INTERNATIONAL JOURNAL OF
# ENERGY EFFICIENCY ENGINEERING

# Performance Analysis and Optimization of a Dual-Source Heat Pump System: Evaluating Bivalent Point Strategies for Enhanced Efficiency

## Md Tarif Raihan[a] and Ryoichi S. Amano[b,1]

[a] Mechanical Engineering, University of Wisconsin–Milwaukee, Milwaukee, WI, USA

[b] Richard & Joanne Grigg Fellow Professor, Mechanical Engineering, University of Wisconsin–Milwaukee, Milwaukee, WI, USA

## Abstract

This study presents a comprehensive performance analysis and optimization framework for a dual-source heat pump (DSHP) system integrating Air Source Heat Pumps (ASHP), Ground Source Heat Pumps (GSHP), and Parallel Source Heat Pumps (PSHP). A MATLAB–Simulink model, developed using the CARNOT toolbox, simulates various configurations to identify optimal operational strategies. Results show that hybrid operation improves the Annual Performance Factor (APF) by approximately 5 % compared to a standalone GSHP system and allows a reduction in borehole depth by ~28 % (from 70 m to 50 m) while maintaining stable brine temperatures. The optimized bivalent switching (ASHP > 0 °C; GSHP < 0 °C down to – 10 °C) minimizes temperature lift and enhances thermal balance in the ground loop. The findings highlight the importance of coordinated source management for achieving higher energy efficiency and long-term stability in hybrid heat pump systems.

**Keywords:** Hybrid heat pump; Bivalent temperature; Ground source heat pump; Air source heat pump; Energy efficiency; System optimization

---

[1] Corresponding author: Dr. Ryoichi Amano: amano@uwm.edu

**Nomenclature:**

| Symbol | Description | Unit |
|---|---|---|
| ASHP | Air Source Heat Pump | - |
| Cd | Degradation Ratio | - |
| cp,f | Filling Heat Capacity | J/kg·K |
| cp,g | Ground Heat Capacity | J/kg·K |
| EIR | Energy Input Ratio | - |
| EWTmin | Minimum entering Brine Temperature | °C |
| FH | Run Fraction in heating mode | - |
| GB | Ground Thermal Resistance | K/W |
| GSHP | Ground Source Heat Pump | - |
| GSHX | Ground Source Heat Exchanger | - |
| LWTmin | Minimum leaving Brine Temperature | °C |
| PSHP | Parallel Source Heat Pump | - |
| PLF | Part Load Factor | - |
| PLR | Part Load Ratio | - |
| PSHP | Parallel Source Heat Pump | - |
| RB | Borehole Thermal Resistance | K/W |
| TG | Average Ground Temperature | °C |
| $\dot{m}_b$ | Brine Mass Flow Rate | kg/s |
| $\rho_f$ | Filling Density | kg/m³ |

## I.    Introduction

Hybrid heat pump systems that integrate Air Source Heat Pumps (ASHP), Ground Source Heat Pumps (GSHP), and Parallel Source Heat Pumps (PSHP) have emerged as effective solutions for enhancing energy efficiency while reducing operational costs in heating and cooling applications. To optimize performance. These systems intelligently switch between different heat sources depending on environmental conditions. Berkane et al. (2023)[1] highlighted that hybrid heat pump configurations significantly improve seasonal efficiency and reduce energy consumption. Traditional ASHPs lose efficiency in colder climates, while GSHPs provide stable year-round performance but require higher installation costs. Hu et al. [2] emphasized that hybrid systems balance these limitations, ensuring improved performance under varying climatic conditions. Yuan et al. [3] found that hybrid heat pump systems improve seasonal performance factors (SPF) by up to 30% compared to single-source configurations, demonstrating their effectiveness in diverse climates. Proper system sizing and control strategies are crucial in optimizing hybrid heat pump efficiency. Kaneko and Yoshinaga [4]

reported that incorporating PSHPs in hybrid systems reduced peak electricity demand by 20%, while Staffell et al. [5] demonstrated that dynamic control strategies could achieve energy savings of up to 25%. Parallel Source Heat Pumps (PSHP) provide further optimization by allowing seamless transitions between ASHP and GSHP modes based on external temperature and demand. A study by Rony et al. [6] found that PSHPs improved efficiency by 27% compared to ASHPs alone and reduced required ground loop installations by 15%. Similarly, Dworkin et al. [7] observed that PSHPs enhanced system stability and long-term reliability. The economic feasibility of hybrid heat pump systems has also been extensively studied. Xia et al. [8] conducted a cost-benefit analysis revealing that ASHP-only systems have a payback period of approximately six years, while GSHP-only configurations require 14 years for return on investment. Hybrid ASHP-GSHP configurations offered an optimal balance, achieving a payback period of 8-10 years with 20% lower lifetime costs. Abbasi et al. [9] also identified further financial benefits, particularly in energy cost savings over the system's lifespan. Integrating hybrid heat pumps with renewable energy sources has also been explored. Hou and Taherian [9] found that combining hybrid heat pumps with photovoltaic (PV) systems reduced grid electricity consumption by 45% and peak demand charges by 60%. Similarly, Sommerfeldt and Madani [10] demonstrated that integrating geothermal energy with hybrid heat pump systems improved heat exchange efficiency by 25% in urban environments. Despite the many benefits, challenges remain in the long-term performance of hybrid heat pump systems. Zhang et al. [11] emphasized the need for machine-learning-based predictive models to dynamically adjust ASHP-GSHP utilization based on real-time weather conditions and energy prices. Finally, hybrid heat pump systems offer a promising solution for improving energy efficiency and sustainability in heating and cooling applications. Hybrid systems can achieve greater efficiency and lower operational costs by optimizing system sizing, integrating renewable energy sources, and employing intelligent control mechanisms. Future advancements in AI-driven predictive analytics and long-term monitoring will improve system performance and ensure widespread adoption of hybrid heat pump technology.

## II.    Objectives

Despite significant progress in hybrid heat pump research, existing studies seldom quantify how bivalent temperature settings and borehole sizing jointly affect system performance, ground temperature stability, and long-term efficiency. This gap limits the development of

predictive control strategies for dual-source configurations. The present study addresses this issue by developing a dynamic supervisory control algorithm that coordinates the operation of Air Source Heat Pump (ASHP), Ground Source Heat Pump (GSHP), and Parallel Source Heat Pump (PSHP) modes according to ambient conditions. Using a MATLAB–Simulink model with the CARNOT library, the research investigates (i) the effects of bivalent switching temperatures and borehole depth on the system's Annual Performance Factor (APF), (ii) the improvement achieved by hybrid operation compared to a standalone GSHP, and (iii) the optimal temperature zoning strategy for maximizing efficiency while maintaining ground thermal balance.

