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LOW ENERGY HOUSE WITH GROUND SOURCE HEAT PUMP IN HOKKAIDO

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ABSTRACT

This study describes the construction and evaluation of a low energy house which should be in harmony with the environment, assisted by hybrid natural energy resources as well as supplied by unused energy. An experimental house with ground source heat pump (GSHP) was built at Hokkaido University, Japan in March, 1997. As a result of experiments, it was shown that approximately 80% of the total energy was provided from photovoltaic (PV) modules, solar collectors, underground and exhaust heat. The annual energy consumption was 12.5% of a typical house in Hokkaido.

1. INTRODUCTION

A low energy house with GSHP was constructed at Hokkaido University, Japan in March, 1997 (Nagano et al., 1997a, b, Hamada et al., 1997, 1998, Ochifuji et al., 1999). This study is one link in the national project “Development of Urban Metabolic Systems for Sustainable Cities” (the Project representative: Prof. T. Kashiwagi), which is part of the research on “Realization of Environment Friendly Society” (the Leader: Prof. Y. Kaya). It has been supported by the Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Corporation. It started in 1996, and has been carried out by the research group of eleven members (Prof. K. Ochifuji et al.) from Hokkaido University and Hokkai Gakuen University.

In order to minimize energy consumption, an ideal house should be in harmony with the environment, assisted by natural energy resources and supplied by unused energy. The construction and evaluation of a low energy house is a step towards an autonomous house that is individually decentralized and utilizes renewable energy. This study is focused on unification and integration of various passive and active strategies including GSHP which take account the annual energy balance.

2. OUTLINE OF LOW ENERGY HOUSE

Fig. 1 and Fig. 2 show an elevation and plan of the low energy house. Its building area is 64 m^2, which is close to the average house in Japan. The house has a semi-basement in order to utilize underground thermal energy storage (UTES). A total floor area including the basement is 192 m^2.

This house is super insulated and air-tight for which a thermal insulation panel construction was adopted. This method may be effective for saving materials and energy. These panels have expanded polystyrene boards of 236 mm thickness for the insulation of all walls and the roof. The glazing in the south wall is 21 m^2. Double-glazed, argon-filled windows with low-emissive coating, which have 1.38 W/(m^2·°C) heat transfer coefficient, are used. In addition, awnings are used for solar shading. A calculated value of a coefficient of heat loss was 0.97 W/(m^2·°C). The measured value of an equivalent leakage area per floor area was 0.81 cm^2/m^2 with sealed ventilation inlets. The house has two kinds of main passive strategies; direct solar heat gain and natural ventilation with an exhaust stack. Daily variation of room temperature is reduced in range by the large heat capacity of concrete slabs and phase change material (PCM) in the second floor. The PCM has a 20°C melting point.

3. EQUIPMENT DESIGN

Fig. 3 shows an equipment design for the low energy house. An electric power is supplied by grid-connected PV. This is composed of single-crystalline silicon PV modules (24 m^2: 3.1 kWp) and triple amorphous silicon PV modules (24 m^2:1.3 kWp) integrated with roofing materials. Also, a 0.6 kWp-wind power generator was adopted.

GSHP was adopted for floor heating and cooling. Two steel wells (i.d. 81 mm) are used as vertical earth heat exchangers (VHE). The two VHE were installed 5 m apart. Each of them was buried into the borehole which was 30 m in depth and 110 mm in diameter. Gaps between the VHE and soil were filled up with mortar. Brine is injected at the bottom part in the VHE and returns from the upper part. In this process, heat is exchanged between brine and soil. Propylene glycol solution (35 wt%) is used as brine. In summer, a floor cooling, which directly brings underground cold into the house, is operated.

Solar heating and an exhaust heat recovery system supply the domestic hot water (DHW). Flat plate type solar collectors, which have 8 m^2 gross area, are used. An 1.0 m^2-flat plate type evaporator of a heat pump (rated output 0.4 kW) for heat recovery was installed outside of an opening at the top of the exhaust stack. The volume of a hot water tank is 0.3 m^3. The underground is charged in summer and fall by means of solar collectors. The horizontal earth heat exchanger(s) (HHE) at a depth of 2.15 m are used for UTES in order to reduce a heating load in winter. They consist of 300 m cross-linked polyethylene pipes. Each pipe has a distance of 0.2 m, which are all subdivided into three parallel segments.

