ZEB ready for children care center in cold region in Japan; - GSHP floor heating combined with exhaust air heat recovery

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Abstract

Amount of energy consumption for heating in cold regions could be significantly reduced by the utilizing Ground Source Heat Pump (GSHP), which is one of the promising system for achieving a net-zero energy building (ZEB) in cold regions. Our team had related to planning, designing and construction of Rusutsu children care centre which has opened from May, 2015 in cold and snowy region in Japan. This building oriented to “ZEB ready” which is similar to “near ZEB” and is defined as a building which can reduce the amount of primary energy consumption by half compared to conventional buildings. Typical passive design techniques and installations which use renewable thermal energy resources including GSHP have been adopted. Here, Rusutsu village is well known as a sky resort area and one of the coldest villages with heavy snowfall in Japan. The minimum air temperature often reaching below -25 ºC. In this research, the analysis of the actual annual energy balance and measuring results of the indoor thermal environment and the air quality are shown. Then the optimization control methodology of GSHP for the floor heating was examined by using our own developed “ZEB simulator “, which could reproduce the actual annual electric power consumptions of GSHP and the room temperatures. Annual energy balance was evaluated and the effectiveness of GSHP for low temperature floor heating was clarified.

Keywords: ZEB; Ground source heat pump; meeasument; simulation; energy consumption; indoor thermal environment, indoor air quality

1. Introduction

The recent research of self-sufficient in energy building have been pushed forward all over the world. In Japan, The Ministry of Economy, Trade and Industry of Japan held working group of the ZEB Roadmap Review Panel [1]. This Roadmap stipulates the political goal aiming to realize the ZEB concept in newly-constructed public buildings by 2020 and to achieve average net zero emissions in newly-constructed buildings by 2030. Here, a ZEB is defined as a building which consumes zero or nearly zero primary energy consumption for a whole year (METI, 2015). In Europe, the Energy Performance of Building Directive specified that all newly-constructed building must be nearly ZEB by 2020 (EPDB, 2010) [2]. Combination of various technologies have been considered to achieve ZEBs, for example, improving building envelope performance, developing high efficiency equipment and generating energy by using renewable energy. GSHP can help to greatly reduce energy consumption for heating in cold regions.

Our team is related to planning for constructing Rusutsu children care center from 2013, which oriented to ZEB ready. Here, ZEB ready is defined as a building which reduces half of the amount of primary energy consumption in comparison with conventional building by the Roadmap. Rusutsu village (42.7º N, 140.8º E) is located in southwestern Hokkaido, which is in north part of Japan. Rusutsu village is well known as one of the coldest villages with heavy snowfall, with the minimum air temperature often reaching -25oC and annual average temperature is 9.4ºC. The population is approximately 2,000 and an area is 120 km^2, the main local industries is agriculture. In this research, first we show the first winter measuring results of energy balance and indoor environment of low-energy children center with GSHP heating system in Rusutsu village, Hokkaido Japan. Next, we developed a simulation program which predicted the room temperature and the energy flow of heating, and considered the optimization control method of GSHP for floor heating by changing the circulating water temperature and operation time [3]. Finally, the energy flow of heating and effectiveness of GSHP system in cold region are evaluated from simulating.

2. Approaches for Nearly ZEB

Rusutsu children care center was built in May 2015 (Figure 1). The center has nursery, child care support center, children's house and after school children club. Meanwhile the center is working as a child welfare core facility of the region and also as a shelter of disasters. It is single story building made of wood, the site area is 6,300 m^2, construction area is 1,601.4 m^2 and total floor area is 1,500 m^2. This building is well insulated. For example, the roof was made by rigid urethane foam with a thickness of 200 mm, the outside wall was made by glass wool with a thickness of 200 mm, and the floor was made by polyethylene foam plates with a thickness of 100 mm. Moreover, windows are Low-E of argon-filled triple glazed window, the heat transfer coefficient is 1.22 W/(m^2・K). In addition, this center has large heat capacity by using much concretes and bricks in the floor and outside wall. Also, skylights are equipped in order to take natural light into rooms on the north side.