### III.     Methodology

A MATLAB-Simulink model has been developed for this research utilizing the MATLAB CARNOT library. The developed Simulink model integrates empirical heat pump data with dynamic heat exchanger simulation to represent realistic hybrid system behavior. The simulations in this study were carried out using the CARNOT Toolbox integrated within the MATLAB–Simulink environment. The CARNOT Toolbox (version 6.1) extends Simulink's modeling capability by providing dynamic component blocks for building energy and heating system simulation. It includes validated modules for heat pumps, heat exchangers, fluid storage, and HVAC system controls. In this research, three major blocks from the CARNOT library were utilized: the Heat Pump, Ground Source Heat Exchanger (GSHX), and Building Load modules. Each block solves energy balance equations using finite difference time-domain (FDTD) or lumped-parameter approaches, depending on the block type. Manufacturer performance maps for the selected ASHP and GSHP units were interpolated and linked to the Heat Pump block, allowing the model to calculate heating capacity and power input at any ambient condition. The GSHX module represents transient heat transfer in vertical boreholes, accounting for radial and axial discretization of the soil domain and thermal resistances of the borehole, grout, and ground. Time-step integration was configured to 1 s to ensure numerical stability. The toolbox's open-source framework provides flexibility to customize component equations, making it particularly suitable for research on control optimization and hybrid operation. Figure 1 illustrates the annual space heating load profile of a single family house from [12] which serves as load in this study.
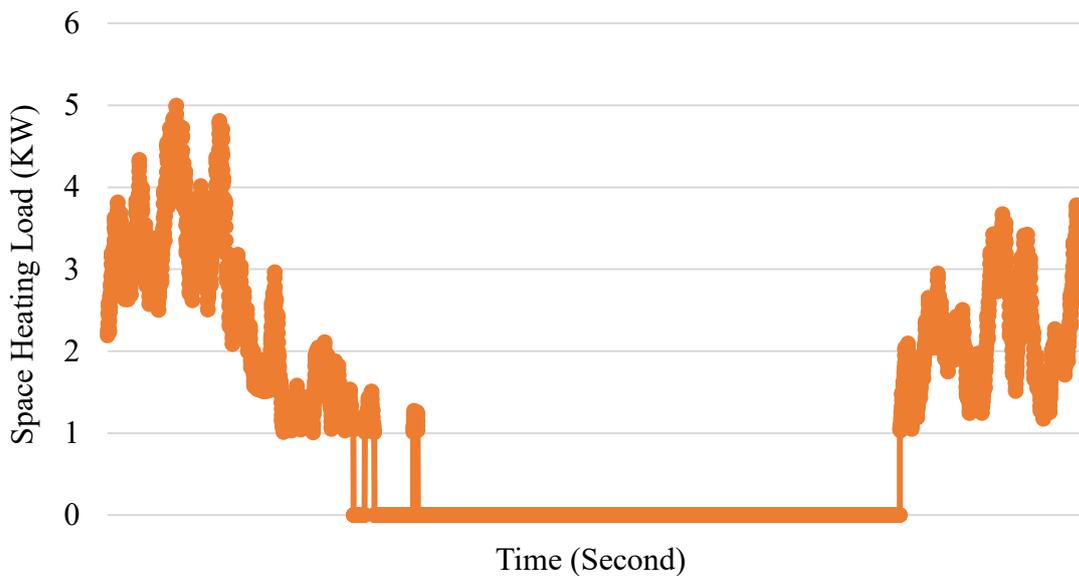
Figure 1: Space Heating Demand of a Single Family House for a whole year

**Operational Principles of the Hybrid Heat Pump System**

The operation of the Hybrid Heat Pump (HHP) system is structured into two main steps, as outlined below:

Step 1: No-Load Screening – At each time step, the algorithm evaluates the building's heating demand which has been drawn in Figure 1. If there is no heating load, Heat Pump is turned off. This helps to avoid unnecessary standby energy losses and prevents wasteful energy consumption during periods of zero heating demand.

Step 2: Temperature Zoning Criteria for ASHP, GSHP, and PSHP Activation – The algorithm reads the current ambient temperature and categorizes the system operation into one of three modes:

**Air-Source Only Mode:** ASHP is activated under mild ambient conditions (for initial case above 5 °C). The Air-Source Heat Pump (ASHP) model uses three primary input parameters: ambient temperature, sink temperature (35°C for this study), and the required heating load (building demand). Based on these inputs, the heating capacity and corresponding electrical power consumption of the ASHP are determined through interpolation. For this study, the Black Diamond LN35 series from Mitsubishi Electric [13] was selected as the reference heat

pump. Heating capacity and electrical consumption data were extracted from the manufacturer's catalog, which provides values across different ambient and sink temperatures. These catalog values were interpolated to develop a continuous performance model, allowing the ASHP to estimate its heating output and required electrical input at any given operating condition within the tested range.

**Ground-Source Only Mode:** The Ground-Source Heat Pump (GSHP) is activated during moderate ambient temperature conditions, initially set between ambient temperature of +5°C and –5.4°C, to take advantage of the thermally stable subsurface environment. The GSHP model uses three input parameters: the temperature of the brine leaving the Ground-Source Heat Exchanger (GSHX), the sink temperature (i.e., the desired supply temperature), and the required heating load (building demand). Sink temperature has been fixed as 35 °C for this study. The flexoTHERM ground-source heat pump (5 kW) [14] has been selected as the reference GSHP. Heating capacity and electrical consumption data were extracted from the manufacturer's catalog and interpolated to build a continuous performance model. This model enables the GSHP to predict its heating output and electrical input under a variety of operating conditions within the validated temperature range.

**Ground Source Heat Exchanger (GSHX)**: A Ground-Source Heat Exchanger (GSHX) from the MATLAB CARNOT Library was integrated with the GSHP model for transient simulation of vertical boreholes. A single-borehole setup was used to explore minimum required depth while maintaining performance. The brine flow rate was chosen from literature to match real applications and target the desired Annual Performance Factor (APF), while other thermal and geometric parameters were kept as default. These parameters were cross-checked and verified to ensure consistency with practical field data. Table 1 represents important GSHX parameters.

Table 1: Ground Source Heat Exchanger (GSHX) parameters

| Parameter | Value | Unit |
|---|---|---|
| Borehole depth | 70 | m |
| Borehole diameter | 0.12 | m |
| Pipe outer diameter | 0.032 | m |

| | | |
|---|---|---|
| Shank spacing[2] | 0.032 | m |
| Pipe wall thickness | 0.003 | m |
| Brine mass flow rate | 0.4 | kg/s |
| Ground thermal conductivity | 2.5 | W/m·K |
| Ground heat capacity | 1000 | J/kg·K |
| Ground density | 2200 | kg/m³ |
| Filling thermal conductivity | 0.81 | W/m·K |
| Filling heat capacity | 3040 | J/kg·K |
| Filling density | 1180 | kg/m³ |
| Pipe thermal conductivity | 0.48 | W/m·K |
| No. of vertical nodes | 5 | – |
| No. of radial nodes | 10 | – |

**Parallel Mode:** This mode represents the combined operation of the air-source heat pump (ASHP) and the ground-source heat pump (GSHP). It activates during extreme low-temperature ambient conditions (for initial case less than -5°C). In parallel hybrid operation, the contribution of the ground-source heat pump (GSHP) increases as the ambient temperature decreases. When ambient conditions are relatively mild, the GSHP's share of the heating load remains limited. However, as temperatures drop, the GSHP gradually assumes a larger proportion of the total demand. The initial design strategy followed a 70–30 distribution, meaning that during parallel mode, the GSHP was intended to cover approximately 70% of the heating load, while the air-source heat pump (ASHP) contributed the remaining 30%. Simulation results indicated that increasing the ASHP's share beyond this threshold led to a noticeable decrease in the Annual Performance Factor (APF). Importantly, the load-sharing ratio in the HHP control algorithm is not fixed. Instead, it dynamically adjusts based on the selected bivalent temperature points. When the parallel source heat pump (PSHP) is required to operate over a broader temperature range, the GSHP's cumulative share naturally increases. Nonetheless, in the baseline scenario, the GSHP accounted for about 70% of the heating contribution, while the ASHP supplied the remaining 30%.

---

[2] distance between the centers of the two legs of the U-pipe inside the borehole.

