Field performance of a Japanese low energy home relying on renewable energy

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Abstract

This paper describes the construction and evaluation of an experimental low energy home assisted by a hybrid system using natural energy resources and unused energy. The home, for which a ground source heat pump (GSHP) system has been installed, was built on the campus of Hokkaido University, Japan in March 1997. The total floor area of the home is 192 m^2. This home is super insulated and airtight; the calculated coefficient of heat loss is 0.97 W/m^2 K. It has various passive strategies including direct solar heat gain and a ventilation system with an exhaust stack. Photovoltaic (PV) modules, wind power and solar collectors are adopted in order to achieve self-sufficiency in electric power and domestic hot water (DHW) supply. A GSHP is used for space heating and cooling. Two vertical steel wells are used as vertical earth heat exchangers (VHE). In summer, there is a floor cooling system using piped cold water from the VHE.

Approximately 80% of the home's total energy was provided by PV modules, solar collectors, as well as underground and exhaust heat. The annual amount of purchased energy during the test period was 12.5% that of a typical home in Hokkaido. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Field performance; Energy; Hokkaido

1. Introduction

In order to harmonize with the environment, we must minimize energy consumption. In addition, it is desirable that it be accomplished through the use of natural energy resources and unused energy. Various techniques of passive, active and hybrid energy efficiency technologies have been developed in Japan and other countries [1–7]. The details of these leading results have been published by the Florida Solar Energy Center of the University of Central Florida [1], Solar Heating and Cooling Programme of International Energy Agency [2], the Centre for the Analysis and Dissemination of Demonstrated Energy Technologies [3] and so forth. However, few design procedures for combining various elemental techniques have been presented, though many utilization techniques of natural energy resources and exhaust heat are considered to have been proposed through these projects. Moreover, for cold regions, technologies for space heating and DHW supply systems without the dependence on fossil fuel, are still relatively primitive.

The authors analyzed the characteristics of energy consumption in Hokkaido, revealing an over 80% dependence on kerosene [8]. We have developed a method for predicting earth temperature, and evaluated long-term underground thermal energy storage. We also examined the applicability of underground thermal energy to space heating/cooling systems for residential houses, and examined the effectiveness of GSHP [9–13].

The present study describing the construction and evaluation of a low energy home is a step toward creating an autonomous home utilizing renewable energy. This study focuses on the unification and integration of various passive and active strategies including GSHP.

2. Outline of low energy home

A low energy home with GSHP was constructed on the campus of Hokkaido University, Japan in March 1997 [14–18]. The physical appearance of the low energy home is shown in Fig. 1. Table 1 describes the home and Fig. 2 is a cross-sectional view of the home. The building area is 64 m^2, which is close to average for detached houses in

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Fig. 1. Physical appearance of low energy home.

Table 1
Description of low energy home

Location	Hokkaido, Japan
Climate	Sub-frigid zone
Status	Completed March 1997
Structural system	Thermal insulation panel (wood-frame)
Housing type	Two-story detached house with semi-basement
Total floor area	192 m^2 (including semi-basement)
Architectural volume	500 m^3

Japan. The home has a semi-basement in order to utilize it for underground thermal energy storage (UTES). Total floor area including the basement is 192 m^2.

