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Subsurface Investigation and Numerical Simulation of a Ground-Coupled Heat Pump System Under Construction: A Laboratory Setup Toward Autonomous Heating in The Canadian North

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ABSTRACT

Shallow geothermal solutions for heating buildings are being considered in remote cold climates like northern Canada, where buildings are often isolated and off-grid. Diesel heating remains the conventional choice in these areas, posing significant environmental and economic challenges, including fuel transportation logistics and spill risks. Ground-Coupled Heat Pump (GCHP) operations in off-grid settings need to be better documented, a challenge to be addressed by the Centre TERRE that is constructing a research facility in Jonquière (Quebec) to demonstrate the use of various renewables for remote regions. The borefield of the main building at this research facility will supply base heating and cooling loads. The research presented herein has the objective of characterizing the subsurface and simulating the operation of the GCHP system to be constructed to evaluate its long-term reliability and impact on this demonstration facility. A proper assessment of the undisturbed ground temperature and the ground thermal conductivity was initially made with a conventional thermal response test. Using the FEFLOW software, numerical simulations were performed to predict the system performance over 30 years. The study compared three heating alternatives: the current GCHP system being constructed, an electric heater combined with an air conditioning (AC) unit, and an oil boiler coupled with an AC unit. Results revealed that the GCHP system has the highest reliability, with an expected annual energy consumption of 13,781 kWh. Moreover, it achieved significant energy savings compared to other solutions, outperforming the other systems by 26,640 kWh/year and 30,818 kWh/year, respectively.

1 INTRODUCTION

The integration of renewable heating systems in Arctic and subarctic climates is a critical step for ensuring sustainability and energy resilience in isolated communities. Among several advanced heating technologies, GCHP stands out as a promising solution. It offers higher energy efficiency, adaptability to fluctuating weather conditions, and can helps reduce reliance on fossil fuels. Currently, integrating multiple renewable energy sources in remote off-grid buildings is an attractive solution, particularly in the Canadian North (Karanasios and Parker, 2017). Several studies have been conducted to demonstrate the feasibility and applicability of GCHP system. Langevin et al. (2024), Maranghi et al. (2023) and Gunawan et al. (2020) proposed solar-assisted ground-coupled heat pumps in the northern portion of Quebec, and their modelling results indicated that a significant reduction in fuel consumption can be achieved. Moreno et al. (2022) studied different renewable energy mix (geothermal, solar photovoltaic, and biomass) and concluded that a mix of these three options is likely more attractive than using a single alternative. Nevertheless, complete reliance on renewables has not been demonstrated for remote northern buildings.

The Centre TERRE is a case study with the ongoing construction of a multi-energetic experimental setup in Jonquière, Quebec. Despite the location not being in the far north (48.40117° N), this project is to demonstrate the feasibility of full reliance on renewable resources for remote building heating. A research center covering an area of 1065 m^2 is being built and will be heated and cooled with a GCHP system enclosing eight borehole heat exchangers (BHE). Two cottages with a floor area of 68 m^2 each are currently under construction. Each cottage will be linked to an individual borehole, enabling controlled experiments and performance monitoring under operating conditions. The heating system of the cottages will combine solar, geothermal and biomass systems, selected based on the local availability of the resource at the study site. Each cottage will be connected to a single BHE used for experiments in a living-lab fashion. Research presented in this manuscript concerns the borefield of the main building whose construction is most advanced and where a thermal response test (TRT) was conducted, which provided an opportunity to document the subsurface of this research facility. The

objective of the work presented was to evaluate the thermal state and properties of the subsurface at the study site to determine its impact on the performance of the GCHP system to be constructed for the main building. More work will follow on the experimental cottages as construction and detail subsurface characterization advance.

1.1 Background Information

Geologically, the subsurface at the study site consists of two primary layers: quaternary deposits and bedrock. The quaternary deposits, mainly fine marine sediments composed of clay and silt, range from 5 to 15 m in depth (Davidson, 1998). Beneath, the bedrock layer is largely made of anorthosite with occasional granite intrusions. The dominant mineral in the anorthosite is plagioclase feldspar, and the thermal conductivity of this rock type is expected to be relatively low, around 2–2.5 W m^{-1} K^{-1} (Schön, 2011).

Metrologically, Jonquière has a humid continental climate, with average temperatures of -14.1 ℃ in January and 18.7 ℃ in July. During the summer months, rainfall averages about 93 mm in July and 97 mm in August, while substantial snowfall typically begins in December, with snow cover lasting from November to April. The city experiences an average of 5,142 heating degree days annually as shown in Figure 1. Despite not being as remote and cold as true subarctic regions where heating degree days can reach nearly 8,500 per year, it presents a practical and accessible environment for testing autonomous heating systems through the Centre TERRE initiative.