The geological condition of this site was mainly consisted of silt and volcanic ash. The results of thermal response test (TRT) indicated that the effective thermal conductivity of the ground was 1.45 W/(m・K), thermal resistance of ground heat exchanger is 0.060 (m・K)/W and initial ground temperature is 9.8ºC. Density and specific heat of the ground were estimated from the geological condition of the site, 1200 kg/m^3 and 1850 J/(kg・K), respectively.

Schematic diagram of floor heating system is shown in Figure 2. GSHP system (rated heating output 28 kW × 3 units) is used to supply heat with fifteen vertical ground heat exchangers (ID 25 mmΦ single U-tube 85 m in length × 15), and secondary side is floor heating. Fan coil units in the staff room and the kitchen are adopted to perform free cooling using underground heat. An air-source heat pump (heating capacity 7.2 kW or more) and evacuated tube solar collectors (3 m^2 × 2 units) are used to supply hot water to the kitchen. In order to reduce the heat demand for ventilation, four heating and cooling tubes and high efficient heat recovery ventilation units have been introduced. Four tubes with average total length of 38.8 m, diameter of 400 mm and burial depth of about 2.5 m from GL are adopted for pre-heating and pre-cooling of outside air. In addition, passive humidity and odor control chamber is introduced using underfloor pit filled with natural mesoporous rock (Wakkanai siliceous shale) and charcoal. In the air handling unit, all heat recovery mechanical ventilation systems (heat exchange efficiency more than 70%) is adopted. An exhaust heat collection coil can be used to raise the primary side outlet temperature from the heat pump unit. Sensible heat recovery mechanical ventilation systems are adopted into toilets and kitchen. LED lamps and top lights on the roof are adopted for lighting. The thermal performance of insulation is shown in Figure 1 (c). Due to the high-efficiency equipment and high thermal insulations, overall heat loss coefficient per total floor area of this center is 0.93 W/(m^2・K). Introduced energy conservation techniques for ZEB are shown in Table 1.

Also, BEMS (Building Energy Management System) has been equipped. It can show the energy consumption and thermal environment on the monitor. It is very effective to know and to improve the operation of the heating. The energy consumption, thermal outputs and temperatures in rooms and floors are measured.

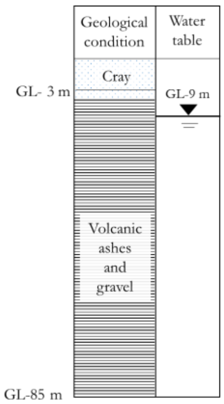
Table 1. Introduced energy conservation techniques

Heating and cooling	Floor heating by GSHP (Max. 33 kW X 3) and natural cooling Ground heat exchanger (25 mmϕ single U-tube 85m deep X 15)
DHW	Evacuated solar thermal collectors (3.3 m^2 X 2) + 1000 L storage tank + CO_2 air-source heat pump (7.2 kW X 1) + 1000 L hot water tank
Ventilation system	Heating and cooling tube (PVC 400 mmϕ, L=38.8 mX 4,) + passive humidity control by natural meso-porous rocks and charcoals in underfloor chamber → total heat recovery mechanical ventilation (AHU) for play rooms → sensible heat recovery mechanical ventilation for utility space

b) Appearance of the building,

c) Plan view and photo of nursery room

Fig 1. Rusutsu children center, Rusutsu village, Hokkaido, Japan



Effective thermal conductivity by TRT;
λ=1.41 W/(m・K)