This home is so called super insulated and airtight. Thermal insulation panel construction using sandwich
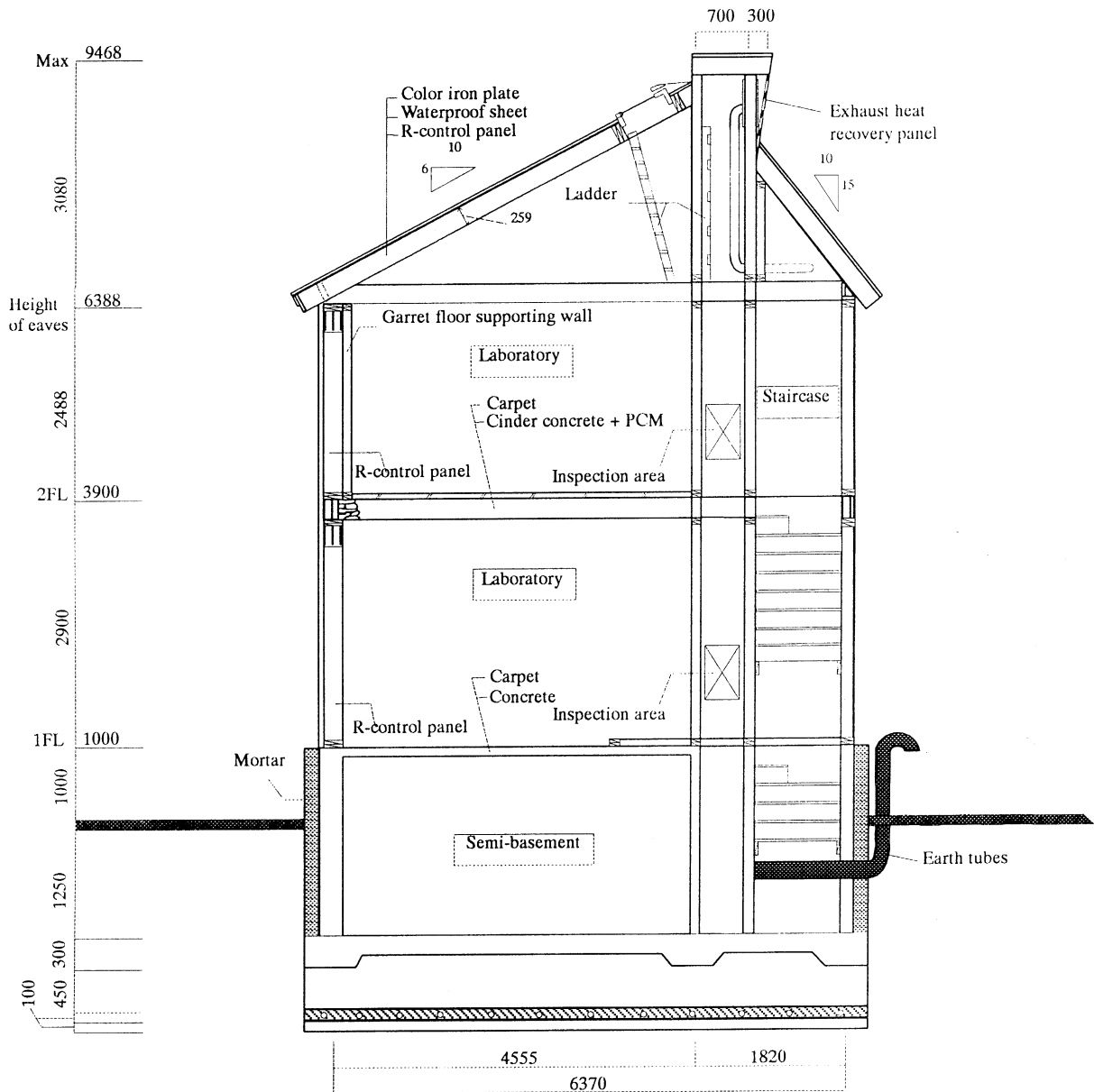

Fig. 2. Cross-sectional view of low energy home.

panels, with expanded polystyrene boards, and coated with oriented strand boards on both sides, was adopted. This method is effective for saving materials because the panel itself works as a structural material. It is also cost-effective because the panel is easily prefabricated. These panels (236 mm thickness) are used for all walls and the roof. The glazing in the south wall is 21 m². Double-glazed, argon-filled windows with low-emissive coating are used, which have a heat transfer coefficient of 1.38 W/m² K. In addition, awnings are used for solar shading. The calculated coefficient of heat loss was 0.97 W/m² K. The measured value of an equivalent leakage area per floor area was 0.81 cm²/m² with ventilation inlets sealed. The home has two main passive strategies; direct solar heat gain and natural ventilation with an exhaust stack. Daily variations in room temperature are reduced by using concrete slabs of large heat capacity and phase change materials (PCM) in the 2nd floor. The PCM, which has a 20°C melting point, was installed for the purpose of reducing heating load through latent heat storage as well as preventing the overheating of the room temperature by solar heat gain. Also, it is considered that the PCM is effective for the reduction of the energy demands for cooling. This technology is still under research and development in Japan. Its target level, however, is to realize a reduction of 10–20% of the energy currently used for space heating and cooling.

3. Equipment design

Fig. 3 shows an equipment schematic for the low energy home. Electric power is supplied by a grid-connected PV system. This is composed of single-junction crystalline silicon PV modules (24 m²: 3.1 kW) and triple-junction amorphous silicon PV modules (24 m²: 1.3 kW) integrated with roofing materials. Also, a 0.6 kW wind power generator was installed.

A GSHP system was adopted for floor heating and cooling. Two vertical steel wells (inside diameter 81 mm) which were installed 5 m apart were used as VHE. Each of them was buried into a borehole which is 30 m in depth and 110 mm in diameter. Gaps between the VHE and soil were filled with mortar. Brine is injected in the bottom through a cross-linked polyethylene tube (inside diameter 23 mm) inserted in the VHE and extracted from the upper area via a return tube. In this process, heat is exchanged between the brine and the soil. A propylene glycol solution (35 wt.%) is used as the brine medium. Flat plate solar collectors, which have 8 m² gross area, are used. A 1.0 m² flat plate evaporator of a heat pump (rated output 0.4 kW) for heat recovery from exhaust air was installed outside of an opening at the top of the exhaust stack.