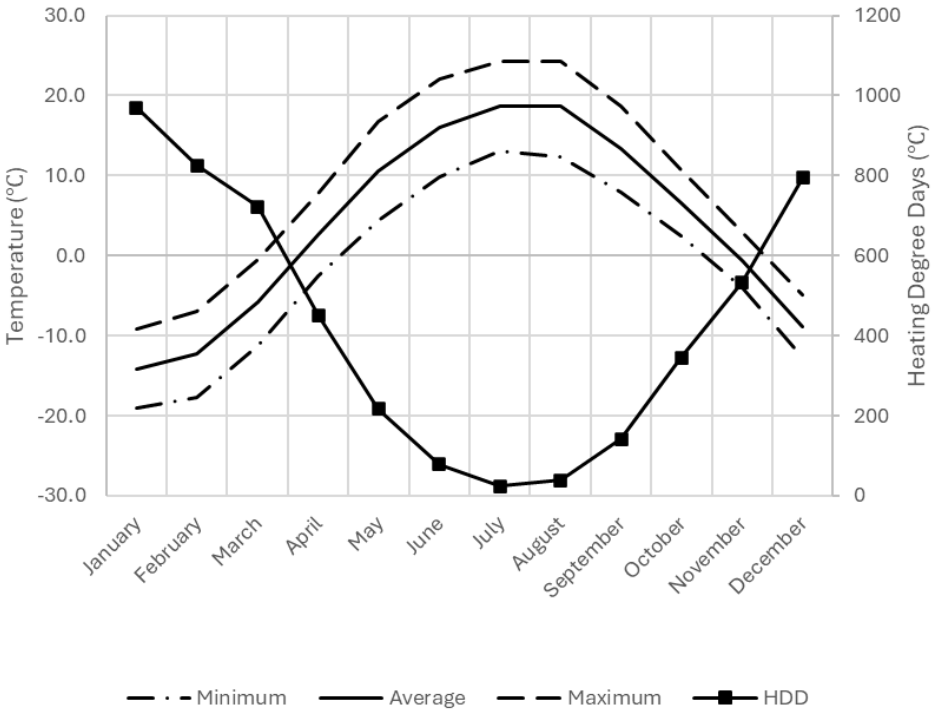


Figure 1. Jonquière climate for a typical year

A heating demand profile for the main building was provided by CIMA+, the engineering firm responsible for designing the GCHP system, as shown in Figure 2. The reference energy model represents a building compliant with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 90.1–2010) and the National Energy Code of Canada for Buildings (NECB 2017 standards). The energy simulation was performed using the IES Virtual Environment software (Building Performance Modelling for Architects 2025). Climate data were obtained from the Canadian Historical Climate Database. The building is occupied Monday to Friday from 7:00 a.m. to 6:00 p.m. The designed indoor temperature and relative humidity are maintained between 21–25 °C and 30–60%, respectively.

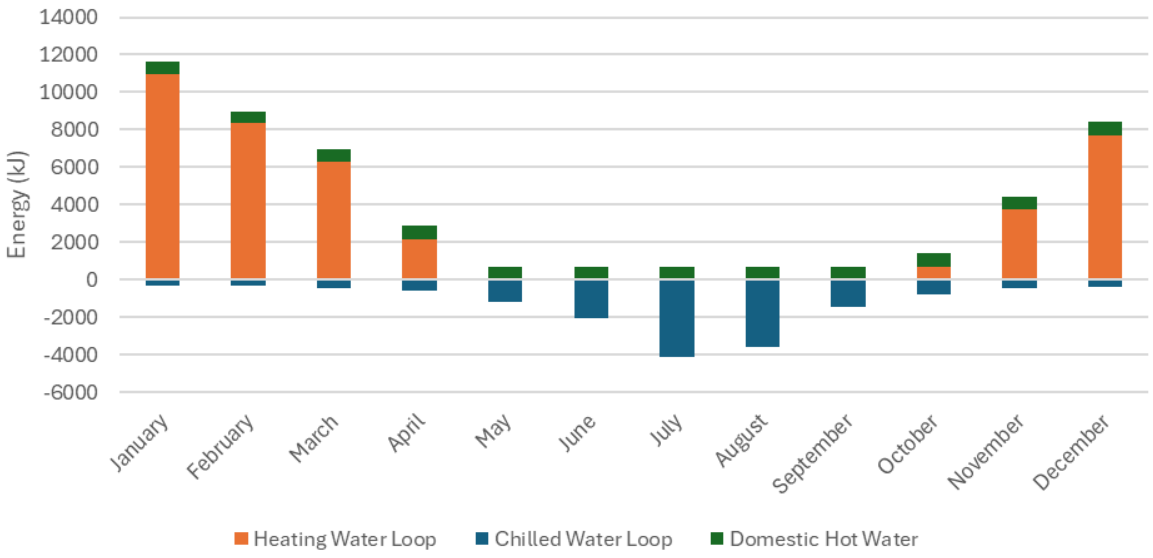


Figure 2. Simulated heating and cooling loads for Centre TERRE main building

2 METHODOLOGY

2.1 Subsurface Characterization

A TRT is a field method used to determine the undisturbed ground temperature, the effective thermal conductivity of the ground and the borehole thermal resistance. The test involves injecting heat at a constant rate into a BHE with water circulation. During the test, the average fluid temperature and flow rate are continuously monitored over time. These measurements enable an accurate determination of the heat injection rate, which is critical because it directly affects the interpretation of the results. A simplified interpretation known as the slope method (Raymond et al. 2021), derived from the infinite line source equation, is commonly applied and can be expressed as :

