Performance evaluation of a ground-source integrated heat pump for residential net-zero energy buildings across different climates

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ABSTRACT

Ground-source integrated heat pumps (GSIHPs) can save energy in residential buildings by providing both space conditioning and domestic hot water (DHW) using a single efficient appliance. The efficiency is enabled through use of the thermodynamically favorable heat sink/source of a ground heat exchanger (GHX), and can be enhanced by using variable-speed components. We conducted a TRNSYS simulation to explore the GSIHP's performance in a residential net-zero energy building located in different climates. Compared to a conventional ground-source heat pump (GSHP), the GSIHP reduced the heating, cooling, dehumidifier, and DHW energy consumption by (25 to 63) %. The baseline GHX length was determined based on the building loads at each climate zone using the Kavanaugh and Rafferty method. The photovoltaic (PV) array was sized to achieve net-zero energy use. Furthermore, the variation in entering liquid temperature (ELT) was studied for long-term operation implications.

1. INTRODUCTION

The climate crisis stands as a critical challenge for our generation. Rising carbon dioxide emissions are directly linked to global energy consumption patterns, reflecting an urgent need for sustainable energy consumption practices. Heating, ventilation, and air-conditioning (HVAC) and domestic hot water (DHW) systems account for a significant portion of global energy consumption in buildings. Consequently, there is a pressing need to develop innovative systems that significantly enhance HVAC efficiency.

Among various innovative energy efficiency systems, ground-source heat pumps (GSHPs) are particularly effective, achieving a higher operating coefficient of performance (COP) than air-source heat pumps (ASHPs) due to the ground's more favorable temperatures for use as a heat source or sink. Wu *et al*. (2018) analyzed the energy usage, comfort levels, and economics of various HVAC setups for a residential net-zero energy building, including options for ventilation, dehumidification, and heat pumps. The configuration combining a GSHP, an energy recovery ventilator (ERV), and dedicated dehumidification achieved the most significant reduction in energy use while maintaining comfort. Wu and Skye (2018) evaluated different combinations of HVAC and photovoltaic (PV) systems for reaching net-zero energy goals in residential buildings across different U.S. climate zones, reporting the GSHPs used (24 to 39) % less energy than the ASHPs in the same house design, though at greater first cost.

In the early 2000s, Oak Ridge National Laboratory (ORNL) initiated the development of Integrated Heat Pumps (IHPs), targeting efficient heating, cooling, and DHW through a single system capable of recovering waste energy from cooling processes for use in DHW tanks (Tomlinson *et al*., 2005). ORNL developed and tested air-source IHP (ASIHP) and ground-source IHP (GSIHP) prototypes under various conditions (Baxter *et al*., 2008). Validation of a heat pump simulation model against lab data revealed that ASIHP and GSIHP systems offer (46 to 67) % and (52 to 65) % energy savings, respectively, over conventional ASHPs. Following optimization, this innovative product was commercialized in 2012 (Baxter *et al*., 2013). The product is designed with four operating modes of space heating, space cooling, DHW, and combined space cooling and DHW (C+DHW).

In this study, we examined the efficiency of GSIHPs when applied to a residential net-zero energy building (NZEB). Five different cities across the U.S. were selected to assess the effect of various climates on the performance characteristics. Building simulations were performed using the Transient System Simulation program (TRNSYS) (Klein *et al*. 2017). We compared the performance of the GSIHPs to that of two-capacity GSHPs in terms of energy consumption. Additionally, the minimum PV size was adjusted for each climate and HVAC system to achieve net-zero annual energy use. The variation in entering liquid temperature (ELT) was also studied for long term operation implications.