In summer, cold water from the VHE is directly supplied into floor cooling piping. Heat from solar collectors and an exhaust heat recovery system is supplied for DHW. The volume of the hot water tank is 0.3 m³. In summer and fall, surplus heat obtained from solar collectors was charged into the ground by using horizontal earth heat exchangers (HHE) at a depth of 2.15 m. They consist of 300 m of cross-linked polyethylene pipes. Each pipe has a distance of 0.2 m, then all the pipes are subdivided into three parallel segments. It is considered that heat stored by the underground HHE contributes to a reduction of heating load in the semi-basement without increasing cooling load owing to a time lag of the
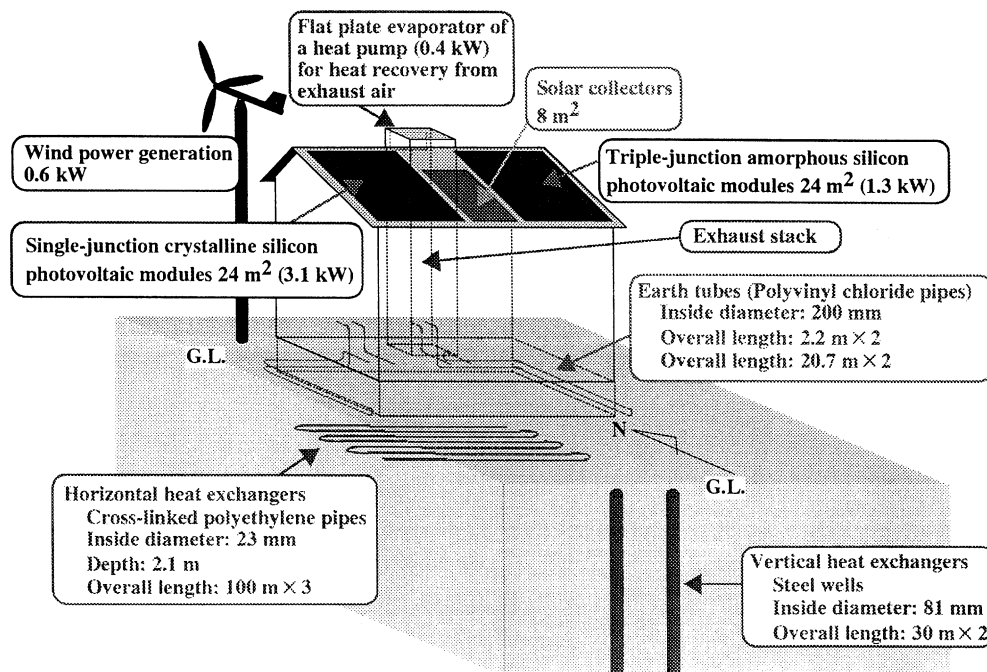

Fig. 3. Equipment schematic for low energy home.

heat conduction in the underground. Though the amount of heat which could passively reach the semi-basement after several months is considered to be less than 30%, it was installed on the assumption that only surplus solar heat would be utilized.

A ventilation system using the exhaust stack was designed as one of the passive strategies. It is driven by the temperature difference between indoor and outdoor air. Earth tubes of polyvinyl chloride (inside diameter 200 mm) are used for pre-heating/cooling of supply air for ventilation. The temperature of outdoor air introduced, rises in winter and lowers in summer through the earth tubes. Two different types of earth tubes were symmetrically installed at a depth of 1.3 m in order to compare their effects on temperature changes. One is 2.2 m long, and the other is 20.7 m. Either of the two may be utilized for air supply in the semi-basement.

4. Methodology of experiments

Experiments on the low energy home were carried out without occupants from 1 June 1997 to 31 May 1998. The measured values of electric power for heating, cooling, ventilation and DHW as well as energy demand patterns for cooking, lights and appliances were used in order to evaluate annual energy balance. These patterns were calculated using a program from the Society of heating,

air-conditioning and sanitary engineers of Japan, and are considered standard for a typical single family in Japan [19]. Regarding DHW, producing 0.3 m^3 of hot water (45°C), draining the water from the storage tank and supplying cold city water to the tank were automatically carried out every day to replicate the average use of a typical family in Japan.

Fig. 4 shows an outline of GSHP with the VHE. This figure does not include the HHE referred to in Chapter 3. The rated output of the installed heat pump is 0.82 kW. A heat storage tank (0.93 m^3) was set up for peak demand. Surplus solar heat is utilized as the heat source of the heat pump and for the recovery of the ground temperature around the VHE. Cold water for cooling is produced from the VHE by using a plate type heat exchanger.

