15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Study on the implementation effects of a district renewable heat utilization system using ground source heat pumps and cogeneration waste-heat

Kunning Yang[a], Takao Katsura[a,*], Katsunori Nagano[b]

[a]Environmental System Research Laboratory, Division of Human Environmental Systems, Faculty of Engineering, Hokkaido University, Sapporo, Hokkaido, Japan
[b]National Institute of Technology, Tomakomai Collage, Tomakomai, Hokkaido, Japan

Abstract

This study investigates the effectiveness of implementing a district renewable heat utilization system that combines ground source heat pumps (GSHPs) with cogeneration (CHP) waste-heat recovery. The target site is a building complex (buildings A–D) within the Faculty of Engineering, Hokkaido University. Annual heating and cooling loads for each building were estimated, and based on these results, a comprehensive system model was developed using a simulation tool developed by our laboratory. This model incorporates multiple GSHP units connected through a shared thermal loop and considers both geothermal exchange and the use of waste-heat from an on-site CHP system. Simulation results showed that incorporating CHP waste-heat into the system enabled a large reduction in the required number of ground heat exchangers (GHEs) while further reducing CO_2 emissions. These findings confirm that the combination of GSHPs and CHP waste-heat in a district heating and cooling system can substantially enhance energy efficiency and reduce environmental impact. The study underscores the practical advantage of underground utility tunnels for routing district-loop mains and the benefits of thermal energy sharing among multiple buildings, demonstrating the potential of hybrid renewable heat systems in supporting carbon-neutral goals, especially in cold-climate regions like Hokkaido. This approach is expected to contribute to the advancement of energy management strategies for campuses, industrial zones, and urban communities.

Keywords: ground source heat pumps, simulation, district heating and cooling, heat recovery ;

1. Introduction

Thermal demands (space heating, cooling and domestic hot water) account for a large share of energy use in residential and commercial buildings [1]. Globally, building operations consume 30% of final energy and generate 26% of energy-related emissions [2]. Achieving net-zero targets therefore requires the large-scale deployment of renewable heat sources and high-efficiency heat-pump technologies.

A district renewable heat utilization system is an area-wide thermal network that, rather than serving a single building, optimizes energy use by coordinating heat exchange among multiple buildings, while interconnecting heat pumps with renewable sources and thermal storage. Ground source heat pump (GSHP) systems are well suited to such networks because they provide stable, high-efficiency operation and can be readily integrated with shared thermal loops. As illustrated in Fig. 1(a), through ground heat exchangers (GHEs) and circulation of the heat transfer fluid (HTF), GSHPs extract heat from the ground in winter for heating and reject heat to the ground in summer for cooling. Combined heat and power (CHP), or cogeneration, is an energy system that simultaneously generates electricity and recovers waste-heat (Fig. 1(b)). The recovered heat is supplied as steam or hot water for space heating, domestic hot water, or industrial processes, which is also

* Corresponding author. *E-mail address:* katsura@eng.hokudai.ac.jp

suitable for district heating applications. By avoiding separate production of heat and power and reducing distribution losses, CHP systems can achieve overall fuel utilization efficiencies of up to 80% [3].

In Europe, district energy systems have been developed for decades, and recent work has increasingly focused on fifth-generation district heating and cooling (5GDHC) networks serving entire districts. Existing implementations demonstrate a wide range of low-temperature heat sources, including groundwater, shallow geothermal energy, and seawater, as well as smart operation strategies that combine renewable heat and waste-heat with AI-based optimal control [4-5]. In contrast, the deployment of district-scale renewable heat utilization in Japan remains limited, with design methodologies and implementation effectiveness prediction tools yet to be fully established.

This study assesses the feasibility of a campus-scale district renewable heat utilization system incorporating GSHPs and evaluates the additional benefits of coupling with waste-heat recovery from CHP generation.

