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Preliminary Study on Utilizing Closed-Loop Geothermal Systems for Seasonal Storage of Surplus Solar and Wind Energy

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ABSTRACT

The transition to renewable energy is crucial for mitigating climate change, yet the inherent intermittency of solar and wind power presents significant challenges for energy reliability. Seasonal energy storage solutions are essential to balance supply and demand, particularly in remote northern regions where extreme seasonal variations affect energy generation. This study explores the feasibility of utilizing a multilateral closed-loop geothermal system for long-term thermal energy storage, integrating surplus solar energy into the subsurface for use during high-demand winter months. A case study in Resolute Bay, Nunavut, Canada, is conducted to assess the system's effectiveness in providing stable heat supply to a remote Arctic community. A thermodynamic model is developed to simulate heat injection and extraction dynamics, considering local geological formations, thermal conductivity, and operational parameters. Sensitivity analyses are performed to evaluate the influence of reservoir properties and wellbore configurations on system performance. Model validation is achieved through comparisons with numerical simulations. Preliminary results indicate that geothermal energy storage can smooth seasonal fluctuations in renewable energy supply, maintaining stable outlet temperatures over long-term operation. The system demonstrates potential for reducing reliance on imported fossil fuels in off-grid Arctic settlements while enhancing energy security. This study provides a foundation for future research on optimizing geothermal-based thermal energy storage solutions in cold-climate regions.

1. INTRODUCTION

The transition to clean energy is a crucial step toward achieving global climate goals and reducing reliance on fossil fuels. This transition is largely driven by the rapid deployment of renewable energy sources, with solar and wind power playing dominant roles due to their abundant availability and declining costs. However, a key challenge associated with these renewable sources is their inherent variability—solar power is limited to daylight hours and affected by weather conditions, while wind power is intermittent and unpredictable. Especially in the northern regions of Canada, extended periods of midnight sun and polar night significantly affect solar energy availability, while ice accumulation on turbine blades increases the maintenance frequency and operational constraints of wind energy systems in winter (Fig. 1, ECCC, 2016). These fluctuations in energy supply and demand necessitate the development of innovative energy storage technologies capable of capturing excess energy during peak generation periods and releasing it during times of low production. Long-duration energy storage solutions, particularly those capable of storing energy across seasons, are critical to ensuring grid stability, enhancing energy security, and facilitating the full integration of renewables into the energy system (Budischak et al., 2013; Denholm & Hand, 2011).

Several approaches to long-duration energy storage have been investigated in recent years, including battery energy storage, pumped hydro storage, hydrogen storage, and thermal energy storage (TES). While lithium-ion batteries have been widely deployed, their energy density, cost, and degradation over repeated charge cycles limit their viability for seasonal applications (Zakeri & Syri, 2015). Pumped hydro storage is the most established large-scale storage technology, but it is geographically constrained and requires substantial infrastructure investment (Rehman et al., 2015). Hydrogen storage, though promising in terms of high energy density, faces challenges related to storage efficiency, conversion losses, and infrastructure requirements (Staffell et al., 2019). In contrast, TES has gained attention as a viable approach for storing excess energy in the form of heat, which can later be utilized for district heating, industrial processes, or electricity generation (Pielichowska & Pielichowski, 2014).

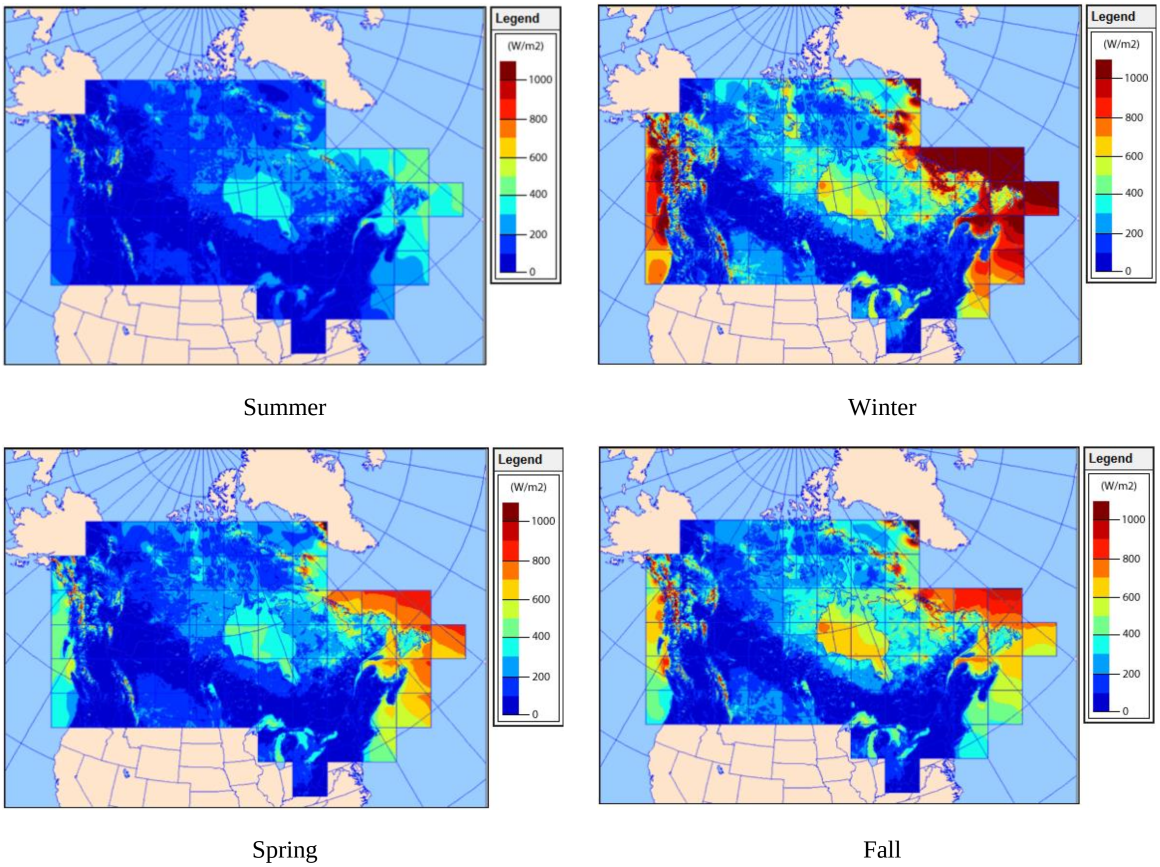

Figure 1: Overview of numerical simulated mean wind energy in four seasons across Canada (ECCC, 2016).

Geothermal-based TES, in particular, has been proposed as an effective means of storing and retrieving thermal energy over long durations. The concept of using the subsurface for seasonal heat storage has been explored in various configurations, including aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and mine thermal energy storage (MTES) (Nordell & Hellström, 2000; Zhang et al., 2022). Closed-loop geothermal systems, which circulate a working fluid through underground heat exchangers without direct contact with the reservoir, offer an alternative method of subsurface TES with minimal environmental impact and reduced geological uncertainty (Yuan et al., 2021; Shah et al., 2024). Previous studies have demonstrated the potential of closed-loop geothermal systems for heating and cooling applications (Lanahan & Tabares-Velasco, 2017), as well as their effectiveness in stabilizing intermittent renewable energy supply by providing a buffer against seasonal variations (Yang et al., 2021).

Despite the promise of geothermal TES, several challenges remain in its widespread implementation. Key factors influencing system performance include the thermal conductivity and heat capacity of the host rock, the efficiency of heat transfer through wellbores, and the long-term stability of stored thermal energy (Zhu and Chen, 2019). In regions such as the Canadian Arctic, additional uncertainties arise due to permafrost conditions, variations in thermal conductivity, and limited subsurface data, which can impact the feasibility and effectiveness of geothermal storage systems (Majorowicz & Grasby, 2010). Furthermore, previous modeling efforts have primarily focused on simplified geological settings, whereas real-world applications require detailed site-specific assessments to optimize system design (Zhang et al., 2024).