Experiments on floor cooling with the VHE were conducted in the summer of 1997. We measured the indoor thermal environment, cooling load, system coefficient of performance (SCOP) and so forth. Three tests were carried out as shown in Table 2: (1) room temperature of the 2nd floor was controlled at 26°C thermostatically for 3 days; (2) 4 h intermittent cooling periods were held for 3 days; and (3) continuous cooling was initiated for 19 days. The thermostatically controlled operation is a typical method of space cooling, while intermittent and continuous operations were examined to compare the performance of the VHE. From the viewpoint of thermal output per unit time and the power required for circulating pumps, the intermittent operation
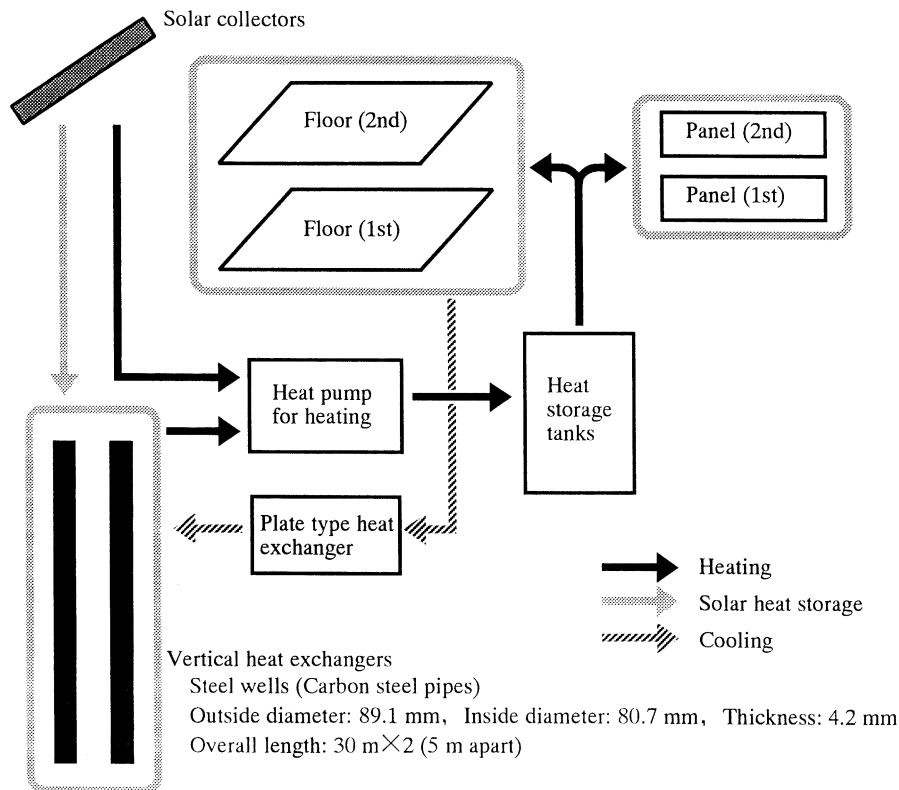

Fig. 4. Outline of ground source heat pump.

Table 2
Conditions of cooling experiments

Cooling period	Mode of operation
13–15 July 1997 (3 days)	Thermostatically controlled operation (2nd floor, 26°C)
22–24 July 1997 (3 days)	4 h intermittent operation (2nd floor, 9.00–13.00 h)
25 July 1997 to 12 August 1997 (19 days)	Continuous operation (2nd floor)

proved desirable in order to utilize underground thermal energy more effectively. Therefore, underground cold was stored in the floor concrete slabs and the PCM during the morning, and the system was not operated during the afternoon. The continuous cooling for 19 days was examined in order to verify stability of the VHE for underground cold utilization. An experiment on heating started on 5 November 1997. The floor heating system is controlled thermostatically, coming into operation when the room temperature falls below 18°C.

The measuring system consisted of three kinds of data loggers and a personal computer used for processing the collected data. Approximately 230 measurement points, including temperatures, humidity, solar radiation, flow rate, electric power and so forth, were tracked. Measurements for solar systems and wind velocity were taken every 30 s. The remaining data were recorded every 5 min.

5. Experimental results

During the experiments, the annual average outdoor air temperature was 9.5°C, which was 1.3°C higher than normal. Monthly mean temperatures in January and August were −5.5°C (normal value −4.6°C) and 19.8°C (normal value 21.7°C), respectively. It can be said that the experiments were carried out under near normal conditions, because the temperature differences between actual and normal values were within 2°C. The annual daily average horizontal global irradiance, the average wind velocity and the average relative humidity of outdoor air were 12.4 MJ/m^2 per day (normal value 11.9 MJ/m^2 per day), 2.7 m/s

(normal value 2.3 m/s) and 69% (normal value 71%), respectively. These weather parameters were also near normal annual values.