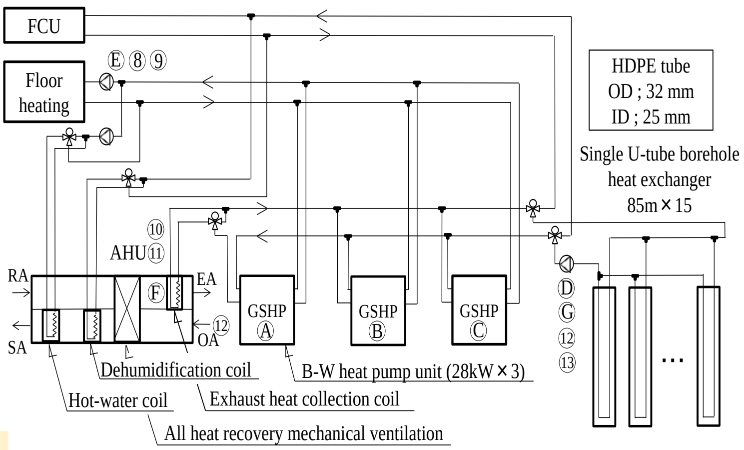


Fig 2. Geological condition and schematic diagram of GSHP floor heating system

3. Measuring results of energy consumption, indoor thermal environment and indoor air quality

3.1 Annual variation of temperature and energy

Figure 3 shows seasonal variation of the daily thermal energy demand of GSHP for floor heating system and the indoor air and circulated brine temperatures from October 1st 2015 to April 30st 2016 during heating season. At the beginning of the heating season, GSHP heating output was fluctuated due to the intermittent operation. It is because the lack of the operating experiences of GSHP floor heating system at the first year of this building. The

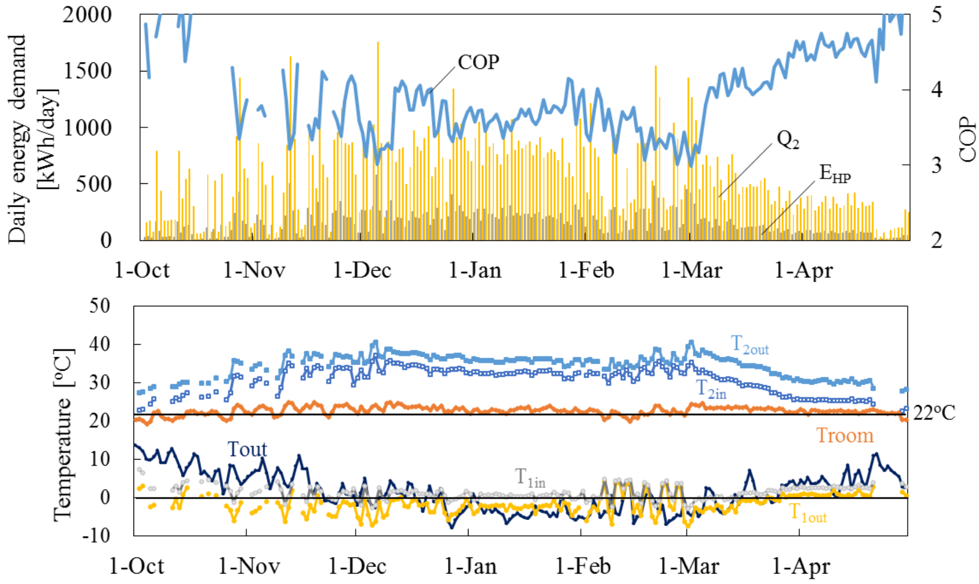


Fig 3. Annual variation of the temperature and energy from Oct. 2015 to Apr. 2016

COP in January became higher according to the proper floor temperature control by continuous GSHP operation although heating demand is much higher. The monthly energy consumptions and average room temperatures are shown in Table 2. The output of GSHP is in the heating period is 125 MWh, and total amount of electric power consumption is 33.6 MWh. As a result, the seasonal average COP was obtained at 3.72. The seasonal and spatial average room temperature was kept at above 22°C in this season. Here the supply temperature from the GSHP to the floor heating was around 35.9 °C. In this case, the minimum monthly average outlet brine temperature of the primary side of GSHP was -3.6 °C in January.

Table 2. The monthly heating energy balance

	Tout [°C]	Troom [°C]	T_{2out} [°C]	ΣQ_2 [kWh]	$\Sigma Q_{1,ground}$ [kWh]	$\Sigma Q_{1,ehxaust}$ [kWh]	ΣE_{HP} [kWh]	COP [-]
Oct. 2015	8.5	21.6	30.7	11,404	7,959	2,896	2,632	4.33
Nov.	4.1	23.3	35.9	18,488	12,010	4,100	4,996	3.70
Dec.	-0.5	23.5	37.3	25,585	15,856	5,008	7,219	3.54
Jan. 2016	-3.6	22.9	35.9	25,819	15,507	5,498	7,036	3.67
Feb.	-2.8	22.1	35.6	19,353	12,239	3,714	5,722	3.38
Mar.	0.0	23.4	35.0	16,477	13,073	351	4,255	3.87
Apr.	5.3	22.4	30.2	7,869	6,323	505	1,697	4.64

