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Comparative Thermodynamics Analysis of Geothermal and Air Source Heat Pump for Heating and Cooling - A Case Study in Beijing#

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ABSTRACT

The heat pump is a highly efficient and environmentally friendly technology for converting electricity into heat with efficiencies larger than one. Recently, air-source heat pumps (ASHPs) have seen widespread deployment across various climate zones for building heating and cooling purposes. Conversely, ground-source heat pumps (GSHPs) offer even greater efficiencies but have seen 15% of total heat pump installations. This article intends to conduct a comprehensive thermodynamic comparison analysis of adopting an Air-source heat pump (ASHP) and a ground-source heat pump (GSHP) for building heating and cooling in Beijing using TRNSYS simulation. The TRNSYS model leverages city-level building information to simulate the load profile of the building. Additionally, it incorporated the impact of occupants' energy behavior including the window-opening schedule, heating and cooling temperature, effective area, and number of heat pumps to form 3 scenarios. As a result, the GSHP outperform the ASHP with around 30% higher efficiency and 45% reduction of total power consumption.

Keywords: Heat pump, carbon neutrality, thermodynamic analysis, TRNSYS, cost prediction, renewable energy, energy-saving

NONMENCLATURE

Abbreviations	
ASHP	Air-source heat pump
GSHP	Ground-source heat pump
U-factor	Thermal transmittance (W/m^2K)

1. INTRODUCTION

The combustion of fossil fuels for heating is a fundamental driver of the global economy, spanning from chemical to metallurgical, manufacturing to food processing and power generation to buildings [12]. However, heat-intensive processes produce a significant amount of greenhouse gas emissions, contributing negative impact on the global environment [1][2]. Between 2012-2022, emissions from the heating industry accounted for approximately 39% of total annual greenhouse gas emissions. China, with its large population and role as the world factory, generates 47.6% of total greenhouse gas emissions from heating industries [11]. However, the heating processes vary from end-use to intermediate energy needs, from industrial to daily use. This complexity adds to the challenges of decarbonizing heating, requiring specific technology pathways for different industries.

Building heating and cooling energy contributes around 46% of total heating energy consumption [13]. Generally, the heating temperature required for building sectors is below 80 degrees [14]. Heat pumps are a mature technology to recover waste heat to low-medium (0-100 degrees) high-grade heat energy. Coincident performance range and cost-competitiveness of heat pump make it a techno-economically feasible solution to decarbonize building heating. Advanced heat pumps now could supply heat up to 168 degrees, however, with higher technical maturity of low-medium heat pumps due to the limitation of high-temperature compressors. Heat pumps utilized for building heating and cooling can be mainly classified into air-source heat pumps (ASHP) and geo-source heat pumps (GSHP) [14]. The difference between ASHP and GSHP is, that the prior recovers heat stored in the underground soil while the follower utilizes air heat energy [15][17]. Nowadays, heat pumps only provide around 10% of building heating energy and the market is expected to expand with increasing penetration of heat pump deployment [17].

Many Researchers focus on the innovation of system design to improve the thermodynamics performance of ASHP or GSHP. Guo and colleagues explored how different fin designs in evaporators impact the frosting dynamics of air-source heat pumps [16]. [18] focused on the performance of a novel frost-free air-source heat

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pump system. Research on the appropriate refrigerants also attracts significant attention from researchers. Koury et al. simulated the dynamic behavior of a prototype using R134a, R410a, and R22 applications. The efficiency of utilizing R134a outperformed the R22 by 20% [19]. Recently, Wang presented an innovative design that integrates a frost-free mechanism with energy storage and dehumidification, aiming at enhancing energy efficiency and user comfort in residential heating solutions.

Researchers also evaluate the performance of deploying GSHP and ASHP in different locations. For instance, this study evaluated the application potential of ground source heat pumps (GSHP) across different regions in China, focusing on Shenyang. Violante evaluated the techno-economic performance based on data from the pilot GSHP and traditional ASHP project, showing that GSHP is more power efficient. [6] investigated the feasibility and performance of GSHP in three cities in cold climate zones. The result provided the guideline for deploying GSHP in cold climate zones.

In 2022, the global sales of heat pumps grew by 11%, with ASHP accounting for 85% of the total deployment. Nonetheless, ASHP application is hindered by lower Coefficients of Performance (COP) in colder climates, where efficiency drastically drops, reflecting a need for alternative solutions. In contrast, Ground-source Heat Pumps (GSHPs) present superior efficiency, which promises significant energy savings and reduced carbon emissions over their lifecycle. Despite these advantages, the adoption of GSHPs is constrained, attributed to the perceived high initial costs and a lack of comprehensive evaluation of their economic benefits over time.