2. METHODS

2.1 TRNSYS Model

The residential NZEB located on the National Institute of Standards and Technology (NIST) campus in Gaithersburg, Maryland, USA was the basis for the TRNSYS building energy simulation. The house generates electricity using thirty-two 320 W PV modules, providing a 10.24 kW DC rated output (nominal efficiency of 19.6 % under standard test conditions: normal irradiance at 1000 W m^{-2} and module cell temperature at 25 °C). Detailed specifications of the house are outlined in the open literature (Fanney *et al*., 2015). Fig. 1 shows a schematic of the TRNSYS model used for the energy simulation of the NZEB. The GSIHP performance was implemented in the model based on the manufacturer's data (ClimateMaster, 2022). All heat pump configurations were modeled with quasi-steady operation.

Five representative cities were selected based on the U.S. climate zones that are classified using the heating and cooling degree days and ambient moisture level: Miami (1A: very hot–humid zone), San Francisco (3C: warm–marine zone), Baltimore (4A: mixed–humid zone), Chicago (5A: cool–humid zone), Duluth (7: very cold zone). The hourly weather files used in TRNSYS were the TMY2 (Typical Meteorological Year) data sets including temperature, humidity, wind, and solar radiation. The heat pump size was selected to range from (2.0 to 3.0) ton, in 0.5-ton increments, to match the building's heating and cooling demands. The minimum PV installation capacity, (4.4 to 9.3) kW, was adjusted in each simulation to achieve net-zero energy use on an annual basis. The borehole depth required for the system was determined based on the design method proposed by (Kavanaugh and Rafferty, 2014), which includes an analytical calculation of the borehole length, L_b, based on a 1-dimensional transient cylindrical conduction ground model. This method also required specifying the block loads, rated efficiency of the GSHP, and the maximum and minimum ELTs where we used the recommended values of 37 °C and −3 °C, respectively. More details about modeling the house and its subsystems are described in (Wu and Skye, 2018).

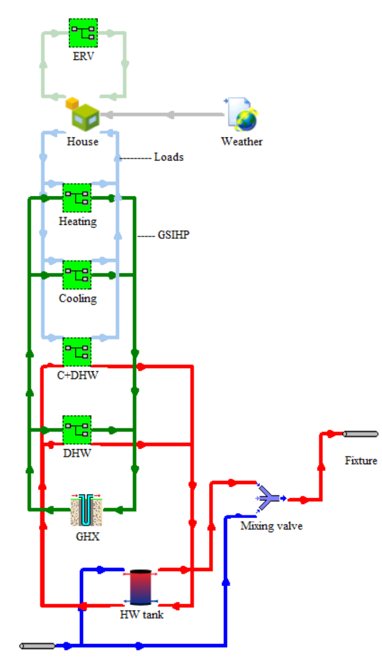

Figure 1: TRNSYS model of the NZEB with the GSIHP.

2.2 Thermal System in NZEB

Two kinds of systems for HVAC and DHW were evaluated and compared in the simulations. The first system consists of a GSIHP (Fig. 2), and the second system consists of a two-capacity GSHP and a heat pump water heater (HPWH). A separate whole-house dehumidifier is utilized to manage the relative humidity, and it is especially needed during periods when the heat pump is not operating in the cooling season. An ERV is employed to facilitate sensible and latent heat recovery between the incoming outdoor air and the exhausting indoor air.
The GSIHP has four different operating modes: heating, cooling, DHW, and C+DHW, which are determined by setpoints and temperatures of the air and DHW tank, as well as capacity demand, which is continuously updated by a proportional–integral controller. The temperature setpoint is 20.5 °C in the heating season and 23.9 °C in the cooling season, and the relative humidity setpoint is 48 %. The hot water (HW) temperature setpoint is 48.9 °C. Within this system, DHW production is prioritized over space conditioning, except when the ‘cutout mode’ is activated. The GSIHP control logic is detailed in Table 1. The GSHP provides two cooling stages and three heating stages. The DHW is entirely produced by the standalone HPWH (COP = 2.5). Table 2 lists the GSHP control logic, with further system details available in previous studies (Wu *et al*., 2018).