A ventilation system using the exhaust stack is one of the passive strategies. It is driven by the temperature difference between indoor and outdoor air. The fluctuation of temperature is stabilized by utilizing earth tubes and thermal capacity of the semi-basement temperature stable. The earth tubes are used for pre-heating/cooling of supply air for ventilation. They are made of polyvinyl chloride pipes (i.d. 200 mm). Two different types of earth tubes were symmetrically installed at the depth of 1.3 m. One is 2.2 m long, and the other is 20.7 m. Either of the two is utilized to provide air supply in the semi-basement.

4. ESTIMATED ANNUAL ENERGY USE

In Fig. 4, the estimated annual energy use of the low energy house is shown. Utility power in this figure was calculated by subtracting the reverse power through PV modules from the total amount of electric power. The total amount of annual energy use in the low energy house is 43.8 GJ which is almost half of a typical house (Nagano et al., 1993). Approximately 91 % of the total energy is provided from PV modules, solar collectors, underground and exhaust heat while the rest is from utility power. A calculated value of total purchased secondary energy (4.1 GJ) is less than 5 % of a typical house in Hokkaido (93.8 GJ) (Nagano et al., 1993).

5. EXPERIMENTAL RESULTS

5.1 Cooling Experiment

A floor cooling experiment with VHE was operated in summer, 1997. Table 1 shows conditions of cooling experiments. Indoor thermal environment, a cooling load, system coefficient of performance (*SCOP*) and so forth were measured. Three kinds of tests were carried out. A thermostatically controlled operation and a 4 hour-intermittent operation were running for 3 days. A 19 day-continuous operation from July 25, 1997 to August 12, 1997 was tested in order to verify the performance and stability of the VHE for underground cold utilization. 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 glazing. A 2.2 m-earth tube was utilized for air supply. The ventilation rate by the tubes ranged between 23 and 230 m^3/h.

Table 2 shows experimental results in each cooling operation. A particular day was chosen for each operation; July 15 for the thermostatically controlled operation, July 24 for the 4 hour-intermittent one and July 28 for the continuous one. These results are daily average values. The average value of the outdoor air temperature was 22.4 °C on July 15, 23.9 °C on July 24 and 24.9 °C on July 28. The maximum value was 28.6 °C on July 15, 30.6 °C on July 24 and 29.2 °C on July 28. The room temperature (1^{st} floor and 2^{nd} floor), was higher in the 2^{nd} floor throughout all the operations. The average daily temperature difference between the 2^{nd} floor's room and the outdoor air was 3.1 °C in the thermostatically controlled operation and 3.2 °C in the 4 hour-intermittent one. The average daily temperature of the 1^{st} floor's room was 23.4 °C in the thermostatically controlled operation and 24.9 °C in the 4 hour-intermittent one. In both operations, the average daily temperature difference between the 1^{st} floor's room and the outdoor air was approximately 1 °C.

The operation time of the thermostatically controlled operation was 8.3 hours. The heat rejection rate of the VHE into 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 hour-intermittent operation, the heat rejection rate of the VHE was 30.3 W/m and *SCOP* 9.1. Therefore, it was experimentally found that GSHP utilizing about 10°C-constant earth temperature layer was efficient 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 about 41 % lower than that of 4 hour-intermittent operation.

5.2 Heating Experiment

A heating experiment started from November 5, 1997. Fig. 5 shows an outline of GSHP with the two VHE. The rated output of an installed heat pump is 0.82 kW. A heat storage tank (0.93 m^3) was set up for peak demand. Floor heating is controlled thermostatically and starts when the room temperature is below 18 °C.