In this study, we investigate the feasibility of using a multilateral closed-loop geothermal system to store surplus solar energy in the subsurface for seasonal heat supply. A case study is conducted for a remote Arctic community, Resolute Bay, Nunavut, where extreme climate conditions and energy security concerns highlight the need for innovative storage solutions. The study integrates a thermodynamic model of heat injection and extraction with a sensitivity analysis of key geological and operational parameters. The results are used to assess the storage efficiency and long-term performance of the system, comparing its effectiveness with other TES methods. This preliminary analysis aims to provide insights into the potential of geothermal-based seasonal storage in extreme climates, contributing to the broader understanding of renewable energy integration in off-grid northern communities.

2. METHODOLOGY

2.1 General heat loop system

The conceptional model of the heat supply and demand system is simplified as shown in Figure 2. In the subsurface, geothermal energy is extracted by using multiple horizontal wellbores sealed at the wall of the wellbore. This closed-loop geothermal system is treated as the function of extracting and storing heat energy by the temperature difference between the working fluids with the formation. The heat is transferred through the wall of wellbores by means of the heat conduction mechanism. In the surface part, together with the produced heat from the closed-loop geothermal system, heat energy generated from unconsumed renewable power sources such as solar panel and wind mills, will be used for supplying the heat demand of a remote community. The reduced/increased temperature working fluid (water in this study) will be injected back into the subsurface closed-loop geothermal system for another round of energy extraction or storage.

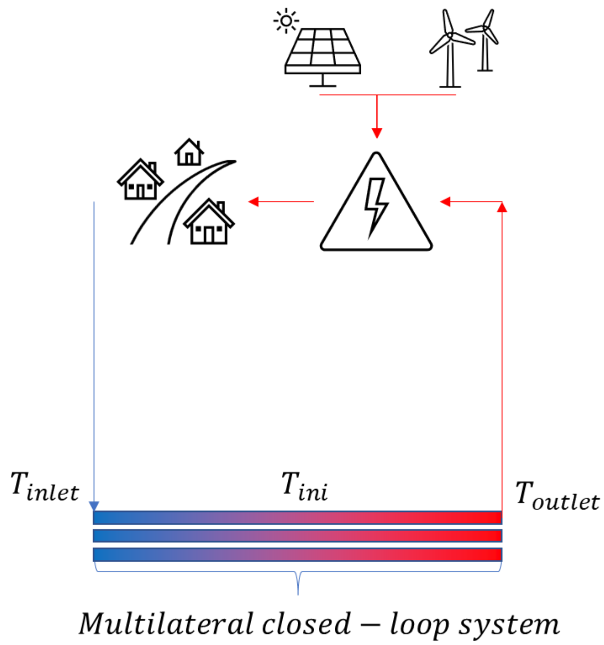

Figure 2: Illustration of the General heat loop system.

2.2 Multilateral closed-loop geothermal system

The thermodynamic model of the multilateral closed-loop geothermal system is modified based on the model proposed by Yuan et al (2021). A small volume of the horizontal wellbore and its near wellbore region has been chosen (Fig. 3) to demonstrate the heat balance mathematically using the following equation:

$$A\rho_f c_f \frac{\partial T(x,t)}{\partial t} = -vA\rho_f c_f \frac{\partial T(x,t)}{\partial x} + q_c(x,t) \tag{1}$$

where, A is the area of cross-section of the horizontal wellbore, m^2; ρ is the density of the working fluid, kg/m^3; c_p is the specific heat capacity, J/kg/K; T is the temperature of working fluid, K; v is the velocity of the local fluid, m/s; x is an index for location; t is time, s; q_c is the heat flux transferred by conduction from reservoir to wellbore, W/m.

Yuan et al (2021) presented two analytical techniques without the use of meshes for modeling the thermodynamics of a closed-loop geothermal system. Duhamel's convolution theory was utilized to understand the relationship between the transient temperature and heat flux in the wellbore. This method is appropriate for a single wellbore system without the consideration of wellbore interference in a multilateral closed-loop geothermal system. The transient temperature T_{outlet}, K, at the end of the lateral wellbore in Laplace domain can be expressed as below:

$$\overline{T_{outlet}} = \frac{(T_r - T_{inlet})}{s} \cdot exp\left(-\frac{sL}{Av\rho_f c_f} \cdot \overline{q_{cu}} - s \cdot \frac{L}{v}\right) \tag{2}$$

where, T_{inlet} is the temperature of working fluids at the beginning of lateral wellbore, K; T_r is the reservoir temperature, K; D is length of the vertical wellbore which is also the depth of the target wellbore, m; q_{cu} is the conductive heat flux under unit temperature difference calculated from the standard source and sink functions; and s signifies the Laplace transform parameter; symbols with "‾" means parameters in Laplace domain. The temperature out of the surface demand system (Fig. 2) will be used as the input to the calculation for the multilateral wellbores system. Similarly, the temperature at the end of the multilateral wellbore will also be used as the input to the calculation of surface heat supply and demand system.

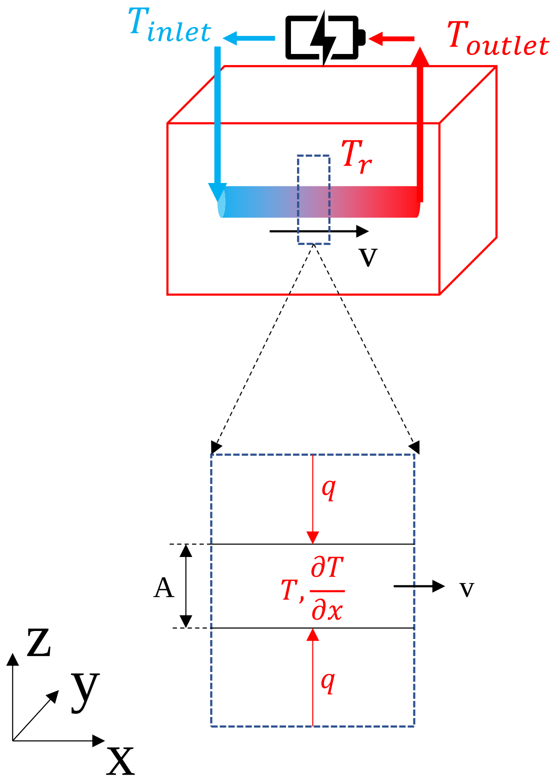

Figure 3: Schematic diagram of fundamental heat transfer model of closed-loop geothermal system.

2.3 Heat demand and supply in the surface

In order to study the general effect of the intermittent heat demand from the community and heat supply from the common renewable energy, e.g., solar panel and wind turbine, the heat load from the renewable sources and heat demand are treated as a type of continuous changeable duty defined by a periodic function. However, the total annual heat demand and the actual renewable energy generation are constrains to the definition of the periodic function. The heat demand and renewable energy generation parameters are supposed based on available data and this study will try to use these projected heat demand and heat generation to optimize the closed-loop geothermal system in target geological formations.

3. MODELING VALIDATION

Before starting the case study, how the closed-loop geothermal system handling the periodic inlet temperature needs to be validated by comparing the results generated from this study with a commercial finite element numerical simulator. In this validation case, the initial temperature of the reservoir is 200 °C. The periodic temperature function of the inlet water is shown in Figure 4. The average temperature is 60 °C and the temperature reaches highest 70 °C on 151st day. Other important parameters used in the validation case are listed in Table 1. The COMSOL Multiphysics® was used to build the same system and run for 5 years operation to compare the outlet temperature values. The physical model is shown in Figure 5 and this COMSOL solution used extreme meshed method with total of 16478 elements for calculation.

Table 1: Key parameters used for validation case.