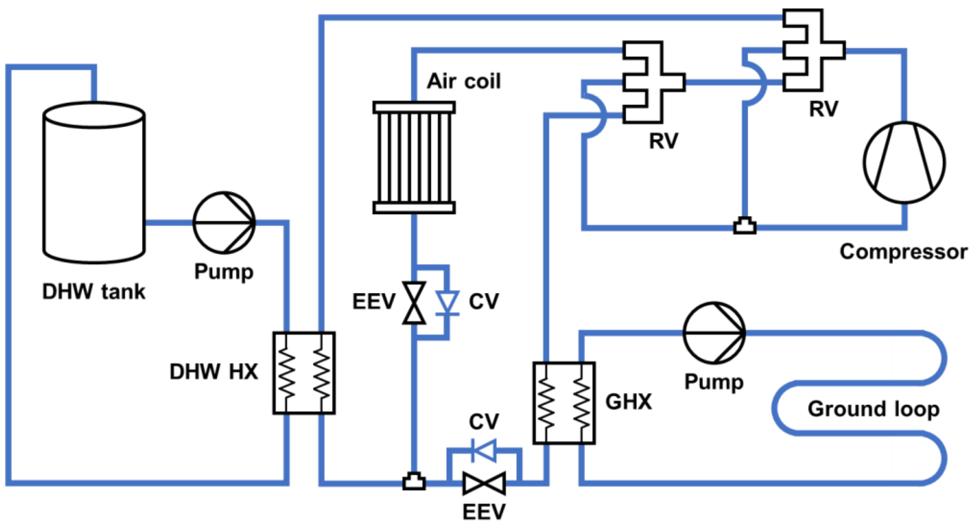

Figure 2: Schematic of the GSIHP.

Table 1: GSIHP control logic.

Parameter / Mode	Setpoint (°C)	Turn-on Deadband (°C)	Turn-off Deadband (°C)	HW Cutout Offset Temp. (°C)	HW Cutout Capacity (%)
Heating	20.5	0.056 1.1 (AUX)	0.56	0.56	> 90
Cooling	23.9	0.056	0.56	0.56	= 100
DHW	48.9	8.3	0	–	–
C+DHW	23.9 (Cooling) 48.9 (DHW)	0.056 (Cooling) 8.3 (DHW)	0.56 (Cooling) 0 (DHW)	–	–

Table 2: GSHP control logic.

Parameter / Mode	Setpoint (°C)	Turn-on trigger	1st stage	2nd stage	3rd stage (AUX)
Heating	20.5	Deadband (°C)	0.1	1.1	3.3
		Time delay (min)	–	10	40
Cooling	23.9	Deadband (°C)	0.2	2.8	–
		Time delay (min)	–	40	–

2.3 Data Reduction

The total building energy consumption, Eq. (1), was the sum of energy for the GSIHP, dehumidifier, ventilation, lighting, plug loads, and appliances. The GSIHP energy consumption, Eq. (2), was that of the heating, cooling, C+DHW, DHW, and standby modes.

$$E_{\text{building}} = E_{\text{GSIHP}} + E_{\text{dehumidifier}} + E_{\text{ventilation}} + E_{\text{lighting}} + E_{\text{plug}} + E_{\text{appliance}} \quad (1)$$

$$E_{\text{GSIHP}} = E_{\text{heating}} + E_{\text{cooling}} + E_{\text{C+DHW}} + E_{\text{DHW}} + E_{\text{standby}} \quad (2)$$

The energy performance of the GSHP was evaluated using Eq. (1) and (2) with the substitution of E_{GSHP} for E_{GSIHP}, E_{HPWH} for E_{DHW}, and 0 for $E_{\text{C+DHW}}$.