$*$ COP $= Q_2/E_{HP}$

The fraction of the annual electric power consumption of each purpose from June 2015 to May 2016 are presented in Figure 4. The total amount of electric power consumption was 131,225 kWh and it is 87.5 kWh/(m²·a). Here, 33,934 kWh is used for GSHP floor heating, which occupied 26% of total energy consumption. Though this fraction is very small by adapting the high efficient GSHP floor heating system. However, it is still 22.6 kWh/(m²·a) and this value is bigger than expected. The authors think that this can be reduced by modifying the operating control method according to the commissioning and computer simulation analysis of this system.

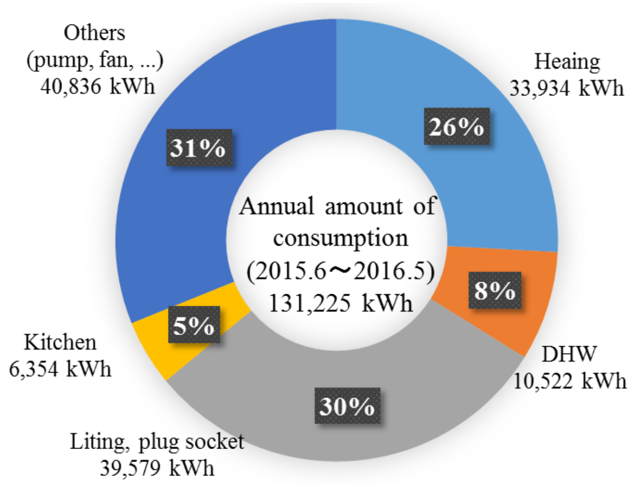


Fig 4. The details of the electric power consumption from June 2015 to May 2016

3.2 Indoor air quality

The thermal comfort and indoor air quality in the center were measured two times. On 4th August 2015 for summer and on 21st November for winter. The measurement items were bacteria, fungi, particle diameter less than 10 μm, temperature, relative humidity (RH) and CO_2. These items measured at four different building zones, indoor air (hall in nursery), supply air and exhaust air at the ventilation system, outside air. The collected bacteria and fungi were cultured at 30°C for two days or at 25°C for five days, respectively.

Here, measured IAQ concentration data is checked according to the standard, AIJES-A0002-2013 (AIJ, 2013) [4]. In this standard, there is no standard of nursery, so the standard of house and elderly welfare was used in this research.

1) An air sampler measuring air polluted by bacteria and fungi
2) An air temperature and humidity and CO_2 concentration sensor
3) A measuring device for collecting particles in the air

Table 3 shows the measuring results in summer and winter. All values in both seasons were corresponded to 'usual level' in standard of house, and corresponded to 'maintenance standard level' in elderly welfare. The CO2 concentration of indoor air was at least 1,000 ppm, which considered as a guide for ventilation. Judged from these survey, the indoor air quality of this center is highly adequate. Besides, the kind of fungi in the heating and cooling tubes is similar to outside air. This result indicates that there is no outbreak of fungi in the tubes.

Table 3. Seasonal differences of air quality

	Indoor air (Hall)		Supply air		Exhaust air		Outside air	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Bacteria [CFU/m^3]	306	656	10	20	110	155	70	21
Fungus [CFU/m^3]	863	65	600	81	556	17	930	97
PM_{10} [mg/m^3]	0.024	0.004	0.024	0.005	0.021	0.002	0.030	0.002
Temperature [°C]	25.4	24.8	20.4	13.8	-	7.5	24.9	3.5
RH [%]	80	34	100	51	100	97	84	66
CO_2 [ppm]	540	877	543	794	493	787	404	488

4. Development of "ZEB simulator" and optimization control methodology of floor heating

4.1 Development of "ZEB simulator"

The authors developed a simulator to predict the room temperature or energy consumption of the building which introduced GSHP system like this center (Takuya Ijima et al., 2015). The overview of the simulator is shown in Figure 6. This simulator consists of six analysis modules: Building; Heat source machine; Ground thermal heat exchanger; Domestic hot water supply (DHW); Ventilation and Room facility. Various data such as the room temperature and energy consumption could be calculated per hour for a whole year.

