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Numerical investigation of the thermal performance of a partially loaded thermo-active foundation pile system in a cold climate

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Abstract

As the global transition toward net-zero greenhouse gas emissions accelerates, decarbonizing space heating in cold climates remains a critical challenge. Ground source heat pumps (GSHPs) coupled with thermo-active foundation piles offer an efficient and low-emission alternative to conventional heating systems by integrating ground heat exchange within structural foundation elements. However, their application in heating-dominated regions is constrained by long-term thermal performance considerations, as well as by structural and geotechnical requirements that are not addressed through thermal design alone. The objective of this study is to numerically evaluate the thermal and operational performance of a partially loaded thermo-active foundation pile system coupled with a GSHP under a cold-climate load profile representative of Calgary, Canada. Two per-pile design capacities of 0.4 ton and 0.5 ton are examined under three operating conditions corresponding to 60 percent, 70 percent, and 100 percent of the normalized per-pile peak heating load. In the partially loaded cases, the remaining load fraction is supplied by an auxiliary electric resistance heater. Transient three-dimensional simulations are conducted over a five-year equivalent period to assess ground temperature evolution, pile inlet and outlet fluid temperatures, and system coefficients of performance (COP). The results show that all configurations exhibit near steady ground temperature behaviour over the considered period, with small year-to-year variations consistent with heating-dominated operation. Relative to unshaved operation, partial-load configurations show smaller long-term ground temperature shifts and slightly higher minimum entering water temperatures during peak winter conditions. System reliability, defined in this study as thermal operability based on the duration of sub-threshold entering water temperature, improves modestly for the 0.4-ton configurations under partial-load operation. Heating COP values decrease slightly over time for all cases, while cooling performance remains mostly unaffected by load-shaving.

Keywords: Thermo-active foundation pile; Ground source heat pump; Cold climate; Load-shaving; Partial-load operation; Ground thermal balance;

1. Introduction

Decarbonizing space heating in Canada is a critical challenge due to the sector's high energy demand and its reliance on fossil fuel–based heating systems, particularly in regions with long and severe winters. The residential sector accounted for 11% of the country's total energy consumption in 2021, with approximately 78% of that energy used for space and water heating. A significant portion of this energy comes from natural gas, at 53% and 68%, respectively, with electricity accounting for around 31% and 29%, respectively [1]. Given Canada's extreme winter climate, where average temperatures in some regions drop well below freezing, per capita energy use for heating is among the highest globally [2]. As the country moves toward its target of net-zero greenhouse gas (GHG) emissions by 2050, there is increasing pressure to replace conventional fossil fuel-based heating systems with low-carbon alternatives that are both reliable and cost-effective in cold climates.

Ground source heat pumps (GSHPs) have seen significant global adoption, with installed capacity growing by over 4,000% between 1995 and 2020. The market is expected to grow from $ 7.9 billion USD in 2024 to $ 11.4 billion USD by 2030 [3][7][8]. In the Canadian context, GSHPs could play a key role in displacing fossil fuel heating, especially in areas where electric infrastructure is already partially supplemented by another energy source. Heat pump usage is projected to grow steadily nationwide in the coming years, with installations expected to account for 15% of all new heating device purchases by 2025 in both new constructions and retrofits and is projected to rise to 30% by 2040, reflecting a broader transition toward cleaner, energy-efficient heating technologies [9]. In cold-climate conditions, ground source heat pumps have been shown to maintain higher efficiency than air source systems due to their decoupling from low ambient air temperatures [4].

Despite their potential, GSHP systems face significant obstacles to widespread implementation, particularly in urban or retrofit applications, due to the high capital costs associated with installing a ground heat exchanger (GHE). GHEs typically involve deep vertical boreholes or extended horizontal trenches, which can account for more than 30% of the total system cost [10]. These challenges are even more significant in dense urban areas, where limited land availability, access constraints, and proximity to existing buildings complicate installation and often make conventional GHEs systems impractical [11]. As a result, urban projects face higher costs and greater logistical complexity, which has constrained their market penetration in both North America and Europe [12]. Addressing these economic and spatial limitations is essential for scaling GSHP adoption in cities and realizing their full decarbonization potential.

One solution gaining traction is the use of thermo-active foundation piles, also known as energy piles. These are structural elements embedded with heat exchange piping, allowing the building's foundation to double as a ground heat exchanger. Typically installed at depths of 10 to 25 m compared to 60 m to over 300 m for conventional ground heat exchanger boreholes, energy piles are shallower and less expensive than standard boreholes, and their integration into foundation systems eliminates the need for additional land. This makes them especially suitable for new construction, urban developments, and retrofits with limited space. Recent studies have validated the thermal performance of energy piles in residential settings, showing that they can significantly reduce system costs while maintaining acceptable heat transfer characteristics [13].

However, even energy pile-based GSHP systems face performance degradation over time in cold climates due to ground thermal imbalance. In many cold-climate regions, such as Canada, annual space heating demand exceeds cooling demand, which can result in net heat extraction from the ground over time, depending on climate, building characteristics, and system operation. While energy for cooling has increased in recent decades, residential buildings in Canada commonly remain heating-dominated on an annual energy basis [5]. This can cause a net decrease in ground temperature over time, leading to reduced system efficiency and potential inoperability of the heat pump [13], [14], [15]. Long-term studies have reported year-over-year ground temperature drops of 0.2–0.4 °C in such systems, resulting in a steady decline in the heat pump's COP [13], [16]. Eventually, the ground may become too cold to serve as an effective heat source, undermining both reliability and energy savings.