Figure 2 represents the flowchart illustrating the decision-making process used to determine which heat pump—ASHP, GSHP, or PSHP—operates under different ambient temperature conditions. The control algorithm implemented in MATLAB follows a hierarchical decision structure. It has been designed to closely simulate real-world field operation while maximizing energy efficiency and protecting system components.
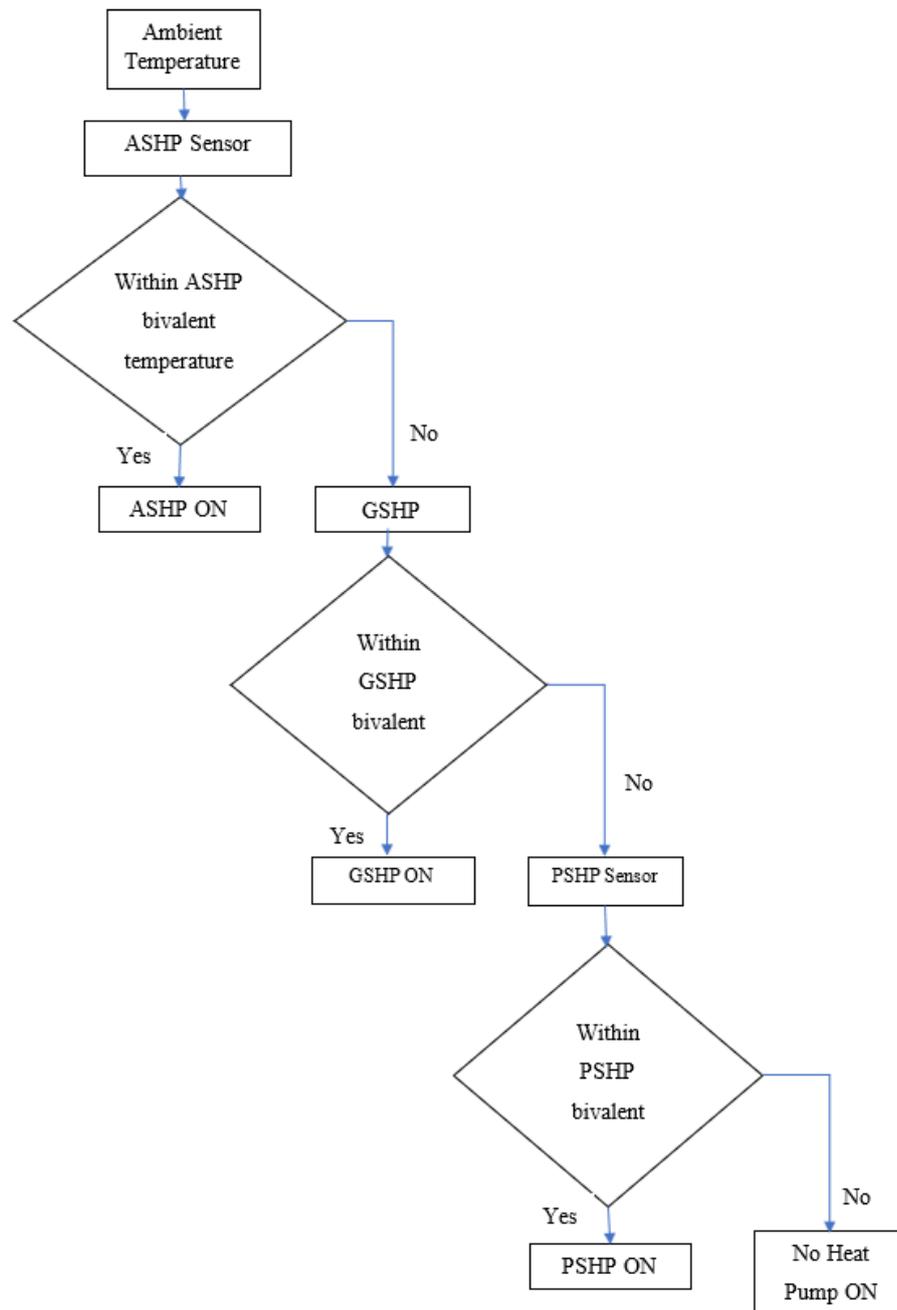


Figure 2: HHP Decision Logic Algorithm

**Mass Flow Rate –** A brine mass flow rate of 0.4 kg/s was chosen in the Ground Source Heat Exchanger to keep the borehole depth as small as possible. According to Spitler et al. [15], an increase in flow rate from around 0.22 to around 0.4 kg/s for a 100 m deep borehole shows an improvement in effective thermal resistance. Also after a certain point, increasing flow rate does not help much because the improvement becomes very small [16]. This happens because the ground cannot send more heat fast enough, even if the brine moves faster. One study showed that after some increase, significantly higher flow rate does not improve heat transfer anymore [16]. Furthermore, it is important to consider that when the inlet flow rate increases, the pumping power undergoes exponential growth [17]. Such high flow is not practical in real GSHP systems. Usually, single borehole systems use about 0.1–0.5 kg/s [18].

**Optimizing Borehole Depth for Hybrid Operation –** One of the primary objectives of this study is to determine the minimum single-probe borehole depth for the Ground-Source Heat Exchanger (GSHX) required to meet the system's heating demand. Based on the simulation results, it was found that a borehole depth of at least 50 meters, paired with a brine flow rate of 0.4 kg/s, provides sufficient heat exchange area to maintain the brine inlet temperature within safe operational limits. Reducing the borehole depth below 50 meters caused the simulations to fail, with brine outlet temperatures dropping dangerously low during peak winter conditions, approaching the Ground-Source Heat Pump's (GSHP) minimum allowable operating temperature. An undersized borehole poses significant risks, including fluid freezing or heat pump shutdown, both of which result in a loss of capacity and overall system efficiency [19]. This finding is consistent with real-world practice, where vertical ground loops are commonly drilled to depths ranging from approximately 50 meters to 200 meters depending on the project requirements [20]. While minimizing borehole depth can significantly reduce initial installation costs, the ground loop must still be able to supply adequate heat, particularly during the coldest periods.

**Optimizing Borehole Depth for Standalone GSHP System –** A key objective of this study was to compare the performance of a hybrid heat pump (HHP) system with that of a standalone ground-source heat pump (GSHP). Simulation results show that the standalone GSHP requires a borehole depth of at least 70 meters to maintain safe brine inlet temperatures, while the HHP achieves the same performance with only 50 meters. This difference is due to the support provided by the air-source heat pump (ASHP) in the hybrid system, which shares the load during low ambient temperatures, reducing stress on the ground loop. In contrast, the GSHP-only system operates continuously, limiting opportunities for ground thermal recovery. As a result, deeper boreholes are needed to compensate for declining ground temperatures and to maintain system efficiency and reliability over time.

## IV.   RESULTS AND DISCUSSION

The observed performance trends can be interpreted based on thermodynamic principles governing heat pump operation. As borehole depth increases, the effective ground temperature surrounding the heat exchanger becomes more stable, reducing the temperature lift between the evaporator (source) and the condenser (sink). Since the Coefficient of Performance (COP) of a heat pump is inversely related to the temperature lift ($\Delta T = T_{sink} - T_{source}$), a smaller $\Delta T$ directly leads to higher COP and consequently a higher Annual Performance Factor (APF).

In the hybrid configuration, the ASHP supplements the GSHP during moderate outdoor conditions, minimizing the continuous extraction of heat from the soil. This intermittent operation allows the ground to undergo thermal regeneration, where heat naturally recovers through conduction and groundwater movement. The process mitigates long-term soil cooling, preventing the formation of a "cold plume" around the borehole and sustaining higher ground-source temperatures throughout the heating season.

Furthermore, the flattening of the APF curve beyond approximately 180 m (as seen in Figure 3) indicates that deeper drilling does not proportionally enhance performance because axial thermal gradients become negligible beyond the thermally active zone. Therefore, optimal design focuses not solely on depth but on dynamic load distribution between ASHP and GSHP to maintain thermal balance.

These findings collectively emphasize that the hybrid system's advantage lies not only in immediate efficiency gains but also in long-term sustainability, reducing soil degradation and maintaining stable operation over multiple seasons.

Figure 3 compares ground temperatures around the borehole. The observed values are lower than typical undisturbed temperatures because they represent annual averages. Continuous heat extraction by the GSHP lowers the ground temperature over time. Even in hybrid mode, the GSHP supplies about 70% of the heating load, sustaining thermal draw and contributing to further ground cooling.
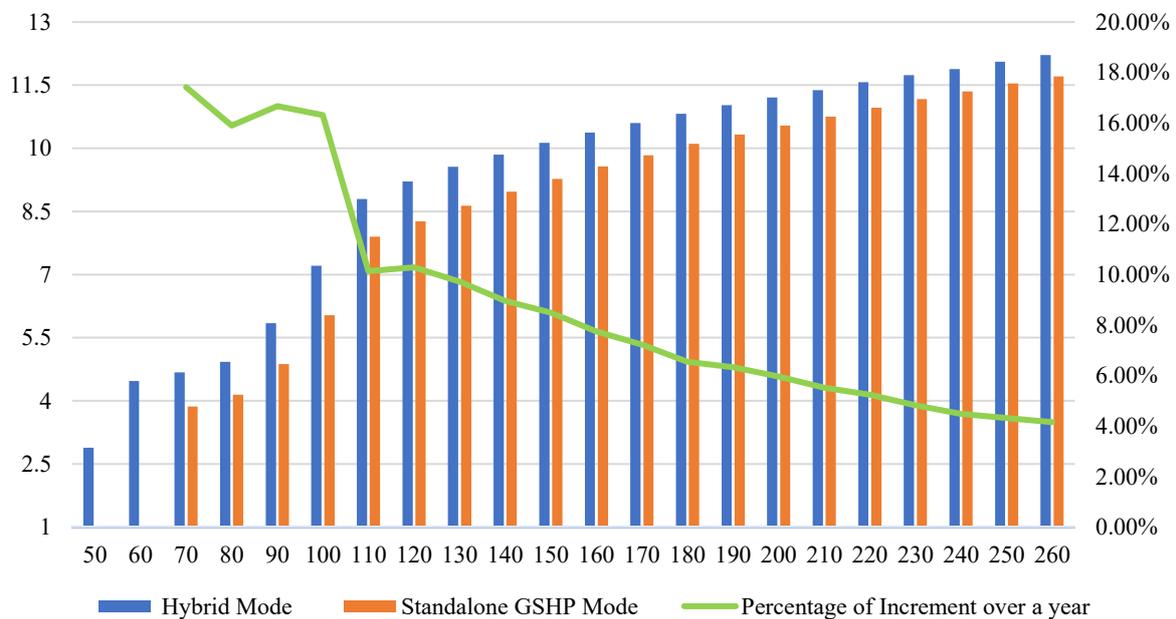


