

# Development of Sky-source Heat Pump System

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**Abstract.** In order to realize a decarbonized society, which is an urgent global issue, the introduction of renewable energy is being expanded. Currently, renewable energy is mainly used to create electricity, such as via photovoltaic cells and wind turbines, while the high introductory costs of other renewable energy sources, such as solar and geothermal, is an impediment to its popularization. We have developed a high-efficiency, low-cost “Sky-sourced Heat Pump System<sup>®</sup> (SSHP<sup>®</sup>)” that utilizes renewable heat, and is operating at a demonstration site in eastern Japan. Unlike conventional air conditioning systems, our SSHP<sup>®</sup> system is a unique water heat-sourced heat pump system which connects various renewable energy heat sources, such as solar, air, and geothermal heat, with air conditioning units and hot water heat pumps via a heat source water loop. Based on measurements taken from March 19 to August 28, 2022, and system simulations, primary energy consumption and CO<sub>2</sub> emissions were significantly reduced by about 22%, or 32% when compared to typical electric heat pumps. The results indicate that the introduction of SSHP is highly effective.

## 1 Introduction

The introduction and expansion of renewable energy is being promoted in order to realize a decarbonized society, which is becoming an urgent issue all over the world. Currently, renewable energies are mainly used to generate electricity, such as by photovoltaic and wind-powered generation, but the high cost of introducing solar heat, geothermal heat, and other renewable heat sources is an impediment to their dissemination and promotion. This research aims to develop a low-cost, high-efficiency “sky-sourced heat pump (SSHP) system” that utilizes renewable energy heat within the framework of the “Cost Reduction Technology Development for Renewable Energy Heat Utilization” project funded by the New Energy and Industrial Technology Development Organization (NEDO). In this paper, we present the basic concept of the SSHP system, and provide an outline of the demonstration system installed in an actual building and the performance evaluation results for cooling in Summer 2022, in order to evaluate the operational performance under actual loads for a future market launch.

## 2 Basic Concept of SSHP system

Figure 1 shows the basic concept underpinning the SSHP<sup>®</sup> system. This is a unique aquatic heat source heat pump system which combines various renewable energy heat sources, such as solar, air, and geothermal heating with air conditioning units and hot water heat pumps via a heat source water loop. SSHP is expected to both reduce energy consumption and CO<sub>2</sub> emissions compared to conventional air conditioning systems by utilizing a variety of renewable heat sources.

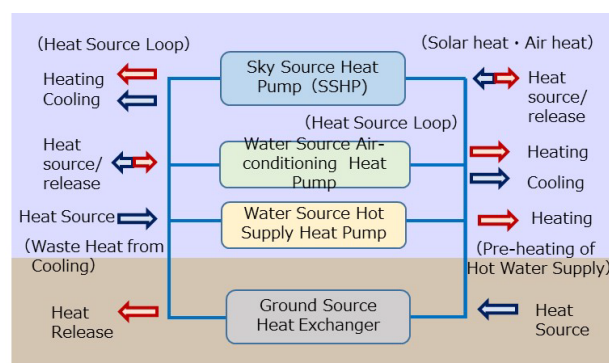


Fig. 1 Basic concept of SSHP system

## 3 Overview of Actual Demonstration System in a Building

### 3.1 Outline of building

This demonstration system is installed in a cafeteria (approx. 452 m<sup>2</sup>, Photo 1) of a factory for approximately 800 employees in Aichi prefecture, in the east of Japan. Since the working schedule for this plant is based on a day/night shift, the cafeteria is in use even late at night, and the kitchen operates fulltime, so the air conditioning and hot water supply loads occur not only during the day, but also at night. The existing air conditioning system in the cafeteria uses gas heat pump air conditioners (“GHP”), and the SSHP demonstration system was installed by modifying the existing GHP in the perimeter system (“old GHP”).