To address thermal performance limitations of energy pile GSHP systems operating in cold climates, this study examines the performance limitations such as low entering water temperatures through the application of partial-load operation, in which the geothermal system is intentionally sized to meet 60 percent and 70 percent of the peak heating demand associated with representative normalized 0.4-ton and 0.5-ton per-pile design capacities, with the remaining load supplied by a supplementary heating source. Load-shaving strategies of this type are a common feature of hybrid heating systems during peak demand periods [5].

Partial-load operation may reduce peak ground heat extraction during extreme winter conditions and alter long-term ground temperature evolution relative to systems designed to meet 100 percent of the peak load. In addition, the use of an auxiliary heating source can provide operational flexibility during extreme cold periods without requiring the geothermal system to be sized for peak demand. While hybrid configurations are well established in practice, their long-term thermal implications for thermo-active foundation piles under cold-climate conditions remain insufficiently quantified.

This research builds upon prior work that validated the long-term thermal performance of energy pile systems [13] by extending the analysis to include partial-load operation. The objective of this study is to numerically evaluate the thermal and operational performance of a load-shaved energy pile GSHP system under a representative cold-climate residential load profile. Transient three-dimensional simulations are used to examine ground temperature evolution, pile inlet and outlet fluid temperatures, and system coefficients of performance for multiple per-pile design capacities and load-shaving levels. Structural behaviour, thermo-mechanical effects, and economic performance are not considered and are outside the scope of the present study.

2. Methodology

2.1. Physical System

The proposed system consists of a thermo-active foundation pile system integrated with a ground source heat pump (GSHP). The pile is installed at ground surface level, providing practical advantages for retrofitting existing residential or commercial buildings, as shown in Figure 1 and highlighted by Jathunge et al. [13]. Unlike systems designed to meet 100% of the peak heating load, this study introduces a load-shaving approach in which the energy pile system is sized to meet 60%, 70% or 100% of the representative peak of 0.4- and 0.5-ton/pile maximum heating load profiles. The selected per-pile capacities of 0.4 ton and 0.5 ton are consistent with previously validated numerical and experimental studies of identical helical energy-pile geometry operating under cold-climate residential loads, where higher per-pile loading was shown to accelerate long-term ground thermal degradation [13], [20].

The pile is hollow and helical, fabricated from A514 structural steel, which is selected for its high strength and excellent thermal conductivity. A detailed cross-sectional schematic of the helical pile geometry and internal heat transfer fluid configuration is provided in Jathunge et al. [20]. The pile has an outer diameter of 0.139 m, a wall thickness of 0.01 m, and is installed to a depth of 18.288 m. To form a closed-loop ground heat exchanger, the pile is completely filled with a heat transfer fluid (HTF) and sealed at the top using a cap that has an inlet and outlet piping attached to it.

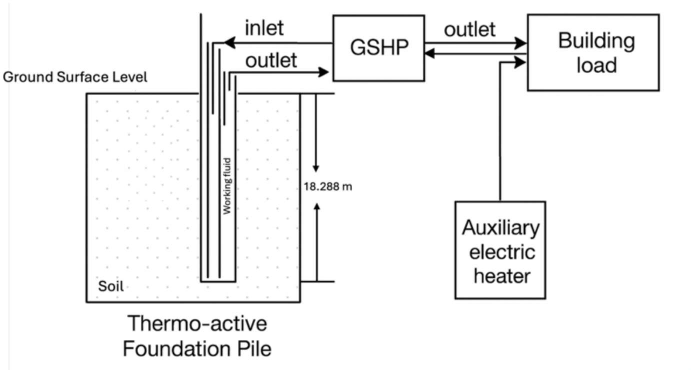

Figure 1. Schematic diagram of the system investigated in this study.

The working fluid is a 30% glycol–water mixture. The surrounding soil is assumed homogeneous and isotropic, with properties representative of Calgary, Alberta, Canada. Material properties are assumed constant with depth as shown in Table 1 [13].

The fluid circuit inside the pile has an eccentric inlet and outlet configuration using cross-linked polyethylene (PEX) pipes. This arrangement minimizes thermal short-circuiting while ensuring effective heat transfer to the steel pile wall. The inlet pipe extends 17.983 m downward from the pile cap, while the outlet pipe only extends 0.15 m below the cap. Both pipes have an outer diameter of 0.016 m and a wall thickness of 0.002 m.

Although this work models a single pile, in real-world applications, multiple piles may be required to meet building loads. The number and spacing of piles would depend on the building's thermal demand and per-pile thermal capacity. The required number is calculated using the normalization factor, which equals the building's total load and the per-pile normalized capacity (0.4 tons and 0.5 tons in our cases). This results in 8 piles for the 0.4-ton cases and 6.4 piles for the 0.5-ton setting. In reality, the fractional result would typically be rounded up to 7 piles in order to cover the total building load.

Table 1. Thermophysical properties of materials used in the simulation [13]

Material	Thermal Conductivity (W/m·K)	Volumetric Heat Capacity (J/m³·K)
Soil	1.460	1.63×10^6
A514 Steel	46.600	3.55×10^6
PEX Pipe	0.380	2.16×10^6
30% Glycol HTF	0.456	4.00×10^6

The outlet of the pile is connected to the heat pump's source-side inlet, and the heat pump's source-side outlet is connected to the pile inlet (see Fig. 1), thus completing the closed-loop ground heat exchanger fluid loop.

