Field study of system efficiency of detached house with solar energy system and fuel cell cogeneration system in Japan

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Abstract. In this study, the energy flow in detached houses in Sendai City in the Tohoku region of Japan where photovoltaic power generation system, solar thermal collection system, and fuel cell cogeneration system were installed was analyzed based on measured data. Hot water obtained by solar heat collected in the house is used to supply hot water to the kitchen throughout the year, to supply hot water to floor heating and to preheat the air supply of the HVAC system in winter, and to regenerate the desiccant wheel of the HVAC system in summer. A hybrid hot water supply system using city gas and a heat pump is used as an auxiliary heat source for a solar thermal system. As a result, the monthly energy self-sufficiency rate, energy efficiency and heat loss rate of the house for three years were calculated, and the necessity of the optimization of the operation method of the solar thermal system was found. In addition, daily analyses of solar thermal system in winter and summer suggested the importance of the operation corresponding to the weather.

1 Introduction

The energy self-sufficiency rate of Japan in 2019 was 12.1% [1]. As described above, the energy self-sufficiency rate of Japan is very low, and so active use of renewable energy in houses is required. In particular, the use of solar energy is suitable for the energy consumption structure of houses because it can supply electricity and heat by photovoltaic power generation and solar thermal collection. Fuel cell cogeneration system, which generate electricity and heat by chemically reacting hydrogen from city gas with oxygen in the air, are also suitable for houses.

In this study, the energy flow in detached house in Sendai in the Tohoku region of Japan where photovoltaic power generation system, solar thermal system, and fuel cell cogeneration system were installed was analyzed based on measured data, and the operation method to improve the system efficiency was discussed.

2 Methodologies

2.1 Outline of house

The system was introduced in a two-story wooden house that was completed in April 2015. The total floor area is 163 m^2. In terms of heat loss factor, the UA value is 0.52 W/m^{2}K and the Q value is 1.69 W/m^{2}K. The measurement of air-tightness carried out in September 2020 showed that the equivalent leakage area per floor area was 2.51 cm^2/m^2.

2.2 Outline of systems

Fig. 1 shows the flow of energy source, generation, load, and waste in the surveyed house. The house produces and use heat and electricity from sources such as city gas and commercial electricity supplied from outside and solar energy obtained from two kind of panels on the roof. Heat is produced by solar thermal system and fuel cell cogeneration system. The solar system provides hot water for the kitchen, floor heating on the second floor, and the coils in the HVAC system, while the fuel cell cogeneration system provides hot water for floor heating on the first floor, bathroom and others. As for electricity, each system and home appliances are operated using commercial power and electricity produced by fuel cell cogeneration system and solar power generation, and surplus electricity is sold.

Fig. 2 shows a schematic of the solar thermal system in summer. The system is based on a system that the authors have researched and developed [2]. The solar thermal collector has an area of 12 m^2 and the thermal storage tank has a volume of 300 L, and the auxiliary heat source is a hybrid system of high-efficiency gas water heater and heat pump. Solar heat collected by the collector is stored as hot water in the storage tank for use in hot water supply and heating. In winter, solar heat is used to preheat the supply air of HVAC system and floor heating, and in summer, it is used to regenerate desiccant wheel using titanate nanowire (TiO_2) as a dehumidifier in HVAC unit. The desiccant wheel is able to regenerate at low temperatures of about 40-60 degrees centigrade. If sufficient solar heat is not available, the auxiliary heat source will operate automatically. The HVAC system has five operating modes: air blowing, dehumidification, dehumidification and cooling, heating and heating and humidification. Non-CFC indirect evaporative cooler is used to cool the introduced outside air in the dehumidified cooling mode in summer. On the other hand, in the heating and humidifying mode in winter, the humidified air from the evaporative cooler is mixed with the introduced outside air.

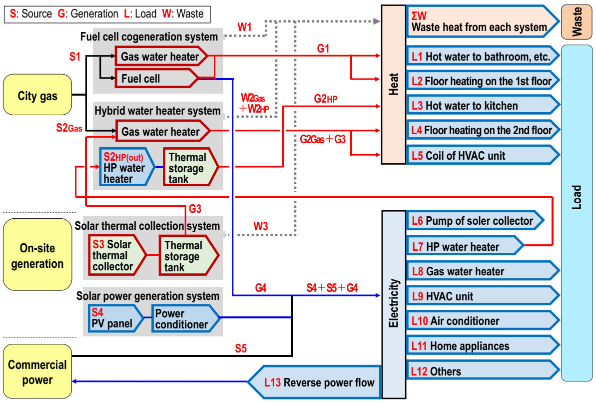

Fig. 1. Energy flow diagram of surveyed house.