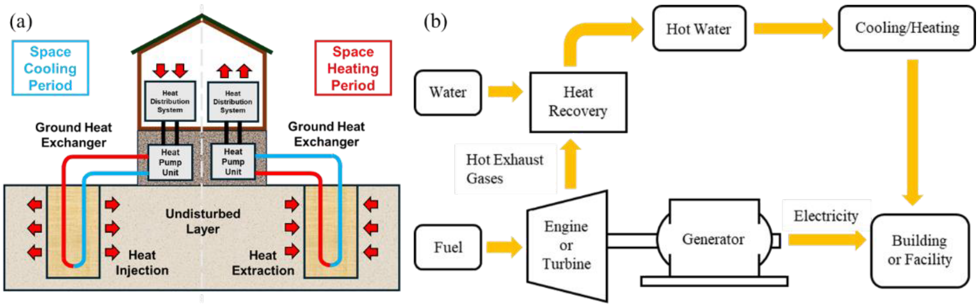

Figure 1. (a) Schematic operation of a GSHP system; (b) schematic of a CHP system with heat recovery.

2. Methodology

The study site is the Faculty of Engineering at Hokkaido University, comprising multiple detached buildings (Buildings A–D), key building information is summarized in Fig. 2(b). At present, winter space heating is supplied by steam produced at the campus Power Center (central energy supply station) using city gas. The Power Center serves as the thermal distribution hub for this area and is also considered as the integration node for CHP waste-heat recovery. To improve efficiency and reduce emissions, we propose retrofitting the existing system into a district renewable thermal energy utilization system. This system enables inter-building heat sharing and integrates GSHP systems with CHP systems, thereby reducing overall fuel consumption and associated emissions across the area.

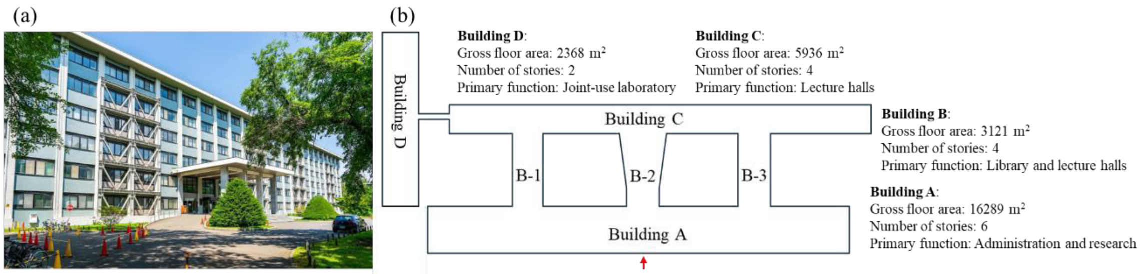

Figure 2. Faculty of Engineering, Hokkaido University: (a) front view; (b) site plan of Buildings A–D with building information.

The campus features underground utility tunnels (shared corridors for power, steam, water supply, and sewage pipelines for large industrial/institutional/commercial sites), providing a low-cost and practical route for installing HTF pipelines of the district loop. As indicated by the green lines in Fig. 3(a), the tunnel connects the Power Center and the GHE field to Buildings A–D. Using this corridor, we routed a pair of supply and return mains (Fig. 3(b)) to form a shared water loop that links the building-side heat pump units with the GHEs. Because occupancy in the engineering buildings is irregular and requires room-by-room control, we selected water-cooled multi-split (VRF) heat pump units.

Building B consists of three wings, treated as an equivalent single building in the base configuration and served by one heat pump unit, consistent with Buildings A, C, and D (one unit per building). In Fig. 3(b), the red line denotes the supply pipe delivering HTF to the building's heat pumps, and the blue line denotes the return pipe conveying HTF back to the GHE field. The CHP system at the Power Center utilizes gas engines for electricity generation while recovering waste-heat for hot water production. In this study, the recovered hot water transfers heat to the district return flow via plate heat exchangers, thereby increasing the return temperature before the flow enters the GHE field, reducing net heat extraction from the ground and improving heat pump performance.