The primary research gap resides in the inadequate valuation of GSHPs' long-term thermodynamic and environmental returns. Addressing this gap necessitates a comprehensive approach that evaluates both the immediate and extended implications of GSHP across various climatic conditions. This study for the first time comprehensively analyzes the thermodynamic performance of deploying GSHP and ASHP in Beijing considering 1 year and 10 years of operation. A novel ASHP and GSHP evaluating framework is also proposed in the study.

2. METHODS

This article employs TRNSYS 17.0 [8] to simulate the heat pump operation for heating and cooling a standard resident building, as depicted in Fig. 1. This novel ASHP and GSHP comparison framework incorporates the local data including weather information and building physical parameters. Then, the framework also considers the three factors related to resident behavior to form 3 simulation scenarios. For each scenario, a building load profile was first determined. Subsequently, ASHP and GSHP were designed according to the load profile, and 1-year simulations were then performed to analyze the thermodynamics performance.

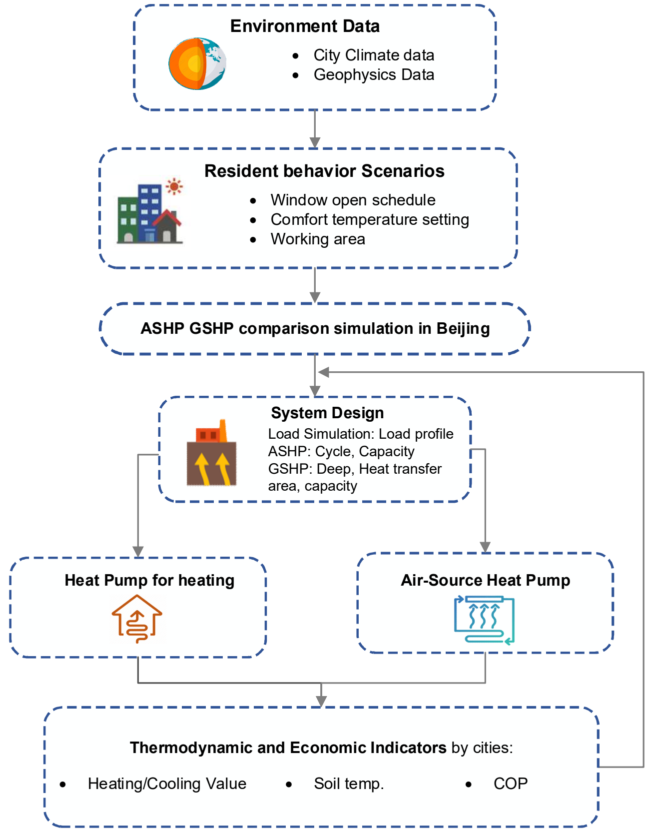

Fig. 1 Comparison framework of GSHP and ASHP

2.1 Design of analyzed buildings and scenarios

The target resident building is designed according to the data from China's Seventh National Population Census in 2020 [7]. The house in Beijing has an average space of 77.64 m^2, consists of 2 rooms, and accommodates 2.32 people per house. Based on the findings, a 15-floor resident building with 4 houses per floor was chosen with room layout information detailed in Table 1 and Fig. 2. According to the [9][10], the physical property of the selected building was attached in Table 2. Building in different climate zones has varying U-value according to the code requirement. Beijing, as in cold climate zone, requires the building materials with lower U values for better thermal insulation and energy savings.

Item	Value
Total Space (m2)	77.64
Room1 (m2)	18

Room2 (m2)	12
Bedroom (m2)	29.64
Kitchen (m2)	10
Bathroom (m2)	8

Table 1: Room layout information

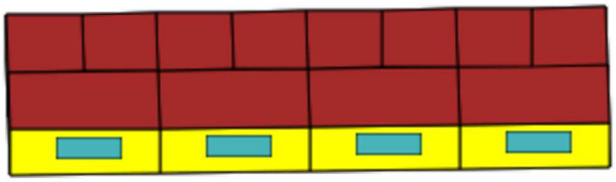

Fig. 2: Room layout

Property	C-Beijing
Area (m2)	5832
Window - Wall ratio	0.3
Out-wall U	2.1
Roof U	0.23
Window U	1.1
infiltration	0.5
No. of People	225

Table 2: Building physical properties

2.2 *The dynamic loadings and heat pumps operation simulation*

Besides the physical properties of the selected building, the residents' behaviors also have a significant impact on the building load profile. The room temperature setting directly decides the hourly power output of heat pump systems. In this model, different room temperatures as listed in Table 3, represent the 2 comfort levels. In addition, the window opening schedule decides the frequency of ventilation, which greatly affects the total power needed for the heat pump system. The window opening behaviors were classified by season and weekday to simulate how environmental temperature and working affect the building energy consumption.