$$\Delta\overline{T_w} \cong m\,ln(t) + b \qquad \text{Equation 1}$$

$$m = \frac{q}{4\pi\lambda_s} \qquad \text{Equation 2}$$

$$b = m\left(ln\frac{4\alpha_s}{r_b^2} - \gamma\right) + qR_b + T_\circ \qquad \text{Equation 3}$$

where $\Delta\overline{T_w}$ (°C) is the mean water temperature increment in the BHE, m (K s^{-1}) is the slope of the regressive straight line, t (hr) is the time, q (W m^{-1}) is the heat injection rate per unit length of borehole, and b (K) is the intercept. λ_s (W m^{-1} K^{-1}) and α_s (m s^{-2}) are the thermal conductivity and diffusivity of the subsurface, r_b (m) is the borehole radius, $T_\circ$ (K) is the undisturbed ground temperature, and γ (≈ 0.577215) is the Euler-Mascheroni constant. R_b (m K W^{-1}) is borehole thermal resistance and can be determined using intercept analysis ($b = m\left(ln\frac{4\alpha_s}{r_b^2} - \gamma\right) + qR_b + T_\circ$ Equation 3). In this method, the rise in the mean fluid temperature is plotted against the natural logarithm of time. The slope of the resulting linear trend provides the effective thermal conductivity of the ground, while the intercept (after correcting for a known theoretical constant) yields the borehole thermal resistance per unit length.

The TRT made at the field site was conducted in an exploratory borehole by the consulting firm Akonovia in October 2023 for subsurface characterization. The borehole was previously drilled on September 5, 2023. The undisturbed ground temperature was recorded with a temperature profile made after waiting for a period of approximately three weeks to ensure the heat generated by drilling friction dissipated and the subsurface returned to its natural thermal equilibrium. The borehole has a depth of 152 m, a diameter of 0.154 m, with 11 m of casing, including 10.36 m through soil. The heat exchanger consists of a 1¼-inch SDR11 U-pipe with an outer diameter of 42.16 mm, inner diameter of 33.98 mm, and wall thickness of 4.09 mm. The pipe thermal conductivity is 0.42 W m^{-1} K^{-1}, while the grout conductivity is 1.73 W m^{-1} K^{-1}. EZ-Snap spacers were used at 3.05 m intervals. The test duration was 46.6 hours. The subsurface characterization results presented below, including the undisturbed ground temperature, thermal conductivity, and volumetric heat capacity, provided essential input parameters for the FEFLOW model.

2.2 GCHP System Simulation

A comprehensive numerical model was developed using FEFLOW to assess the performance of the proposed GCHP system. The process began with the development of a conceptual model that established the foundational framework for simulating conduction-based heat transfer. The main assumptions included uniform ground temperature, a homogeneous subsurface, and no groundwater flow as shown in Figure 3. Subsequently, a three-dimensional numerical model was constructed to simulate the system's behavior over a 30-year operational period, allowing for the evaluation of long-term performance, including predictions of borehole heat exchanger (BHE) outlet temperature and potential degradation in the heat pump's coefficient of performance (COP).