3. RESULTS AND DISCUSSION

3.1 Energy Performance

The GSIHP affects the energy consumption for heating, cooling, dehumidifier (HCD), and DHW, thus the GSIHP and GSHP were compared based on the summation of these energy uses, across five different climates (Fig. 3). The GSIHP exhibited lower energy consumption than the GSHP in Miami and Baltimore, particularly in the cooling season. In Chicago and Duluth, the energy consumption of the GSIHP was relatively lower, particularly in the heating season. However, in San Francisco, the difference in energy consumption between the two systems was minimal, and the GSIHP showed even slightly higher consumption in the cooling season.

Fig. 4 shows the annual energy consumption breakdown of HCD and DHW. In Miami, the GSHP in cooling and the dehumidifier showed high energy consumption, accounting for 61 % and 29 %, respectively, due to the climate's high outdoor air temperature and humidity. In San Francisco, space-conditioning energy was markedly lower due to the mild climate, and DHW accounted for approximately half of the energy use. In Baltimore and Chicago, heating was a major energy consumer, representing 38 % and 55 %, respectively. In Duluth, heating comprised 80 % of energy consumption due to the extremely cold weather conditions.

The GSIHP generally exhibited lower energy consumption than the GSHP in both space conditioning and DHW, which was primarily attributed to the more efficient and variable-speed components in the GSIHP. The GSIHP cooling COP was higher than that of the GSHP, so it used significantly less energy in hot, humid climates (e.g., Miami or Baltimore in the summer). The GSIHP also had superior dehumidification due to a wider range of fan speed control, which reduced the need for additional energy consumption by the less-efficient separate dehumidifier. Additionally, the efficient DHW production by the GSIHP in C+DHW mode recovered the heat extracted from the air into the water. This operating mode provided a modest benefit with a maximum energy savings of 5 % for the Miami climate. In heating, the GSIHP used less energy than the GSHP due to its higher heating COP. Furthermore, the variable-speed GSIHP was able to maintain full capacity even at low ELTs and thus eliminated the need for auxiliary heating in Chicago and Duluth, where it respectively accounted for 4 % and 25 % of the heating energy with the GSHP (none of the other climates required the auxiliary heater). In San Francisco, the GSIHP used less energy than the GSHP, although the GSHP cooling and dehumidifier energy use were lower because the air cooling effect of the HPWH was large relative to the cooling loads. Across all climates, the DHW energy consumption of the GSIHP reduced by (45 to 92) % compared to that of the GSHP due to its efficient DHW production. With a more efficient HPWH (COP = 4), the DHW energy reduction was (25 to 89) %. For the GSIHP, compared to the GSHP, the HCD and DHW energy consumption decreased by the following: 58 % (Miami), 22 % (San Francisco), 40 % (Baltimore), 34 % (Chicago), and 31 % (Duluth).