Figure 3: Comparison of Average Ground Temperature with respect to borhole depth over the year during Hybrid mode and Standalone GSHP mode

Figure 4 and Figure 5 compares brine inlet and outlet temperatures for Hybrid and Standalone GSHP modes. The HHP consistently maintains warmer brine temperatures, which lowers electricity use and improves the Annual Performance Factor (APF). The underlying mathematical explanation is discussed in the next section.
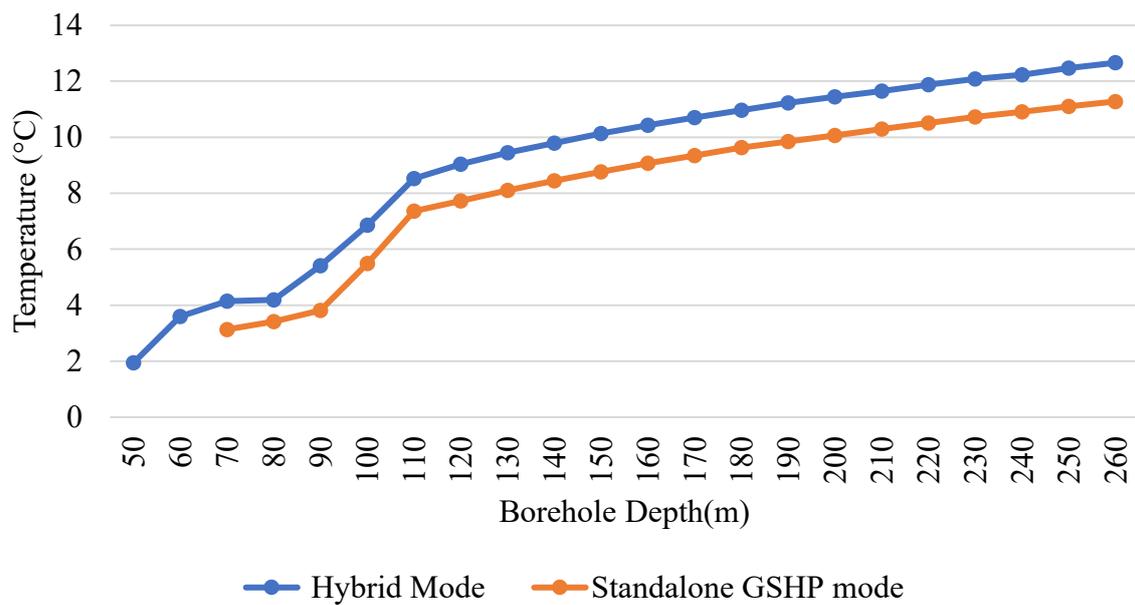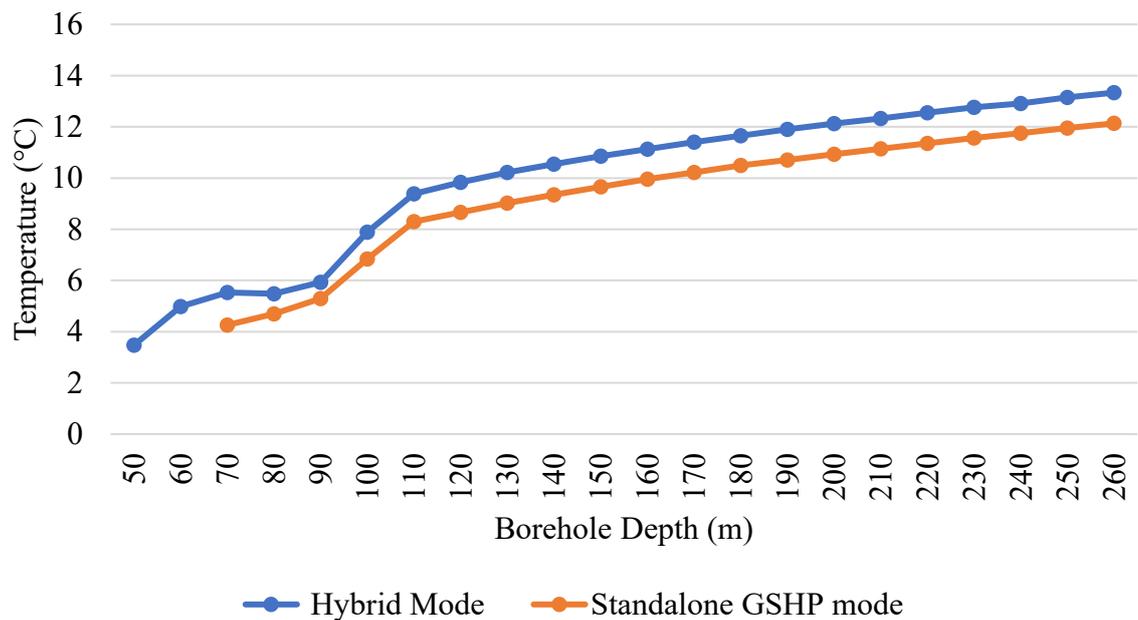
Figure 4: Comparison between Temperature of Brine entering GSHX in Hybrid mode and Standalone GSHP mode



**V.**

Figure 5: Comparison between Temperature of Brine leaving GSHX in Hybrid mode and Standalone GSHP mode

The hybrid heat pump (HHP) system performs more efficiently than the standalone ground-source heat pump (GSHP) by switching between heat sources based on ambient temperature, reducing temperature lift and improving the Annual Performance Factor (APF). While GSHP-only systems require deeper boreholes for efficiency (e.g., APF from 2.9 to 3.6), the HHP

system reduces ground load, resulting in a smaller APF gain with depth (e.g., from 3.34 to 3.7). Thus, borehole depth has a greater impact on standalone GSHP systems than on hybrid ones. Figure 6 shows the comparison of Annual Performance Factor (APF) between the Hybrid mode and the Standalone GSHP mode.
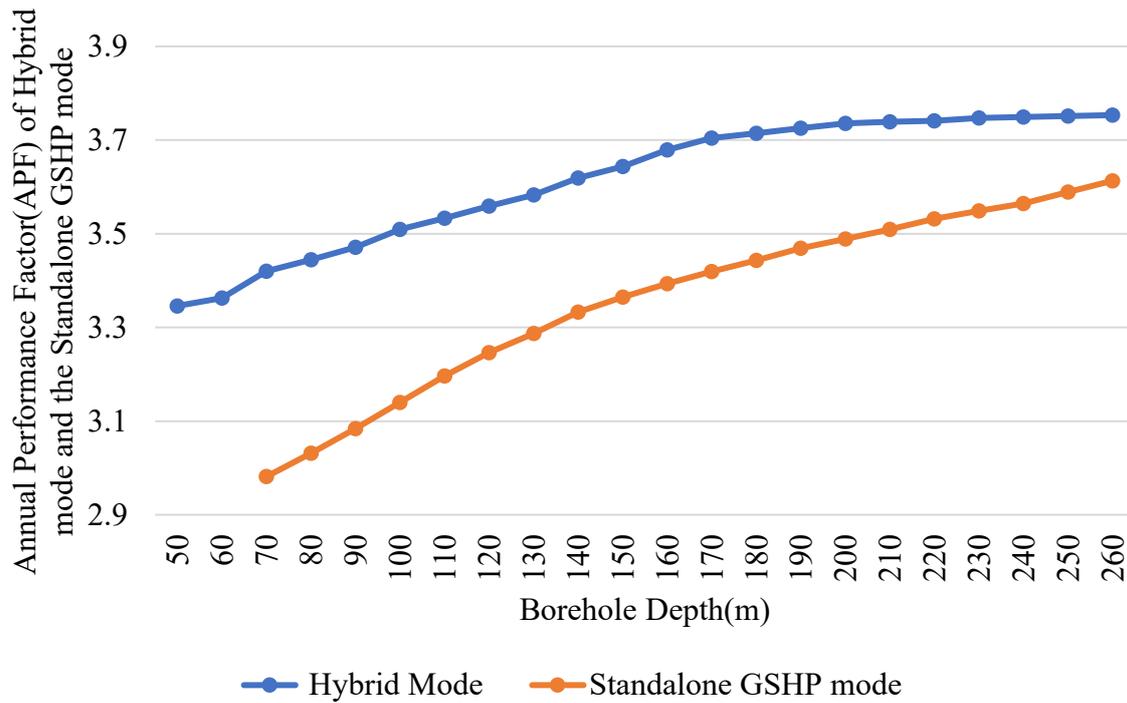