### 3.2 Outline of demonstration system

#### 3.2.1 Basic configuration

The cafeteria perimeter system is air-conditioned by two conventional multi-package type water-sourced heat pumps (“WHP”) featuring 12 HP units (three indoor units each). In order to reduce installation costs and increase efficiency, a capacity design was adopted in which approximately 50% of the air conditioning load is preferentially treated with geothermal heat, and the remainder is provided by a unit-type SSHP featuring 16 HPs. For geothermal heat (“GHEX”), borehole U-tubes (one single 100 m and seven double 100 m) were adopted in consideration of the ground conditions at the installation site. A 5HP unit for water-sourced hot water supply (“HU”) was developed this time to preheat the supply water to the existing gas boiler for hot water. Figure 1 shows the system configuration, and Photos 1 and 2 show the unit-type SSHP and water-sources hot water heat pump developed in this study.

#### 3.2.2 Unit-type SSHP

In order to improve performance throughout the year, the unit-type SSHP determines whether to use solar and/or air heat as the heating source for the SSHP, either alone or in combination, or as a direct heating source for the source water, based on measured outdoor air temperature, solar radiation, and refrigerant temperature. Table 2 shows the operation modes, and a summary is given below for each mode.

##### a. Operation Modes 1 and 4

Air heat is used as the heat source on the SSHP brine side (“zero-level side”) to cool (Mode 1) or heat (Mode 4) the source water. In the case of heating, the system is operated when the inlet brine temperature of the primary side is less than the temperature of the primary side heat source water and



**Photo. 1.** Interior view of cafeteria

the solar radiation drops below the standard value.

##### b. Operation Modes 2 and 7

Direct cooling (Mode 2) or heating (Mode 7) of the source water with air heat as the secondary-side heat source. In the case of heating, the system is operated when the inlet brine temperature of the primary-side heat source water temperature exceeds the temperature of the primary-side heat source water, solar radiation is below the standard value, and the temperature of the primary-side heat source water is less than the ambient air temperature.

##### c. Operation Mode 3

Solar heat is used as the heat source on the zero primary side of the SSHP to heat the source water. Heating is performed when the temperature of the primary-side heat source water is lower than that of the primary-side inlet brine and solar radiation exceeds the standard value.

**Table 1.** Operation Modes of SSHP

| Operation Mode |   | SSHP    | DHEX | SC  | AHEX |
|----------------|---|---------|------|-----|------|
| 1              | Heat Pump Heating by Air Heat           | Cooling | ON   | OFF | ON   |
| 2              | Direct Cooling by Air Heat              | Cooling | OFF  | ON  | OFF  |
| 3              | Heat Pump Heating by Solar Heat         | Heating | ON   | OFF | ON   |
| 4              | Heat Pump Heating by Air Heat           | Heating | ON   | OFF | OFF  |
| 5              | Heat Pump Heating by Solar and Air Heat | Heating | ON   | OFF | ON   |
| 6              | Direct Heating by Solar Heat            | Heating | OFF  | ON  | ON   |
| 7              | Direct Heating by Air Heat              | Heating | OFF  | ON  | OFF  |
| 8              | Direct Heating by Solar and Air Heat    | Heating | OFF  | ON  | ON   |

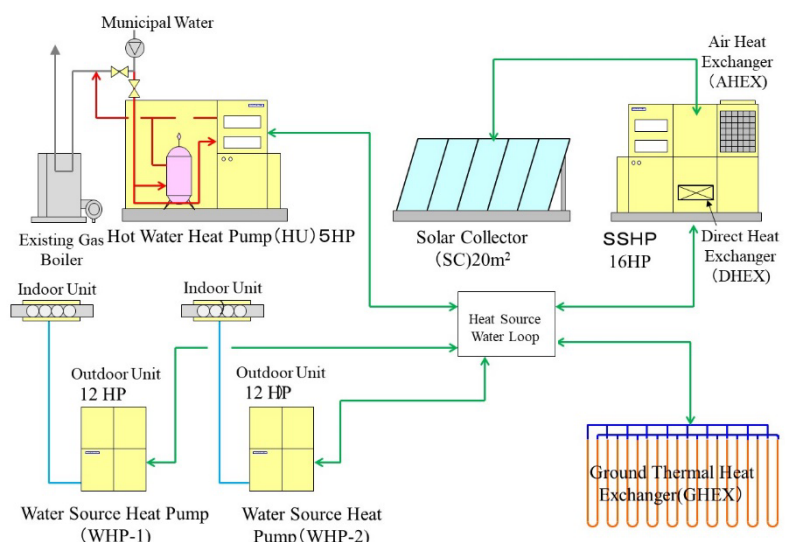
\*DHEX: Direct Heat Exchanger, SC: Solar Collector, AHEX: Air Heat Exchanger



