °C – 30 °C was about 3.8. Floor heating tubes were laid in both the concrete slab of the first floor and on the wooden floor of the second floor, and covered by a mortar finish.

(2) Domestic hot water supply; An exhaust air heat pump (compressor capacity 0.4 kW, R-22) integrated with a 300 l storage tank, with four flat-panel type thermal solar collectors of 8 m^2 on the centre of the roof was used for hot water supply. A simple finned-tube type heat exchanger of 1 m^2 as an evaporator for heat recovery was installed at the exit of the ventilation tower. On a clear day, the solar thermal panels collect heat and can produce hot water during the daytime. However, on cloudy or rainy days, a heat pump unit operates from 3 PM

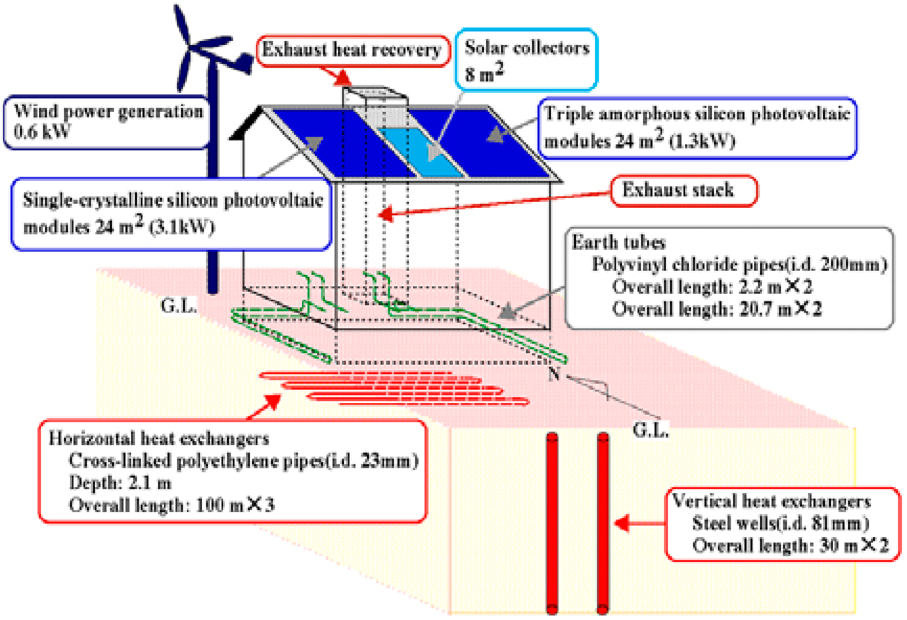


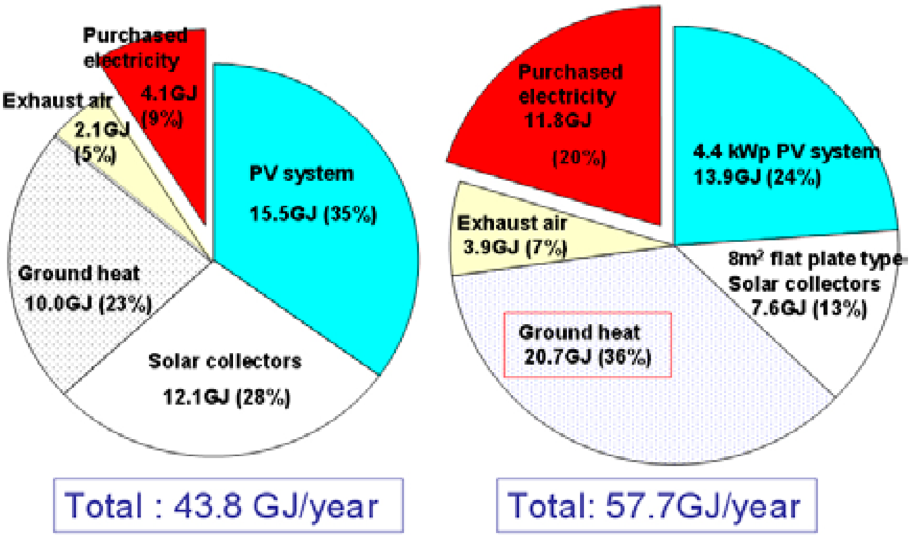
Figure 2 Active and passive energy systems and features

according to the stored hot water and heats up the water up to 65 ^{o}C.