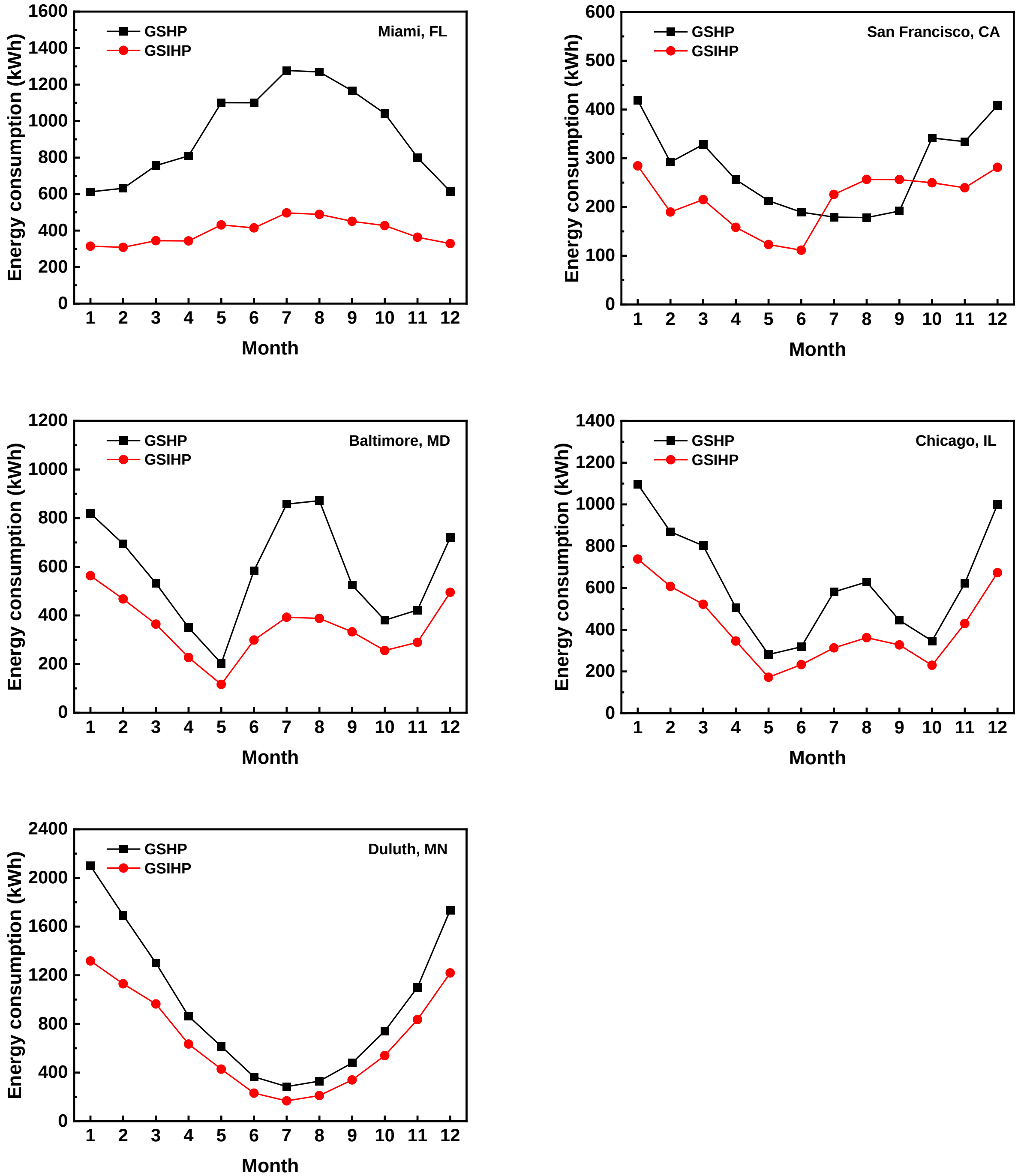

Figure 3: Monthly HCD and DHW energy consumption of the GSHP and GSIHP.

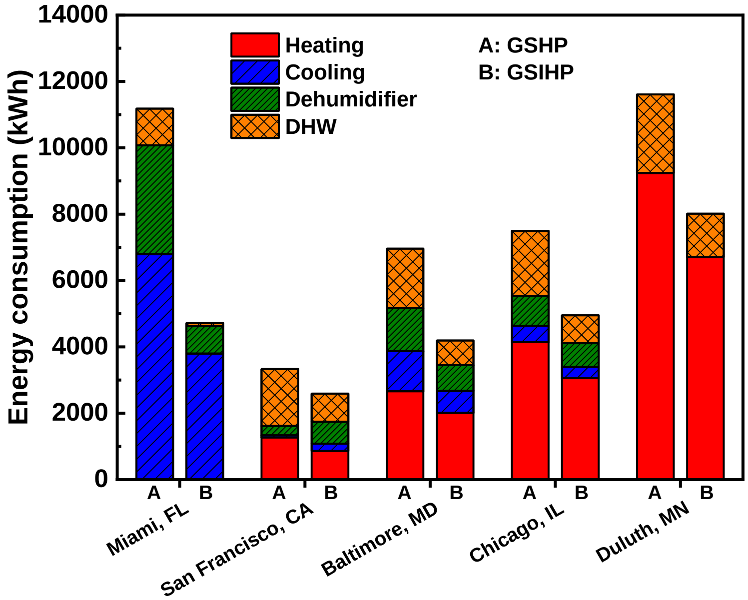

Figure 4: Annual HCD and DHW energy consumption: (a) GSHP and (b) GSIHP.