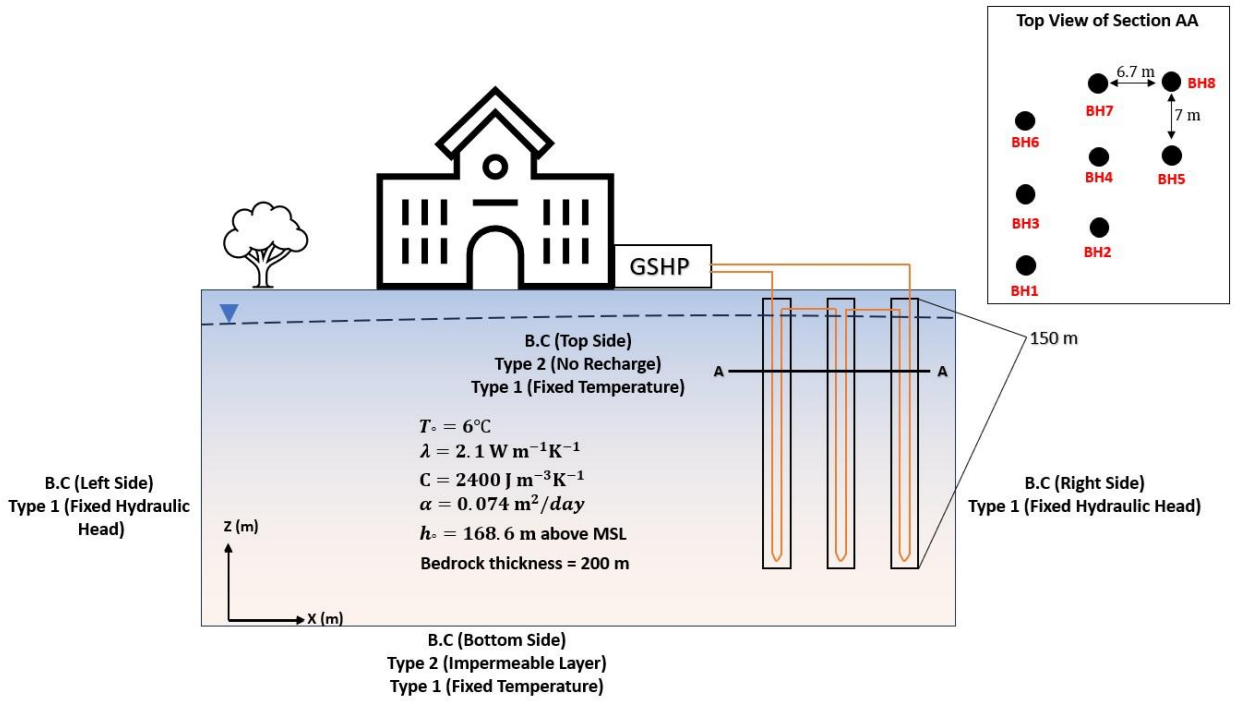


Figure 3. Conceptual model for Centre TERRE GCHP system

The model domain is defined as a 3D volume of 70 m × 70 m × 200 m, generated from a 2D triangular mesh with vertical discretization at 0.5 m intervals, resulting in approximately 6,230,800 elements as shown in Figure 4. A daily time step (1 day) is selected as an optimal balance between computational efficiency, numerical stability, and accuracy. Finally, mesh and time-step independence tests were performed to verify the reliability of the simulation results, supported by evaluations of the Peclet and Courant numbers.

Special attention is given to the horizontal mesh around the BHEs to ensure an accurate representation of the borehole radius and to avoid distortions caused by the virtual radius. This was achieved by imposing an appropriate nodal distance between the central BHE nodes and the surrounding nodes, complemented by a dedicated horizontal mesh sensitivity analysis to verify that the chosen discretization reliably captures the thermal processes near the BHEs. In the FEFLOW model, the BHE was implemented to simulate heat transfer between the ground loop and the surroundings, with the system configured as a single U-shaped BHE operating at a flow rate of 0.568 L s^{-1}. The input parameters for the numerical simulation are based on the aforementioned assumptions. All input parameters play a critical role in accurately capturing the heat transfer dynamics between the circulating fluid and the surrounding ground. As a result, all parameters must be carefully assessed. The input design parameters are summarized in Table 1 while the input parameters that relate to the ground properties are given in the TRT results sections.