(3) Electric power generation; Glass-covered monocrystalline silicon solar photovoltaic modules, with a peak generating capacity of 3.0 kW, were fitted on the left side of the roof. The right-hand side of the roof carried three layered amorphous silicon-coated on metal roof materials, covered by fluorine-resin sheets, to produce 1.4 kW of the peak generating capacity. These cells also provided the roofing cover material. It was expected that the total amount of generation power would be approximately 4200 kWh per year.

Annual energy balance

Figure 3 shows the estimated and actual secondary energy quantities used in 1998. It is estimated that annual energy consumption is 43.8 GJ/year, with 91 % of consumption being covered by the PV system, solar thermal collectors and ground heat for the heat source of the heat pump. Only 9 % is supplied from utility. On the other hand, 57.7 GJ was actually used, and the house purchased 11.8 GJ from the utility. This was because power generation and the amount of collected heat were smaller than expected, due to snow covering on the devices and heating demand and energy consumption for pumping to drive the heating system being larger. The final balance was that 80 % of the consumed energy was supplied by natural energy resources.



(a) Estimated

(b) Actual measured

Figure 3 Estimated and actual energy supply

Photo 2 External appearance

3. An actual modern low-energy house in Hokkaido [5]

Characteristics of the building

The actual modern low-energy house has been constructed in Naganuma, 30 km east of Sapporo, Hokkaido in November, 2005. Photo 2 shows an external appearance. An externally insulated timber-framed construction method with a concrete basement was adopted. The total residential floor area is 200 m^2 and the house has two occupants. Overall heat loss coefficient is estimated as 0.96 W/m^2/K including the effect of heat recovery from mechanical ventilation (0.5 times/h, temperature efficiency is 0.9). The structure has a high thermal capacity from its 300 mm thick concrete slab and 50 mm thick cement mortar finish, in which polyethylene tubes have been laid for the floor radiative heating. Large, south-facing triple-glazed low-E argon gas-filled windows (K=1.3 W/m^2/K for the standard size) provide significant passive solar input. The air leakage equivalent area ratio C-value was measured at 0.4 cm^2/m^2.

System configuration

Figure 4 shows a system configuration of the house.

Heating and cooling: a standard ground source heat pump (GSHP) system from SUNPOT Co Ltd. is used for heating and cooling. Two 100 m deep boreholes each contain a single U-tube. The natural ground temperature is 10.8 ºC. The geological layer mainly consists of mudstone 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 uses R-410A as the refrigerant and it has an inverter-controlled rotary compressor. Measured partial load efficiencies for the heating operation are shown in Figure 5. It can be seen, for example, that maximum heat output of 10 kW can be obtained with the highest power supply frequency and an inlet temperature on the primary side (T_{1in}) of 0 ºC and an outlet temperature on the secondary side (T_{2out}) of 35 ºC. This gives a COP of 3.7. Heating output can be varied by varying the compressor drive frequency, with the COP increasing to (for example) 4.5 at a moderate heating output of 4 kW. The diagram also shows lines calculated by a multi-regression analysis, which are useful for calculation of performance predictions. The heat pump provides a constant supply temperature T_{2out}, which is set by the house owner according to preference.

Ventilation system: The outside fresh air for the ventilation is taken in and preheated through a 50 meter long earth tube, which is buried 1.55 m below the ground. Condensate during the summer season can drain from the lowest point of the slightly sloping tube. The fresh air is introduced to a mechanical ventilation unit with 90 % efficient heat recovery and is supplied to the room.

Hot water supply: An EcoCute CO_2 heat pump water heater, designed for use in the cold areas of Japan, has been installed. The hot water generated by the heat pump during the night is stored in a 460 l tank at a temperature from 65 ^{O}C up to 90 ^{O}C.

Power generation: Glass covered polycrystalline silicon PV modules integrated with a steel roofing material are fitted on the roof. Total maximum output power is 6.8 kW with 1000 W/m^2 insolation.