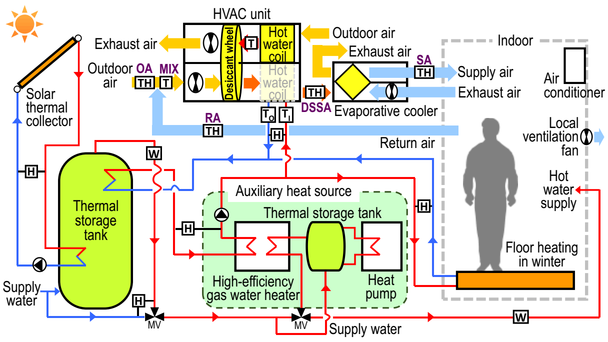

Fig. 2. Schematic diagram of a solar thermal system in summer.

2.3 Outline of measurements

Long-term measurements of temperature, humidity, amount of heat and amount of water in the systems were carried out. Power consumption and power generation were measured by home energy management system. In this study, using the energy flow diagram shown in Fig. 1, the monthly system efficiency was analyzed based on measured date from 2016 to 2018 [3]. In addition, the daily system efficiency of solar thermal system in winter and summer was analyzed using the measured data in January and July 2018.

3 Results of monthly total energy flow analysis for each season

3.1 Results of energy self-sufficiency rate

Energy self-sufficiency rate is the ratio of solar energy to total energy input, and according to Fig. 1, it is the sum of S3 and S4 divided by the sum of S1 to S5 minus L13. Fig. 3 shows the results. Energy self-sufficiency rate tended to decrease in summer and winter and increase in the middle season. This is because solar power generation decreases and energy consumption for heating and cooling increases in summer and winter. One of the methods to increase energy self-sufficiency rate is to store solar generated electricity during the day and use it at night when energy demand is high in surveyed house.

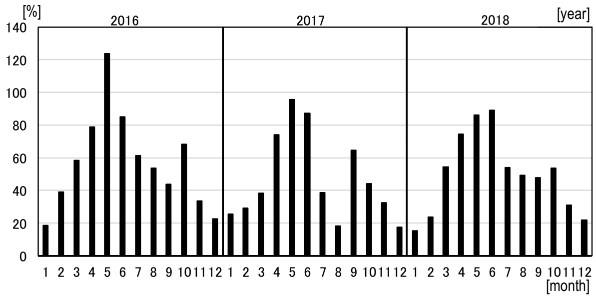

Fig. 3. Energy self-sufficiency rate of surveyed house from 2016 to 2018.

3.2 Results of total energy efficiency

Total energy efficiency is the ratio of energy consumption to total energy input, and according to Fig. 1, it is the sum of L1 to L12 divided by the sum of S1 to S5 minus L13. Fig. 4 shows the results. There were 12 months in 3 years when total energy efficiency exceeded 100%. The reason for this is thought to be the addition of the gain associated with the increase in power generation efficiency of the fuel cell cogeneration system as evaluated by primary energy. In addition, since the coefficient of performance of the hybrid water heater is 5.0, it is considered that heat five times the power consumption was produced in the hybrid water heater, and the heat produced minus the power consumption was added as the gain.

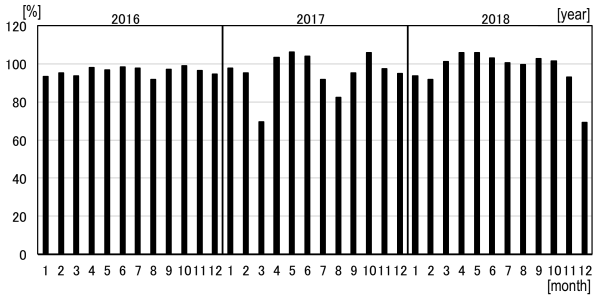

Fig. 4. Total energy efficiency of surveyed house from 2016 to 2018.

Table 1. Correlation coefficient between each item of the energy flow diagram and total energy efficiency.