2.2. Building Load Analysis

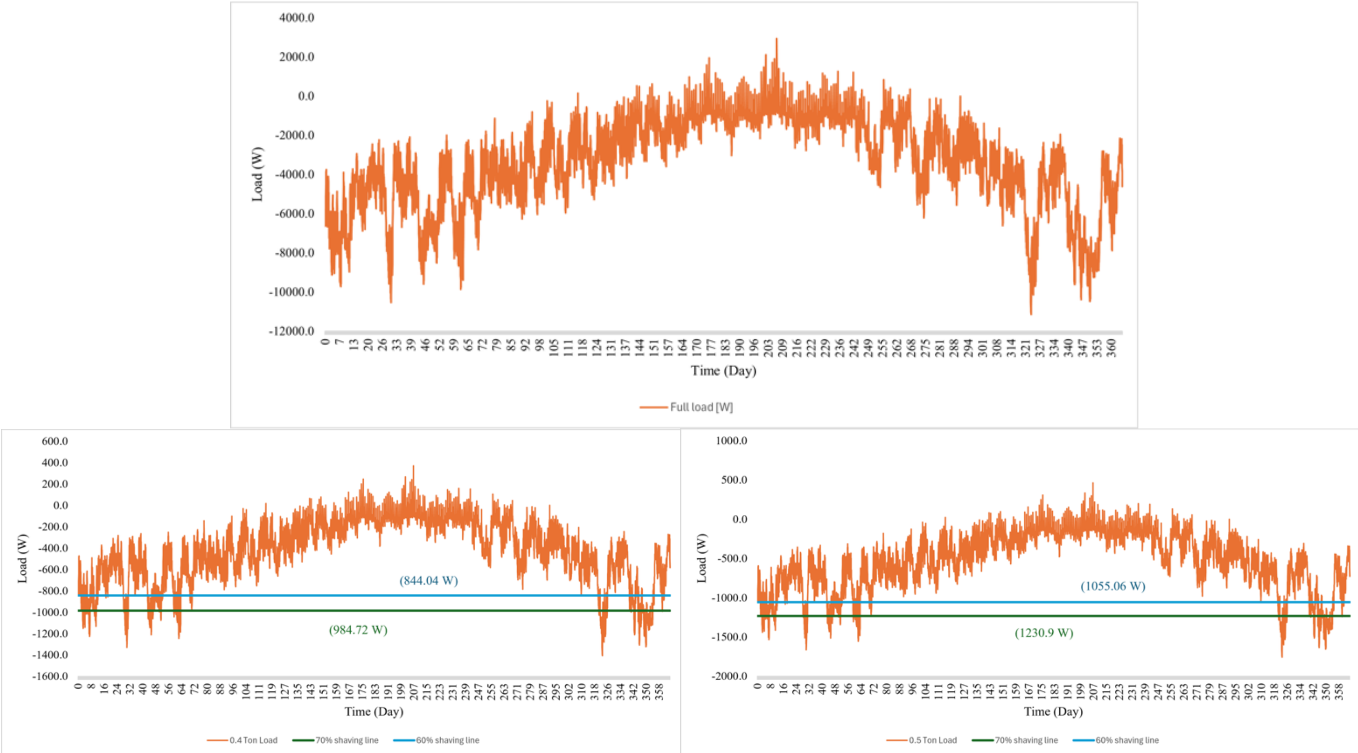

Figure 2. Building energy load profile. (a) full load profile, (b) 0.4 ton/pile normalized load profile, (c) 0.5 ton/pile normalized load profile.

The representative thermal load profile corresponds to a 210 m² single-family detached house in Calgary, Alberta. The load data were generated from a calibrated building energy model implemented in OpenStudio [18] using 30-year typical meteorological year (TMY) data, yielding peak heating and cooling loads of 11.1 kW and 2.9 kW, respectively [13]. The normalized hourly building load data was then exported for use in the transient numerical simulations. The load results in heating-dominated operation (98% of annual load), consistent with cold-climate behaviour [13]. Figure 2a is a representation of this load over 1 year. Negative load values indicate the system is in heating mode; positive load values indicate the system is in cooling mode. Figure 2(b) and 2(c) shows the normalized building load profiles corresponding to the 0.5-ton and 0.4-ton per-pile design cases, along with the 70% and 60% load-shaving thresholds applied in the simulations.

2.3. Mathematical Model for Energy Pile

2.3.1. Governing Equations

The energy pile is modelled numerically using the finite volume method-based tool ANSYS Fluent 2021R1. The computational domain includes solid (soil) and fluid (HTF) regions. The flow in the PEX pipes is laminar and incompressible, governed by the continuity and momentum equations:

$$\nabla \cdot u = 0 \tag{1}$$

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\nabla p + \mu \nabla^2 u \tag{2}$$

where u is the fluid velocity vector (m/s), p is the pressure (Pa), ρ is the fluid density (kg/m³), μ is the dynamic viscosity of the fluid (Pa·s), and t is time (s). The energy equations for heat transfer in the fluid and solid domains are:

$$\rho_f c_f \frac{\partial T}{\partial t} + \rho_f c_f u \cdot \nabla T = k_f \nabla^2 T \tag{3}$$

$$\rho_s c_s \frac{\partial T}{\partial t} = k_s \nabla^2 T \tag{4}$$

where T is temperature (K), c_p is the specific heat capacity (J/kg·K), k is the thermal conductivity (W/m·K), and subscripts f and s denote the fluid and solid domains, respectively.