Results of performances

Temperature variations and heating output: Measurements were mainly made during the winter season from 2006 to 2007. Figure 6 indicates seasonal variations of temperatures and daily average heating output of the heat pump. The temperatures are the daily average ones during operation period: weather conditions were relatively mild during this winter season. The observed minimum outdoor air temperature was -6.8 ºC. The supply temperature to the floor heating T2out was adjusted by the inhabitants depending on their thermal sensation. The highest value was around 40 ºC for only a few days in the beginning, but was generally between 30 ºC and 35 ºC.

The return temperature from the ground T1in was relatively stable above 0 ºC in mid-winter, and it recovered again in March as the demand for heating decreased. T1in was mostly higher than the outdoor air temperature.

The figure also indicates a variation of average room air temperature, which is the temperature of the return air to the ventilation unit. The room temperature varied from 16 ºC to 25 ºC, but was generally around 22ºC as a daily average.

Figure 7 shows indoor temperature differences with height on January 17th in 2007. T_{2out} was set at 30 ºC in the day. In the early morning, room temperature was around 20 ºC when the outdoor air temperature was -4.1 ºC. However, the room temperature increased to 28 ºC due to the solar heat gain in

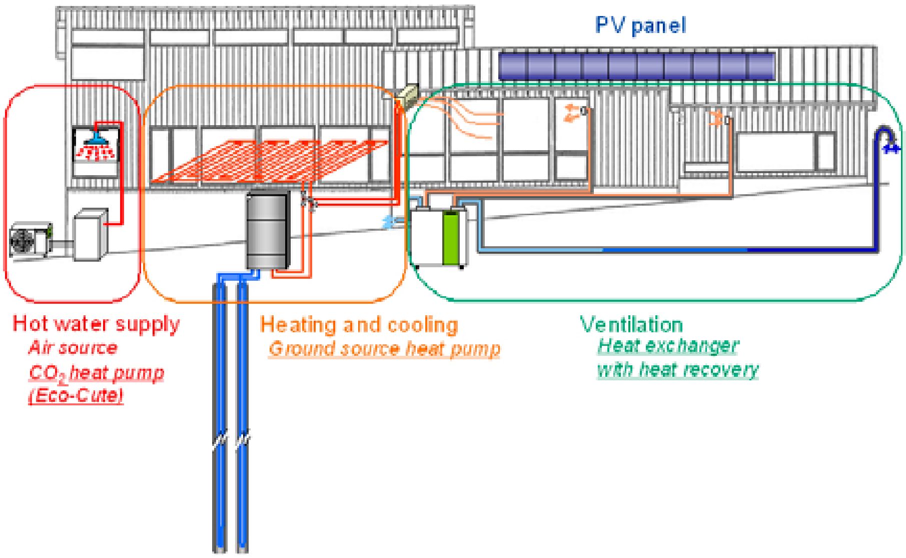


Figure 4 System configuration

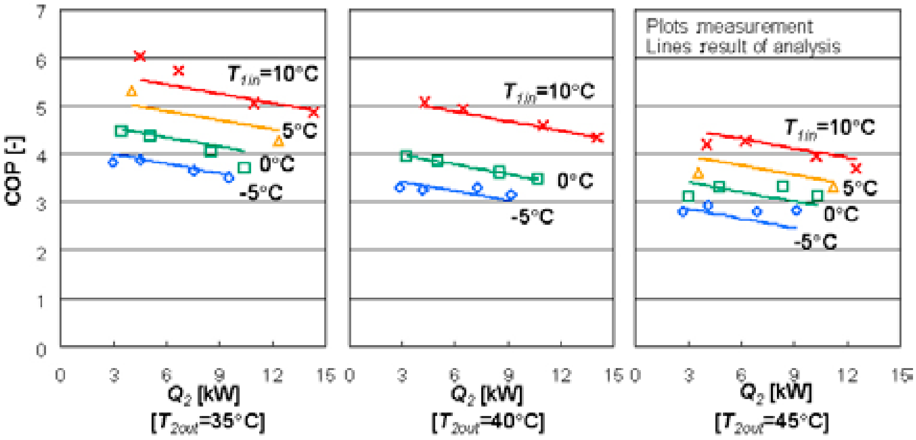


Figure 5 Partial load efficiency of the GSHP unit

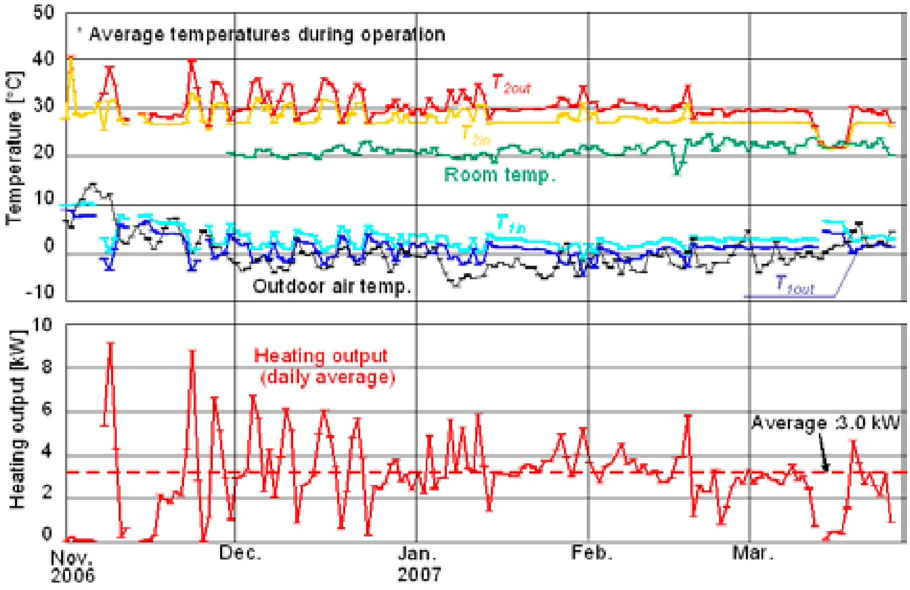


Figure 6 Seasonal variations of temperatures (upper) and daily average heating output (lower) (Nov 2006-March 2007)