Parameter	Value	Unit
Initial Temperature	200	˚C
Lateral wellbore length	2000	m
Flow rate of each lateral well	20	m^3/hr
Diameter of each lateral well	0.156	m
Thermal conductivity of the rock	3.5	W/m/K

Specific thermal capacity of the rock	1100	J/K/kg
Density of the rock	2500	kg/m^3
Density of the working fluid	1000	kg/m^3
Thermal conductivity of the working fluid	0.6	W/m/K
Specific thermal capacity of the working fluid	4180	J/K/kg

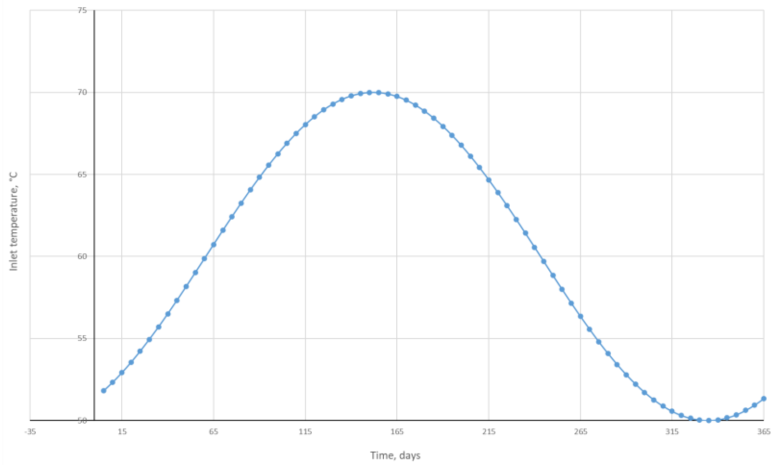

Figure 4: The curve of the periodic inlet temperature.

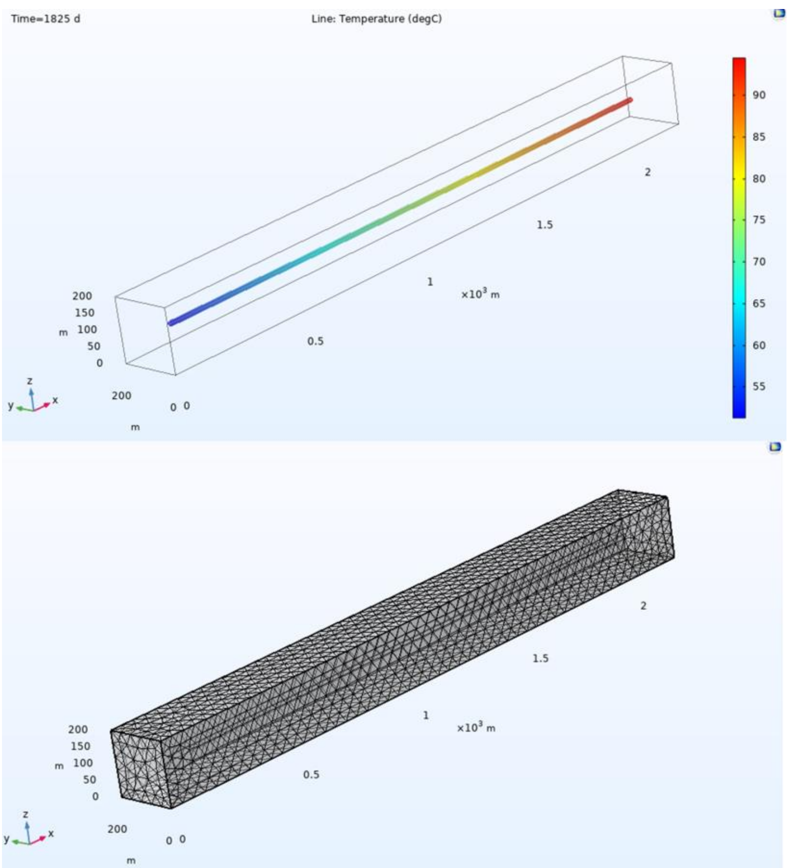

Figure 5: Screenshot of the validation model and the meshed model in COMSOL Multiphysics.

The results of outlet temperature calculated from COMSOL and this study are plotted in Figure 6. The temperature changing trend is similar as it decreases in the fall and winter seasons, and increases during the spring and summer seasons. And from a long-term perspective, the average value of the outlet temperature is continuously decreasing but becomes stable at the later years of operation. However, the results from the numerical simulator look more sharp when the temperature change its trend, which makes the orange curve not smooth. As a result, under the periodic inlet temperature function, the modeling method used in this study have higher accuracy than the numerical simulation, and can be further extended to study the heat loop performance under seasonable heat storage system.

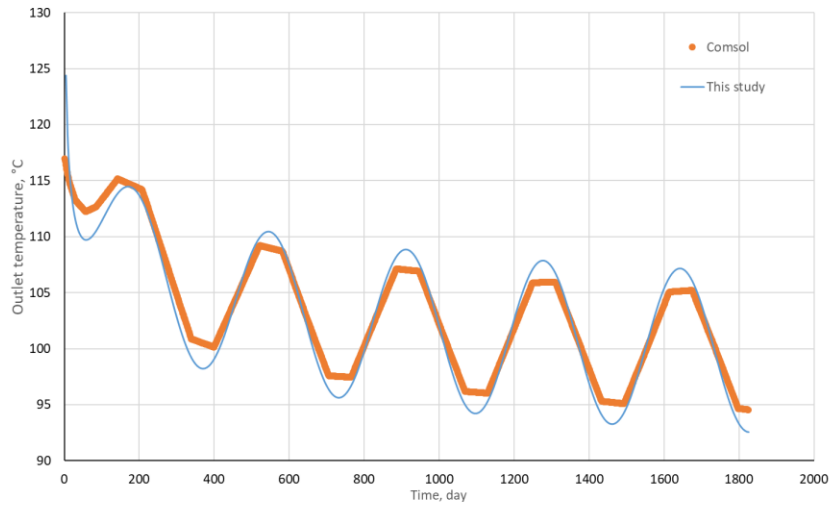

Figure 6: Results of the outlet temperature calculated by this study and a commercial numerical simulator.

4. CASE STUDY AND ASSUMPTIONS

Resolute Bay, an Inuit hamlet located on Cornwallis Island in Nunavut, Canada (Fig. 7), was selected as the study site to evaluate the feasibility of seasonal thermal energy storage using a multilateral closed-loop geothermal system. As the second northernmost community in Canada, Resolute Bay experiences a significant heating demand due to its cold climate and reliance on imported fossil fuels for space heating. According to the 2021 census, the hamlet has a population of 183, supplemented by seasonal residents associated with the Polar Continental Shelf Program research facility and the Canadian Armed Forces Arctic Training Centre. The total annual heating demand of Resolute Bay is approximately 5,690 MWh, primarily met through imported diesel fuel. The extreme seasonal variations in solar insolation present unique challenges for renewable energy integration. The region experiences continuous darkness for 89 days per year and uninterrupted daylight for 100 days per year, with highly variable cloud cover leading to an average annual sunshine potential of 29.4%, ranging from 0% in winter to 41.4% in summer (ECCC, 2024). These conditions significantly affect the efficiency and performance of solar photovoltaic (PV) systems, requiring an effective energy storage solution to manage surplus energy generated during the summer months. Additionally, wind power potential is hindered by severe winter icing on turbine blades and efficiency losses in battery storage at low temperatures.