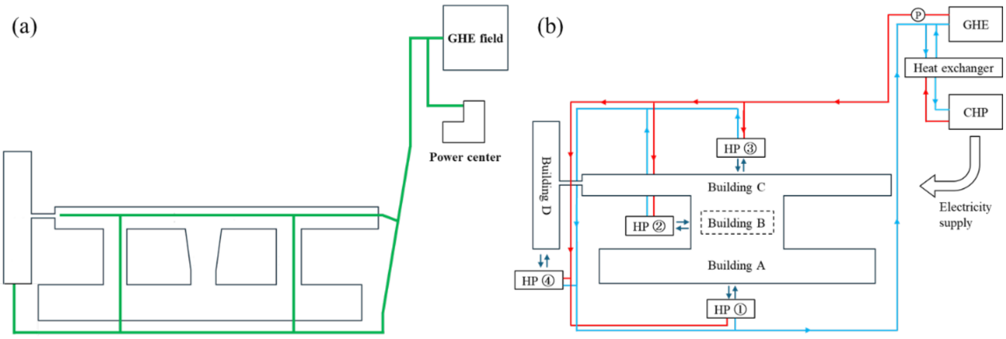

Figure 3. (a) Underground utility tunnel (green) connecting the Power Center and GHE field to Buildings A–D; (b) Proposed thermal distribution: supply (red) and return (blue) mains connecting heat pumps with the GHE field.

We used the BEST (Building Energy Simulation Tool) to model the thermal load of these buildings. BEST is a building energy simulation program widely used in Japan for research and design evaluation, developed by the Institute for Built Environment and Carbon Neutral for SDGs (IBECs) [6]. Based on the campus floor plans, building geometry and operation schedules were defined, and thermal loads were calculated under the following settings: weather data for Sapporo, Japan; heating season from November to April; indoor temperature setpoint range of 22–24 °C; double-glazed low-emissivity windows (6 mm air gap, 10 mm glass thickness); outdoor air rate of 2–5 m³/h per m²; exterior walls consisting of reinforced concrete with insulation; sound-insulating partitions between rooms; and fire-resistant partitions between rooms and corridors. Fig. 4(a) presents the resulting winter heating load for Buildings A–D, and Fig. 4(b) shows the hourly thermal load for the district over a full year. Because the campus is located in a cold climate region and the annual demand is heating-dominated, the performance assessment in this study focuses on the heating period from November to April. A comparison with recorded building energy consumption indicates that the BEST-derived load estimates are in reasonable agreement with real-world measurements.

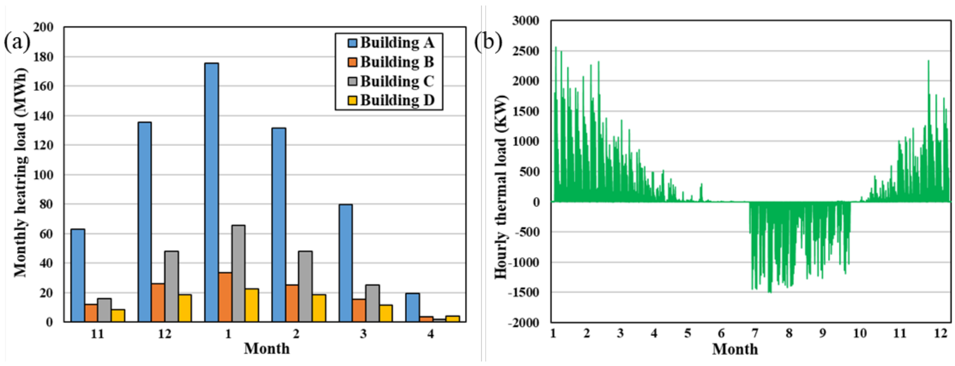

Figure 4. Building heating loads estimated by BEST: (a) Winter (Nov–Apr) space heating loads for Buildings A–D; (b) Hourly district thermal load over a full year (positive for heating and negative for cooling).