Table 3 shows the experimental results during the heating period (from November 5, 1997 to April 30, 1998). The average operation time per day was 12.5 hours. The temperature of the brine between flow and return of the VHE during the heating period was 2.1°C. The average heat extraction rate from the underground (per unit well length) of the VHE was 40.8 W/m. Each average value was 4.0 for coefficient of performance (*COP*) [= (Thermal output) / (Electric energy for compressor of heat pump)] and 3.1 for *SCOP* [= (Thermal output) / ((Electric energy for compressor of heat pump) + (Power of circulating pumps for heating))] . The value of *COP* was quite high due to the adoption of low temperature floor heating. However, the *SCOP* was about 23 % lower than the *COP*. The total amount of a seasonal heating load was 20.9 GJ.

Fig. 6 shows the relation between *COP* of GSHP and primary energy reduction rate for typical heating (conventional boiler system). In this figure, Ep/Eh is a ratio of power of circulating pumps to electric energy for compressor of heat pump. Ep/Eh was 0.24 in this experimental condition. On the other hand, each value of 0.15 and 0.10 is for an improved case of the efficiency of circulating water pump. An experimental value of primary energy reduction rate to typical heating was approx. 34 %. In the case of Ep/Eh=0.1 and *COP*=4.5, the rate is approximately 50 %. Therefore, it is possible to say that GSHP would be a quite effective heating system for saving energy.

5.3 Annual Energy Balance

Table 4 shows experimental annual energy use of the low energy house. Conveyance in this table is power of circulating pumps for heating/cooling or DHW, and a control unit means total electric power use of each control equipment. The total amount of electric power use was 25.61 GJ, and 54% of the amount (13.86 GJ) was supplied from PV modules. The total amount of annual energy use in the house was 57.7 GJ. A 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 the exhaust heat recovery. The experimental electric energy consumption from utility power was larger than the predicted value because of the low efficiency of PV modules and solar collectors as well as lack of internal heat gain in winter.

Fig. 7 shows the annual purchased secondary energy consumption of a typical house, a super insulated house and the low energy house (Nagano et al., 1993). Energy consumption of the super insulated house including direct solar heat gain was 71.50 GJ. The value of the low energy house was 11.75 GJ which is 12.5% of a typical house. Therefore, energy reduction rate compared to a typical house was 87.5 %. From the viewpoint of environmental protection, CO_2 reduction rate was 77 %.

6. CONCLUSIONS

This paper described an outline of a low energy house with GSHP and its equipment design which was built in Hokkaido, Japan in March, 1997. The following results were obtained through experiments and analyses of the energy balance of the house.

It was experimentally found that GSHP utilizing about 10 °C-constant earth temperature layer was efficient for cooling. *SCOP* in the 4 hour-intermittent cooling was 9.1. The experimental results of the heating operation with GSHP showed that *COP* and *SCOP* were quite high at 4.0 and 3.1, respectively. The primary energy reduction rate to typical heating was approximately 34 %.

The amount of annual purchased energy for the house was 11.75 GJ. Therefore, the energy reduction rate compared to a typical house in Hokkaido was 87.5 % and CO_2 reduction rate was 77 %.

ACKNOWLEDGEMENTS

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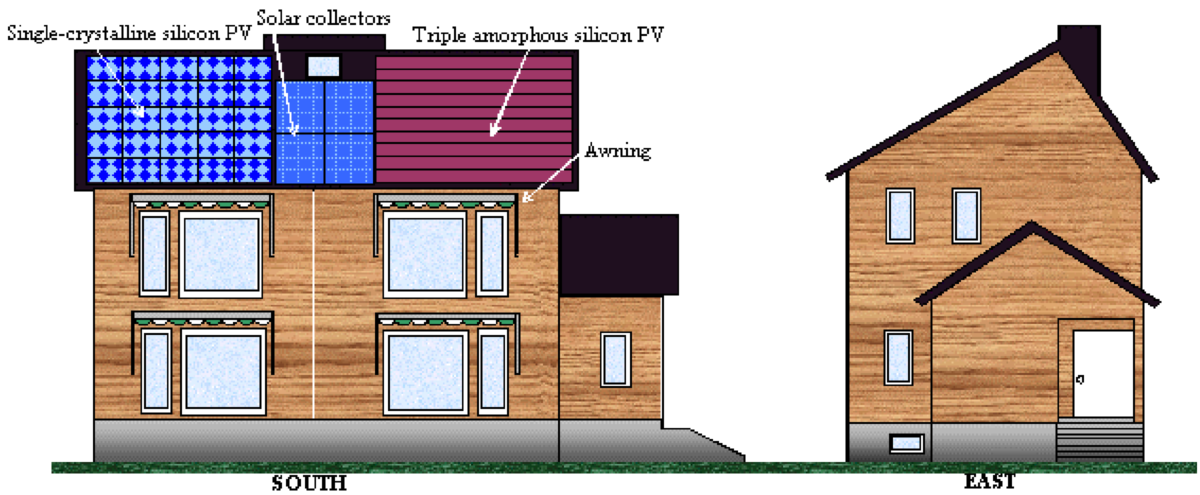