Geologically, Cornwallis Island is predominantly composed of Ordovician to Devonian sedimentary rocks of the Franklin Basin, with minor occurrences of Lower Cretaceous and Eocene strata from the Sverdrup Basin exposed in localized grabens. The sedimentary sequence includes intertidal, shelf, and basin deposits that provide potential reservoirs for geothermal energy storage. A historical petroleum exploration well, Resolute Bay L-41, drilled 3 km east of the hamlet, intersected 1,475.2 m of sedimentary formations, including the Allen Bay, Irene Bay, Thumb Mountain, and Bay Fiord Formations. Stratigraphic interpolation suggests that these formations are underlain by the Eleanor River, Baumann Fiord, and Copes Bay Formations, with deeper sequences consisting of Cambrian clastics overlying Precambrian crystalline basement (Sodero & Hobson, 1979). Shallow geothermal gradient measurements from Resolute Bay suggest higher-than-average heat flow, with estimated thermal gradients of 121 mW/m^2, exceeding those typically observed in Arctic permafrost regions. However, to ensure a conservative assessment, this study adopts the lower gradient value of 14.9°C/km derived from the detailed well log of Resolute Bay L-41. The key thermal and lithological properties of the target formations beneath Resolute Bay are summarized in Table 2. This geological and climatological context underscores the necessity for an efficient seasonal thermal energy storage system that can mitigate the constraints imposed by Arctic conditions. The closed-loop geothermal system examined in this study aims to leverage these subsurface thermal characteristics to store excess summer heat and provide stable heating during the winter months, reducing the hamlet’s dependence on imported fuels.

Figure 7: Satellite images of the location of Resolute Bay. Images are screenshotted from Google Earth.

Table 2: The major formations under Resolute Bay having geothermal energy potential.

Formation	Temperature (°C)	Lithology	Thermal Conductivity (W/m/K)
Eleanor River Fm.	16 to 21	Limestone	2.8
Baumann Fiord Fm.	21 to 31	Anhydrite	4.8
Christian Elv Fm.	31 to 36	Limestone	2.8
Cape Clay Fm.	36 to 38	Dolomite	3.1
Cass Fjord Fm.	38 to 77	Limestone, Siltstone	2.4

Figure 8 shows the daily temperature range through the whole year in Resolute Bay. The daily average temperature could be as low as -31 °C in February and reaches the peak in July to 5 °C. We estimated the heat demand of Resolute Bay based on the daily average temperature curve by firstly using a periodic function to match the data. Then, the heat demand is generated by reversing the temperature curve because we assume the heat demand is higher when temperature is lower. And another constrain is the integration of the annual heat demand should be close to 5690 MWh. As a result, the heat demand could use a periodic function to be described (Fig. 9):

$$H(t) = 0.325 \cdot cos\left(\frac{2\pi}{365}t - 0.775\right) + 0.65 \tag{3}$$

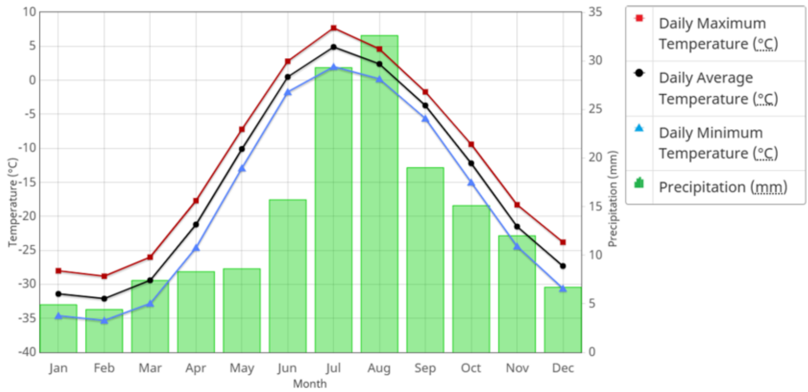

Figure 8: Diagram of the daily temperature range and precipitation in Resolute Bay.

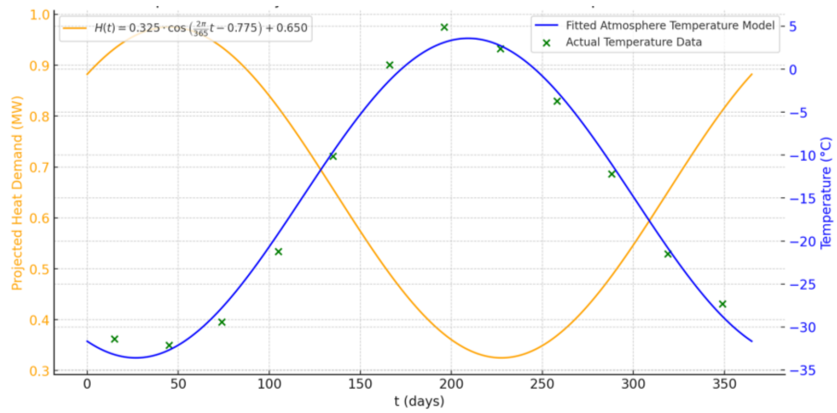

Figure 9: Projected heat demand based on the fitted temperature model.

Due to the winter condition, we only consider the solar panel as the additional surface renewable energy source to the heat loop system. Currently, there are no large solar project in Resolute Bay. We referenced the Vuntut Gwitchin Government's Old Crow Solar Project in Yukon territory. That project uses a 940 kilowatt solar array to create the largest solar energy project in this remote Yukon community. It was assumed around 620 kilowatt solar energy at the peak will need to be stored through the geothermal system. And this solar energy supply will follow the monthly solar PV potential data (NRCan, 2020) with fixed south-facing orientation. The generate heat supply by solar panel system could be described in Figure 10 as:

$$H(t) = -0.309 \cdot cos\left(\frac{2\pi}{365}t - 0.775\right) + 0.309 \tag{4}$$

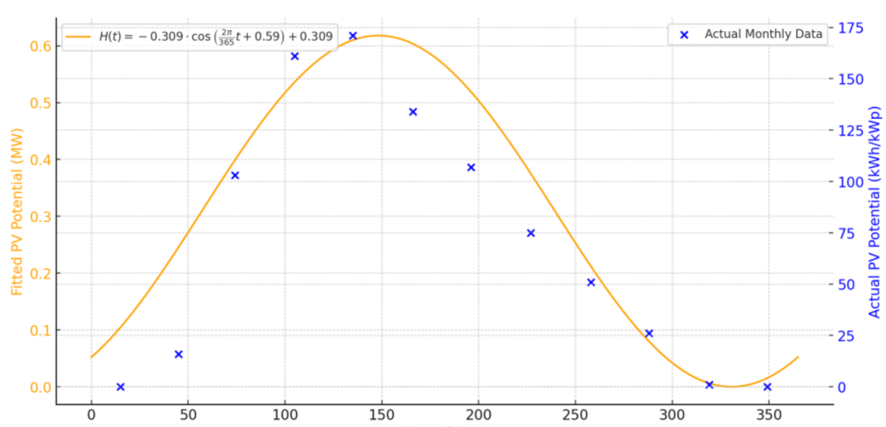

Figure 10: Projected solar heat supply based on the actual monthly solar PV potential.

In the base case study, we choose the Baumann Fiord Fm. as the target geothermal heat reservoir for the implement of the multilateral closed-loop geothermal system. Because the Baumann Fiord Fm. is mainly the evaporite rock, it has the highest rock thermal conductivity, which is preferred for the closed-loop geothermal system (Yuan et al., 2021). The reservoir is supposed to have initial temperature of 31 ˚C. The wellbore system is completed with 4 laterals of 2200 m long for each wellbore. Other parameters are listed in Table 3.

Table 3: Reservoir and closed-loop system properties used in base case study.

Parameter	Value	Unit
Initial Temperature	31	˚C
Lateral wellbore length	2200	m
Number of lateral well	4	
Flow rate of each lateral well	20	m^3/hr
Diameter of each lateral well	0.156	m
Thermal conductivity of the rock	4.8	W/m/K
Specific thermal capacity of the rock	1112	J/K/kg
Density of the rock	2663	kg/m^3
Density of the working fluid	1000	kg/m^3
Thermal conductivity of the working fluid	0.6	W/m/K
Specific thermal capacity of the working fluid	4180	J/K/kg

5. RESULTS

The performance of the multilateral closed-loop geothermal system was assessed over a 30-year operational period to evaluate its seasonal temperature variations, heat extraction and storage capacity, long-term stability, and system feasibility. The results highlight the cyclical thermal behavior of the system, reflecting seasonal fluctuations in energy demand and supply. Statistical analyses were conducted to quantify long-term trends and determine the system's efficiency in stabilizing heat delivery for Resolute Bay.