Figure 6: Comparison of Annual Performance Factor (APF) with respect to borehole depth for the Hybrid mode and the Standalone GSHP mode

Figure 7 and Figure 8 illustrate the relationship between brine temperatures and the Annual Performance Factor (APF) for the Hybrid mode and the Standalone GSHP mode, respectively.
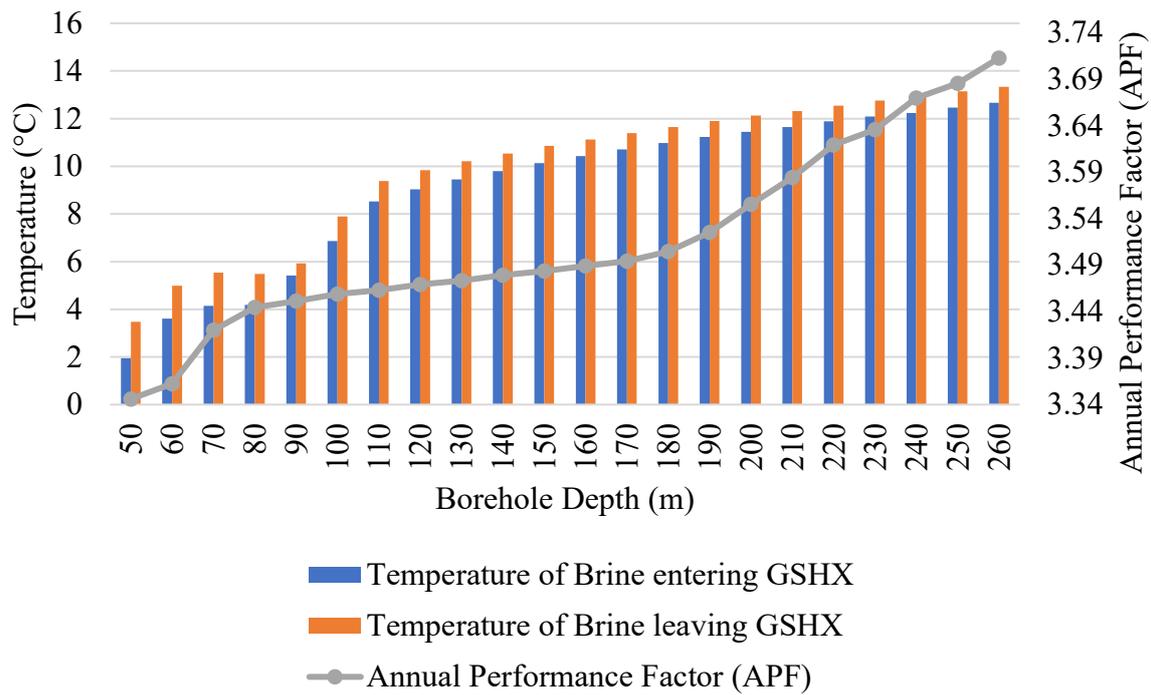
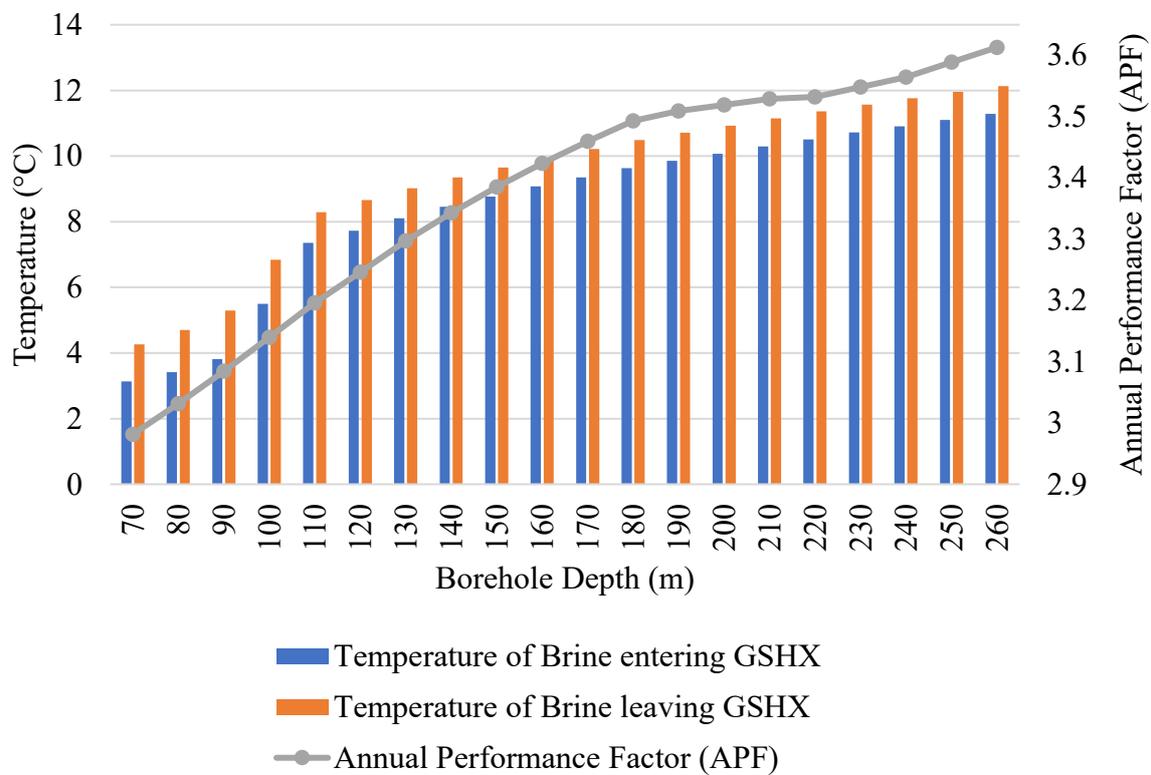Figure 7: Temperature of Brine entering and leaving GSHX and APF in HHP System



Figure 8: Temperature of Brine entering and leaving GSHX and APF in Standalone GSHP System

Previous analysis confirmed the superior efficiency of the hybrid heat pump (HHP) system over the standalone ground-source heat pump (GSHP). This section compares different HHP cases to identify optimal bivalent temperature setpoints for switching between heat sources. A 70 m borehole was used consistently in all cases, based on earlier findings showing effective performance at this depth and to avoid the brine temperature issues seen in shallower GSHP-only simulations. Eleven cases were tested, varying the ambient temperature thresholds for ASHP, GSHP, and PSHP operation. Initially, the GSHP's lower operating limit was set at −5.4°C (Case 1), following manufacturer guidelines, but reliable performance down to −10°C was later achieved with PSHP assistance, which was then used in all following cases. The study then examined how far GSHP operation could extend above 0°C. Since ASHP in hybrid systems typically operates up to +13°C and the results across Cases 1 to 10 showed a clear trend, analysis was concluded at Case 10. Table 2 summarizes the bivalent temperature switching points used in the HHP system.