5.1. Cooling experiment

Table 3 shows experimental results on a particular day for each cooling operation: 15 July for thermostatically controlled; 24 July for 4 h intermittent; and, 28 July for continuous. The total volume flow rate in the VHE was 3.1×10^{-4} m^3/s. During the period of cooling operations, awnings were used for solar shading of the south-oriented glazing. Earth tubes of 2.2 m length were used for the air supply. The ventilation rate provided by the tubes ranged between 6.4×10^{-3} and 6.4×10^{-2} m^3/s. The daily average outdoor air temperatures were 22.4°C on 15 July, 23.9°C on 24 July, and 24.9°C on 28 July, respectively. The highest outdoor air temperatures were 28.6°C on 15 July, 30.6°C on 24 July, and 29.2°C on 28 July. The 2nd floor temperature was higher than that of the 1st floor throughout all of the operations, as shown in Table 3. The temperature difference between the 2nd floor and the outdoor air was 3.1°C in the thermostatically controlled operation and 3.2°C in the 4 h intermittent one. Daily average temperature of the 1st floor was 23.4°C in the thermostatically controlled operation and 24.9°C in the 4 h intermittent one. In both operations, the temperature difference between the 1st floor and the outdoor air was approximately 1°C.

The operational duration of the thermostatically controlled experiment was 8.3 h a day. The heat rejection rate of the VHE to the underground, per unit well length, was 20.9 W/m. At this time, SCOP, (amount of heat rejection/power of circulating pumps for the VHE), was 7.0. In the 4 h intermittent operation, the heat rejection rate of the VHE was 30.3 W/m and SCOP 9.1. These results indicate that a GSHP utilizing a 10°C constant earth temperature layer is effective for cooling. On the other hand, the heat rejection rate of the continuous operation was 18.1 W/m and SCOP 5.4. SCOP's value was approximately 41% lower than that of the 4 h intermittent operation. These results of the continuous operation were caused by the soil temperature increase around the VHE. Therefore, it was determined that

Table 3
Experimental results of each cooling operation

Mode of operation	Thermostatically controlled	4 h intermittent	Continuous
Date	15 July 1997	24 July 1997	28 July 1997
Outdoor air temperature (°C)	22.4	23.9	24.9
Room temperature (1st floor) (°C)	23.4	24.9	24.2
Room temperature (2nd floor) (°C)	25.5	27.1	25.8
Brine temperature[a] (°C)	15.3	15.6	16.0
Amount of heat rejection (MJ per day)	37.4	26.2	93.7
Heat rejection rate (W/m)	20.9	30.3	18.1
Operation time (h per day)	8.3	4.0	24.0
SCOP (ND)	7.0	9.1	5.4

[a] Average temperature of brine's flow and return.

Table 4
Experimental results of heating operation[a]

Operation time (h per day)	12.5
Outdoor air temperature (°C)	1.5
Room temperature (°C)	18.6
Relative humidity (% RH)	33.1
Brine temperature (°C)	2.1
Heat extraction rate (W/m)	40.8
COP (ND)	4.0
SCOP (ND)	3.1

[a] Average daily values in 5 November 1997 to 30 April 1998.

the intermittent operation with floor thermal storage is desirable for the underground cold utilization. Problems such as the optimization of operation times will be the subjects of our next study.

5.2. Heating experiment

Table 4 shows the experimental results during the heating period (from 5 November 1997 to 30 April 1998). The average operation time per day was 12.5 h. The average temperature between flow and return of the VHE during the heating period was 2.1°C. The average heat extraction rate

from the VHE was 40.8 W/m. The heat extraction rate is high because the groundwater velocity of the experimental site is approximately 40 m per annum. The average coefficient of performance (COP) (thermal output/electric energy for compressor of heat pump) was 4.0 and the SCOP (thermal output/(electric energy for compressor of heat pump + power of circulating pumps for heating)) was 3.1. In comparison with conventional researches, the high COP was obtained by adopting a low temperature floor heating system [20]. However, the SCOP was about 23% lower than the COP. The experimental value of the primary energy reduction rate to typical heating (conventional boiler system) was approximately 34%. Based on these results, The GSHP system can be identified as a heating system quite effective for saving energy.