5.1 Seasonal Temperature Variability

The calculated inlet and outlet temperatures over a full operational cycle are presented in Figure 11, illustrating seasonal patterns driven by variations in solar energy availability and heat demand. The highest recorded inlet and outlet temperatures occur in July, coinciding with peak solar radiation and relatively low heating demand. In contrast, the lowest values are observed in February, when solar energy supply is absent and heating demand is at its maximum.

The temperature profiles indicate that during most of the year, the outlet temperature remains higher than the inlet temperature, demonstrating that the system is functioning as a net heat extraction mechanism. However, during the summer months (June to September), the inlet temperature surpasses the outlet temperature, signifying a shift to heat storage mode, where excess thermal energy from solar input is retained in the subsurface. This dynamic confirms that the closed-loop geothermal system is capable of both energy storage and regulated heat extraction, ensuring seasonal heat availability.

Additionally, Figure 11 shows that while the temperature fluctuations are more pronounced in the inlet temperature, the outlet temperature exhibits a smoother trend. This highlights the geothermal system's ability to buffer external temperature variations, ensuring a more stable heat supply to the surface demand system.

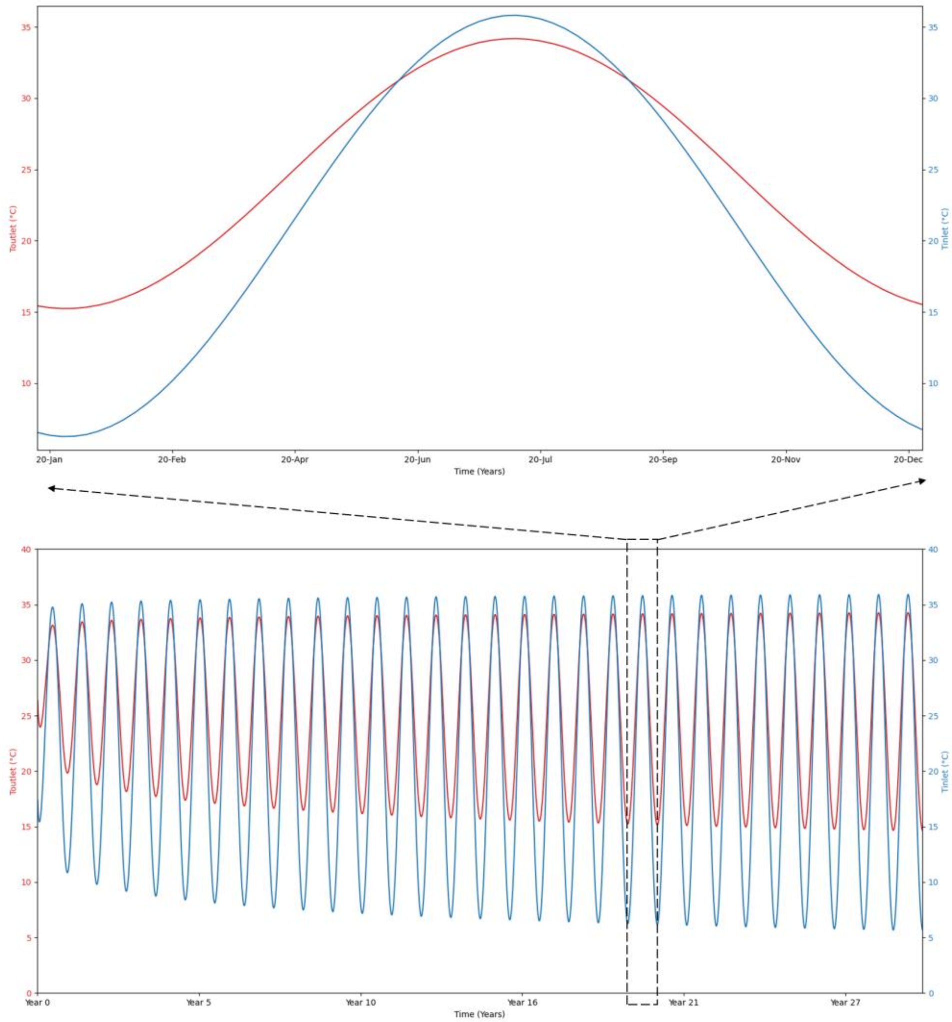

Figure 11: Outlet and inlet temperatures of the base case through 30-years operation.

5.2 Long-Term Temperature Trends and Stability

The long-term thermal performance of the multilateral closed-loop geothermal system was evaluated by analyzing annual temperature trends over a 30-year operational period. The results, illustrated in Figure 12, show a gradual decline in both inlet and outlet temperatures during the early years of operation, followed by a stabilization phase as the system approaches thermal equilibrium.

Initially, the decrease in temperature is attributed to heat dissipation into the surrounding rock formations, which occurs as the system undergoes thermal adjustments. However, as the heat transfer process stabilizes over time, the system establishes a stable heat extraction trend. The box plot in Figure 12 provides a statistical summary of the annual variability in inlet and outlet temperatures, highlighting the following trends:

- Outlet temperature remains more stable than inlet temperature: While the inlet temperature exhibits more fluctuation, the outlet temperature remains relatively stable, indicating the geothermal system's effectiveness in buffering external variations and providing a reliable heat supply to the surface system.
- Cold-weather performance: The lowest recorded inlet temperature was 6°C, while the lowest outlet temperature was 15°C, demonstrating that the system maintains operational efficiency even during the harshest winter months, ensuring a steady heat supply for the community.
- Slightly expanding temperature range over time: The variation in both inlet and outlet temperatures decreases, suggesting that the system is adapting to thermal cycling and achieving greater thermal stability.

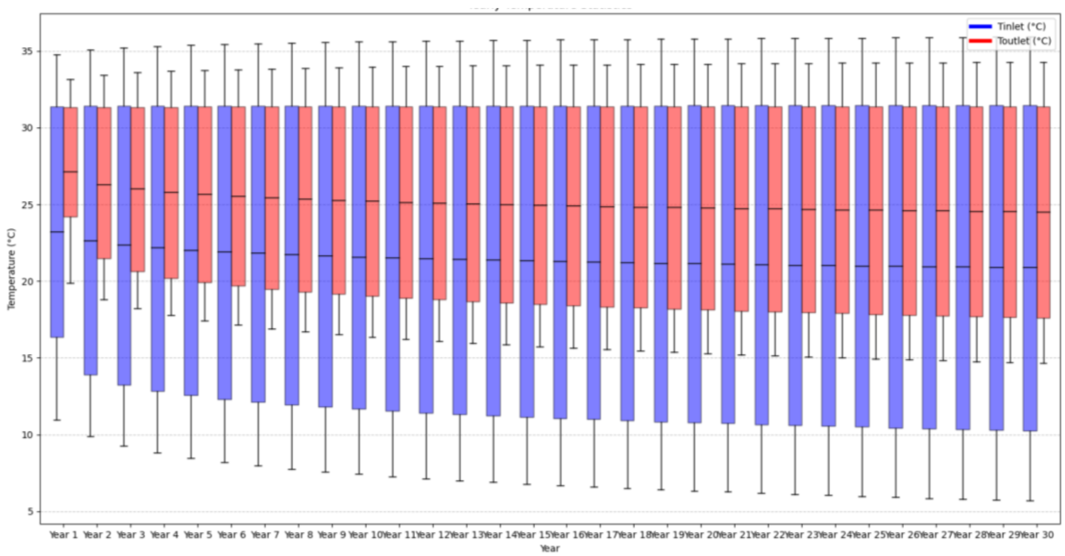

Figure 12: Box chart plot of the outlet and inlet temperature of each year.