Item	Class	Item name	Regression coefficient	Correlation coefficient	Significance probability
L1	Load	Hot water supply	0.0054	0.45	P<0.01
L13	Load	Reverse power flow	0.0027	0.34	
S4	Source	Solar power generation system	0.0023	0.31	
G3	Generation	Solar thermal collection system	0.0054	0.30	
L8	Load	Gas water heater	-0.026	-0.50	P<0.01
W3	Waste	Solar thermal collection system	-0.014	-0.50	
S2gas	Source	Gas water heater	-0.002	-0.55	
G2gas	Generation	Gas water heater	-0.002	-0.55	
W2gas	Waste	Gas water heater	-0.012	-0.55	

Correlation coefficients between each item of the energy flow diagram and total energy efficiency are shown in Table 1. Total energy efficiency tended to increase due to the increase in heat production of fuel cell cogeneration system and solar thermal collection and the increase in surplus electricity by the increase in power generation. In addition, because total energy efficiency was negatively correlated with items related to solar thermal system, especially hybrid water heater, the way solar thermal system is operated needs to be analyzed in detail and optimized.

3.3 Results of heat loss rate

The heat loss rate is the ratio of the waste heat of the systems to the total energy input, and according to Fig. 1, it is the sum of W1 to W3 divided by the sum of S1 to S5 minus L13. Fig. 5 shows the results. The heat loss rate increased in winter when the use of hot water increased. According to the correlation coefficient between each item of the energy flow diagram and heat loss rate shown in Table 2, the exhaust heat from the solar thermal collection system (W3) had the strongest positive correlation among the exhaust heat from each system (W1 to W3). Based on the above, it is considered that heat loss from the piping connecting the hot water coil to preheat the outside air in HVAC unit, the floor heating and the thermal storage tank was high, and also heat loss from the storage tank was high.

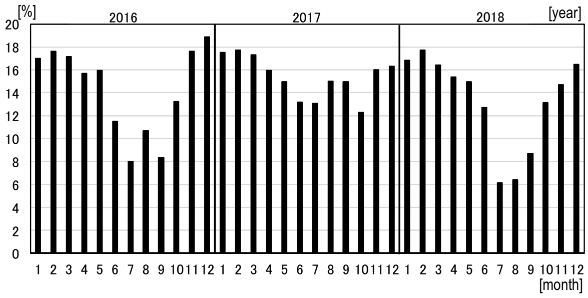

Fig. 5. Heat loss rates of surveyed house from 2016 to 2018.

Table 2. Correlation coefficient between each item of the energy flow diagram and heat loss rate.

Item	Class	Item name	Regression coefficient	Correlation coefficient	Significance probability
W3	Waste	Solar thermal collection system	0.0097	0.84	
G2$_{HP}$	Generation	HP water heater	0.0519	0.80	
L3	Load	Hot water supply	0.0519	0.80	
S2$_{HP}$	Source	HP water heater	0.0193	0.76	
L7	Load	HP water heater	0.0355	0.76	P<0.01
S1	Source	Fuel cell cogeneration system	0.0012	0.74	
G4	Generation	Fuel cell cogeneration system	0.0031	0.73	
W1	Waste	Fuel cell cogeneration system	0.0087	0.70	
W2$_{HP}$	Waste	HP water heater	0.0258	0.67	
S5	Source	Commercial power	-0.002	-0.49	
L9	Load	HVAC unit	-0.003	-0.58	P<0.01
G3	Generation	Solar thermal collection system	-0.006	-0.77	

4 Results of daily energy flow analysis of solar thermal system

4.1 Results of daily analysis in January 2018

Solar thermal energy self-sufficiency rate is the ratio of solar thermal energy to total input energy, and according to Fig. 1, it is the value of S3 divided by the sum of S1 to S5. Fig. 6 shows the results. The amount of heat collected was dependent on the weather, and rain or snow was observed in the day when the amount of heat collected was 0 MJ. Solar thermal energy self-sufficiency rate tended to increase with increasing solar thermal collection.

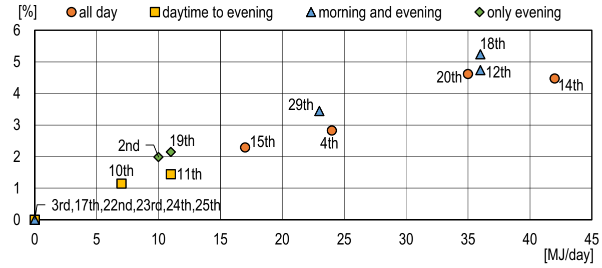

Fig. 6. Daily solar thermal energy self-sufficiency rate and amount of solar thermal collection in January 2018.