2.3.2. Boundary Conditions

The normalized hourly building load data were imported into ANSYS Fluent 2021 R1 [19] through a user-defined function (UDF) and used to update the pile inlet temperature at each simulation time step.

The inlet boundary condition for the HTF corresponds to the heat pump outlet temperature, updated at every time step using a UDF that accounts for the instantaneous building load and heat pump performance. The UDF implements coupled thermal feedback through equations derived from Jathunge et al. [13], incorporating the heat pump manufacturer's COP–temperature correlation to represent instantaneous heat pump performance during transient operation.

The outer ground boundaries are treated as adiabatic to approximate undisturbed far-field conditions. The ground surface temperature is applied as a time-varying sinusoidal function derived from the two-harmonic ground temperature model developed by Xing et al. [17], implemented in the UDF. The initial depth-varying undisturbed ground temperature is used as an initial condition, employing the same harmonic model. The pile outlet is modelled as a pressure outlet (0 Pa gauge). A detailed description of the boundary conditions and the related equations can be found in Jathunge et al. [13].

2.4. Data Processing, Numerical Implementation and Load Normalization

The building load data file was read into the solver through the UDF. At each time step, the pile outlet temperature was extracted, area-averaged over the outlet cross-section, and recorded for post-processing. The corresponding inlet temperature for the next time step can be computed dynamically using:

$$T_{inlet}^{(n)} = T_{outlet}^{(n-1)} + \frac{Q_{load}}{\rho c_p \dot{V}} \left(1 + \frac{i}{COP\left(T_{outlet}^{(n-1)}\right)} \right) \tag{5}$$

where $T_{\text{inlet}}^{(n)}$ and $T_{\text{outlet}}^{(n-1)}$ are the inlet and outlet fluid temperatures at time steps n and $n-1$, respectively, Q_{load} is the instantaneous normalized building thermal load (W), $\dot{V}$ is the volumetric flow rate of the heat transfer fluid (m³/s), and the parameter i takes a value of $+1$ for cooling mode and -1 for heating mode. The COP is modelled as a quadratic function of entering water temperature T_{EWT}:

$$COP = aT_{EWT}^2 + bT_{EWT} + c \tag{6}$$

where COP is the heat pump coefficient of performance (dimensionless) and T_{EWT} is the entering water temperature (K). With coefficients $a = -0.00037, b = 0.27048, c = -42.8784$ for heating and $a = 0.002104, b = -1.3812, c = 229.6998$ for cooling, as used in Jathunge et al. [13].

The simulation outputs were post-processed to evaluate the system's thermal and energy performance under all load-shaving scenarios. At each simulation time step (1800 s), the inlet and outlet temperatures of the pile were extracted from the solver reports that record the instantaneous thermal state of the heat-transfer fluid. These temperature values were then used to evaluate instantaneous heat pump performance for both heating and cooling modes using the same COP–temperature correlation (Equation 6).

For each time step n, the normalized energy consumption of the heat pump and overall system, $E_{norm,n}$, was calculated as:

$$E_{norm,n} = \frac{|Q_{load,n}|}{COP_n} \tag{7}$$

where $E_{\text{norm},n}$ is the normalized energy consumption at time step n, $Q_{\text{load},n}$ is the normalized building thermal load (W), and COP_n is the heat pump coefficient of performance at time step n.
The total system energy consumption for each case was then obtained by multiplying the normalized energy

by the corresponding normalization factor representing the number of piles required to meet the total design load (8 for the 0.4-ton case and 6.4 for the 0.5-ton case).

To quantify the contribution of the auxiliary heating source, an auxiliary load profile was generated for each load-shaving case by subtracting the shaved system load from the unshaved (100%) baseline load on a per-time-step basis:

$$Q_{aux,n} = Q_{100\%,n} - Q_{shaved,n} \tag{8}$$

The auxiliary system was modelled with a constant $COP = 1.0$, representing an electric resistance heater. The auxiliary normalized and total energy consumptions were then calculated using the same formulation as for the heat pump system.

The cumulative energy use was evaluated for each simulation year (years 1-5) to assess long-term performance and degradation trends. Additionally, the percentage of time when the entering water temperature to the heat pump (i.e., the pile outlet temperature) dropped below −6.15 °C or 267 (the minimum recommended EWT for the considered heat pump) was computed for each scenario as an indicator of potential inoperability under extreme cold conditions.

For further analysis, a post-processed heat pump COP was determined from the ratio of total building load to total energy consumption for each year:

$$COP_{post} = \frac{\sum_n Q_{load,n}}{\sum_n E_{total,n}} \tag{9}$$

The seasonal heating and cooling COP values were also computed separately to examine mode-specific performance.

To enable consistent comparison across different operating scenarios, the building's hourly heating and cooling profiles were normalized to a single energy pile's load. The total peak load of the modelled house is 11.1 kW, or around 3.2 tons. This load was distributed among multiple piles based on their design capacities. Two representative design thermal loads, 0.4 tons/pile and 0.5 tons/pile, were selected to represent unshaved cases. These values correspond to systems requiring approximately eight and seven piles, respectively, to meet the total building demand. Each "load setting" therefore refers to the normalized per-pile load rather than the total building load.

2.5. Numerical Parameters, Grid Dependency Test, and Model Validation

Each simulation was run for a 5-year period. The convergence criteria were set to 10^{-6} for energy and 10^{-4} for continuity and momentum residuals. A 3D unstructured mesh was generated with local refinement near the eccentric pipes and pile–soil interface to accurately resolve temperature and velocity gradients.