6. DISCUSSION

6.1 Comparison to pure closed-loop geothermal system

A key objective of this study was to evaluate the impact of solar-assisted heat injection in a closed-loop geothermal system. To assess this, a comparison was conducted between the hybrid system (solar + geothermal) and a pure closed-loop geothermal system without external heat injection. The results, illustrated in Figure 13, reveal several differences in performance:

- Long-term temperature stability: The hybrid system maintains a more stable outlet temperature over time, whereas the pure closed-loop system exhibits a gradual decline in outlet temperature. This suggests that solar-assisted heat injection reduces long-term heat depletion and enhances system sustainability.

- Seasonal temperature variations: In the hybrid system, inlet temperatures peak significantly higher during summer due to the injection of surplus solar energy, whereas the pure geothermal system operates at a relatively constant but lower inlet temperature throughout the year.

- Heat extraction and recharge: The hybrid system enters a heat storage mode between June and September, with inlet temperatures surpassing outlet temperatures. In contrast, the pure closed-loop system continuously extracts heat without replenishment, leading to a more pronounced decline in thermal performance over extended operation.

These results indicate that integrating solar thermal energy with a closed-loop geothermal system improves seasonal heat retention and prevents long-term thermal depletion. Without an external heat source, the pure closed-loop system relies entirely on natural heat conduction from the reservoir, which may be insufficient for sustainable operation over multiple decades. In contrast, the hybrid system exhibits a more balanced energy cycle, replenishing stored heat during summer and extracting it efficiently in winter. This highlights the importance of hybrid heat storage strategies in optimizing geothermal energy use, particularly in low-enthalpy Arctic environments.

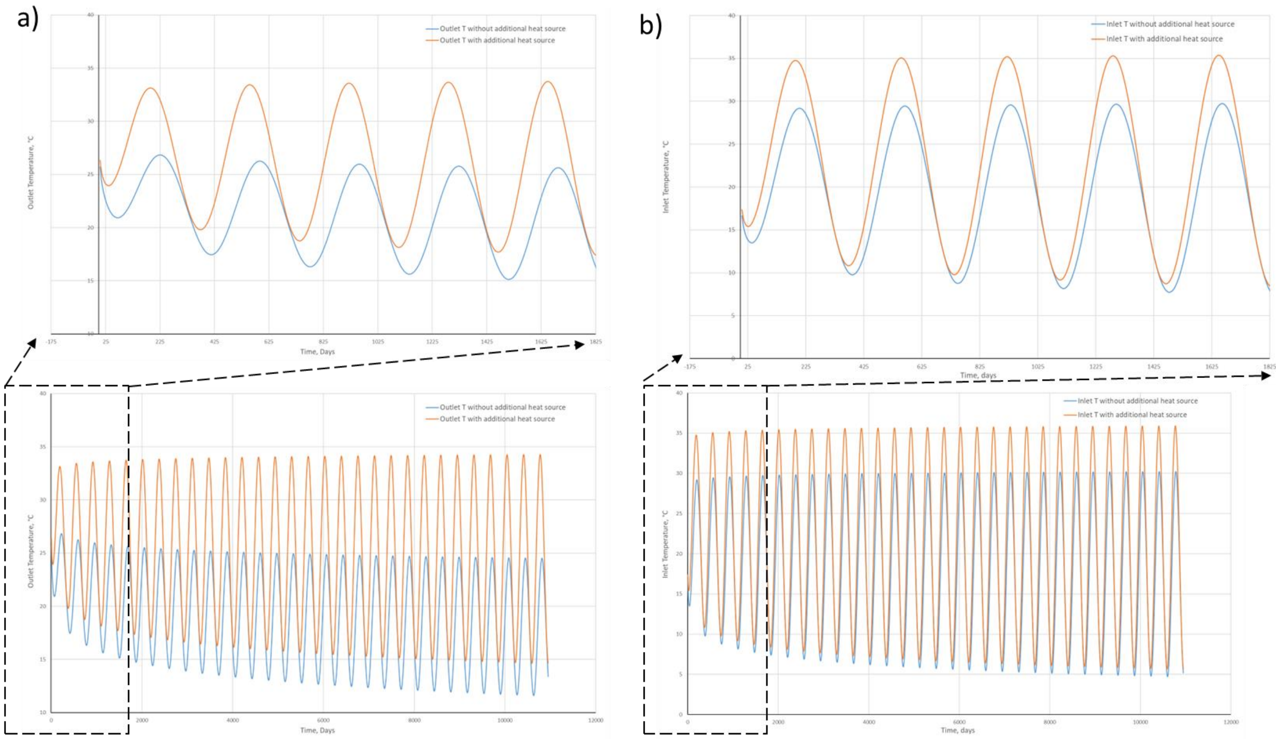

Figure 13: The comparison of the temperatures the solar assisted system with no solar assisted system.

6.2 Sensitivity analysis

In order to figure out how the system's parameter influence the general heat loop system. Sensitivity analysis on key parameters are conducted, and the values are chosen as shown in Table 4. One important purpose of this analysis is to investigate the proper multilateral wellbore completion design under different geological formation properties. Based on the interpretated geological setting, the reservoir temperature ranges from 16-77 °C depending on the depth. Rock thermal conductivity is another critical factor that determines the heat transfer efficiency for the closed-loop geothermal system. We set up 3 different values for this property. The major well configuration design factors are the length and numbers of the lateral wellbore. These two parameters could help represent the capital cost the project. As a result, a total of 630 cases of different parameter combinations were conducted for this sensitivity analysis. The inlet and outlet temperature results of some cases are below zero, which makes the system not feasible. After filtering, 307 cases have all results that are larger than zero, and were shown in Figure 14. Five series of data can be clearly identified through the plot.

Table 4: Properties values in sensitivity analysis.

Sensitive parameters	Values
Initial reservoir temperature, °C	16, 31*, 46, 61, 77
Rock thermal conductivity, W/m/K	2.4, 3.6, 4.8*
Length of the lateral wellbore, m	1000, 1400, 1800, 2200*, 2600, 3000
Number of the lateral well	1, 2, 3, 4*, 5, 6, 7