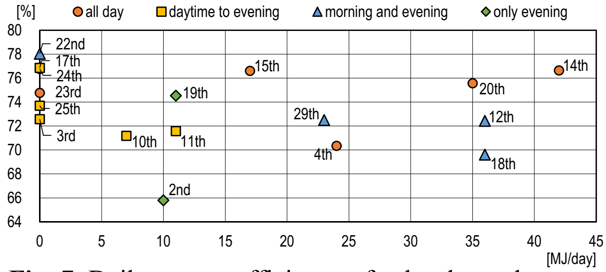

Fig. 7. Daily energy efficiency of solar thermal system and amount of solar thermal collection in January 2018.

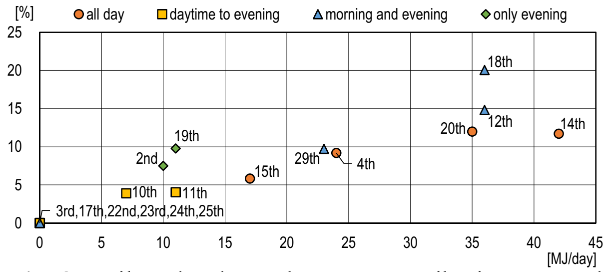

Fig. 8. Daily solar thermal energy contribution rate and amount of solar thermal collection in January 2018.

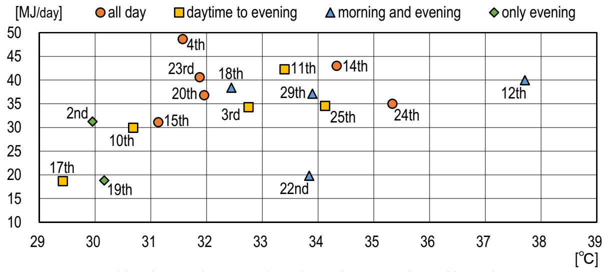

Fig. 9. Daily heat loss of solar thermal collection system and temperature difference between thermal storage tank and outside air in January 2018.

According to Fig. 1, the energy efficiency of a solar thermal system is the sum of L4 and L5 divided by the sum of S2gas and S3, and the solar thermal energy contribution rate is the value of S3 divided by the sum of S2gas and S3. Fig. 7 and Fig. 8 show the results, respectively. On days when the amount of heat collected was 0 MJ, the hybrid water heater operated and the energy efficiency was relatively high at 72.6 to 78.0%. When the HVAC system was operated all day with solar radiation, the energy efficiency was high at 75.6 to 76.6% due to efficient heat production by solar thermal energy and city gas. Similarly, on the 4th, when the HVAC system was operated all day, the heat loss of the solar thermal collection system (W3) shown in Fig. 9 was high and the energy efficiency was low at 70.3%. It is given as one of the factors that less of the surplus heat (G3) produced by the hybrid water heater came back through the HVAC system than on other days. Solar thermal energy contribution rate when the HVAC system was operated all day increased as the solar thermal collection increased, but the contribution rate was higher on 12th and 18th when the HVAC system was operated for shorter periods. On the other hand, when the HVAC system was operated only in the morning and evening, or only in the evening, except for 2nd when G3 was lower than on other days, energy efficiency tended to decrease due to increased heat loss in the thermal storage tank as the solar thermal collection increased.

4.2 Results of daily analysis in July 2018

Solar thermal energy self-sufficiency shown Fig. 10 increased with increasing heat collection and reached a maximum of 19.0%.

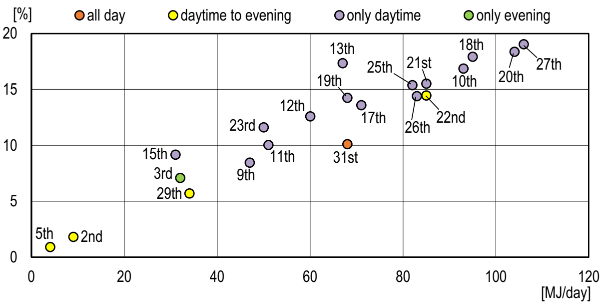

Fig. 10. Daily solar thermal energy self-sufficiency rate and amount of solar thermal collection in July 2018.