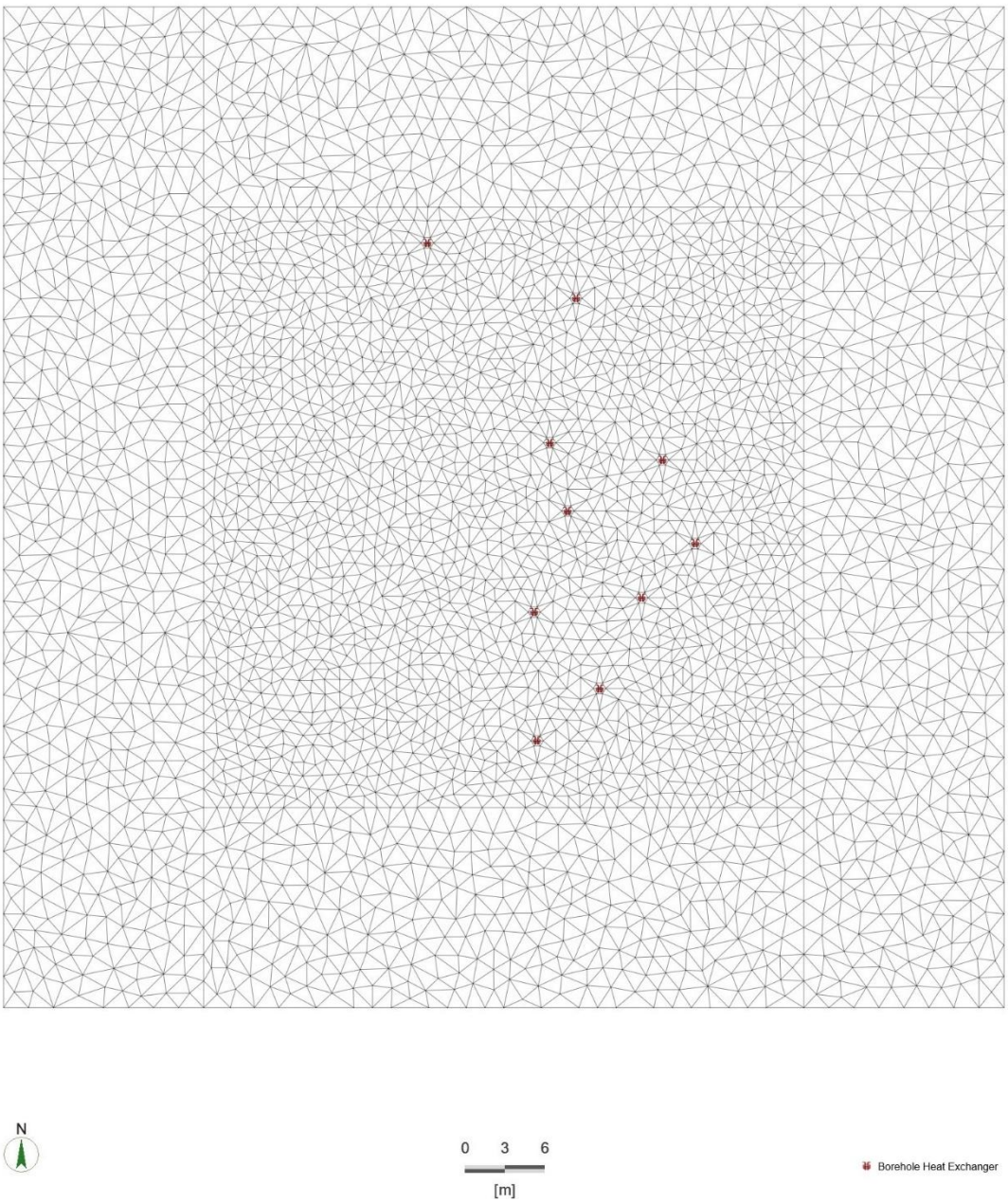


Figure 4. Boreholes Mesh Model Top View

Table 1. Input Design Parameters for the FEFLOW GCHP Model

Property	Value
Borehole diameter	0.15 m
Borehole spacing in x direction	6.7 m
Borehole spacing in y direction	7 m
Shank spacing	3.05 m
BHE geometry	Single U – Shaped

Pipe distance	0.04 m
Inlet pipe diameter	0.032 m
Inlet pipe wall thickness	0.0029 m
Outlet pipe diameter	0.032 m
Outlet pipe wall thickness	0.0029 m
Grout thermal conductivity	1.73 W m^{-1} K^{-1}
Pipe thermal conductivity	0.42 W m^{-1} K^{-1}
Heat carrier fluid thermal conductivity	0.48 W m^{-1} K^{-1}
Heat carrier fluid volumetric heat capacity	4 MJ m^{-3} K^{-1}
Heat carrier fluid dynamic viscosity	3×10^{-3} kg m^{-1} s^{-1}
Heat carrier fluid density	1.052×10^{3} kg m^{-3}

A no-flow (zero fluid flux) boundary condition is applied to the top surface of the model to prevent infiltration from precipitation or surface water. The lateral boundaries were defined as a fixed hydraulic head to suppress lateral groundwater movement, thereby representing symmetry or equal hydraulic head conditions at the model edges. An initial temperature based on field measurements of the subsurface is prescribed at both the top and the bottom boundaries, while the entire model domain is initialized at the same temperature. The lateral boundaries are positioned sufficiently far from the borefield to minimize potential thermal interference, ensuring that the simulated heat transfer around the borehole heat exchangers remains unaffected by boundary effects.

2.3 Energy Savings

Energy saving calculations were made to evaluate the effectiveness of the heat pump system in reducing energy consumption compared to conventional heating method, an oil-based heating scenario that would be expected for northern buildings although uncommon to new buildings in Jonquière. The methodology for this analysis involved comparing the annual energy consumption, operating cost, and environmental impact of three different heating and cooling system configurations for the proposed building. These alternatives are GCHP, electric heater combined with an air conditioning unit, and oil boiler combined with an air conditioning unit. It should be emphasized that in all configurations, the air conditioning unit is considered for cooling purposes only.

The GCHP system simulation allowed to determine the BHE outlet temperature and the COP. The ground loads were modeled dynamically in FEFLOW, being adjusted at each simulation time step according to the updated BHE outlet temperature and the corresponding COP values. The GCHP performance is analyzed by calculating the heat pump energy consumption in each mode. The total annual electricity consumption of the heat pump and the circulation pump is multiplied by the unit energy cost to determine annual operating expenses.