Our laboratory has developed a high-speed GSHP simulation program that calculates the transient ground temperature response using both the infinite cylinder source (ICS) and infinite line source (ILS) theories [7]. In this study, we expanded the tool's functionality to distribute the district load across multiple heat pump units and calculate GHE outlet temperatures $T_{p,\,out}$ and ground temperatures T_s under multi-building operation. The hourly heating loads estimated by BEST were then imported into the district simulation to evaluate the operational performance of the proposed system for the engineering campus. The adopted model inputs and parameter settings for the GSHP system, ground, and heat pump units are provided in Fig. 5, together with an overview of the system configuration.

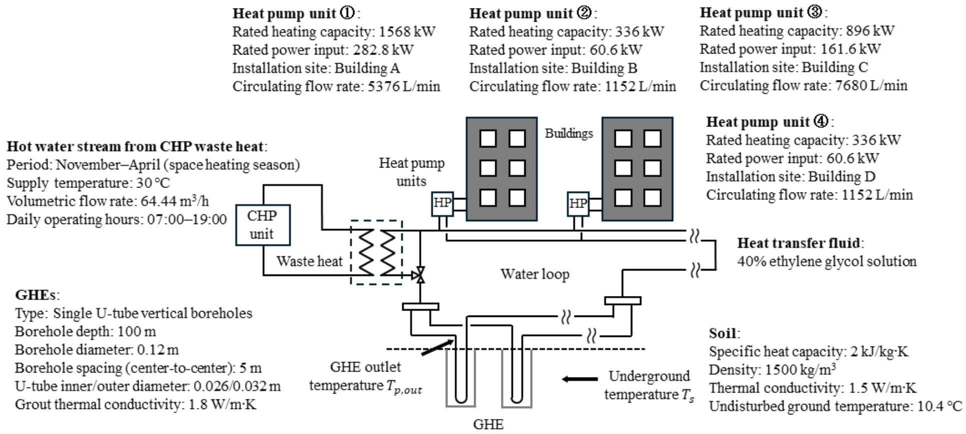

Figure 5. Schematic of the proposed district renewable heat utilization system integrating GSHPs and CHP waste-heat recovery.

3. Result & Discussion

The simulation result produces hourly time series of the GHE inlet and outlet temperature, the surrounding ground temperature, and the electricity consumption of the heat pumps. Using these outputs, the seasonal COP for Nov–Apr is calculated with Eq. (1) as the ratio of the total useful heat delivered to the total electrical input over the period. Here, the subscript "hp" denotes the heat pump and "2" denotes the secondary (load) side.

$$seasonal\ COP = \frac{\sum(Q_{hp2} \times 1h)}{\sum(E_{hp} \times 1h)} \tag{1}$$

3.1. Baseline (GSHP-only)

We first analyze the baseline scenario utilizing only GSHPs. Considering campus land constraints and the need to limit initial costs, the GHE field is initially arranged in a 20 × 7 grid (140 boreholes). Fig. 6 shows the resulting hourly variations in the GHE outlet temperature and surrounding ground temperature. The simulation results indicate that during extreme cold periods, high heat extraction causes the HTF temperature to drop substantially, and the GHE outlet temperature remains below the operational limit of −5 °C for extended periods (Fig. 6(a), highlighted). Here, −5 °C is adopted as an operational constraint to maintain stable operation of HTF and avoid excessive performance deterioration. The surrounding ground temperatures also approach and locally fall below 0 °C (Fig. 6(b), highlighted), raising concerns about long-term ground freezing risks and potential degradation of heat pump performance under heating-dominated operation [8-9].

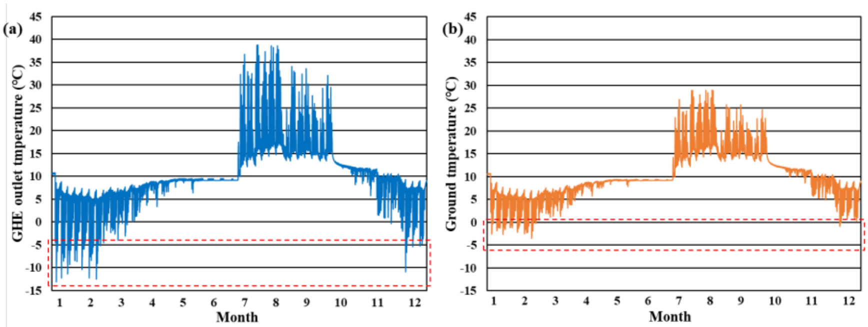

Figure 6. GSHP-only case with 140 GHEs: hourly variation of (a) GHE outlet temperature $T_{p,\,out}$; (b) hourly ground temperature T_s.