Table 2: Operational Ranges of ASHP, GSHP, and PSHP for Each Case Study

|  | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| **ASHP** | ≥ 5°C | ≥5°C | ≥ 5°C | ≥ 0°C |
| **GSHP** | -5.4°C to 5°C | -7°C to 5°C | -10°C to 5°C | -10°C to 0°C |
| **PSHP** | -5.4°C to lowest | -7°C to lowest | -10°C to lowest | -10°C to lowest |
|  | **Case 5** | **Case 6** | **Case 7** | **Case 8** |
| **ASHP** | ≥ + 1°C | + 2°C to above | + 3°C to above | + 4°C to above |
| **GSHP** | -10°C to 1°C | -10°C to 1°C | -10°C to 2°C | -10°C to 3°C |
| **PSHP** | -10°C to lowest | -10°C to lowest | -10°C to lowest | -10°C to lowest |
|  | **Case 9** | **Case 10** |  |  |
| **ASHP** | + 6°C to above | + 7°C to above |  |  |
| **GSHP** | -10°C to 6°C | -10°C to 7°C |  |  |
| **PSHP** | -10°C to lowest | -10°C to lowest |  |  |

Figure 9 illustrates the temperatures of the brine entering and leaving the ground-source heat exchanger (GSHX), along with the corresponding temperature difference. The results show that the brine temperature difference across the GSHX decreases from Case 1 to Case 4 and then increases from Case 4 to Case 10.
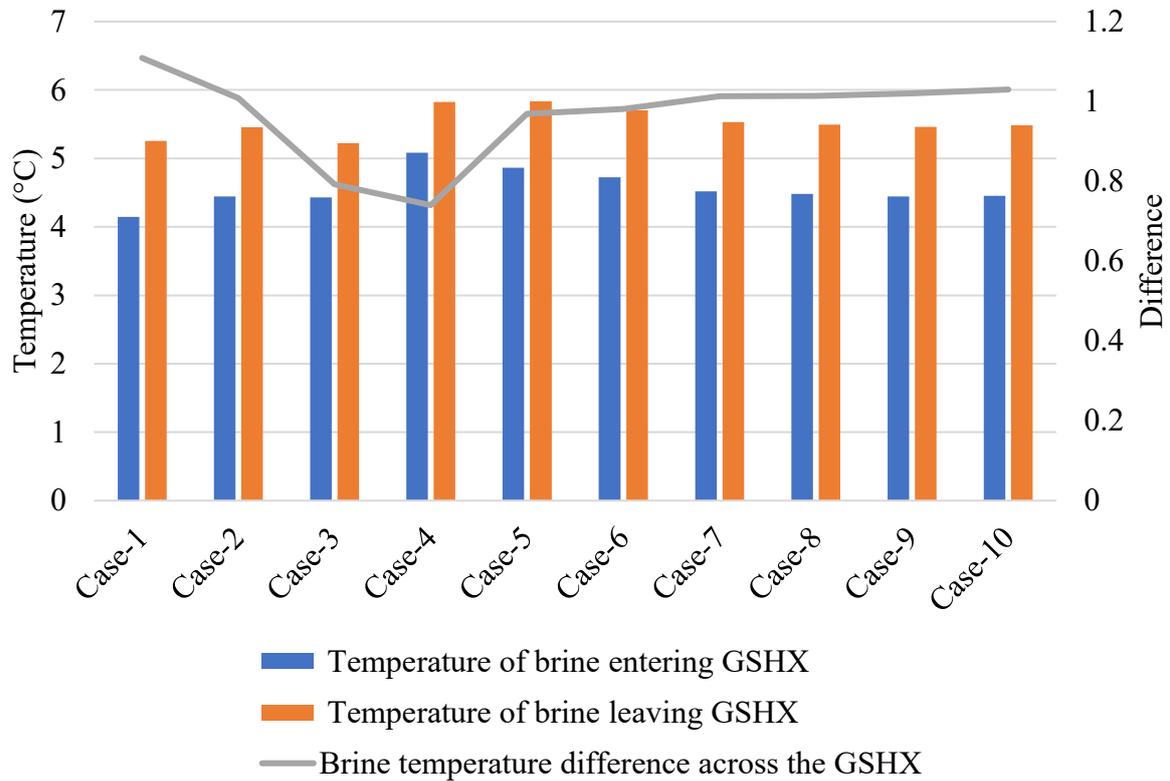


Figure 9: Temperatures of Brine across GSHX and difference between those temperatures

Figure 10 presents the relationship between the ground temperature surrounding the borehole and the brine temperature difference across the GSHX. It clearly demonstrates that a smaller temperature difference between the brine inlet and outlet corresponds to a higher ground temperature.
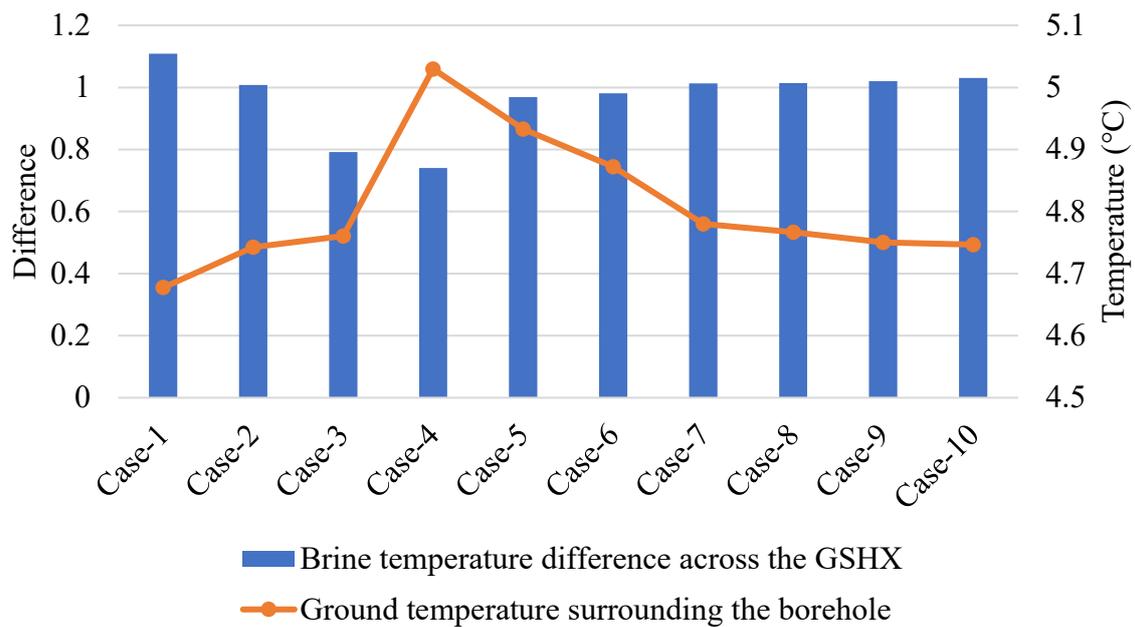
Figure 10: Correlation between Ground Temperature and Brine Temperature Difference across the GSHX

Figure 11 depicts the relationship between the ground temperature and the Annual Performance Factor (APF). The data indicate that as the ground temperature increases, the APF also increases, confirming the positive impact of higher ground temperatures on the overall system efficiency.
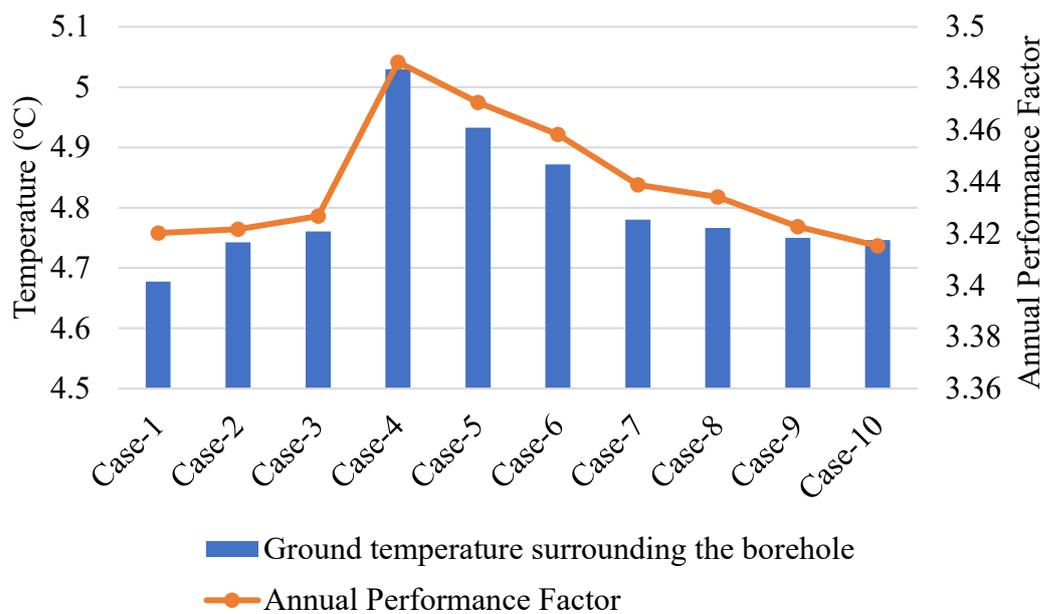