Fig. 1 Elevation of low energy house

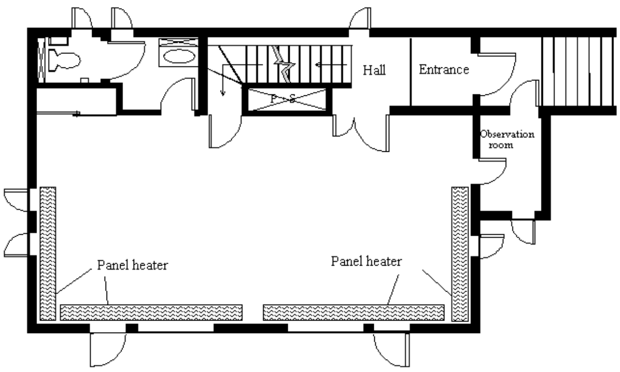

Fig. 2(a) The 1st floor plan

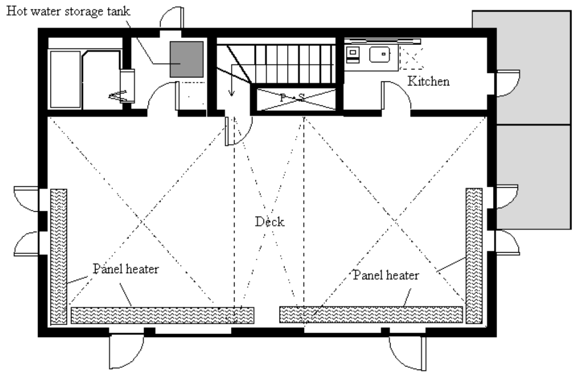

Fig. 2(b) The 2nd floor plan

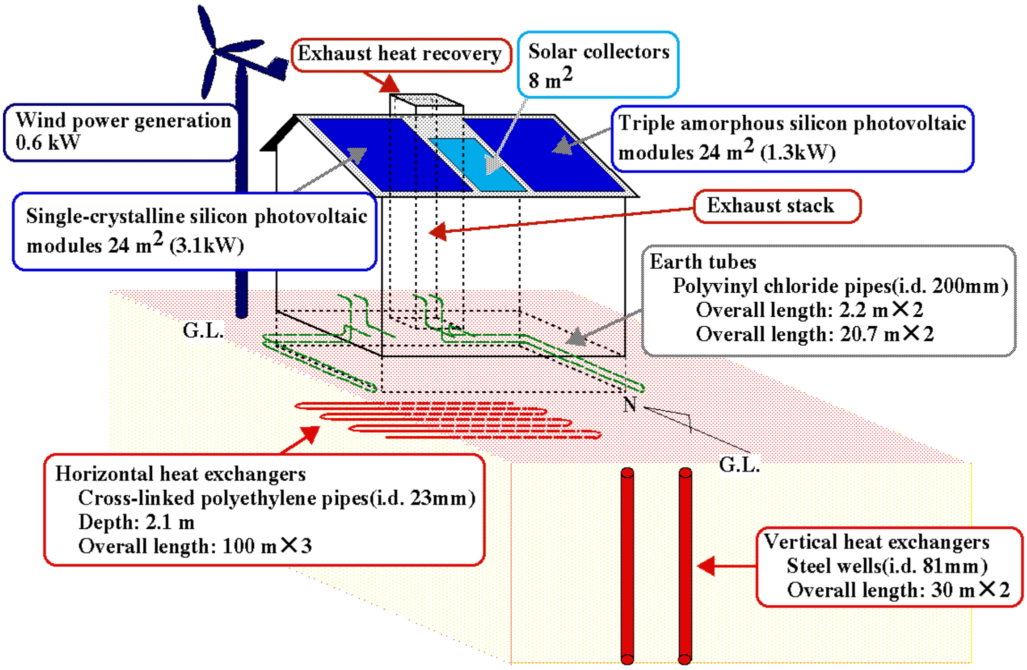

Fig. 3 Equipment design for low energy house

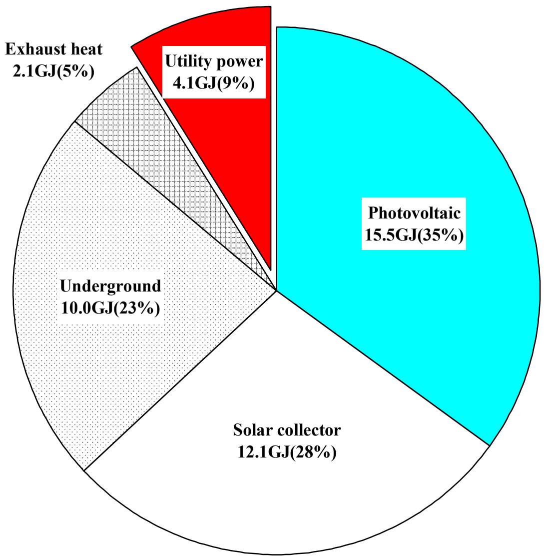

Fig. 4 Estimated annual energy use

Table 1 Conditions of cooling experiments

Cooling period	Mode of operation
Jul. 13, ’97 - Jul. 15, ’97 (3 days)	Thermostatically controlled operation(2nd floor, 26 °C)
Jul. 22, ’97 - Jul. 24, ’97 (3 days)	4 hour-intermittent operation(2nd floor, 9:00-13:00)
Jul. 25, ’97 - Aug. 12, ’97 (19 days)	Continuous operation(2nd floor)