the daytime. Air circulation from the living space to the northern part of the house or to the basement space helps to modify and stabilize the temperature distribution.

Performance of the GSHP system: The daily average heating output ranges from nearly 0 to 9 kW, as shown in Figure 6. It can be seen that output was generally in the range 2 6 kW. The seasonal average is calculated as 3.0 kW, which is less than one-third of the maximum heating capacity. Since this unit has an inverter-driven compressor, such partial load operation can give higher performance, as indicated in figure 5.

Figure 8 shows the monthly integrated heating output and the monthly average COP and $SCOP_1$. The seasonal heat balance of the GSHP system is also shown in Figure 9. $SCOP_1$ is an index of system performance of the GSHP, which includes the power consumption of the circulation pump in the primary side.

The monthly heating output varied depending on the outdoor air temperature. Maximum output was 2,591 kWh and was observed in January. Supposing that the system is operated every day for 24 hours in the period, this would give a daily average heating output of 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 lies in the range from 4.66 to 5.72. For the winter heating season as a whole, the electrical power consumption was 2,455 kWh, the heating output was 12,624 kWh and the average COP was calculated as 5.14. This high performance can be attributed to the following reasons;

1) Low secondary temperature condition: The supply temperature can be set quite low around 30 ℃ even in the coldest period, since the house is well insulated and has a large area of radiant floor heating.
2) Part-load operation: The heat pump can be operated at a lower speed, for higher COP as shown in Figure 5.
3) High primary temperature condition: The temperatures in the primary side can be mostly kept higher than 0 ℃.