To comprehensively analyze the impact of those factors, three scenarios are presented in Table 5. The high I case enables the residents with the highest comfort level, resulting in the highest peak load profile. However, deploying two heat pump systems to prevent the heat pump system frequently operating below the rated power could aid in energy savings. For low I case, only the bedroom area is powered by a heat pump system, simulating a more cost-efficient heat pump using strategy.

	Heat Temperature	**Cooling Temperature**
Comfort I	24	24
Comfort II	18	28

Table 3: Room temperature of different comfort level

	Season	Climate
Weekday	Spring	06:00–13:55
	Summer	19:00–09:40
	Autumn	09:00–18:28
	Winter	08:00–10:27
Weekend	Spring	09:00–16:55
	Summer	08:00–22:40
	Autumn	11:00–20:28
	Winter	10:00–12:27

Table 4: Window opening schedule [11]

	High I	**High I (Two Heat pump)**	**Low I**
Window Open Schedule	Schedule	Schedule	Schedule
Comfort Level	I	I	II
Area	Full room	Full room	Bedroom only

Table 5: Scenario Design

2.3 *The dynamic loadings and heat pumps operation simulation*

The model firstly performs a dynamic building load simulation by TRNSYS, as the system configuration for full room and bedroom depicted in Fig. 3 and Fig. 4 According to the load profile, key parameters including, COP, rated capacity, pump pressure, mass flow rate and buried pipe design could be determined.

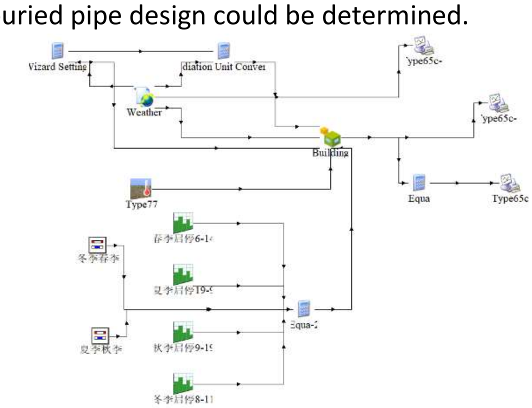

Fig. 3 Full room load simulation

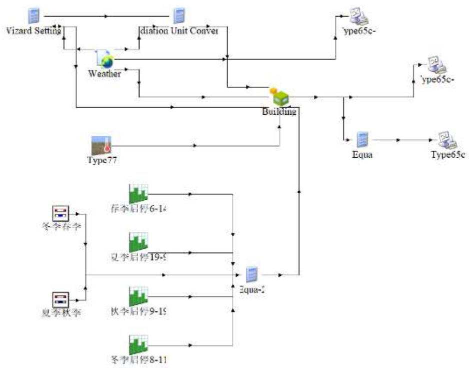

Fig. 4 Bedroom only load simulation

3. RESULTS

3.1 Load profile for full room and bedroom only

Fig.5 records the 1-year heating and cooling load of a full room and bedroom-only operation. The peak load for full room and bedroom-only situations are separately 302KW and 147KW. Load estimation is the key basis of the ASHP and GSHP design.

3.2 Power consumption of ASHP and GSHP

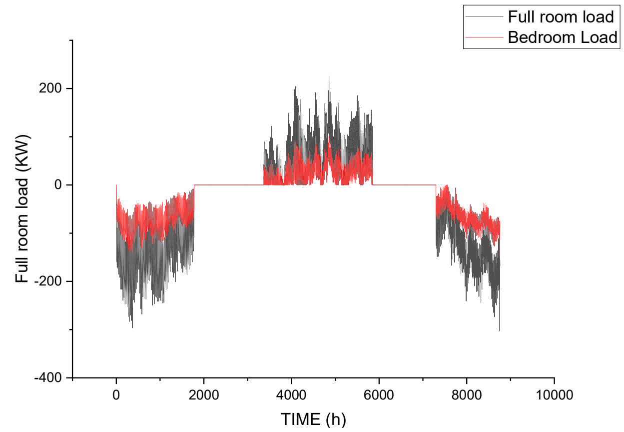

Fig. 5 Building load profile.