**Photo. 2** SSHP unit



**Photo. 3** Hot Water Heat Pump



**Fig. 1** SSHP system configuration

d. Operation Mode 5

Solar heat and air heat are used together as heat sources on the unit-type SSHP plumbing side (“primary 0 side”) to cool (Mode 1) or heat (Mode 4) the heat source water. The system operates when the brine temperature is less than the primary-side heat source water temperature and solar radiation is less than the standard value.

e. Operation Mode 6

This mode heats the source water directly using solar heat as the heat source on the primary side, when the temperature of the inlet brine on the primary side is greater than the temperature of the source water on the primary side, and the inlet temperature of the source water on the primary side is greater than the ambient air temperature, while solar radiation equals or exceeds the standard value. In addition, the system operates when solar radiation exceeds the standard value.

f. Operation Mode 8

This mode heats the source water directly using solar and air heat as heat sources on the primary side, when the inlet brine temperature on the primary side exceeds the inlet water temperature on the primary side, and the inlet temperature of the source water on the primary side is lower than the outdoor air temperature, and solar radiation exceeds the standard value.

3.2.3 Water-sourced hot water heat pump

For cooling in summer, exhaust heat from the building multi-package heat-pump is recovered through a heat source water loop. The inverter frequency of the

compressor is controlled so that the water temperature in the built-in hot water tank reaches the set value.

3.2.4 Geothermal heat system

Geothermal pumps are activated by the WHP and HU operation signals. Initially, the pump operates at its lowest frequency, and whether the geothermal heat utilization is enabled or not is determined by comparison with the heat source water temperature.

4 Operation results of SSHP system

The demonstration system started operation on August 16, 2021 (Monday), but since the operation was adjusted during August, the evaluation of the actual operation performance during cooling (one-minute data) was conducted for the two-month period from July 1 (Fri.) to August 28 (Sun.), 2022.

4.1 Representative day operation performance

August 2, 2022 was the hottest day during summer, so it was used as the representative day. Figures 2 through 7 show the operation results. The COP<sup>\*1)</sup> values indicate primary energy conversion values.

4.1.1 Water-sourced multi-package heat-pump

Figures 3 and 4 show that WHP-1 and WHP-2 operated from 06:00 to 16:00 and from 22:00 to 02:30. Since this plant operates a day/night-shift work schedule, the cafeteria is used early in the morning and late at night, indicating that the air-conditioning system is in