* Values in base case

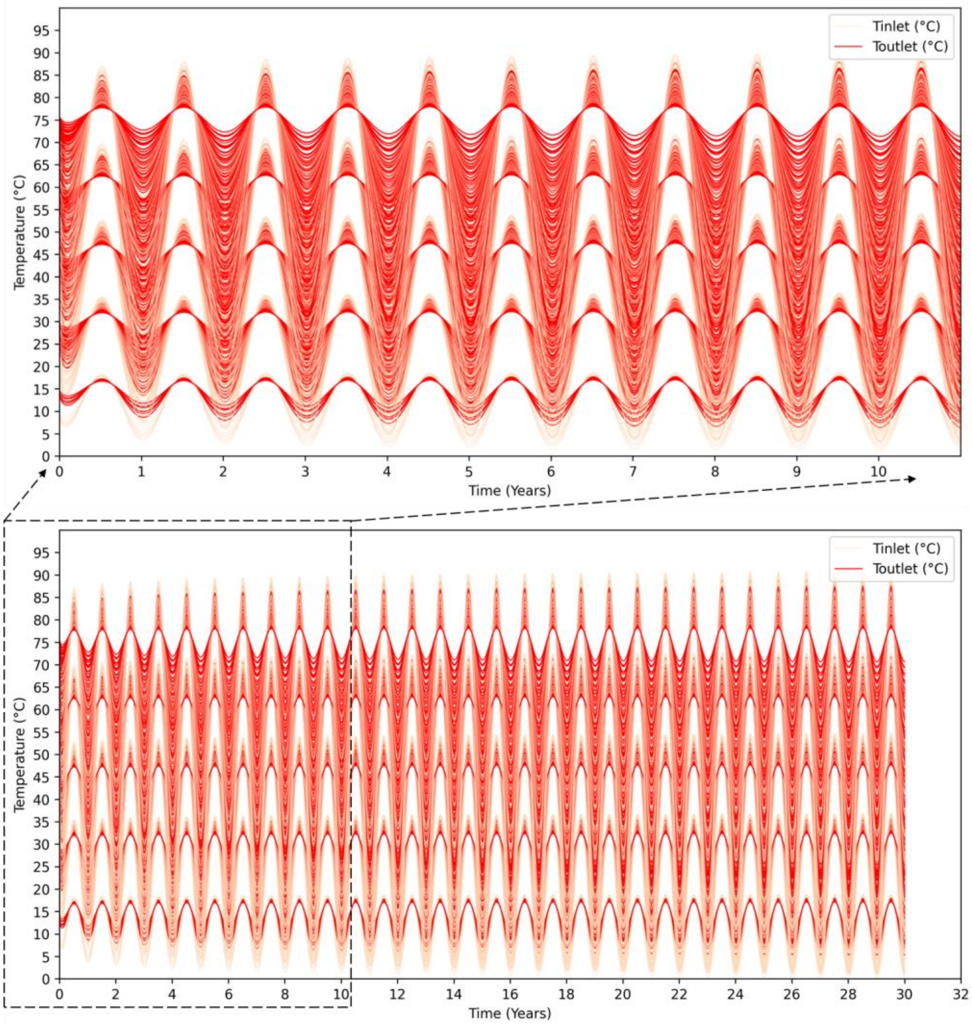

Figure 14: Inlet and outlet temperatures in all 307 cases.

Figure 15 presents the results across five initial reservoir temperatures. At 16°C, only seven combinations yielded feasible outcomes, where both inlet and outlet temperatures remained above zero. Among these, the configuration with 3.6 W/m·K thermal conductivity, seven laterals, and a lateral length of 2600 m resulted in the lowest recorded inlet and outlet temperatures, making it the most conservative design for this reservoir condition. To achieve a more optimized wellbore design with reduced total lateral length and lower inlet temperature, the setup with 4.8 W/m·K thermal conductivity, seven laterals, and 2200 m lateral length was identified as preferable.

As the reservoir temperature increased to 31°C, the number of viable configurations expanded to 46 due to the improved geothermal potential. Within this dataset, the case with the lowest inlet and outlet temperatures featured 2.4 W/m·K thermal conductivity, five laterals, and a lateral length of 2600 m, making it the conservative design for this temperature range. For a more efficient wellbore configuration with minimized lateral length and reduced inlet temperature, the 4.8 W/m·K thermal conductivity, five laterals, and 1400 m lateral length setup was found to be optimal.

With a further temperature rise to 46°C, a total of 71 cases remained feasible. The configuration with 4.8 W/m·K thermal conductivity, two laterals, and a 2600 m lateral length exhibited the lowest recorded temperatures, defining it as the conservative choice for this reservoir temperature. Alternatively, the most efficient design, featuring a shorter total lateral length and lower inlet temperature, consisted of 4.8 W/m·K thermal conductivity, five laterals, and a lateral length of 1000 m.

At 61°C, the number of viable designs increased to 86. The conservative configuration—producing the lowest inlet and outlet temperatures—included 2.4 W/m·K thermal conductivity, six laterals, and a 1000 m lateral length. In contrast, the optimized wellbore setup, with the shortest total lateral length while maintaining lower inlet temperature, was found in the 4.8 W/m·K thermal conductivity, two laterals, and 1800 m lateral length configuration.

Finally, at the highest tested reservoir temperature of 77°C, 97 valid cases were identified. The conservative choice, which resulted in the lowest inlet and outlet temperatures, was the 2.4 W/m·K thermal conductivity, two laterals, and a 2600 m lateral length design.

Meanwhile, the optimized wellbore configuration, prioritizing a reduced total lateral length and lower inlet temperature, featured 4.8 W/m·K thermal conductivity, two laterals, and a lateral length of 1400 m.

The findings, summarized in Tables 5 and 6, suggest that implementing the closed-loop geothermal system in deeper, higher-temperature formations reduces wellbore design complexity. Additionally, higher thermal conductivity enhances heat transfer efficiency, allowing for shorter lateral wellbore lengths. This study does not account for vertical wellbore depth, but based on these results, the optimal formation for this case study would be at a reservoir temperature of approximately 31°C with 4.8 W/m·K thermal conductivity, ensuring a cost-effective closed-loop geothermal system.

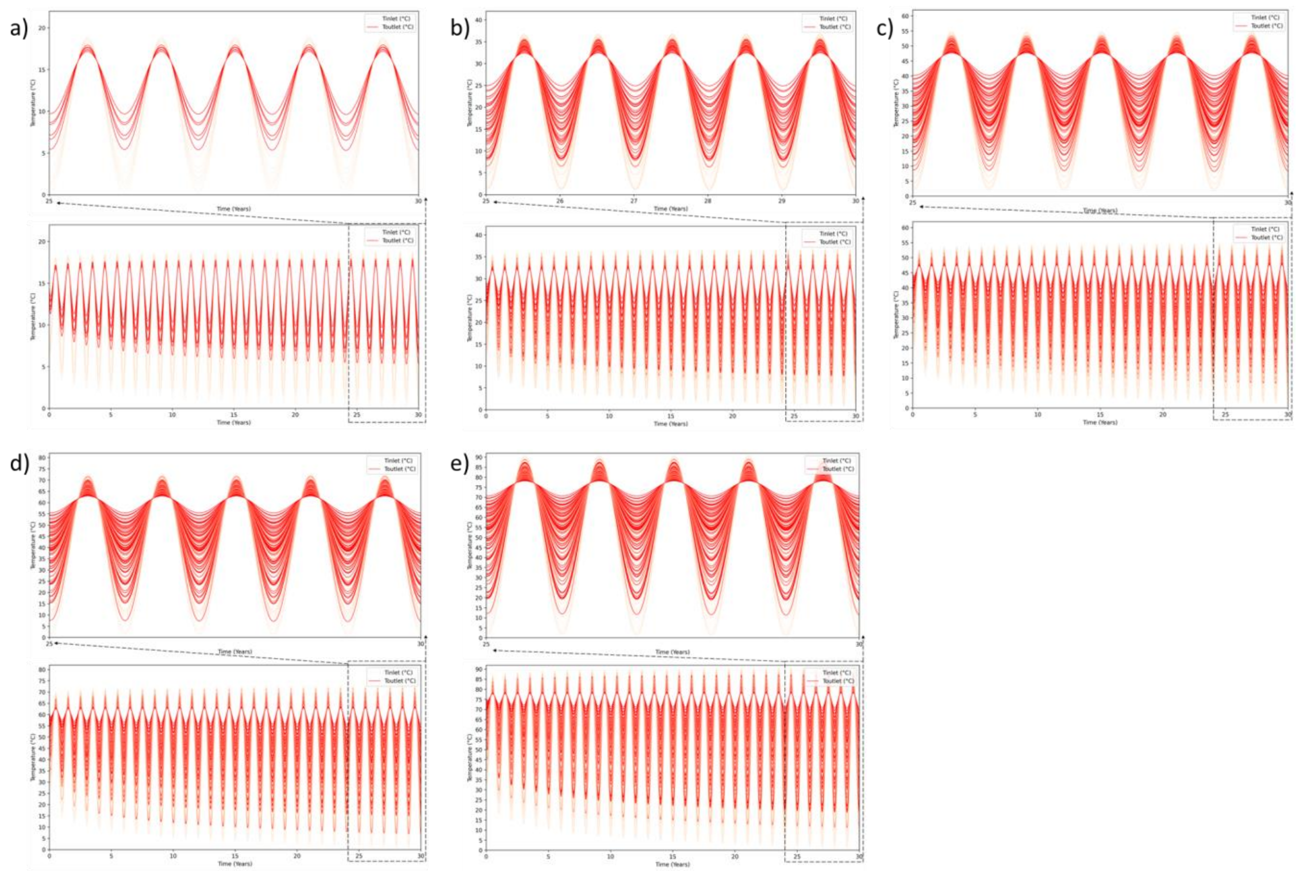

Figure 15: Inlet and outlet temperatures of various properties combinations. a) results of cases with 16 °C reservoir temperature, b) results of cases with 31 °C reservoir temperature, c) results of cases with 46 °C reservoir temperature, d) results of cases with 61 °C reservoir temperature, e) results of cases with 77 °C reservoir temperature.