3.3 COP for 3 scenarios

The COP of GSHP and ASHP in each scenario is depicted in Fig. 8. The average COP for GSHP and ASHP is 4.39 and 2.72, respectively, indicating that GSHP efficiency significantly outperforms that of ASHP.2.72, respectively, indicating that GSHP efficiency significantly outperforms that of ASHP.

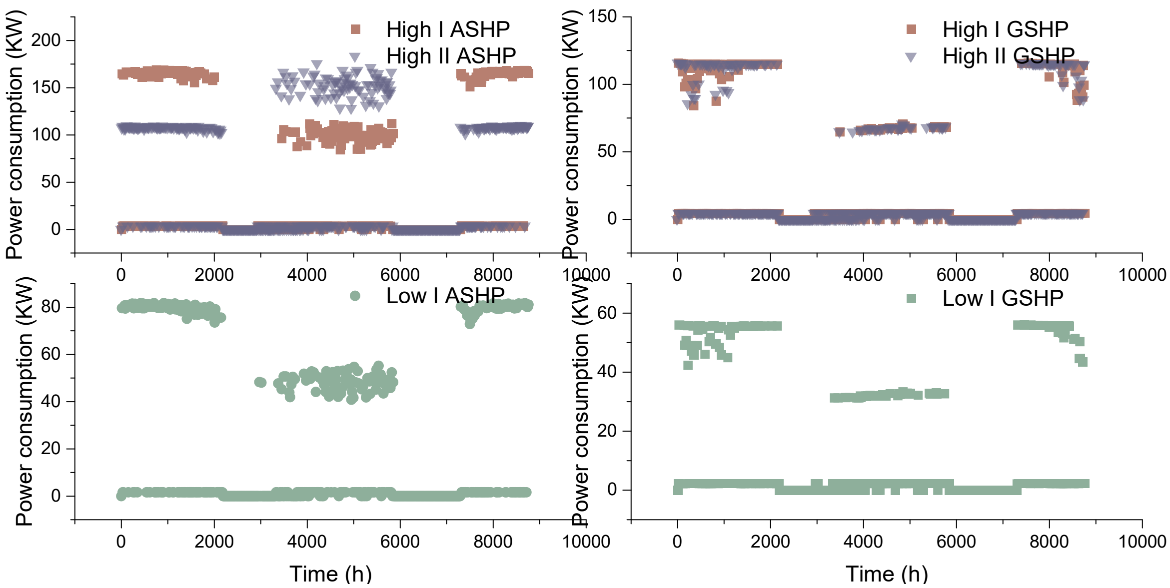

Fig. 6 Power consumption of 6 scenarios

The peak power consumption of ASHP and GSHP for the High I, High II, and Low I cases is illustrated in Fig. 6, with values of 169 kW and 115.9 kW, 188.7 kW and 116 kW, and 81 kW and 56 kW, respectively. In each case, GSHP exhibits greater energy efficiency, consuming approximately 35% less power. The total power consumption of GSHP for High I, High II, and Low I cases are 200,583Kwh, 200,191Khw, and 99,859Kwh, resulting in an average 45% power reduction of corresponding ASHP. The cooling and heating power for each scenario was illustrated in Fig. 7.

3.4 Change of Soil Temperature

One important factor that affects the performance of GSHP is the decreasing of soil temperature due to the imbalance of heat extraction and release, as shown in Fig.9. Lower temperature will decrease the GSHP performance and weaken the economic benefit.