Each alternative was analyzed using the same building loads, with energy inputs calculated based on system efficiency (COP = 1 for the electric heater and 90% boiler efficiency for the oil system). Fuel and electricity consumption values were then multiplied by local energy rates to estimate annual operating costs. Hydro-Québec electricity tariffs were applied to ensure consistency in comparison with the three alternatives. For educational institutions in Quebec, the applicable rate structure is 5.851 ¢/kWh for the first 210,000 kWh consumed per month and 4.339 ¢/kWh for any additional consumption. CO_2 emissions were reported from Hydro-Québec's fact sheet, which reports very low carbon emissions from electricity generation of approximately 0.5 - 0.6 kg CO_2 per kWh (Attarmigiroglu 2021). For oil heating, emissions were calculated by multiplying the total fuel consumption (in liters) by an emission factor of 2.70 kg CO_2 per liter of diesel, as reported by Natural Resources Canada (2014). The local diesel price was assumed to be 1.41 CAD per liter. This energy analysis considered only heating and cooling costs, excluding all other electrical loads in the building.

3 RESULTS

The results of the TRT, subsequent system simulations, and the energy analysis are described below.

3.1 Subsurface Characterization

The TRT previously conducted by Akonovia Consulting was reanalyzed to ensure a refined understanding of the subsurface conditions at Centre TERRE. Because the site will serve as a long-term living laboratory for ground energy research, establishing an accurate and well-documented subsurface thermal profile is essential. This characterization serves as a critical reference point for future experiments and monitoring activities. The undisturbed ground temperature was determined to be 6 °C according to temperature profile measurements on the site, representing the natural thermal condition of the subsurface prior to testing. The heat injection rate fluctuated throughout the heat injection phase of the TRT, as illustrated in Figure 5. For calculation purposes, an average heat injection rate of 60.46 W m^{-1} was considered. The slope method was employed to determine the ground thermal conductivity and borehole thermal resistance as shown in Figure 6. The first 20 hours of the injection phase were excluded from the analysis to minimize the influence of borehole heat storage effects. The volumetric heat capacity was assumed to range from 2.05 to 2.96 MJ m^{-3} K^{-1}, with an average value of 2.44 MJ m^{-3} K^{-1}.

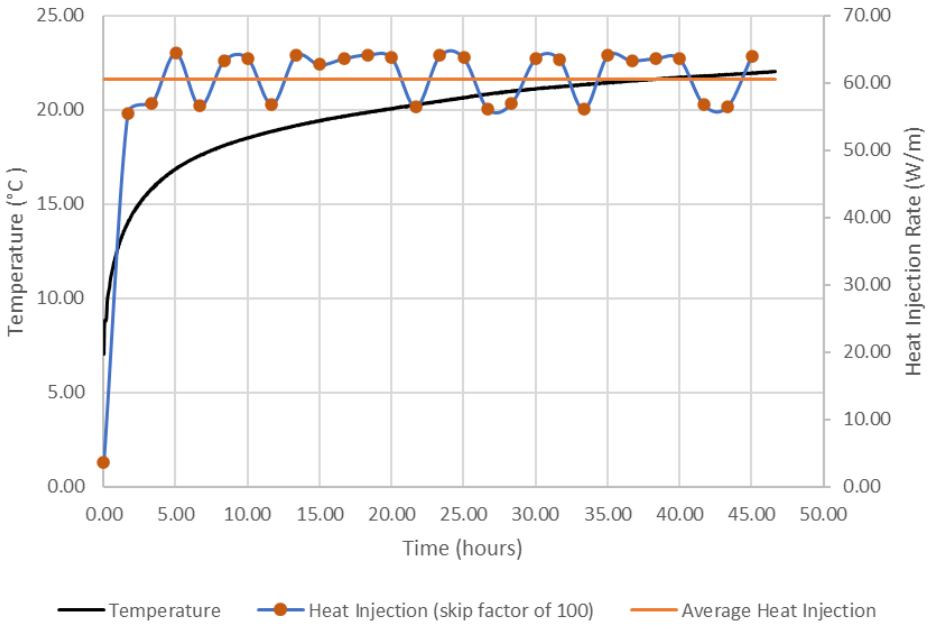


Figure 5. Temperature and heat injection rate during the TRT

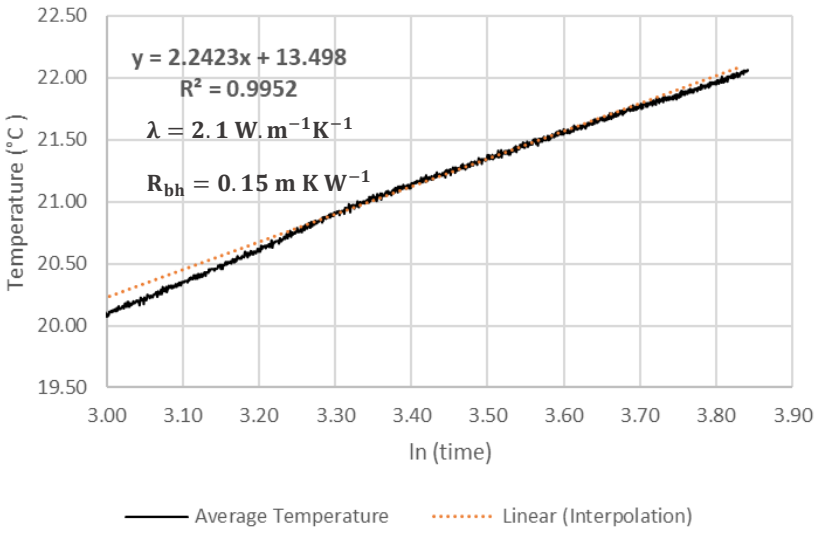


Figure 6. TRT analysis with the slope method for the exploratory borehole

The estimated thermal conductivity is higher than what is typically expected for anorthosite, which supports the presence of granite intrusions in the subsurface. However, the borehole thermal resistance is notably high, suggesting that the intercept method may have led to an overestimation.