Over the full-year simulation, the minimum GHE outlet and ground temperatures reached −12.97 °C and −3.57 °C, respectively, failing to meet the design criteria of $T_{p,\,out} \geqslant -5$ °C and $T_s \geqslant 0$ °C. Although increasing the number of GHEs to a 20 × 11 layout can satisfy these constraints (Fig. 7), it requires a substantially larger installation area and higher initial investment. These results indicate that maintaining long-term stable operation with GSHPs alone is challenging for the study site.

3.2. With CHP waste-heat recovery

When CHP waste-heat recovery is integrated, the district return flow is preheated before entering the GHE field. This increases the source-loop temperature, alleviates net heat extraction from the ground, and mitigates excessive HTF cooling and soil-freezing risk. In the simulation, CHP waste-heat is represented as a 30 °C hot-water stream with a volumetric flow rate of 64.44 m^3/h, available for 12 h per day. This stream exchanges heat with the HTF of return loop through a plate heat exchanger with an overall heat transfer coefficient of 4000 W/(m^2·K) and an effective area of 4 m^2.

To quantify the impact of waste-heat recovery, we simulated configurations with 140–220 GHEs both with and without heat recovery. Fig. 7 summarizes, for each case, the minimum GHE outlet temperature, minimum ground temperature, and seasonal COP (Nov–Apr). Without heat recovery, increasing the number of GHEs rises both temperatures and improves seasonal COP from 3.19 (140 GHEs) to 3.44 (220 GHEs). With CHP waste-heat recovery, thermal conditions are substantially improved: for the same number of GHEs, the minimum GHE outlet temperature increases by about 5 ℃ and the minimum ground temperature by about 4 ℃, accompanied by a noticeable increase in seasonal COP.

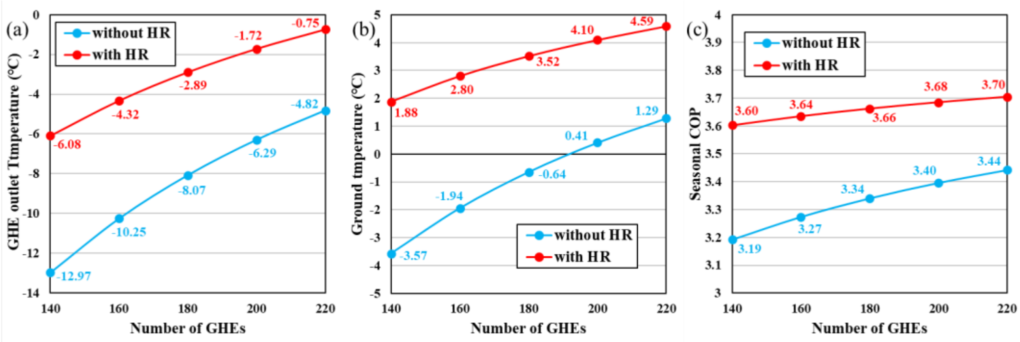

Figure 6. Simulation results: (a) minimum GHE outlet temperature; (b) minimum ground temperature; (c) seasonal COP.