A grid independence study was conducted using five different mesh densities. Based on the results shown in Table 2, the mesh containing approximately 1.4 million elements was deemed grid-independent, as further refinement produced negligible changes in both ΔT and heat exchange rate. This resolution provided an optimal balance between numerical accuracy and computational efficiency for all subsequent simulations.

Table 2. Variation of Mesh Refinements for Grid Dependency

Cell count	Heat Exchange Rate (W)	ΔT=Out Temp – In Temp	%ΔT	%Δ Heat Exchange Rate
668,223	289.88	3.03	-	-
894,096	291.69	2.99	-1.33	0.62
1,402,705	293.80	2.92	-2.37	0.72
2,047,571	294.81	2.87	-1.49	0.34
3,035,320	294.36	2.86	-0.57	-0.15

3. Results and Discussion

3.1. Ground Temperature Variation

Figure 3 illustrates the variation in the average temperature of the ground volume surrounding the energy pile for the different design capacities and load-shaving levels over the five-year simulation period. The plots show the expected sinusoidal trend driven by annual surface temperature fluctuations imposed through the boundary condition. The ground temperature oscillates between approximately 3.85°C and 5.65°C (277 K and 278.8 K), consistent with cold-climate soil conditions in Calgary.

For both the 0.4-ton and 0.5-ton unshaved cases, the seasonal temperature cycles show a slight downward shift in mean value with time, indicating ground cooling due to the heating-dominated load profile. The magnitude of this drop is relatively small (< 0.3 °C over five years), suggesting that the pile and surrounding soil reach a near-steady annual heat balance.

In contrast, the partially loaded cases (60% – 70% coverage) demonstrate improved long-term thermal stability. The amplitude and baseline of the temperature oscillations remain nearly constant through the five-year period, implying that the reduced geothermal load helps maintain the local ground temperature closer to its undisturbed values. This behaviour confirms the effectiveness of the load-shaving approach in mitigating long-term ground thermal imbalance, which is a known issue in cold-climate GSHP systems [13], [16].

Comparing the two design capacities, the 0.5-ton system consistently exhibits slightly lower average soil temperatures than the corresponding 0.4-ton case, reflecting differences in per-pile design capacity and operating conditions. The difference between the 70%-shaved and unshaved 0.5-ton cases remains within approximately 0.1 °C, indicating that the long-term ground temperature response is similar across these operating conditions over the simulated period.

Overall, the thermal behaviour observed across all scenarios aligns with the expected response of thermo-active foundation piles operating under cyclic heating loads. Across all simulations, the amplitude of the annual ground-temperature cycle remained within 1.5–1.8°C, and the mean ground temperature decreased by less than 0.3°C over the five-year period. In contrast, the partially loaded 60% and 70% cases exhibited smaller long-term shifts, typically below 0.15°C, indicating that the system reached a near-steady thermal balance between yearly heat extraction and natural recovery. These results show that all configurations maintain near-steady ground temperature behaviour over the simulated period across the whole domain, while partial-load operation is associated with smaller temperature variations without significantly altering the seasonal response of the system.

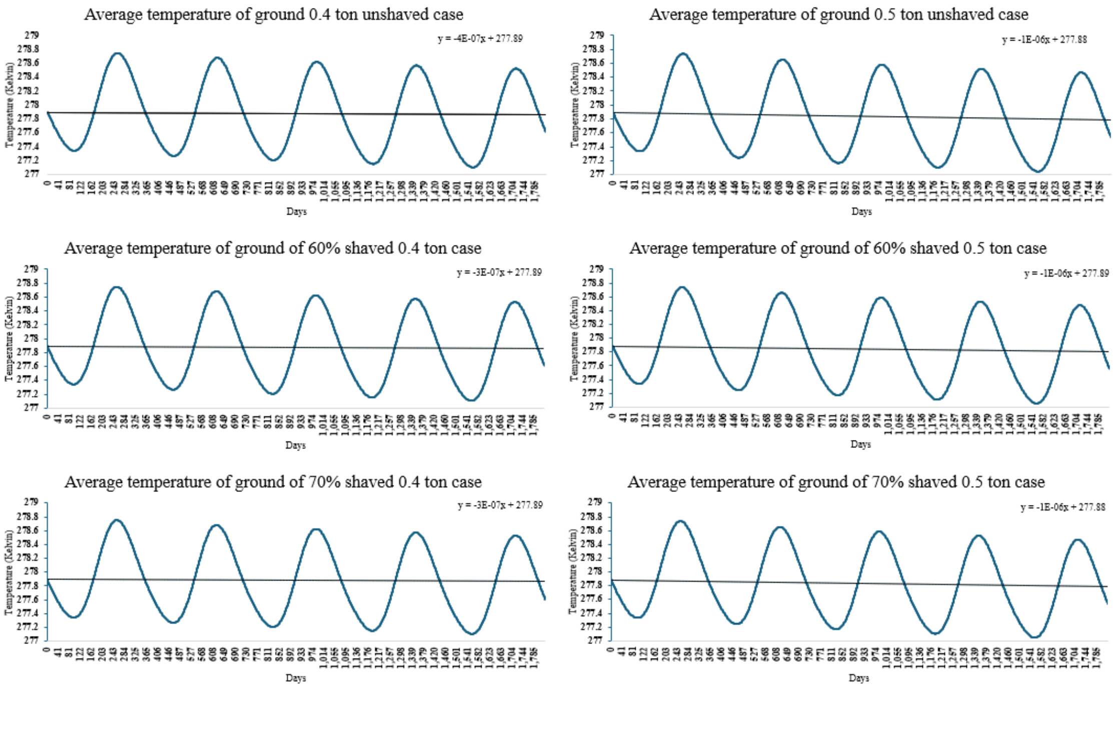

Figure 3. Ground Temperature Variation Over a Five-Year Period for All Simulated Cases