6.3 Guidance of the system optimization

As a summary, this analysis evaluates the impact of reservoir temperature, rock thermal conductivity, lateral wellbore length, and the number of laterals on system efficiency. The results provide guidance for optimizing system design to enhance seasonal thermal energy storage performance.

Influence of Reservoir Temperature. Reservoir temperature is a critical factor influencing the efficiency of heat storage and extraction. Five different initial reservoir temperatures (16°C, 31°C, 46°C, 61°C, and 77°C) were analyzed to determine their effects on system performance. The results indicate that:

- Higher initial reservoir temperatures enhance heat storage efficiency, leading to higher outlet temperatures and improved heat extraction.
- Lower-temperature formations require longer lateral wellbores and more laterals to compensate for reduced thermal energy availability.
- For reservoirs with temperatures below 31°C, fewer configurations yielded feasible results, indicating that shallow, low-enthalpy formations may not be ideal for effective seasonal heat storage.

These findings suggest that targeting deeper formations with higher initial temperatures can improve system feasibility while minimizing the need for excessive wellbore lengths and additional laterals.

Effect of Rock Thermal Conductivity. Thermal conductivity determines the rate of heat transfer between the working fluid and the surrounding formation. Three different values were tested: 2.4 W/m/K, 3.6 W/m/K, and 4.8 W/m/K. The results reveal the following trends:

- Higher thermal conductivity increases heat transfer rates, improving the system's ability to charge and discharge heat.
- Rocks with moderate conductivity (3.6 W/m/K - 4.8 W/m/K) provide an optimal balance between heat transfer efficiency and retention, making them the preferred choice for storage formations.

Thus, the Baumann Fiord Formation (4.8 W/m/K), selected in this study, is well-suited for the closed-loop geothermal system due to its favorable heat conduction properties.

Influence of Lateral Wellbore Length. The length of lateral wellbores significantly affects the amount of heat exchanged between the working fluid and the surrounding rock. A range of 1,000 m to 3,000 m was tested, and the results show that:

- Longer lateral wellbores improve heat exchange capacity, allowing for greater thermal energy storage.
- However, beyond 2,600 m, the marginal benefits decrease, while drilling costs increase significantly, making further extensions less economically viable.
- An optimized lateral wellbore length of 2,200 m - 2,600 m was identified as a practical balance between thermal efficiency and cost-effectiveness.

These results indicate that, while longer wellbores enhance heat transfer, an economic and technical trade-off exists, requiring optimization based on site-specific conditions.

Effect of the Number of Laterals. The number of lateral wellbores was tested from one to seven laterals per well, examining how system performance scales with increased subsurface infrastructure. The findings indicate:

- Increasing the number of laterals enhances heat extraction, but the benefits diminish beyond five laterals, as thermal interference between laterals reduces efficiency.
- The optimum configuration depends on reservoir depth and thermal properties—higher-temperature reservoirs require fewer laterals, while lower-temperature formations benefit from additional laterals.
- For practical implementation, a four-lateral design provides an efficient and cost-effective configuration with minimal thermal interference.

Feasibility and Optimization Strategies. After filtering the results, 307 out of 630 tested configurations yielded feasible outcomes, meaning they maintained positive inlet and outlet temperatures throughout the operation period. The most effective designs featured:

- Reservoir temperatures $\geqslant 31^\circ C$
- Rock thermal conductivity between 3.6 W/m/K and 4.8 W/m/K
- Lateral wellbores of at least 2,200 m in length
- Four to five laterals per well

These findings emphasize that geological conditions play a crucial role in optimizing system design. By targeting higher-temperature formations, fine-tuning lateral lengths, and limiting excessive thermal interference between laterals, the overall performance and economic viability of the system can be significantly improved.

Table 5: Properties values of the case with the lowest inlet temperature under different reservoir temperatures.

Initial reservoir temperature, °C	Thermal conductivity, W/m/K	Length of lateral wellbore, m	Number of lateral well	Total completion length of lateral part, m
16	3.6	2600	7	18200
31	2.4	2600	5	13000
46	4.8	2600	2	5200

61	2.4	1000	6	6000
77	2.4	2600	2	5200

Table 6: Properties values of the case with the lowest inlet temperature and total lateral length under different reservoir temperatures.

Initial reservoir temperature, °C	Thermal conductivity, W/m/K	Length of lateral wellbore, m	Number of lateral well	Total completion length of lateral part, m
16	4.8	2200	7	15400
31	4.8	1400	5	7000
46	4.8	1000	5	5000
61	4.8	1800	2	3600
77	4.8	1400	2	2800

7. CONCLUSION

This study explores the feasibility of utilizing a multilateral closed-loop geothermal system for seasonal thermal energy storage in remote Arctic communities, with a focus on Resolute Bay, Nunavut. The proposed system integrates surplus solar energy into the subsurface during summer months and extracts stored heat in winter, addressing the seasonal mismatch between renewable energy supply and heating demand. Through numerical modeling and sensitivity analysis, this study evaluates the thermal performance, long-term stability, and key design considerations of the system under Arctic conditions.

The results demonstrate that the hybrid geothermal system with solar heat injection significantly improves seasonal heat retention compared to a conventional closed-loop geothermal system. The findings highlight the following key outcomes:

1. Seasonal heat storage and extraction: The system effectively stores excess thermal energy during summer when solar input is high and releases it during winter, ensuring a continuous heat supply. Temperature variations confirm the energy cycle, where the system shifts from heat storage (June–September) to heat extraction (October–May).

2. Long-term thermal stability: Over a 30-year operational period, the system reaches a relatively steady-state thermal equilibrium. The outlet temperature stabilizes, ensuring sustained heating capacity even in extreme winter conditions.

3. Sensitivity to reservoir properties: Higher initial reservoir temperatures (>31°C) improve storage efficiency, while formations with moderate to high thermal conductivity (3.6–4.8 W/m/K) optimize heat transfer. Lower-temperature reservoirs require longer wellbore lengths and additional laterals to maintain performance.

4. Optimized wellbore design: A four- to five-lateral configuration with 2,200–2,600 m wellbore lengths achieves an optimal balance between thermal efficiency and economic feasibility. Increasing lateral numbers beyond this threshold yields diminishing returns due to thermal interference between adjacent wellbores.

5. Comparison with a pure closed-loop geothermal system: The hybrid system maintains higher and more stable outlet temperatures compared to a closed-loop geothermal system without solar heat injection, reducing long-term heat depletion and improving thermal sustainability.

These findings suggest that integrating solar energy with closed-loop geothermal systems can enhance seasonal energy storage, reduce reliance on imported fuels, and improve energy security in Arctic communities. The study underscores the importance of geological site selection, wellbore design optimization, and adaptive control strategies for maximizing system efficiency. Future work should focus on experimental validation through pilot-scale field implementation, economic feasibility assessments, and the integration of additional renewable energy sources (e.g., wind power or waste heat recovery) to further improve system resilience. Additionally, techno-economic analyses should be conducted to evaluate scalability and deployment potential across other cold-climate regions. In conclusion, the multilateral closed-loop geothermal system presents a viable and sustainable solution for seasonal thermal energy storage, contributing to the decarbonization of Arctic heating infrastructure and supporting long-term renewable energy transitions in remote off-grid communities.

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