5.3. Annual energy balance

The annual energy balance of the low energy house is shown in Fig. 5. The amount of heat extraction from the underground through the VHE, and the electric energy consumption of the heat pump for heating, were 19.22 and 6.04 GJ, respectively. The amount of heat rejection into the underground for cooling was 1.47 GJ. It was found that
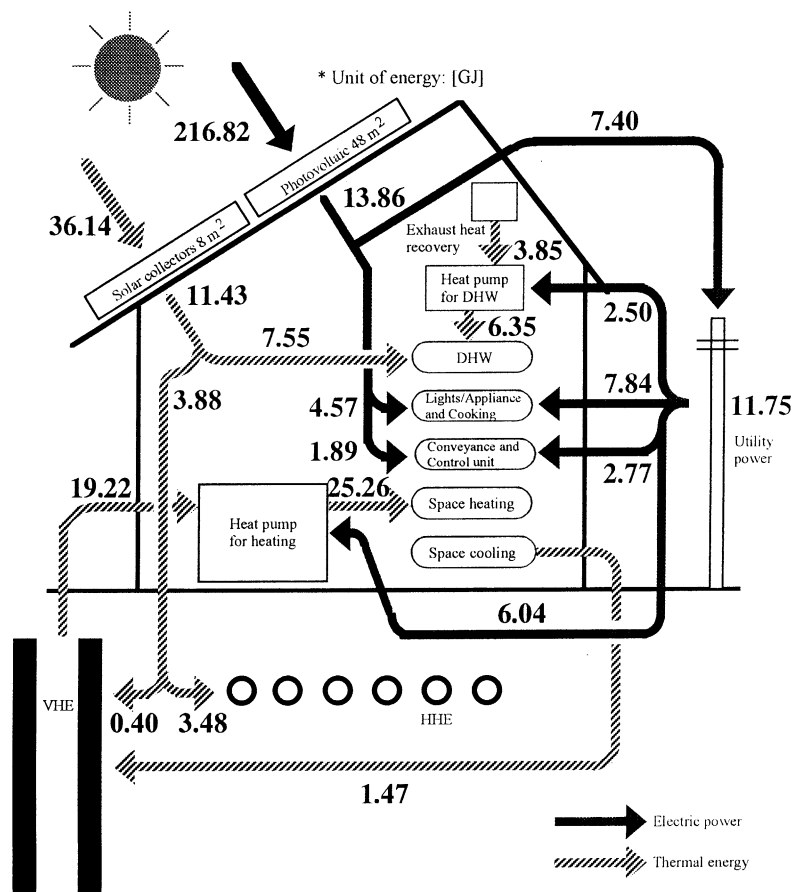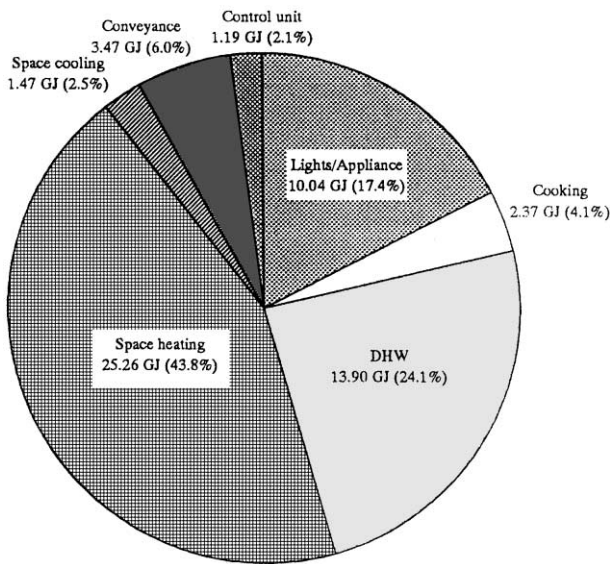

Fig. 5. Annual energy balance.

Fig. 6. Annual energy consumption for specific use.

Fig. 8. Energy conservation through renewable energy utilization.