3.2. Inlet and Outlet Fluid Temperature Variation

Figure 4 shows the pile inlet and outlet temperature variation of the circulating heat-transfer fluid for all simulated cases over the five-year period. The fluid temperatures vary primarily between -8.15°C and 6.85°C (265 K and 280 K), with an oscillatory pattern throughout the entire simulation period. The temperature profiles show a strong annual cycle consistent with seasonal building load fluctuations. Across all cases, the outlet temperature remains consistently higher than the inlet temperature in heating mode, and consistently lower than the inlet temperature in cooling mode, confirming continuous heat extraction from the ground during heating-dominated operation and heat rejection into the ground during cooling operation. The instantaneous temperature difference, generally ranges from 1°C to 2°C, rising slightly during the coldest winter months when heating demand peaks.

In the unshaved configurations, the inlet temperature dips below the -6.15°C (267 K) threshold, which is the minimum recommended entering-water temperature required for reliable heat-pump operation. This occurs during mid-winter periods of sustained high heating demand. However, even under these conditions, the outlet temperature remains above the inlet value, demonstrating that the pile continues to exchange heat with the ground.

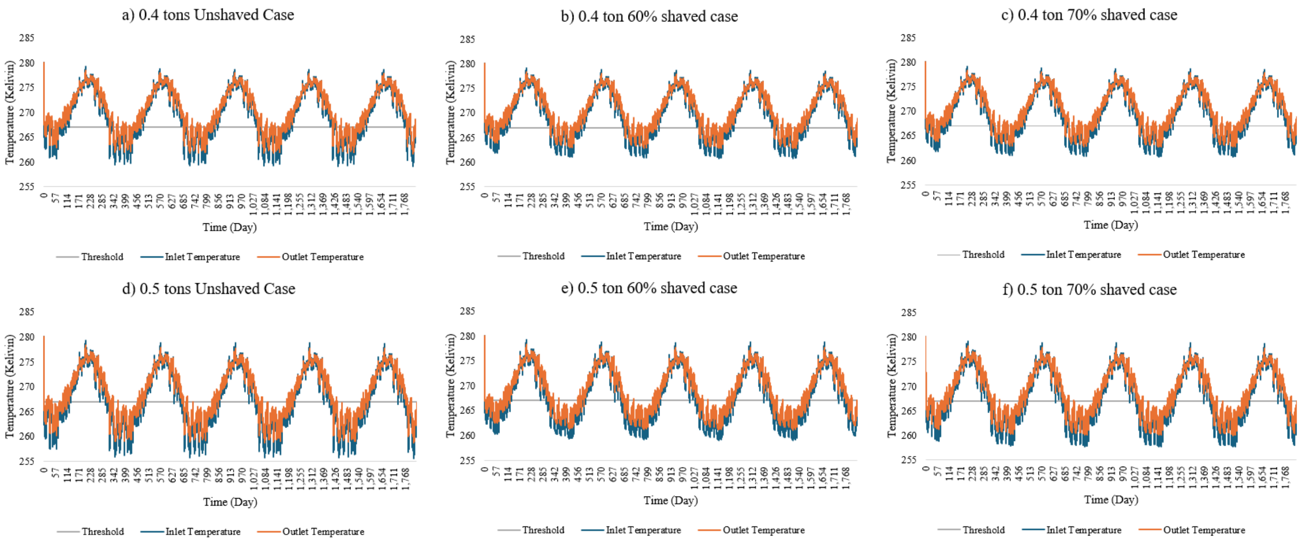

Figure 4. Pile Inlet and Outlet Temperature Variation for All Simulated Cases

The shaved loaded cases (60% and 70%) shown in Figures. 4(b), 4(c), 4(e), and 4(f) exhibit very similar seasonal patterns, but with elevated winter minima and reduced overall temperature fluctuations. Specifically, the 70%-shaved configuration for the 0.5-ton system in Figure. 4(f) maintains inlet temperatures approximately 0.3 °C higher than the unshaved case during the coldest periods of each year, while the 60%-shaved case shows an even more moderate fluctuation range, suggesting lower thermal stress on the ground. This stabilization effect becomes most evident in the fourth and fifth years, where the unshaved systems show brief, sharper dips in inlet temperature, whereas the shaved systems maintain smoother, shallower minima.

Comparing system capacities, the 0.4-ton configurations generally maintain higher winter minimum outlet temperatures than the 0.5-ton cases. The 0.4-ton system is associated with smaller energy extraction rates per unit of soil volume than the 0.5-ton system. Nevertheless, both systems display the same seasonal response and maintain stable year-over-year operation. An additional quantitative assessment of the proportion of simulation time during which the heat pump inlet temperature fell below −6.15 °C (267 K) further illustrates these trends and is summarized in Table 3. The 0.5-ton per-pile configurations operated below the threshold more frequently than the 0.4-ton configurations, indicating greater thermal loading of the surrounding soil for the higher-capacity case.

Table 3. Percentage of simulation time during which the inlet temperature fell below -6.15°C (267 K) for each system configuration.