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

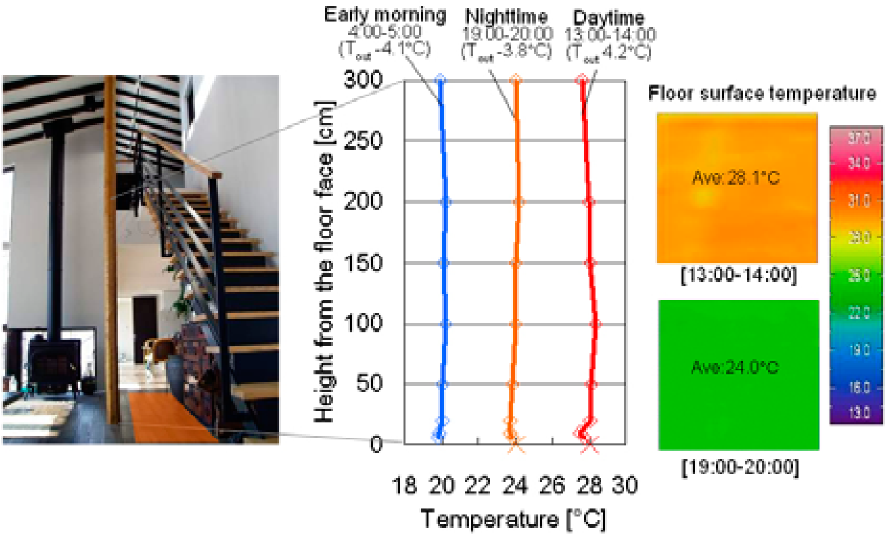


Figure 7 Vertical distributions of room temperature and floor surface temperatures measured by an infrared camera (17th Jan 2007)

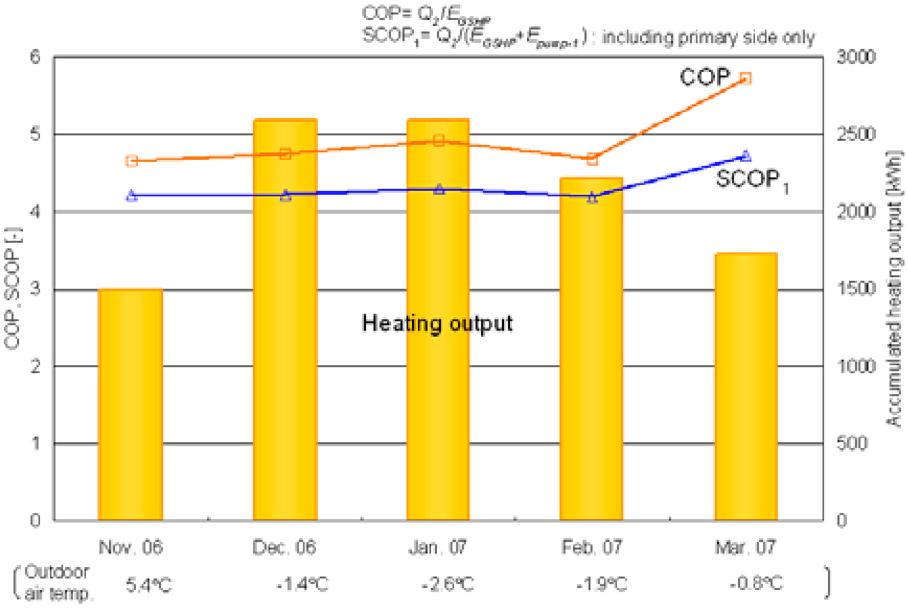


Figure 8 Monthly integrated heating output and monthly average COP and SCOP1 of the GSHP system, (Nov 2006-March 2007)

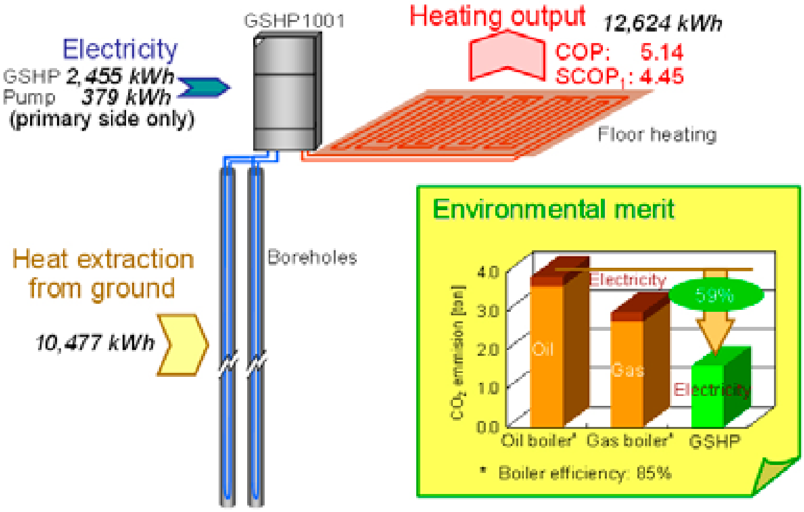


Figure 9 Seasonal heat balance of the GSHP system, (Nov 2006-March 2007)

may reduce the system performance.