3.2 GCHP System Simulation

The simulation results presented in this section form the basis for evaluating the system's performance and identifying key factors that have influence. A relatively modest decline in COP is observed over time, primarily because the heating demand exceeds the cooling demand, as illustrated in Figure 7. The minimum outlet temperature during operation is approximately 2.7 °C, which remains above the freezing point of the heat carrier fluid (−15 °C). The heat carrier fluid consists of 70% water and 30% propylene glycol mixture by volume. Although this temperature drop is modest under the simulated conditions, a more pronounced reduction is expected in arctic climates of northern regions.

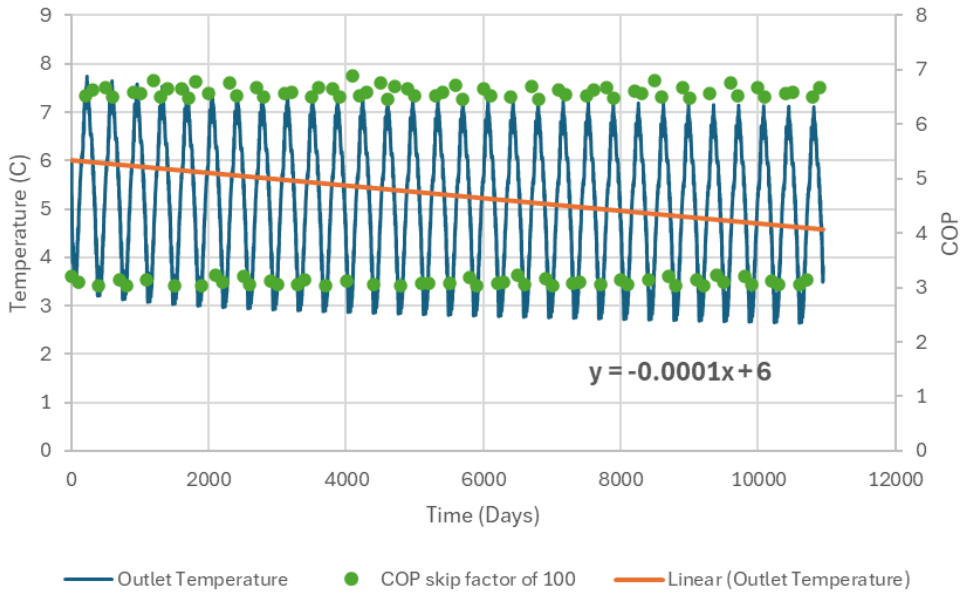


Figure 7. Outlet temperature simulated for the BHE field.

A sensitivity analysis was made to highlight the significant influence of subsurface thermal properties and initial ground temperature on the thermal performance of the GCHP system. By varying one parameter at a time while holding others constant, the impact on borehole outlet temperature was assessed to understand how deviations in input assumptions affect system efficiency. Varying thermal conductivity by 0.1 step in range of 1.9 to 2.3 W m^{-1} K^{-1} showed a notable impact on BHE temperature. An increase from 1.9 to 2.3 3 W m^{-1} K^{-1} resulted in a rise in average outlet temperature from 5.21 °C to 5.37 °C, indicating improved heat transfer efficiency. This emphasis that underestimating thermal conductivity could lead to conservative system designs. Adjusting volumetric heat capacity by 0.1 step within a practical range of 2.05 to 2.96 MJ m^{-3} K^{-1} at constant thermal conductivity and initial temperature produced a negligible effect. Although less sensitive than thermal conductivity, this parameter still affects the system's ability to buffer thermal fluctuations. Among all parameters tested, initial ground temperature exhibited the most pronounced effect. A variation from 5 °C to 7°C led to a corresponding increase in average BHE outlet temperature from 2.99 °C to 4.50 °C. This strong sensitivity emphasizes the importance of accurate in-situ temperature measurements, as even small misestimations can drastically alter heat pump performance predictions and lead to incorrect system sizing or underperformance. Overall, the analysis confirms that accurate subsurface characterization is critical for reliable system design and long-term operational efficiency.