Table 2 Experimental results of each cooling operation

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

[*)] Average temperature of brine’s flow and return

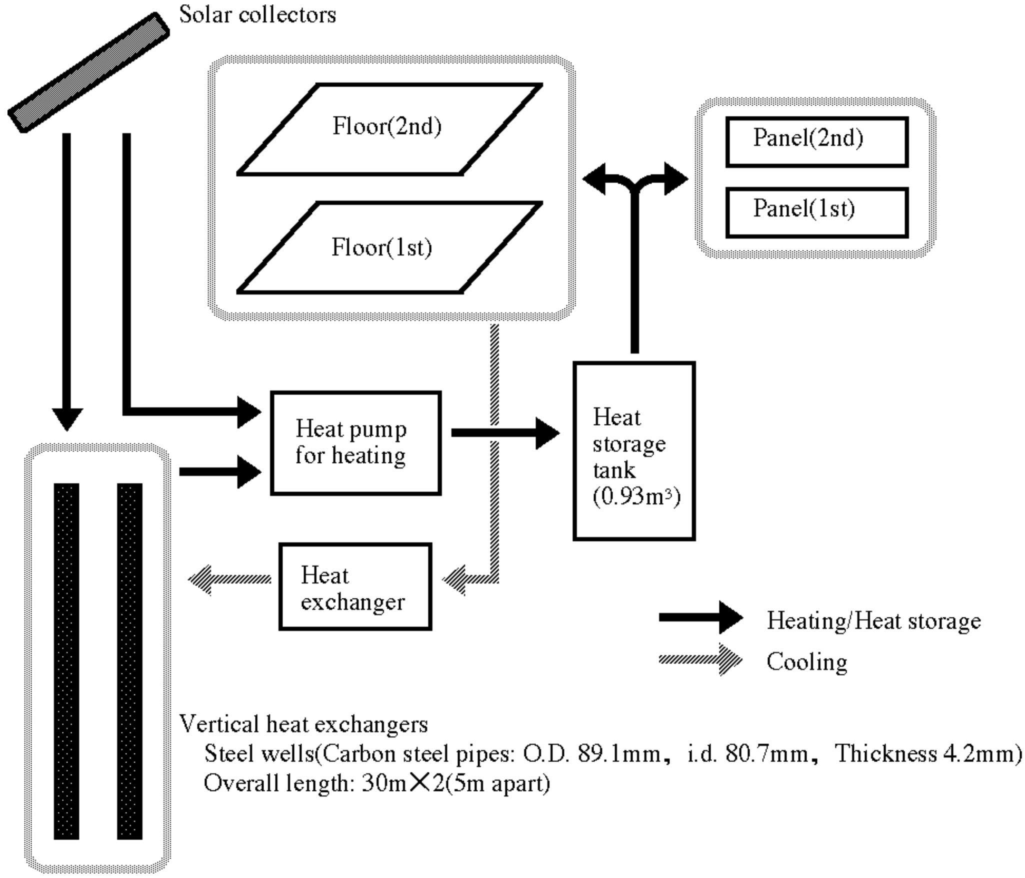

Fig. 5 Outline of GSHP

Table 3 Experimental results of heating operation
(Average daily values in Nov. 5, '97 - Apr. 30, '98)

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

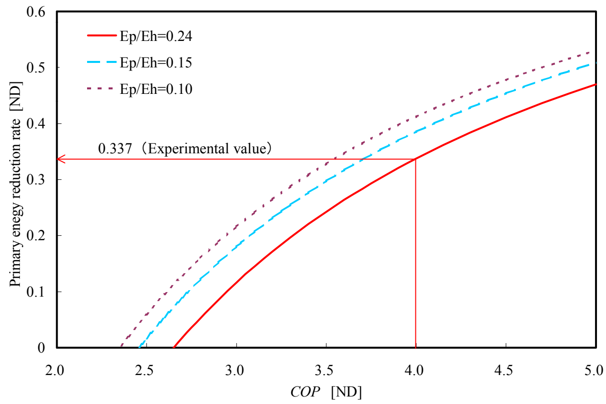

Fig. 6 Relation between *COP* of GSHP and primary energy reduction rate to typical heating