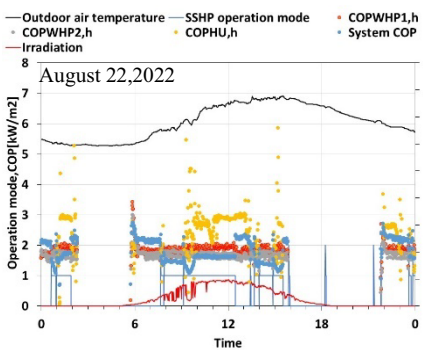


Fig. 2 COP and operation mode

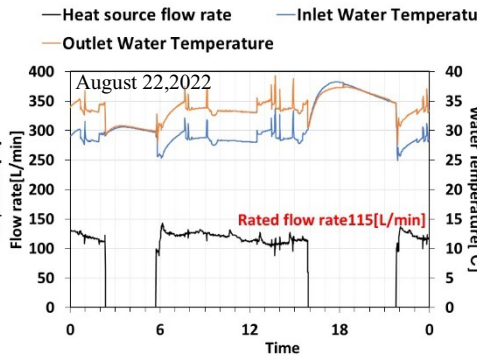


Fig. 3 WHP-1 operation status

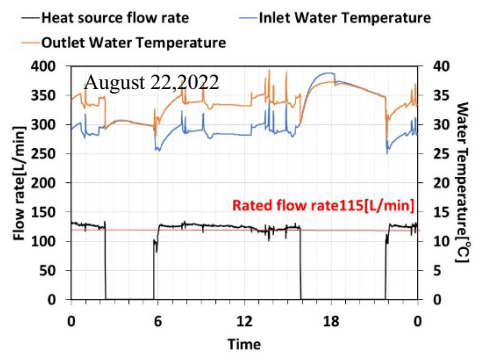


Fig. 4 WHP-2 operation status

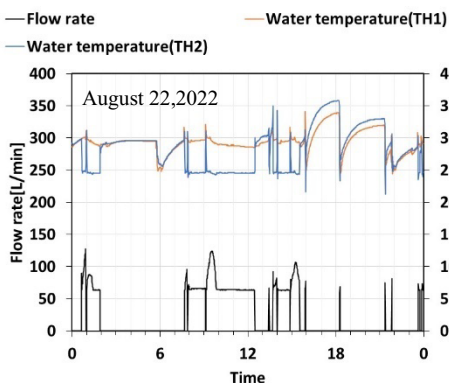


Fig. 5 SSHP operation status

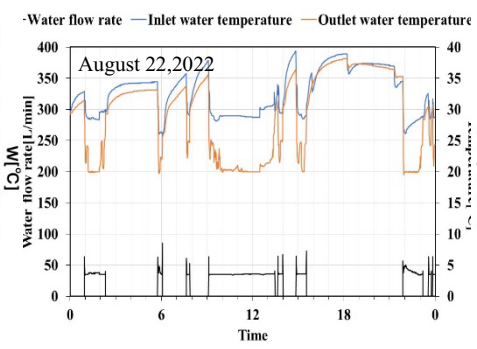


Fig. 6 HU operation status

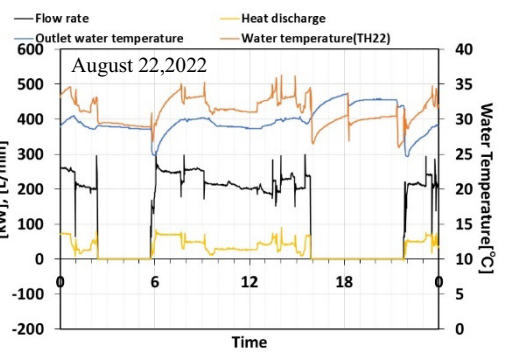


Fig. 7 GHEx operation status

operation. The average daily COP of the equipment alone was 1.84 for WHP-1 and 1.67 for WHP-2 (Fig. 2).

#### 4.1.2 SSHP system

On August 2, the SSHP system was operating in “Mode 1” as shown in Table 1; i.e. as an air-cooled heat pump. As shown in Fig. 5, the outlet temperature of the SSHP heat source water side (“primary side”) is around 25°C, which is the control target, and the inlet/outlet temperature difference is approximately 5°C, which is almost the designed value. As shown in Fig. 2, the daily average COP during operation was 2.21 for the SSHP alone.

#### 4.1.3 Water-sourced hot water heat-pump

As shown in Fig. 6, the HU operates while dishwashing in the kitchen when the cafeteria is used, but it operates alone after 23:30 when there is no air conditioning on. The HU outlet temperature (preheating temperature) during HU operation is 45°C, as shown in Fig. 2, and the daily average COP was 2.36.

#### 4.1.4 Geothermal heat system

As shown in Fig. 7, when the two WHPs are in operation, the heat is dissipated to the ground, but while the WHPs are stopped and the HU is operating alone, heat is extracted from the ground as the heat source water temperature decreases.

#### 4.1.5 Heat balance of heat source water loop

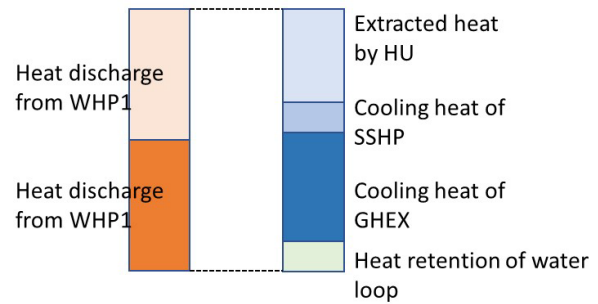
Figure 8 shows the basic concept behind the heat source water loop. Heat discharged from WHP-1 and WHP-2 to the water loop is first cooled by the exchanger. When the water loop temperature exceeds 35°C, the SSHP unit operates to cool the water loop. Besides, heat discharged from WHPs is recovered by the HU heat pump during its operation. The remainder helps to boost the heat source water temperature. Figure 9 shows the heat balance of the water loop on August 2, the representative day.