① Building module; the heat load and room temperature can be calculated. The overall heat transfer of building envelope is calculated as non-steady problem taking into account the thermal storage of building frames. The authors added the multi-room model to calculate for each room. The time variation of each room temperature of large-scale building came to be able to calculate by this model.

② Heat source machine module; the determination of the heat pump operation is done by controlling the room temperature or floor temperature. Also, it is possible to choose in which room temperature sensors are installed. At the time when the heat pump is working, the circulating temperature such as the secondary supply temperature (T_{2out}) can be calculated by the amount of heat release in secondary side (Q_2) and the COP of the heat pump and etc.

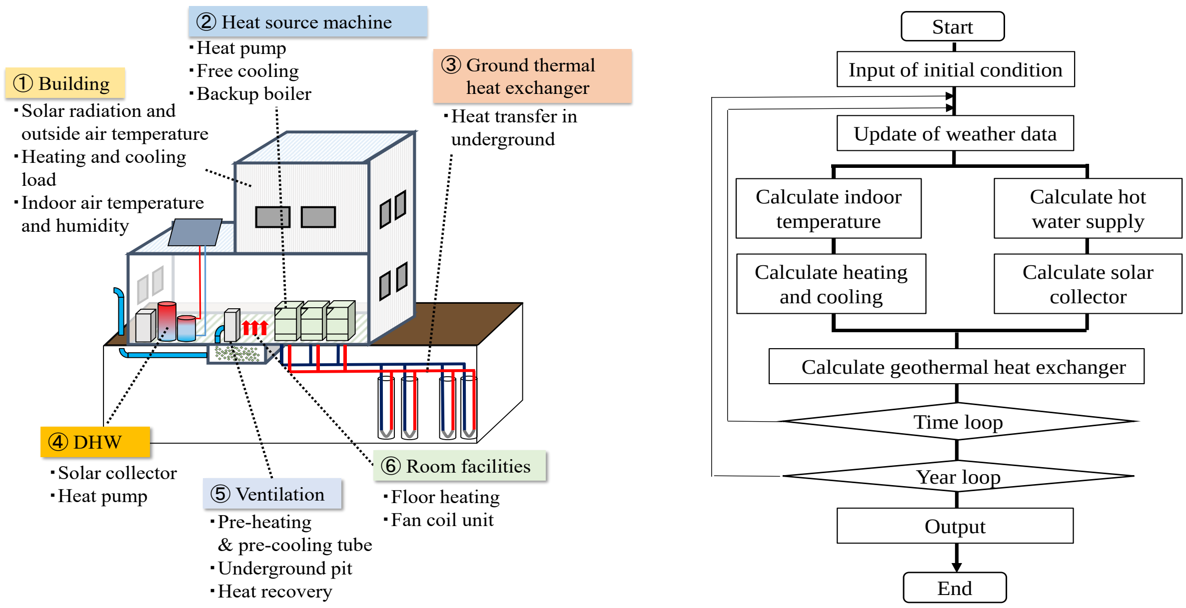
③ Ground thermal heat exchanger module; the circulating return temperature from ground heat exchanger can be calculated from the circulating supply temperature sending into ground heat exchanger by analysing the behaviour of temperature propagations with the theory of infinite cylindrical surface heat flow response. In addition, the authors added a multi-layer model of soil that can be input the property values of each layer so that more detailed heat transfer analysis is possible.

④ Domestic hot water supply module; the performance of heat source machines for hot water supply and solar collectors can be calculated. The output is the amount of heat production, energy consumption, SCOP and etc.

⑤ Ventilation module; the air temperature can be changed through heating and cooling tube and heat recovery systems. First, the temperature of soil and air and humidity in the tube can be calculated from the input of outside air temperature. If the calculated air temperature is lower than the dew point temperature, air temperature is recalculated taken into account the latent heat of condensation. Second, the air sent to chamber is warmed by heat recovery systems in heating period.