There were many days when the HVAC system was operated only during the daytime, and the energy efficiency of the solar thermal system shown in Fig. 11 was 86.1 to 105.4% when the amount of heat collected was 47 MJ or more per day, except for the 13th and 31st. The operating time of HVAC system was short on the 13th, and the hybrid water heater produced more heat because the HVAC system was operated all day on the 31st. On the other hand, the energy efficiency was less than 80% when operated at evening in spite of low heat collection (3rd, 5th, 29th). The energy efficiency on the 2nd and 15th was very high because the HVAC system was not operated and the thermal storage tank was full the previous day and the hybrid water heater did not operate much on the day.

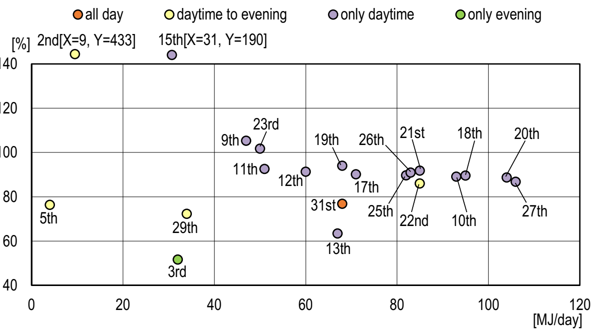

Fig. 11. Daily energy efficiency of solar thermal system and amount of solar thermal collection in July 2018.

Solar thermal energy contribution rate shown Fig. 12 increased with increasing heat collection and reached a maximum of 89.4%. The contribution rate was high on 2nd, 3rd, and 15th, even though the amount of heat collected was small. That reason is mentioned above. The contribution rate was as low as the energy efficiency because the HVAC system was operated all day on 31st.

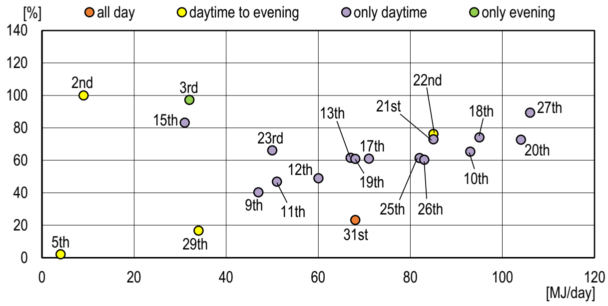

Fig. 12. Daily solar thermal energy contribution rate and amount of solar thermal collection in July 2018.

5 Conclusion

The energy flow in detached house with solar energy system and fuel cell cogeneration system in Sendai of Japan was analyzed based on measured data. As a result of the monthly analysis, it was found that the heat production and power generation of fuel cell cogeneration system, solar thermal collection and solar power generation were factors in the increase of total energy efficiency, while the heat loss of solar thermal system in winter was high. When the HVAC system was operated all day with solar radiation in winter, the energy efficiency was high due to efficient heat production by solar thermal energy and city gas. In order to increase the solar thermal energy contribution rate when HVAC system is operated all day, it is necessary to reduce heat loss in the thermal storage tank. When there was some heat collection in summer, energy efficiency and solar energy contribution rate were higher for daytime only operation of HVAC system. In order to operate a solar thermal system efficiently until evening, it is necessary to devise the flow control of hot water to send the minimum temperature of hot water to the coil.

References

1. Agency for Natural Resources and Energy in Ministry of Economy, Trade and Industry in Japan: Comprehensive energy statistics (2019)
2. R. Takaki, H. Yoshino, A. Satake, H. Kobayashi, K. Moriya, S. Baba, A. Taneichi: *A study on application of ventilation and air-conditioning system using desiccant material and solar thermal energy to real building - Outline of system and results on system performance of field survey in summer-*, Proceedings of the 13th International Conference on Indoor Air Quality and Climate, 7-12 July, 2014, Hong Kong, China (2014)
3. T. Hanabusa, R. Takaki, H. Kobayashi, A. Satake, H. Sakamoto, H. Yoshino: *Field study of system efficiency of detached house with photovoltaic generation system, ventilation and air-conditioning system using solar thermal energy and fuel cell cogeneration system, part 2 Analysis of energy flows in all Season*, Proceedings of Annual Conference of Architectural Institute of Japan, 8-10 September, 2020, Chiba, Japan (2020)