#### 4.1.6 The utilization ratio of renewable heat

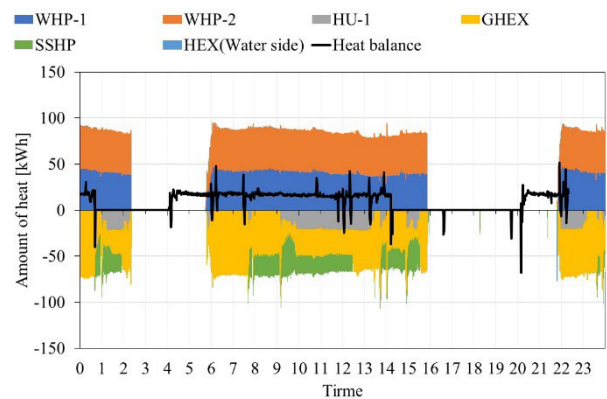
We defined the utilization ratio of renewable heat, geothermal and air heat, in cooling the heat source water loop as follows:

- Geothermal heat utilization ratio = Cooling heat by GHEX / (Discharged heat of WHP1 and WHP2)
- Air heat utilization ratio = SSHP cooling heat rate / (Discharged heat of WHP1 and WHP2)

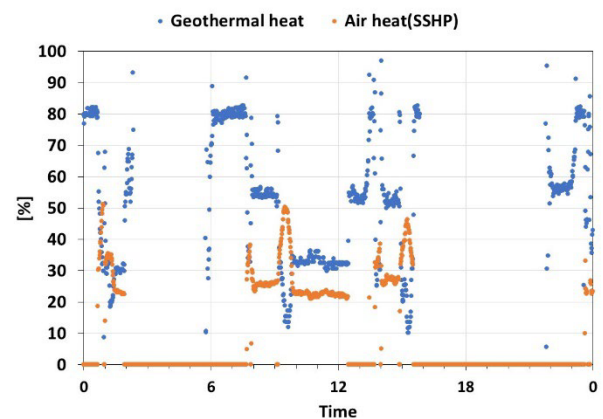
As shown in Fig. 10, the GHEX cooling ratio reached up to 80% and the daily average is 52.3%. Air heat is used as a heat source for SSHP, implementing geothermal heat and reducing the increase in heat source



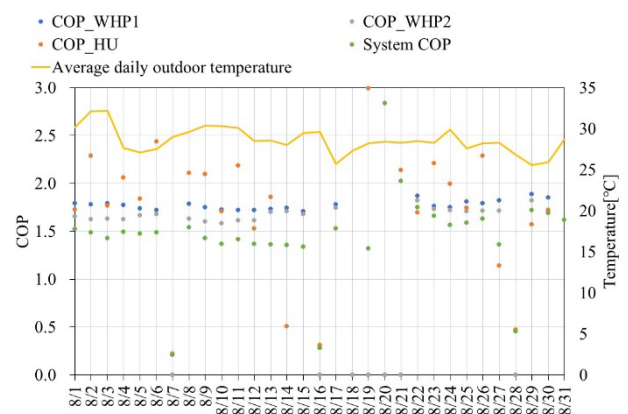
**Fig. 8** Basic concept of water loop heat balance



**Fig. 9** Heat balance of heat source water loop



**Fig. 10** The utilization ratio of renewable heat



**Fig. 11** Average daily COP (August, 2022)

water temperature. The daily average of the utilization ratio by air heat using is 15.6%, indicating renewable heat is effectively utilized.

#### 4.2 Periodic Operation Results

Figure 11 shows the COP of the individual system components and the system COP for the one-month period from August 1 to August 28, 2022. Values of 1.83 and 1.71 were obtained for WHP-1 and 2, respectively, 2.57 for SSHP, and 1.90 for HU, resulting in a system COP of 1.50.