66% (7.55 GJ) of the collected solar heat (11.43 GJ) was utilized for DHW, and the rest was used for thermal energy storage by the HHE as well as for the recovery of the ground temperature around the VHE. The energy flow of thermal conduction in the underground from the HHE to the semi-basement is not shown in this figure because it was not measured. It is considered that the energy efficiency and economical benefits of the HHE require further study. The exhaust heat recovery system accounted for 3.85 GJ which corresponded to 46% of DHW. The annual electric power generation by the PV system was 13.86 GJ, and 53% (7.40 GJ) of the PV power was supplied through the grid as reverse power.
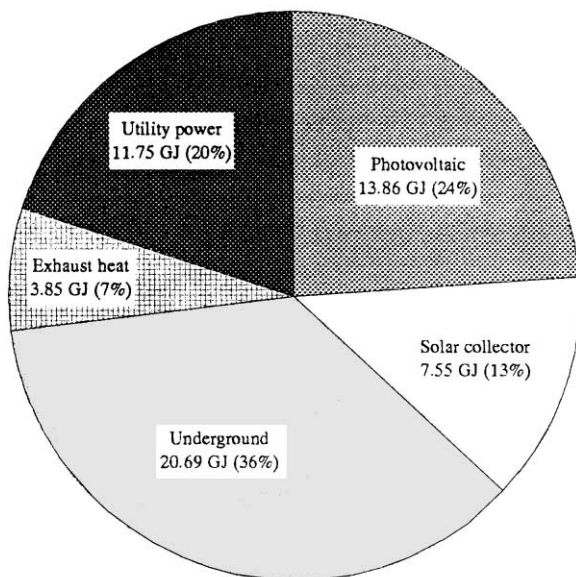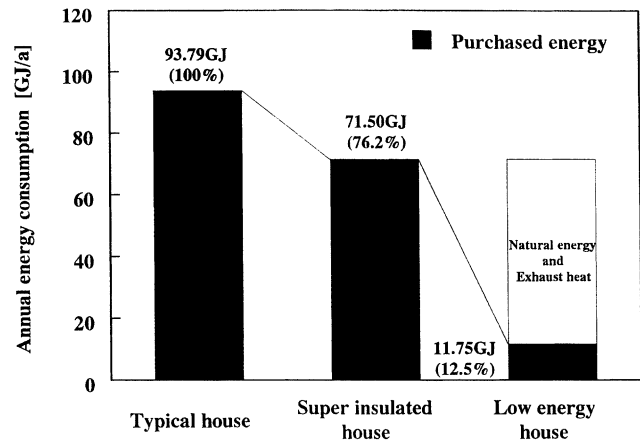
Figs. 6 and 7 show annual energy consumption for specific use and annual fuel distribution, respectively. The net amount of purchased utility power was obtained by deducting the reverse power from the PV system. In Fig. 6, conveyance indicates energy consumption of circulating pumps for heating/cooling or DHW, and control unit refers to total electric power use of all control equipment. Total electric power use was 25.61 GJ, and 54% of this (13.86 GJ) was supplied from PV modules. Total annual energy use in the home was 57.7 GJ. The percentage of each energy source was 20% for utility power, 73% for natural energy resources (PV: 24%, solar collector: 13% and underground: 36%) and 7% for exhaust heat recovery.

Fig. 8 shows annual energy consumption for a typical home, a super insulated home, and the low energy home [8]. The value for the super insulated home shows energy conservation due to thermal insulation, direct solar heat gain, earth tubes, the PCM and the HHE. The energy consumption is 71.50 GJ, which is 76.2% that of the typical home, though the contribution ratio of each technology has yet to be clarified. The value for the low energy home, which includes effects of the solar collectors, the PV system, the VHE and the exhaust heat recovery system, is 11.75 GJ, or 12.5% that of the typical home. Therefore, the low energy home consumes 87.5% less energy than a typical home. Meanwhile, CO_2 emissions of the low energy home and the typical home were calculated by using carbon emission coefficients of fuels, i.e. electricity: 0.139 kg C/kWh, kerosene: 0.706 kg C/l, city gas 6B: 0.320 kg C/m^3 and commercial propane: 1.630 kg C/m^3 [21]. From the view point of environmental protection, CO_2 emissions were reduced by 77% in the low energy home.

6. Discussion of results

Table 5 shows eight types of homes (A–H) classified by thermal insulation and equipment composition. The thermal insulation performance of types A–D is conventional and

Fig. 7. Annual fuel distribution.

Table 5
Eight types of homes classified by thermal insulation and equipment composition

Type	Thermal insulation	Equipment composition				
		Electric power	Cooking	DHW	Space heating	Space cooling
A	Conventional	Utility	City gas	Boiler	Boiler	–
B				Solar collectors and exhaust heat recovery		
C		PV + utility				
D			PV + utility		GSHP	
E	Super insulated	Utility	City gas	Boiler	Boiler	Room cooler
F				Solar collectors and exhaust heat recovery		
G		PV + utility				
H			PV + utility		GSHP	GSHP

that of types E–H is at a level equal to that of the experimental low energy home. Equipment systems of the homes consist of the combination of tested measures and conventional systems, and type H is representative of the low energy home. Comparison of the life cycle CO_2 ($LCCO_2$) and the life cycle costs (LCC) are shown in Figs. 9 and 10, respectively. The calculation was carried out according to the following six processes:

1. production and transportation of building materials;
2. on-site construction of a home;
3. production and transportation of equipment materials;
4. use and operation of the home;
5. maintenance and renovations, and
6. demolition of the home.