Fig. 5 shows the annual total building energy use intensity of the GSHP and GSIHP across different climates, normalized by floor area including the conditioned basement (135 m^2) and two stories of living area (251 m^2). The GSIHP demonstrated a reduction in energy use intensity compared to the GSHP by the following: 40 % (Miami), 9 % (San Francisco), 23 % (Baltimore), 20 % (Chicago), and 21 % (Duluth). Table 3 lists the PV array area and minimum rated output required to achieve net-zero annual energy use.

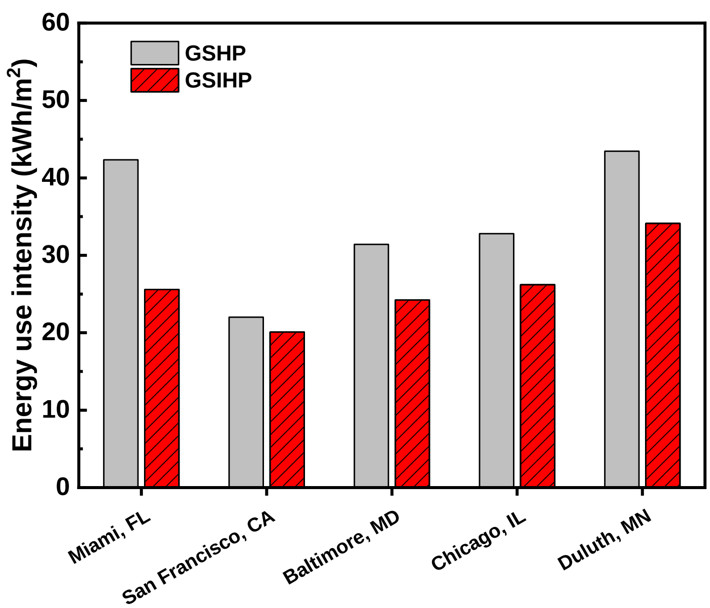

Figure 5: Annual total building energy use intensity of the GSHP and GSIHP.

Table 3: Minimum PV installation to achieve net-zero energy use.

Heat pumps	PV array parameter	Miami, FL	San Francisco, CA	Baltimore, MD	Chicago, IL	Duluth, MN
GSHP	Area (m^2)	45.3	22.2	37.5	40.6	54.5
	Rated output (kW)	9.8	4.8	8.2	8.8	11.9
GSIHP	Area (m^2)	27.4	20.3	29	32.5	42.8
	Rated output (kW)	5.9	4.4	6.3	7.1	9.3

3.2 Entering Liquid Temperature

The ELT varies depending on operating modes and heat pump capacity. Additionally, the ELT is affected by ground temperature, which exhibits variation in response to the geothermal energy utilization as a heat source or sink, based on thermal load characteristics influenced by the climate. In the heating-dominant region like Duluth, the ELT showed a continuous decline over years before the ground reached a thermal equilibrium (Fig. 6). Over a long-term period of 10 years, the ELT for the GSHP in the TRNSYS model went as low as 1 °C. This value was well above the −3 °C minimum expected from the analytical sizing method from (Kavanaugh and Rafferty, 2014). The TRNSYS result is likely more accurate because it uses the more detailed 3-dimensional duct storage (DST) model of the GHX and accounts for hourly load variations. Compared to the GSHP, the GSIHP extracted more thermal energy from the ground for DHW production and therefore had a lower minimum ELT of −3 °C. Consequently, the annual COP decreased by 1 % for the GSHP and 6 % for the GSIHP, respectively.