### 5 Calculation of SSHP Effectiveness

Based on the actual operation during the five-month period from March 18 to August 28, 2022, we compared primary energy consumption, CO<sub>2</sub> emissions<sup>\*2)</sup>, and system COP between (1) a conventional GHP model, and (3) a conventional EHP, to estimate the effect of introducing the SSHP system.

#### 5.1 Calculation Method

First, the old GHP system (three indoor units) before the renovation was modelled on Life Cycle Energy Management Tool (LCEM) based on the actual measurement results, and the actual measured total heat load of indoor units was input to the model. For the conventional GHP and conventional EHP, energy consumption was calculated using the standard model of LCEM while inputting the actual measured WHP processing load. For the GHP and EHP, gas water heating was assumed, and the water heating load was based on the energy consumption for water heating at the HU, divided by the gas boiler efficiency (0.91) and added to the air conditioning load.

#### 5.2 Calculation Results

Figures 12 through 14 show the results of the estimation of the effect of installing the SSHP system by comparing primary energy consumption, CO<sub>2</sub> emissions, and system COP. The system COP of SSHP was 1.54 and improved by 49% from the conventional GHP, and 41% from the conventional EHP, resulting in a 33% and 29% reduction in primary energy consumption, respectively. CO<sub>2</sub> emissions were reduced by 45% and 38% respectively.

### 6 Conclusion

This report presents the results of a performance evaluation during cooling operations in the second year (FY2022) of a demonstration system installed in an actual building to evaluate the operational performance under actual load for the commercialization of SSHPs. Following are the findings obtained.

1. The results of the calculation of the effect of the SSHP installation based on actual operation during the period from July 1 (Fri.) to August 28 (Sun.),