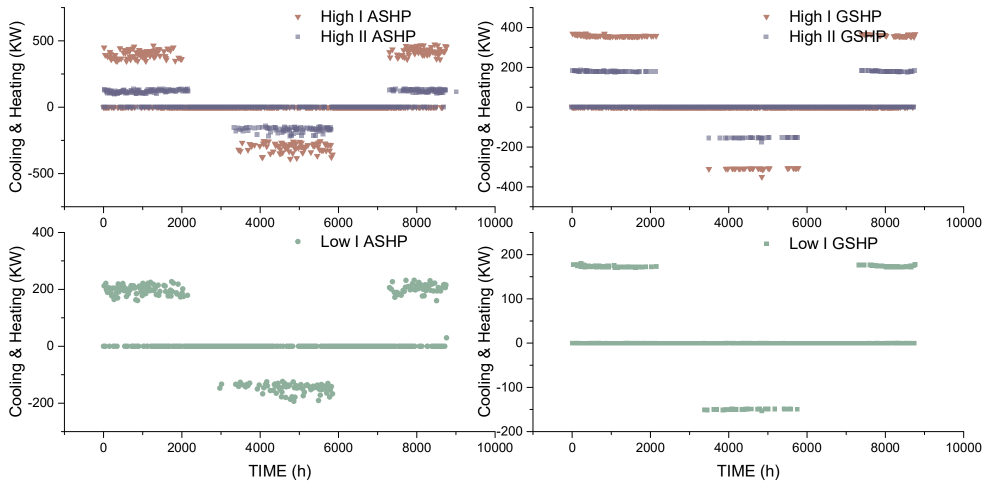

Fig. 7 Cooling and Heating of 6 scenarios

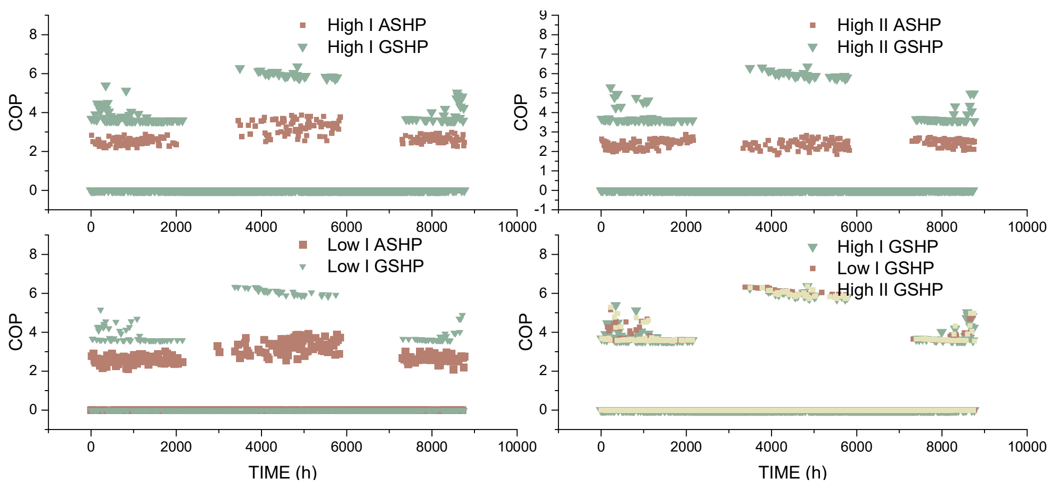

Fig. 8 COP of 6 scenarios

Geothermal farming plan is recommended in the future study.

4. DISCUSSION AND FUTURE WORK

The results indicate that resident behaviors and heating and cooling areas have a significant impact on the building load profile. Additionally, GSHP demonstrates higher energy efficiency with less power consumption compared to ASHP. The energy savings achieved by GSHP could offset the initially higher capital expenditure, making it more economically feasible in the long run. However, this study doesn't simulate the actual cost of each system and provide a quantitative economic result. In the future study, life-cycle economic analyses should be incorporated to evaluate the impact of decreasing temperature, variation of electricity prices to assist investors and customers in making decisions based on economic data. Furthermore, given the significant impact of climate, cities from four different climate zones will be included in the analysis. These updated guidelines will provide valuable guidance to policymakers, investors, and residents in selecting the most technologically and economically feasible options.

5. CONCLUSIONS

The adoption of GSHP outperform the ASHP with around 30% higher efficiency and 45% reduction of total power consumption. However, proper soil farming strategies should be analyzed to improve the decreasing soil temperature. In addition, the residential behaviors also significantly affect the space heating and cooling load.

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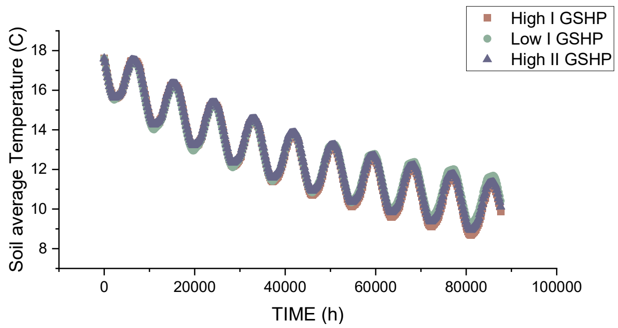

Fig. 9 Change of soil temperature for 10 years

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