Figure 11: Correlation between Ground Temperature and Annual Performance Factor (APF)
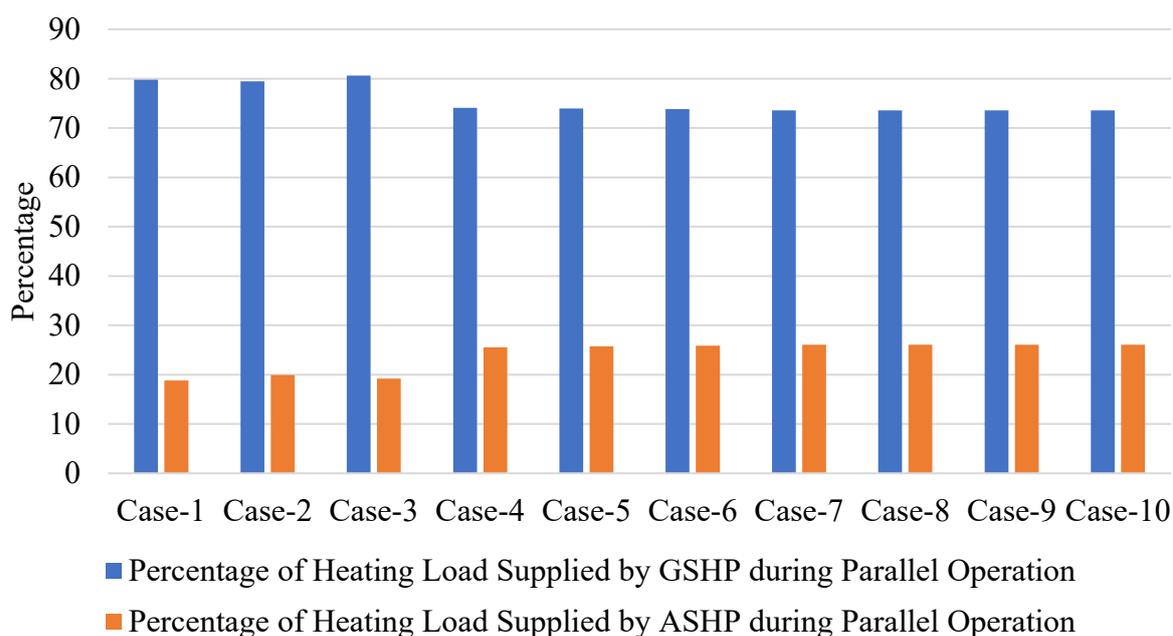
Figure 12: Percentage of Heating Load Supplied by the GSHP and ASHP during Parallel Operationin different cases

Figure 12 illustrates the percentage of the heating load supplied by the GSHP and ASHP during parallel operation across the different cases. The simulation control strategy was designed to prioritize load allocation to the GSHP during parallel operation.

Following the presentation of these results, the subsequent sections discuss these observed patterns and attempt to relate them to practical operational scenarios for hybrid heat pump systems.

The bivalent temperature of GSHP creates important changes in the temperature of the surrounding ground, which directly affects the performance and long-term efficiency of the system because it significantly influences subsurface thermal dynamics [21]. When the GSHP switches between running and resting, it causes the ground temperature to rise and fall [22]. During times when the GSHP is turned off, usually in milder weather or when heating or cooling needs are lower, the ground begins to recover its heat. This process, called thermal regeneration, allows the ground to regain the heat that was removed. Field studies, such as the one conducted in Bialystok, Poland, have demonstrated the crucial link between the annual energy extraction rate and the degree of loop temperature recovery during the regeneration periods [21]. The ability of the ground to recover its temperature is influenced by the duration

of operation and the intensity of energy consumption, as well as factors like groundwater flow [23].

How much the ground temperature can recover depends on several factors, including how long the system rests, the thermal properties of the soil, and the outside air temperature. When the ground around the borehole becomes warmer, the temperature of the brine flowing out of the ground heat exchanger also becomes warmer. This warmer brine improves the inlet temperature to the GSHP, making the system more efficient. However, if the GSHP runs continuously for long periods, especially when heating demands are high, it extracts heat from the ground continuously. This leads to a gradual cooling of the soil, lowering both the inlet and outlet brine temperatures and reducing the GSHP's ability to operate efficiently.

The simulation results clearly show these effects. Cases where the GSHP had more opportunities for rest periods (e.g., Case-4) maintained higher surrounding ground temperatures (5.03 °C) compared to configurations with more aggressive GSHP operation (e.g., Case-10 with 4.75 °C). Systems that run the GSHP (solely and parallelly) almost constantly show lower ground temperatures because they keep removing heat without giving the soil enough time to recover. Although the temperature differences may seem small, they have a major impact on the system's overall performance. This highlights the need to design GSHP operation carefully to maximize efficiency and protect the ground from long-term cooling.

**Temperature Lift and System Efficiency**

The APF of a heat pump is fundamentally influenced by the temperatures of the heat source and heat sink, with the difference between these temperatures being a critical determinant of efficiency. The experimental data [24] confirms that higher APF values are observed when brine temperatures are warmer and the difference between temperature of the brine entering the GSHX and the temperature of the brine leaving the GSHX is smaller.

This relationship is supported by the Carnot formula, defined as Equation (1):

$$\text{Carnot COP} = \frac{\text{Supply Temperature}}{\text{Supply Temperature} - \text{Source Temperature}} \tag{1}$$

This equation mathematically demonstrates that for a given supply temperature, the theoretical maximum COP increases as the source temperature increases and the temperature difference decreases. It is observed that temperature difference between brine leaving from GSHX and entering to GSHX is minimum for case 4 and highest for Case 10. As a result, highest APF has been observed for case 4 and lowest APF has been observed for Case 10.

**Parallel Operation Distribution and System Performance**

The case data reveals an important insight: raising the ASHP cut-in temperature above 0°C (Cases 5-10) might intuitively seem efficiency-friendly by increasing reliance on the air-source component during milder conditions, but the results demonstrate a more complex dynamic. The extended ASHP operation forces the GSHP to operate for longer periods, resulting in colder brine temperatures that lower the GSHP's COP. Since the ground unit dominates the delivered energy, this efficiency reduction outweighs any benefit gained from additional ASHP operational hours.

For example, in Case-4 (ASHP start operation at 0°C), the system achieves the highest APF of 3.49, with the GSHP providing 74.09% of heat during parallel operation. This optimal balance allows the ground temperatures to remain relatively high at 5.03°C. In contrast, Case-10 (ASHP above +6°C) shows a notably lower APF of 3.42, despite having similar GSHP contribution (73.59%), because the ground temperature drops to 4.74°C due to the operational pattern forcing the GSHP to run during less favorable conditions.

**Long-term Thermal Impacts and Performance Degradation**

Extended operational hours of a GSHP system negatively impact its performance due to the progressive cooling of the soil surrounding the ground heat exchanger. The simulation data across the cases shows that control strategies significantly influence ground temperatures, with variations ranging from 4.67°C to 5.03°C. These differences may appear small but have substantial implications for long-term system performance.

Prolonged GSHP operation leads to a decrease in soil temperature at various depths around the buried pipes. This heat extraction over time results in the development of a "cold plume" in

the ground, as described at [25]. Their simulations show a significant decrease in minimum ground temperature over 30 years of operation under non-balanced energy loads.