Load Coverage	0.4 Ton/Pile	0.5 Ton/Pile
100% Unshaved	26.8%	40.3%
70% Shaved	25.8%	40.1%
60% Shaved	25.7%	39.6%

These results demonstrate that the 0.5-ton systems tend to overstress the heat pump, frequently allowing the entering-water temperature to fall below the recommended range for efficient heat-pump performance. The smaller 0.4-ton configurations, with lower extraction per pile, maintain more favourable heat pump inlet water temperatures and exhibit stronger resilience to seasonal ground-temperature depression. This comparison emphasizes the importance of matching heat-pump capacity to pile-field size: even moderate oversizing can substantially increase the duration of sub-optimal operating conditions.

3.3. COP and Energy Performance

The average yearly system coefficients of performance (COP) for both heating and cooling modes are presented in Figures 5 and 6 below. The heating COP values account for the combined performance of the ground source heat pump (GSHP) and auxiliary heater, calculated as the total supplied load divided by the total electrical energy consumption of both components. Cooling COPs represent only the GSHP performance, as no auxiliary cooling was needed after shaving.

3.3.1. Heating Performance

As shown in Figure 5, all configurations exhibit an initial decline in heating COP during the first few years of operation, followed by a period of relative stabilization as the system approaches a near-steady thermal condition. The 0.4-ton system consistently achieved higher COPs than the 0.5-ton system, primarily due to its lower extraction rate per pile and smaller temperature differentials between the ground and the heat pump condenser. For the 0.4-ton unshaved case, the annual system COP decreased from approximately 3.05 in Year 1 to 2.97 in Year 5 (a 2.56% reduction). The 70% shaved case displayed slightly lower initial COPs (around 2.97 in Year 1) but maintained greater stability across subsequent years, reaching around 2.90 at the end of the 5th year (around a 2.3% reduction). The 0.4-ton 60% shaved configuration started at an even lower initial COP (2.82 in year 1) and reduced by around 1.9% by the end of year 5, ending with a COP of approximately 2.76. This indicates that while the overall COP is slightly reduced by partial-load operation (about 3-5% lower than when the heat pump is in operation alone), the rate of COP degradation diminishes over time and transitions toward stable operation, confirming that load-shaving promotes long-term thermal stability and mitigates seasonal performance decay.

The 0.5-ton systems operated at lower overall COPs due to higher heat extraction per pile and greater time spent near or below the -6.15°C (267 K) entering water temperature threshold. The unshaved 0.5-ton case began at 2.90 in Year 1 and declined steadily to about 2.81 by Year 5 (around a 3.2% reduction). The 70% shaved configuration followed a similar trajectory, decreasing from 2.83 to 2.77 (approximately a 2.92% reduction), while the 60% shaved case started near 2.72 and remained between 2.66 and 2.72 over the final three years (approximately a 2.36% reduction), suggesting improved stability despite a lower overall efficiency.

These results demonstrate that load-shaving does not necessarily increase the COP since the auxiliary heaters have a constant COP of 1, but it reduces year-to-year degradation and the long-term effect on ground temperature, especially in heating-dominated regions. The improved long-term performance stability observed in the shaved configurations can likely be attributed to the reduced time the inlet temperatures to the heat pump were below the threshold, as discussed in Section 3.3.

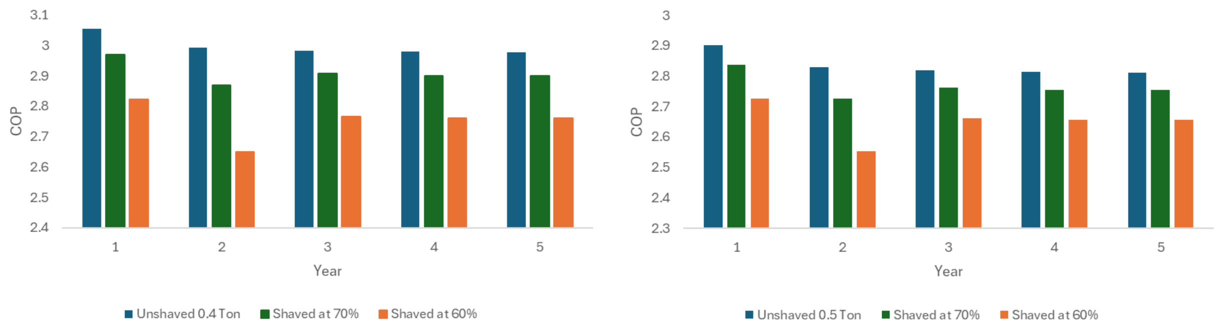

Figure 5. System Average Yearly COP of Heating of 0.4- and 0.5-Ton Cases

3.3.2. Cooling Performance

Figure 6 shows that all configurations exhibit a modest increase in cooling COPs over the five-year period. This trend results from improved heat rejection efficiency, as the average ground temperature has decreased slightly due to cumulative winter heat extraction. For the 0.4-ton system, the cooling COP rose from approximately 8.64 in Year 1 to 8.78 by Year 5, while the 0.5-ton cases increased from 8.78 to around 8.94.

In general, the effect of load-shaving on cooling performance was negligible as both shaved and unshaved configurations followed nearly identical trends. This suggests that moderate thermal recovery during summer cooling periods benefits all systems equally, regardless of the load-shaving percentage during heating.