⑥ Room facilities module; calculation of heating and cooling of rooms can be done. The amount of heat radiation from buried pipe and the underfloor temperature can be obtained by applying the finite element method.

In this study, to evaluate strategies for saving the amount of energy consumption and keeping an indoor environment well of this center cases of controlling GSHP were simulated using this tool. The simulation was based on the measurement outside air temperature from October to January, and on the Expanded AMeDAS Weather Data (AIJ, 1999) at *Kutchan* town during other period [5]. The calculations were carried out to keep room temperature higher 22 ºC in heating period (6th Oct. – 28th May) by controlling underfloor heating.



a) Calculation modules of the ZEB simulator

b) Calculation flow chart

Fig 6. Developed ZEB simulator; energy consumption and performance prediction tool

4.2 Optimization control methodology of GSHP for floor heating

The optimization control methodology of GSHP for floor heating is examined. Here, we focus on minimize the seasonal amount of supply heat. The authors repeatedly calculated by changing the operation time and circulating temperature for floor heating to seek for operation method to keep room temperature appropriate. The calculation conditions are shown in Table 4. Also, control methods are explained in Figure 7. CASE1 and CASE2 are capable of changing the output of based on the heat load, and circulating flow temperature is set to keep room temperature appropriate by repeatedly calculating. On the other hand, CASE3 keeps constant output monthly.

Figure 7 indicates comparison of the calculation results of the amount of energy consumption and average room temperature in child care support center of daytime on January. The amount of energy consumption of GSHP units is 7.1 MWh, and the average room temperature is 21.9 °C in the condition of CASE1. Then, the amount of energy consumption of GSHP units in the condition of CASE2 can be increased 3% in comparison with CASE1. Also,

	Operation method of floor heating
CASE1	Continuous (24 hours)
CASE2	Intermittent：Stopped on Sunday and 10:00-13:00 on weekdays
CASE3	Constant output：Dec.・Jan.・Feb. / 40 kW, Others / 30 kW

Table 4. Calculation conditions

Item	Input	Item	Input
Meteorolog			K)
Heating			n³
Cooling			K)
Floor heating condotions			
			h
Flc			

*AMeDAS :Autom

The average ro … PM

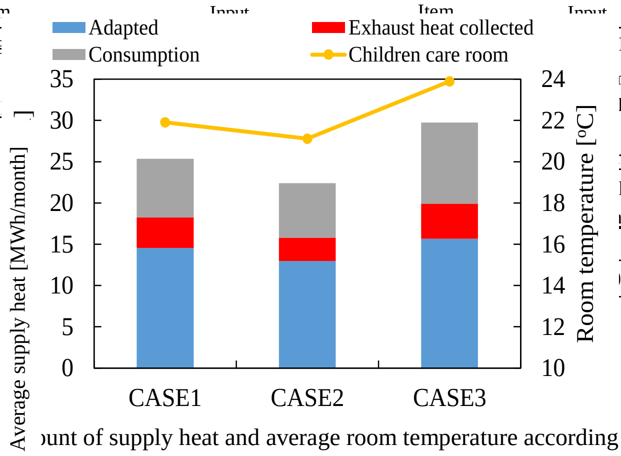


Figure 7 Seasona… ount of supply heat and average room temperature according to the control method

the amount of energy consumption of GSHP units is 9.9 MWh and the average room temperature is 23.9 °C in the condition of CASE3. These results indicate that constant output control method might rise the room temperature and consume much energy.

4.3 Prediction energy flow and performance of GSHP

Figure 8 indicates the calculation results of annual energy flow for GSHP floor heating system combined with heat recovery from the exhaust air of the ventilation system. Here, the fraction of extracted heat from ground and the exhaust air compared to total heating demand are 56% and 17%, respectively. The seasonal GSHP heating SCOP is 3.42, which includes the power consumption of primary side circulation pumps. It is found that heat exchange ability of the heat recovery coil from the exhaust air is equivalent to 4.5 borehole type ground heat exchangers.