Methods for calculating CO_2 emissions and costs, using industry input–output tables and a pile up approach utilizing an energy balance for each material manufacturing process, were cited from the Architectural Institute of Japan and the Society of Heating, Air-conditioning and Sanitary Engineers of Japan and so forth [22,23]. A life span of the home for evaluation was assumed to be 60 years. Regarding main equipment for energy saving, useful lives of the PV, solar

collectors and VHE, were assumed to be 20, 20 and 30 years, respectively, for the calculation on maintenance and renovation. $LCCO_2$ becomes small with the replacement of DHW, electric power and heating/cooling systems with energy saving strategies. $LCCO_2$ of type E (1891 kg C per annum) is smaller than that of type C (2016 kg C per annum). Therefore, it can be said that the super thermal insulation is the most important element. $LCCO_2$ of type E–G are lowered to 76, 65 and 55%, respectively. The low energy home (type H) emits 57% less CO_2 than the typical home (type A). In the meantime, LCC is increased by utilizing renewable energy, though the cost for use and operation is reduced. LCC of type E–G are 68–82% in comparison with type A; LCC of type H, however, is 14% larger. The calculated payback periods were approximately 28 years for the PV, 15 years for the solar collectors and 8–25 years for the GSHP with the VHE.

The authors have carried out experiments on various energy saving techniques for the low energy home in Hokkaido. It has been deduced that super thermal insulation, direct solar heat gain, natural ventilation, earth tubes, solar collectors, and so forth, improve energy efficiency of homes without too much cost, while the payback times of the PV
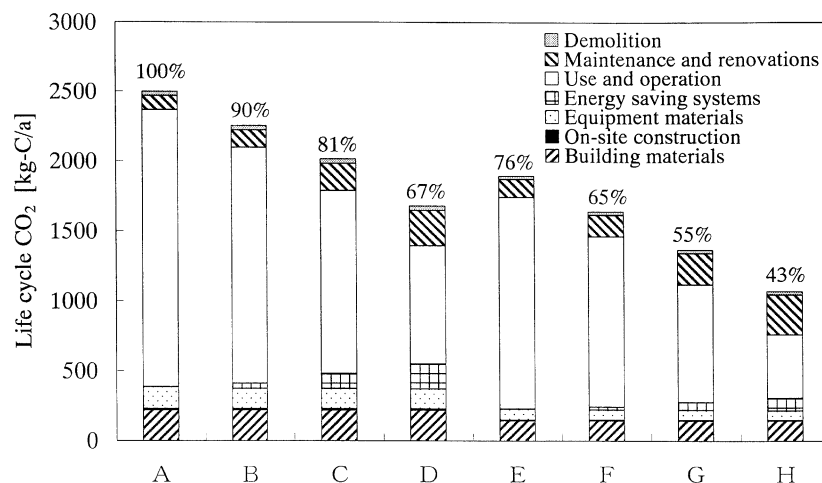
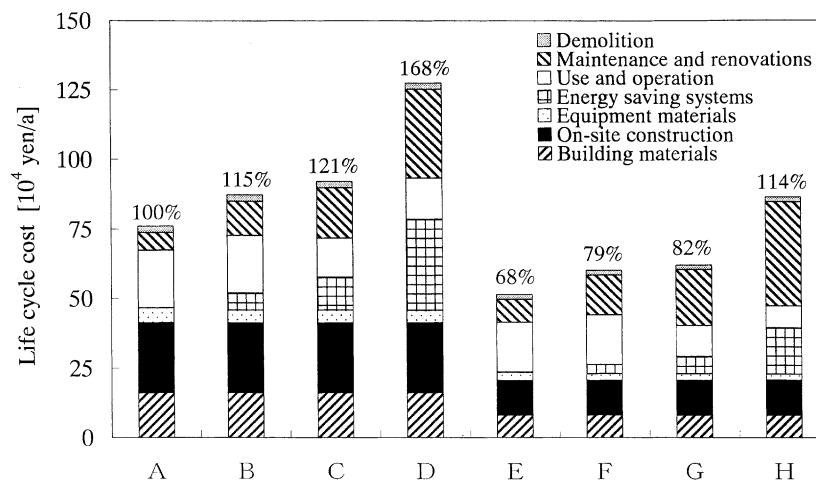Fig. 9. Comparison of life cycle CO_2.

Fig. 10. Comparison of life cycle cost.

and the GSHP are long in the current situation. Regarding the GSHP, it is necessary to reduce the installation cost of the VHE, which is approximately ten times higher than cost in Europe. Energy efficiency and economical benefits of the PCM and the HHE are future themes. Also, it is necessary to verify the applicability of the low energy home to other domestic regions and overseas in the future.

7. Conclusions

This paper describes the equipment design and performance of a low energy home with GSHP which was built in Hokkaido, Japan in March 1997. The following results were obtained.

1. It was experimentally proven that GSHP utilizing a $10°C$ constant earth temperature layer was sufficient for cooling in Hokkaido. SCOP in the 4 h intermittent cooling was found to be 9.1.
2. In heating operations with GSHP, the results of COP and SCOP were quite high; 4.0 and 3.1, respectively. The primary energy reduction rate relative to typical heating was 34%.
3. The amount of annual purchased energy for the low energy home was 11.75 GJ, an energy reduction relative to a typical home of 87.5% and a CO_2 reduction of 77%.

Acknowledgements

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