Based on the simulation results, 3 scenarios were considered for the study district: Case 1, the current system using an existing gas-fired steam boiler; Case 2, a GSHP-only district system that meets the operational constraints with a 20 × 11 GHE field; and Case 3, a hybrid configuration with CHP waste-heat recovery, for which the same constraints can be satisfied with a reduced GHE field of 14 × 11. For a consistent comparison, city gas was assumed as the fuel for both steam production and on-site power generation supplying the heat pumps. A heating value of 45 MJ/m^3 and CO_2 emission factor of 2.29 kg-CO_2/m^3 were adopted, with a boiler efficiency of 0.85 and an electrical generation efficiency of 0.42. Fig. 6(a) compares the resulting monthly gas consumption. Except for April, when the heating demand is small, Cases 2 and 3 consistently require substantially less gas than Case 1. Over the entire heating season, total CO_2 emissions decrease by 41.2% in Case 2 relative to Case 1, and by a further 5% in Case 3 relative to Case 2. In addition, Case 3 achieves a higher seasonal COP (3.63) than Case 2 (3.44) while reducing the required GHE count from 220 to 154. Overall, these results indicate that coupling a district GSHP system with CHP waste-heat utilization can simultaneously improve seasonal efficiency, reduce borefield requirements, and further lower emissions for the study site.

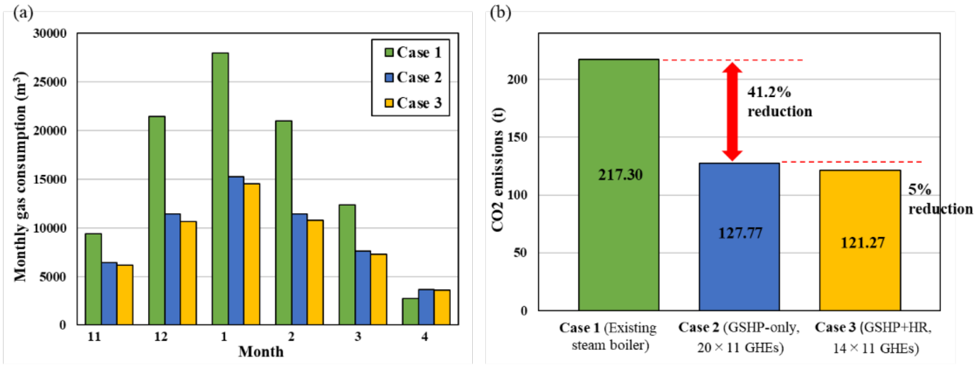

Figure 7. Comparison of the three scenarios: (a) monthly gas consumption; (b) cumulative CO_2 emissions over the heating season.

4. Conclusion

This study evaluated a campus-scale district renewable heat utilization system for the Faculty of Engineering at Hokkaido University, combining GSHP systems with waste-heat recovery from a gas-engine CHP unit. The main findings are:

- A GSHP-only system with a small borefield (20 × 7, 140 GHEs) results in substantial temperature depression, and both the GHE outlet temperature $T_{p,out}$ and ground temperatures T_s frequently violate the operational constraints during space heating season. To satisfy these constraints under heating-dominated operation, the GSHP-only case requires a larger borefield of 20 × 11 (220 GHEs).
- With CHP waste-heat recovery, the district return flow is preheated before entering the GHE field, reducing net heat extraction and improving operational stability. This enables the borefield to be reduced to 14 × 11 (154 GHEs) while maintaining compliance with same constraints (220 → 154).
- The hybrid system achieves a higher seasonal COP (3.63) than the GSHP-only case (3.44). Under consistent city-gas assumptions for steam production and on-site electricity generation, heating-season CO_2 emissions are reduced by 41.2% in the GSHP-only case relative to the current steam-boiler system, with a further ~5% reduction when CHP waste-heat recovery is applied.
- The presence of underground utility tunnels on campus provides a practical, low-cost route for installing district-loop mains, improving the feasibility of district-scale implementation. Overall, the results demonstrate that coupling district GSHP networks with CHP waste-heat recovery is an effective retrofit strategy for cold-climate campuses, enabling higher efficiency, lower emissions, and reduced borefield requirements.

Acknowledgements

This study is based on results obtained from the project "Technological development for the construction of an area renewable energy heat utilization system", commissioned by the Japan national agency NEDO and "Yashima Environmental Technology Promotion Foundation Research and Development/Survey Grant".

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