The connection between ground temperature and GSHP efficiency is clear in our simulation data. Case-4, with the highest ground temperature (5.03°C), achieves the best APF (3.49), while cases with lower ground temperatures show correspondingly lower APFs. This positive correlation between the GSHP's APF and soil temperature indicates that as the surrounding soil cools due to continuous heat extraction, the instantaneous APF of the system decreases.

The reduction in instantaneous efficiency over time directly contributes to a decline in the system's overall performance, as evidenced by the reported COP decline rate of 12.3% over a heating season for operating systems. The variations in APF across our simulation cases (ranging from 3.42 to 3.49) may seem modest, but when projected over decades of operation, these differences compound significantly, affecting both operational costs and environmental impact.

The simulation results from Cases 1-10 validate the theoretical principles regarding thermal dynamics in hybrid heat pump systems. The data demonstrates that control strategies prioritizing ground temperature preservation through proper use of the ASHP and GSHP component yield the highest system efficiencies. The optimal strategy appears to be Case-4, where the ASHP operates at ambient temperatures above 0°C, allowing the ground to maintain favorable thermal conditions for GSHP operation while still utilizing the air-source component efficiently.

These findings highlight the importance of considering not just immediate efficiency metrics but also long-term thermal impacts when designing control strategies for hybrid heat pump systems. The careful balance between ASHP and GSHP operation must account for both the instantaneous APF of each component and the cumulative effects on ground temperature over extended operational periods.

## VI. Conclusion

This study presented a detailed performance evaluation and optimization framework for a dual-source hybrid heat pump (HHP) system that integrates air-source and ground-source technologies. By developing a supervisory control algorithm and validating its operation under

various bivalent temperature settings, the research effectively demonstrated the advantages of dynamic mode switching between ASHP, GSHP, and PSHP configurations. Simulation results confirmed that the HHP system outperforms a standalone GSHP configuration, particularly in terms of ground temperature maintenance, brine temperature stability, and overall Annual Performance Factor (APF). It was observed that hybrid operation enabled a significant reduction in borehole depth—up to 20 meters less—while still maintaining safe thermal limits and high system efficiency.

Furthermore, comparative analysis across different bivalent switching cases identified that optimal performance is achieved when the ASHP is activated at ambient temperatures above $0\,°C$ and the GSHP covers the load during colder conditions down to $-10\,°C$. This approach maintains ground thermal stability through intermittent GSHP operation, facilitating seasonal regeneration and minimizing long-term soil cooling. These findings highlight the critical importance of coordinated load sharing, temperature zoning, and system design choices in maximizing hybrid system efficiency and ensuring long-term operational reliability. The methodology and results contribute valuable guidance for future HHP deployment in residential and commercial heating applications.

## References

1.  HOME-PC (2023) Performance Study of a Hybrid Solar-Assisted Ground-Source Heat Pump System Used for Building Heating and Hot Water Demands. jjmie 17:581–594. https://doi.org/10.59038/jjmie/170413

2.  Hu X, Miao R, Yu Y et al. (2023) Development of a high-efficiency and cost-effective ground source heat pump system for hot-climate applications. Indoor and Built Environment 32:387–407. https://doi.org/10.1177/1420326X221115599

3.  Yuan T, Liu Z, Zhang L et al. (2023) The Review of the Application of the Heat Pipe on Enhancing Performance of the Air-Conditioning System in Buildings. https://www.mdpi.com/2227-9717/11/11/3081. Accessed 20 Feb 2025

4.  Kaneko C, Yoshinaga M (2023) Long-term operation analysis of a ground source heat pump with an air source heat pump as an auxiliary heat source in a warm region. Energy and Buildings 289:113050. https://doi.org/10.1016/j.enbuild.2023.113050

5.  Staffell I, Brett D, Brandon N et al. (2012) A review of domestic heat pumps. Energy Environ Sci 5:9291. https://doi.org/10.1039/C2EE22653G

6.  Rony R, Yang H, Krishnan S et al. (2019) Recent Advances in Transcritical CO2 (R744) Heat Pump System: A Review. Energies 12:457. https://doi.org/10.3390/en12030457

7.  Adam A. Alaica, Seth B. Dworkin (1970+0808:00:00+00:00) Characterizing the effect of an off-peak ground pre-cool control strategy on hybrid ground source he. C.COEK.INFO

8.  Wang X, Xia L, Bales C et al. (2020) A systematic review of recent air source heat pump (ASHP) systems assisted by solar thermal, photovoltaic and photovoltaic/thermal sources. Renewable Energy 146:2472–2487. https://doi.org/10.1016/j.renene.2019.08.096

9.  Hou G, Taherian H (2019) Performance analysis of a hybrid ground source heat pump system integrated with liquid dry cooler. Applied Thermal Engineering 159:113830. https://doi.org/10.1016/j.applthermaleng.2019.113830

10. Sommerfeldt N, Madani H (2019) In-depth techno-economic analysis of PV/Thermal plus ground source heat pump systems for multi-family houses in a heating dominated climate. Solar Energy 190:44–62. https://doi.org/10.1016/j.solener.2019.07.080

11. Li Y, Li S, Xia S et al. (2023) A Review on the Policy, Technology and Evaluation Method of Low-Carbon Buildings and Communities. Energies 16:1773. https://doi.org/10.3390/en16041773

12. (2024) Demand.ninja. http://demand.ninja/. Accessed 15 Feb 2025

13. MITSUBISHI ELECTRIC (2025) MSZ-LN35VGV Black Diamond LN35 High Wall Heat Pump with HyperCore // Mitsubishi Electric. https://mitsubishi-electric.co.nz/heatpump/i/69304B/black-diamond-ln35-high-wall-heat-pump-with-hypercore. Accessed 28 Apr 2025

14. Vaillant (2025) flexoTHERM | Ground Source Heat Pump | Vaillant UK. https://professional.vaillant.co.uk/for-installers/products/flexotherm-ground-source-heat-pump-42432.html#downloads. Accessed 29 Apr 2025

15. Jeffrey D Spitler, Rachel Grundmann, Saqib Javed (2016) Calculation Tool for Effective Borehole Thermal Resistance. In:

16. Pan S, Kong Y, Chen C et al. (2020) Optimization of the utilization of deep borehole heat exchangers. Geotherm Energy 8:1–20. https://doi.org/10.1186/s40517-020-0161-4

17. Li G, Yang J, Zhu X et al. (2021) Numerical study on the heat transfer performance of coaxial shallow borehole heat exchanger. Energy and Built Environment 2:445–455. https://doi.org/10.1016/j.enbenv.2020.10.002

18. (2021) Zone - LoopLink PRO Help. https://help.looplinkpro.com/en/latest/zone/. Accessed 20 Apr 2025

19. Zhang R (2025) Experimental study on operation limit of ground heat exchanger based on ground source heat pump unit. PLOS One 20:e0319430. https://doi.org/10.1371/journal.pone.0319430

20. Gd-admin (2025) How Deep Does a Ground Source Heat Pump Need to Be? https://www.ne01-e.com/news/how-deep-does-a-ground-source-heat-pump-need-to-be. Accessed 20 Apr 2025

21. Piotrowska-Woroniak J (2021) Assessment of Ground Regeneration around Borehole Heat Exchangers between Heating Seasons in Cold Climates: A Case Study in Bialystok (NE, Poland). https://www.mdpi.com/1996-1073/14/16/4793. Accessed 27 Apr 2025

22. Alla E. Denysova, Svitlana G. Antoshchuk, Pavlo O. Ivanov et al. (2025) Modeling of the temperature field in the soil massive for different operating modes of the ground source heat pump. https://ouci.dntb.gov.ua/en/works/7PGnVYz9/. Accessed 27 Apr 2025

23. Li C, Mao J, Xing Z et al. (2016) Analysis of Geo-Temperature Restoration Performance under Intermittent Operation of Borehole Heat Exchanger Fields. Sustainability 8:35. https://doi.org/10.3390/su8010035

24. Liu Z, Xu W, Zhai X et al. (2017) Feasibility and performance study of the hybrid ground-source heat pump system for one office building in Chinese heating dominated areas. Renewable Energy 101:1131–1140. https://doi.org/10.1016/j.renene.2016.10.006

25. Hałaj E, Pająk L, Papiernik B (2020) Finite Element Modeling of Geothermal Source of Heat Pump in Long-Term Operation. Energies 13:1341. https://doi.org/10.3390/en13061341