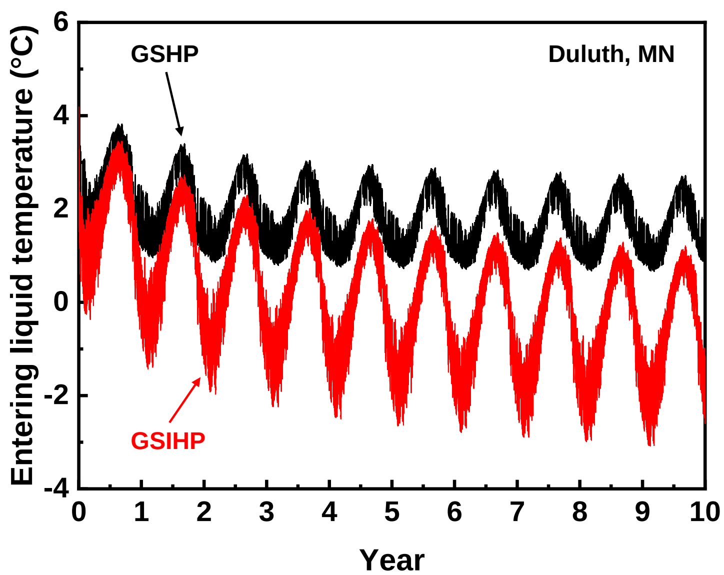

Figure 6: Hourly average ELTs for 10 years in Duluth.

4. CONCLUSIONS

In this study, we investigated and compared the performance of variable-speed GSIHPs and conventional two-capacity GSHPs across different U.S. climate zones. The energy use was simulated using a model of residential NZEB in TRNSYS. The GSIHP generally exhibited lower energy consumption than the GSHP due to its enhanced performance in both space conditioning and DHW, achieved with efficient, variable-speed components. Compared to the GSHP, the heating, cooling, and dehumidifier (HCD) and domestic hot water (DHW) energy consumption decreased by the following: 58 % (Miami), 22 % (San Francisco), 40 % (Baltimore), 34 % (Chicago), and 31 % (Duluth). The GSIHP demonstrated a reduction in whole-house energy use intensity compared to the GSHP by the following: 40 % (Miami), 9 % (San Francisco), 23 % (Baltimore), 20 % (Chicago), and 21 % (Duluth). Accordingly, the minimum PV array size required to achieve net-zero annual energy use was reduced. Over a long-term period of 10 years, the ELT variation for the GSIHP showed a greater decrease than that of the GSHP due to the increased geothermal energy utilization of the GSIHP for DHW production. Consequently, over the 10-year period, the annual COP in Duluth decreased by 1 % for the GSHP and 6 % for the GSIHP, respectively.

NOMENCLATURE

E	energy consumption	(kWh)
L_b	GHX total borehole length	(m)

Acronym

ASHP	air-source heat pump
ASIHP	air-source integrated heat pump
AUX	auxiliary heater
C+DHW	combined space cooling and domestic hot water
COP	coefficient of performance
DHW	domestic hot water
DST	duct storage model of the GHX
ELT	entering liquid temperature
ERV	energy recovery ventilator
GHX	ground heat exchanger
GSHP	ground-source heat pump
GSIHP	ground-source integrated heat pump
IHP	integrated heat pump
HCD	heating, cooling, and dehumidifier
HPWH	heat pump water heater
HVAC	heating, ventilation, and air-conditioning
HW	hot water
HX	heat exchanger
NIST	National Institute of Standards and Technology
NZEB	net-zero energy building
PV	photovoltaic
TMY	typical meteorological year
TRNSYS	Transient System Simulation Program

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ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2020R1A6A3A03038315). The technical assistance of Shawn Hern is gratefully acknowledged.