3.3 Energy Savings

The energy analysis compares three alternatives for heating and cooling for the proposed building. In Case 1 (GCHP), the system operates with an average COP of 3.2 in heating mode and 6.57 in cooling mode, resulting in a total energy consumption of 13,938 kWh/year and an annual operating cost of 815 $CAD and 8.36 ton of CO2 per year. In Case 2 (Electric Heater and AC Unit), the system consumes 40,578 kWh/year, costing 2,374 $CAD and 24.35 ton of CO2 per year, due to the electric heater's low efficiency (COP = 1). Finally, Case 3 (Oil Boiler and AC Unit) resulted in 44,756 kWh/year consumption, and much higher annual cost of 6,062 $CAD, and 13.1

tons of CO_2 emissions per year. Overall, the ground-coupled heat pump demonstrates the lowest operating cost and carbon emissions, making it the most energy-efficient and environmentally sustainable option among the three alternatives.

4 DISCUSSION

The results of the numerical simulation and energy analysis confirm that the GCHP system designed for the Centre TERRE pilot project offers a viable and energy-efficient alternative to conventional heating systems in cities such as Jonquière. Its performance, long-term reliability and energy consumption, clearly demonstrate the suitability of GCHPs for integration into heating strategies. On the other hand, Northern Canadian communities experience extremely cold and prolonged winters, presenting significant challenges for heating systems. In this context, GSHP systems provide a distinct advantage, as they extract heat from the subsurface where temperatures remain comparatively stable throughout the year. This consistent thermal environment supports reliable and efficient system performance, even during severe cold periods. In contrast, technologies such as air-source heat pumps and solar systems are more directly exposed to atmospheric variability and often experience substantial efficiency losses under extreme northern climate conditions.

One of the key findings of this study is the system's relatively stable coefficient of performance (COP) over the 30-year simulation period. Although a gradual decline in outlet temperature is observed, this reduction remains modest under the simulated climatic and subsurface conditions. In environments with similar thermal demands and geological characteristics, GCHPs can maintain efficient heat exchange without significant performance degradation over time. However, it is important to note that in more extreme Arctic conditions, characterized by longer heating seasons and reduced ground recharge from cooling cycles, this decline may be more pronounced. Several field studies have examined the performance of GSHP systems in northern climates, including installations in Alaska, Whitehorse, Yellowknife, and Nunavut. Garber-Slaght and Peterson (2017) reported on a GSHP system installed in Alaska, where the coefficient of performance (COP) averaged 3.7 during the first year of operation but declined to 3.2 by the third winter. The study noted that ice formation began to occur around the heat exchange coils, suggesting gradual ground freezing effects. Kegel et al. (2016) evaluated a hybrid GSHP system in northern Canada, demonstrating that GSHP system configurations can help maintain performance under extreme cold conditions. Therefore, using this system in higher-latitude regions requires further adaptation, such inclusion of different renewable resources to decrease ground heating loads or increasing ground cooling loads.

The comparative analysis between the three heating configurations clearly demonstrates the superior energy efficiency of the GCHP system. With an annual energy consumption of approximately 13,938 kWh, the GCHP outperforms both the electric heater and oil boiler alternative by 26,640 kWh and 30,818 kWh, respectively. This not only translates into lower operational costs especially under Quebec's favorable electricity pricing but also implies a substantial reduction in fossil fuel dependency and associated CO_2 emissions. Even when accounting for long-term inflation over a 30-year period (3% for electricity and 4% for diesel), the GCHP system remains the most economical option. Its projected energy cost is approximately 38,800 CAD, compared with 113,000 CAD for the electric heater and 289,000 CAD for the oil-fired boiler.

The results of the Centre TERRE pilot project are consistent with previous studies on ground-coupled heat pump (GCHP) systems in northern Quebec, confirming their feasibility and energy efficiency. Like the findings of Langevin et al. (2024), Maranghi et al. (2023) and Gunawan et al. (2020), Centre TERRE simulations show that GCHPs can significantly reduce energy consumption and fossil fuel use compared to conventional heating systems. However, some investigations highlight potential long-term limitations of GSHP systems under cold climates. For example, Li et al. (2025) found that in a shallow GSHP installation in a cold region with a heating to cooling load ratio of 2.3:1, the ground temperature declined by 4.7 °C over 10 years, leading to a 12% drop in COP. This points to the important limitation that even well-designed GSHP systems may suffer performance degradation over long terms when cooling is minimal, and ground recharge is limited. However, although the heating to cooling ratio was 2.77:1 in Centre Terre project, the degradation in COP is acceptable.

5 CONCLUSION

The study highlights GCHP as a primary heating solution due to its stable performance. Sensitivity analysis reveals that system efficiency is highly dependent on accurate subsurface characterization. Inaccurate or generalized assumptions about subsurface can significantly impact system performance, leading to increased energy consumption and higher operational costs. Future work will focus on conducting detailed subsurface characterization, incorporating subsurface heterogeneity to better anticipate the system performance. This knowledge will directly contribute to improving the economic feasibility of GCHP systems, ultimately providing

more efficient and reliable autonomous heating solutions for buildings in challenging climates. Moreover, future work, including experimental validation and real-time monitoring of the pilot system performance installed at Centre TERRE, will provide valuable data to demonstrate full reliance on renewable alternatives for building located in northern communities.

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