Figure 9 also shows comparisons of CO_2 emissions from different heat source systems. The thermal efficiencies of the boiler systems are assumed to be 0.85. Calculations indicate that the GSHP system provides a CO_2 reduction effect of 58 % compared to the oil boiler system.

Annual energy balance: The monthly and annual energy balances in the actual low-energy house are analysed in Figure 10. Electricity consumption consists of that for heating, hot water supply and other purposes, including ventilation. Power is supplied by the PV system. The total annual consumption is 9,379 kWh, consisting of 37 % for heating, 10% for hot water supply and 53% for other purposes. The total produced power is 4,534 kWh and the energy self-sufficiency rate, which is shown as the ratio of production to consumption, can be 48 %. The real electric power consumption for all purposes, which is obtained by calculating the difference between consumption and production, is 4,845 kWh (24 kWh/m²).

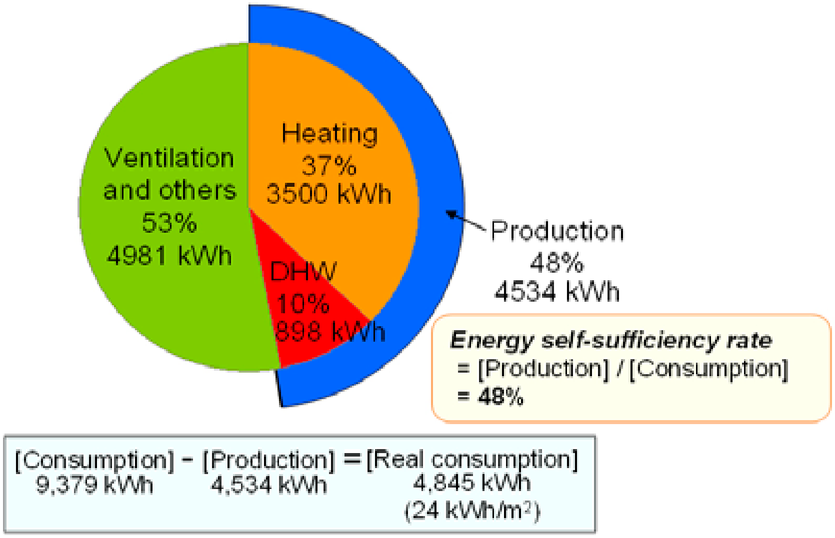


Figure 10 Monthly and annual energy balances in the low-energy house (June 2007-May 2007)

Real power consumption can be reduced in a number of ways. For heating purposes, automatic outlet temperature control according to heating demand will increase the COP of the heat pump unit and therefore reduce power consumption. Additional heat recovery from the exhaust air of a ventilation unit to the primary side of the heat pump unit can be effective in reducing the necessary borehole length and helping to recharge the ground in the autumn. Snow cleaning on the PV modules and pre-heating of supply water for the DHW are also effective. Introduction of a short-term thermal energy storage device such as a phase-change material will reduce overshoot of indoor air temperature.

Conclusions and future development

This report describes two examples of a traditional and a modern low-energy house with two heat pumps for space heating and hot water supply in Hokkaido, Japan. From the heat source point of view, it has been confirmed that ground heat source and exhaust air play very important parts, and are very effective in the cold region. Design of an integrated heat pump system for space heating, hot water supply and ventilation, with a heat recovery unit and also a humidity control device, is expected shortly. An advanced low-energy house can have an air system for heat distribution including ventilation. In this case direct expansion for the secondary side can be acceptable and the system will be very light. It must be very high performance.

Advances in the design of large high-performance windows enables very modern design of the low-energy house, but we have to pay much attention to prevent overshoot of the room temperature even in the winter season. Appropriate eaves are required for outside. The provision of air circulation between the southern part of the building and the northern part or the basement space is very easy and very effective.
In addition to the above, evaluation and publication of the the results of measurement is only one method to promote the reduction of CO_2 emissions through dissemination of low-energy houses integrated with heat pump systems.

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