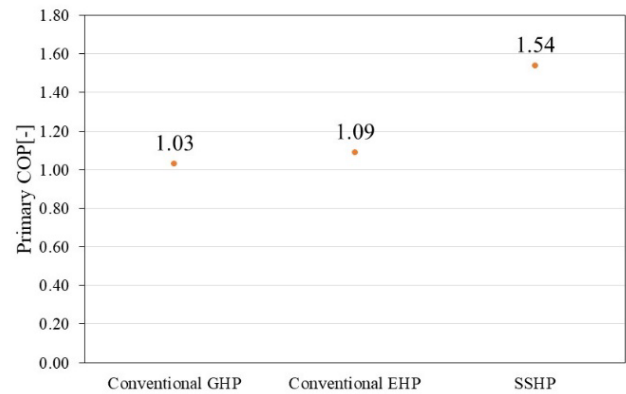


Fig. 12 Effect of SSHP introduction on system COP

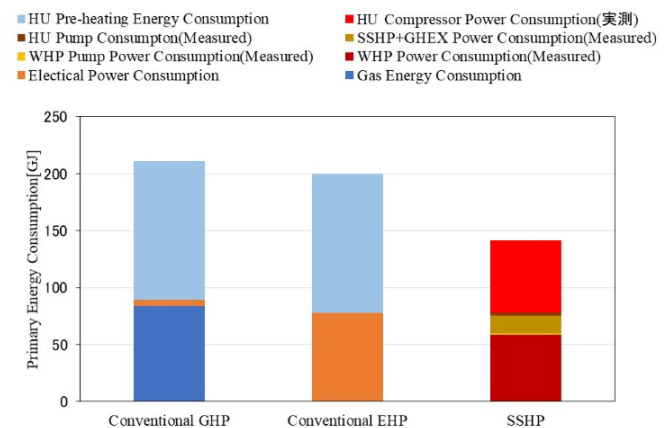


Fig. 13 Reduction of primary energy consumption by introducing SSHP improvement

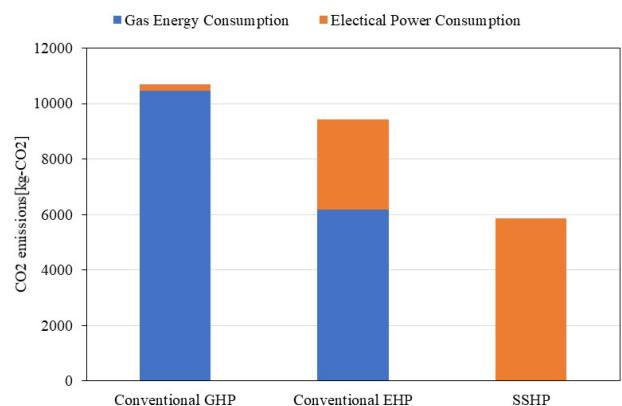


Fig. 14 Reduction of CO<sub>2</sub> emissions by introducing SSHP improvement

2022, showed a significant reduction of 33% in primary energy consumption and 45% in CO<sub>2</sub> emissions, compared to the conventional GHP. Compared to the conventional EHP, the SSHP reduced primary energy consumption and CO<sub>2</sub> emissions by 29% and 38%, respectively.

- The SSHP system showed high operational performance during actual operation. The SSHP system is expected to contribute to the realization of a decarbonized society and the dissemination and promotion of renewable heat sources.
- In FY2023, an annual performance evaluation will be conducted based on the actual operation over the full year, including the interim period, to calculate the effect of the SSHP installation. In addition, LCEM simulations will be conducted to

compare the results with the actual performance to determine further energy savings and room for CO<sub>2</sub> reduction, which will be reflected in the operation and control of the demonstration system.

(\*1) COP calculation formula is shown below.

$$COP_{WHP,c} = \frac{Q_{ld,WHP,c}}{W_{WHP} \cdot f_e} = \frac{Q_{hs,WHP,c} - W_{WHP}}{W_{WHP} \cdot f_e}$$

$$COP_{SSHP,c} = \frac{Q_{SSHP,c}}{W_{SSHP} \cdot f_e}$$

$$COP_{HU} = \frac{Q_{ld,HU}}{W_{HU} \cdot f_e} = \frac{Q_{hs,HU} + W_{HU}}{W_{HU} \cdot f_e}$$

$$COP_{sys} = \frac{Q_{ld,WHP,1} + Q_{ld,WHP,2} + Q_{ld,HU}}{W_{all} \cdot f_e + G_{all} \cdot f_g}$$

where

COP<sub>WHP</sub>: WHP equipment stand-alone COP (primary conversion) [-],

COP<sub>SSHP</sub>: unit-type SSHP equipment stand-alone COP (primary conversion) [-],

COP<sub>HU</sub>: HU equipment stand-alone COP (primary conversion) [-],

COP<sub>sys</sub>: COP<sub>sys</sub> System COP (primary conversion) [-],

Q<sub>ld,WHP</sub>: WHP process heat quantity [kW],

Q<sub>ld,HU</sub>: HU hot water preheating quantity [kW],

Q<sub>SSHP</sub>: SSHP cooling and heating quantity [kW],

Q<sub>hs,WHP</sub>: WHP heat source water side exchange heat quantity [kW],

Q<sub>hs,HU</sub>: HU heat source water side exchange heat quantity [kW],

W<sub>WHP</sub>: WHP outdoor unit power consumption [kW],

W<sub>SSHP</sub>: SSHP power consumption [kW],

W<sub>HU</sub>: HU outdoor unit power consumption [kW],

W<sub>all</sub>: overall system power consumption [kW],

f<sub>e</sub>: primary energy conversion factor (=9,760 [kJ/kWh]/3,600) [-],

G<sub>all</sub>: Total gas consumption [m<sup>3</sup>] (0 for SSHP and EHP),

f<sub>g</sub>: Higher heating value conversion factor for city gas (=45,000[kJ/m<sup>3</sup>]/3,600)[kW/m<sup>3</sup>]

-Subscript -

c: cooling, 1: WHP-1, 2: WHP-2

(\*2) CO<sub>2</sub> emission coefficients used in the calculation of CO<sub>2</sub> emission reductions are: city gas 2.29 [kg-CO<sub>2</sub>/m<sup>3</sup>] = 0.0509 [kg-CO<sub>2</sub>/MJ], electricity 0.406 [kg-CO<sub>2</sub>/kWh] = 0.0416 [kg-CO<sub>2</sub>/MJ]

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