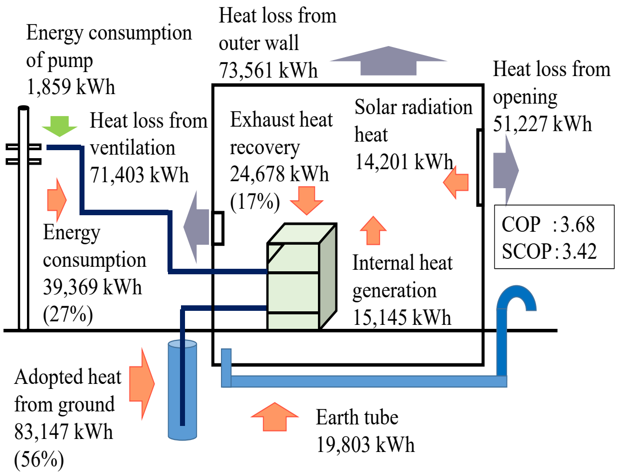


Figure 8 Calculation results of annual energy flow for GSHP heating system combined with heat recovery from exhaust air.

Table 6. Comparison condition

	Overall heat loss coefficient	Heating	DHW	Heating and cooling tube	Lighting
Standard	1.6 W/(m^2·K)	Kerosene boiler	Kerosene boiler	non	fluorescent lamp
Children care center	0.93 W/(m^2·K)	GSHP	ASHP	400mmϕ,40 m long × 4	LED

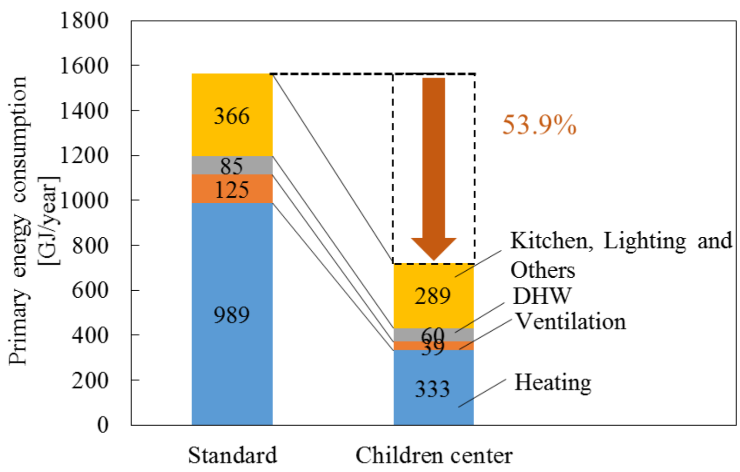


Fig. 9 Amount of reduced primary energy consumption on an annual

Energy reduction amount of this building compared to the conventional performance building heated and DHW by kerosene boilers is evaluated and each effect is clarified. Table 5 shows the comparison of the calculation conditions of these two cases. As a result, Figure indicates that 53.9% of total power consumption is cut. It is also analyzed that effect of adapting GSHP floor heating with higher insulation performance is the biggest and these two combination can reduce the primary energy demand for heating from 989 GJ/year to 333 GJ/year. It is 1/3 and the fraction of the primary energy demand for heating is smaller than a half of the total energy demand.

5. Conclusions

1) Authors measured the energy balance and thermal environment of low-energy children care center with GSHP system. As a measuring result, the average COP of GSHP system is 3.72. The room temperature was kept around 22^{o}C from October 2015 to February 2016.
2) The thermal comfort and indoor air quality in the center were measured two times. The result indicates that the indoor air quality of this center is satisfy the AIJES-A0002-2013.
3) We developed the simulator and confirmed the reproducibility. The calculation result shows the continuous heating is the appropriate condition from the point of thermal comfort and energy conservation. In addition, adopted heat from ground covers 56% of heating demand.

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Nomenclature

T_{out} : temperature of outside air [^{o}C]
T_{room} : temperature of indoor air [^{o}C]
T_{2out} : circulating temperature supplied to floor heating [^{o}C]
Q : Amount of heat [kWh]
E_{HP} : power consumption of heat pump [kWh]
Subscript
1 : primary side
2 : secondary side

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