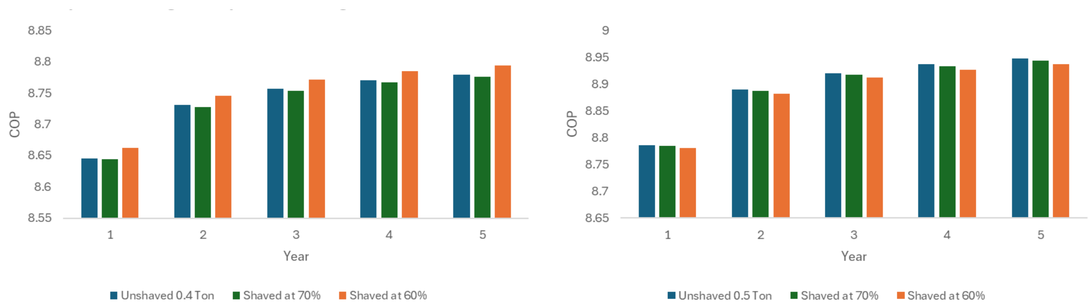

Figure 6. System Average Yearly COP of Cooling of 0.4- and 0.5-Ton Cases

3.3.3. Overall Performance Trends

The combined heating and cooling results indicate that partial-load operation is associated with reductions in year-to-year thermal performance variability without altering the fundamental behaviour of the system. Although shaved systems show slightly lower initial heating COPs, they exhibit less year-to-year COP degradation than unshaved systems. The 0.4-ton configurations consistently outperform the 0.5-ton systems in both absolute COP and stability, confirming that oversizing the thermal load relative to the pile field can increase the duration of below temperature threshold operation and reduce system efficiency.

Overall, the 0.4-ton 60% shaved case achieved the best balance between efficiency and stability, maintaining a high average COP with minimal annual variation, while the 0.5-ton systems benefited less from shaving due to a higher extraction level. These results highlight that strategic partial-load operation can significantly enhance GSHP system long-term performance and energy efficiency in cold climates.

3.4. Auxiliary Energy Contribution

The contribution of the auxiliary electric heater was evaluated to quantify its influence on total system energy consumption and heating COP stability under different load-shaving levels. As discussed in Section 2.4, the auxiliary system was modelled to meet the remaining unmet load fraction when the GSHP operated below the designated coverage level (60% or 70% of the peak demand). The heater operated with a constant coefficient of performance (COP = 1.0), representing resistive electric heating, and its impact is reflected in the total system COP values presented in Section 3.4.

For all configurations, the auxiliary component contributed a relatively small but non-negligible portion of the total annual heating energy. In the 0.4-ton system, auxiliary heating accounted for approximately 5% of the annual load in the 70% shaved case and approximately 14.3% in the 60% shaved case. The auxiliary share was notably higher for the 0.5-ton system, where increased ground cooling and longer sub-threshold inlet temperature durations (Section 3.3) required more frequent supplemental operation. The 0.5-ton, 70% shaved case drew roughly 6%, while the 60% shaved configuration reached about 17% of its total annual heating energy from the auxiliary source.

Although using an auxiliary source reduces the system's COP compared to heat-pump-only performance, it ensures that the total heating load is met during extreme cold conditions without over-sizing the system. These results indicate that partial-load systems achieve a reasonable trade-off between long-term ground thermal stress and a slight increase in reliance on the auxiliary system. Importantly, this trade-off does not compromise overall efficiency: even with auxiliary energy included, the 70% shaved cases for both capacities maintained average COPs comparable to or higher than those of their unshaved counterparts after five years of operation.

This analysis demonstrates that integrating a supplemental electric heater enhances system reliability and mitigates thermal imbalance in cold climates. By limiting geothermal over-sizing and leveraging auxiliary operation only during peak demand periods, the overall hybrid GSHP system achieves improved long-term performance and greater scalability for residential and small-commercial applications.

4. Conclusion

This study presented a detailed numerical investigation of a partially loaded thermo-active foundation pile system coupled with a ground source heat pump (GSHP) operating under a cold-climate load profile representative of Calgary, Canada. The model examined two design capacities, 0.4-ton and 0.5-ton per pile, under different load-shaving levels (60%, 70%, and 100%) to evaluate the effects of partial-load operation on long-term ground thermal stability, seasonal performance, and auxiliary energy requirements. From the study, the following conclusions can be made:

- The partially loaded cases (60% and 70%) showed smaller long-term temperature drift, typically below 0.15 °C, confirming that load-shaving supports near-steady thermal balance between annual heat extraction and ground recovery.
- Among all configurations, the 0.4-ton systems maintained higher minimum inlet temperatures and fewer occurrences of sub-threshold operation (below -6.15°C) compared to the 0.5-ton systems. Partial-load operation showed small reductions (0.5-1%) in the duration of low inlet temperatures.
- Heating performance showed a modest year-over-year decline in system COP during early operation, followed by stabilization as the system approached near-steady thermal conditions. The 0.4-ton systems consistently achieved higher COPs and lower degradation rates than the 0.5-ton systems, while partial-load operation reduced long-term performance decay. Cooling COPs increased slightly over time for all cases due to seasonal ground recovery

Future work could build on these findings by exploring enhanced control strategies and reduced pile capacities to further optimize system performance. For instance, a resistance heater could be implemented in series with the source-side water loop to provide targeted thermal support during periods of high demand or extreme cold, reducing the risk of sub-threshold operation and maintaining higher ground temperatures. This approach could enable the development of a more advanced control mechanism that complements load-shaving strategies, improving long-term reliability, efficiency, and thermal balance in GSHP-coupled thermo-active foundation pile systems.

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