Table 4 Experimental annual energy use

	Utility power	Photovoltaic	Solar collector	Underground	Exhaust heat	Total[GJ/a]
Lights/Appliance	10.04		0.00	0.00	0.00	10.04
Cooking	2.37		0.00	0.00	0.00	2.37
DHW	2.50		7.55	0.00	3.85	13.90
Space heating	6.04		0.00	19.22	0.00	25.26
Space cooling	0.00		0.00	1.47	0.00	1.47
Conveyance	3.47		0.00	0.00	0.00	3.47
Control unit	1.19		0.00	0.00	0.00	1.19
Reverse power	-7.40	+7.40	0.00	0.00	0.00	0.00
Total[GJ/a]	11.75	13.86	7.55	20.69	3.85	57.70

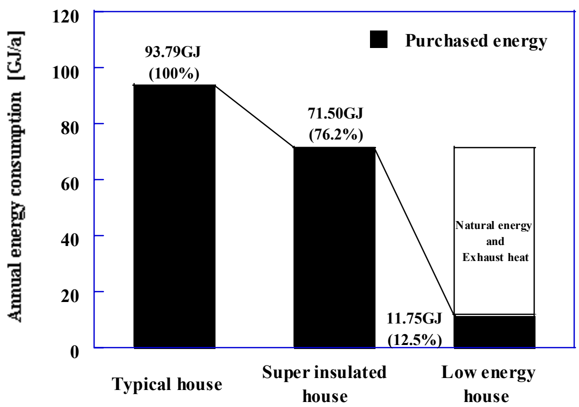

Fig. 7 Annual energy consumption