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Solar-Powered Heating Cable Thermal Response Tests in Existing Wells: A Low-Carbon Solution for Remote Sites

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ABSTRACT

Thermal Response Tests (TRTs) are the industry-standard method for quantifying *in situ* ground thermal conductivity, a critical parameter to size ground heat exchangers and predict the performance of ground-coupled heating and cooling systems. Conventional TRT apparatus require continuous energy input, typically provided by diesel generators—an approach that is logistically challenging, costly, and carbon-intensive. This study presents a TRT methodology using a trailer-mounted solar energy system that integrates photovoltaic panels, an inverter, and battery storage to generate the energy injected into a borehole with an electric heating cable. The study objective was to verify and demonstrate that solar energy can be supplied to conduct TRTs with a low power requirement. Successful implementation at two sites in Whitehorse, Yukon (Canada), demonstrated the feasibility of significantly reducing diesel consumption. Generator runtime was reduced from a continuous 72-hour operation to intermittent periods of 2–4 hours, three times daily, with solar energy meeting the remaining load. Additionally, the use of an electric heating cable enabled TRTs to be conducted in existing groundwater monitoring wells, avoiding the need to drill new boreholes prior to confirming project feasibility. This approach offers a scalable, low-carbon alternative for *in situ* thermal conductivity analysis, especially suited for challenging and remote locations like northern communities. By improving the practicality and economics of TRTs in remote settings while simultaneously reducing their associated greenhouse gas emissions, this work supports broader geothermal potential mapping efforts and facilitates data-driven deployment of ground-coupled heat pump systems as part of climate-resilient infrastructure strategies for the Whitehorse area.

1 INTRODUCTION

As the climate continues to warm, impacting human and ecological communities through the increased severity and frequency of natural disasters, rising sea levels, food and water security issues, urgent climate action is necessary (IPCC, 2023). Renewable energy is recognized as a key pathway to reducing greenhouse gas (GHG) emissions and mitigating continued climate change (IPCC, 2023). Canada's North faces many challenges to implementing renewable energy systems including a lack of electrical infrastructure and connection to larger electrical grids, large seasonal needs for heating when solar energy is less available and logistical challenges in accessing equipment and expertise (NRCAN, 2023). Ground source heat pumps may provide a pathway to reducing GHG emissions for heating applications in Northern Canada (Self, 2013; Kegel et al., 2016). However, more site-specific data on ground thermal properties are required to support system design, particularly ground-coupled heat pumps (GCHP), in northern environments. Collecting this data through conventional thermal response tests can be challenging in remote northern locations due to the need for specialized equipment and the high electrical requirements. We hypothesized that using solar energy to power heating cable TRTs provides a sustainable and practical solution, enabling efficient data collection with a relatively simple apparatus, while reducing reliance on fossil fuel generators and supporting the broader adoption of renewable energy in these communities. The Yukon First Nation Climate Action Fellowship describes how the use of energy should be guided by the needs of the community in a manner that enhances and nourishes life, rather than disrupting it (YFNCAF, 2023). This research seeks to support the development of mutually supportive and beneficial renewable energy projects in a way that advances reconciliation and addresses a community level issue. This paper's objective is to evaluate the feasibility of using portable solar photovoltaic systems to power heating cable TRTs in Whitehorse, Yukon, supporting local-scale thermal property characterization for GCHP deployment.

2 BACKGROUND INFORMATION

TRTs are the standard method to evaluate the in-situ ground TC by analyzing the ground temperature evolution under a known heat injection rate, conventionally achieved by flowing a heat carrier fluid through an installed ground heat exchanger (Gehlin, 2002). It is also possible to conduct TRTs with heating cables combined with temperature data loggers (Raymond et al., 2021). This method requires less overall energy and specialized equipment, which enables its use in a broad range of circumstances (Raymond et al., 2015; Velez et al., 2018). This technique uses a continuous heating cable with a minimum energy input of approximately 10 W m^{-1}, during a heat injection period of 40-60 hours (Raymond et al., 2021). The relatively low heat injection rate enables the use of solar energy to meet a portion of the test's energy needs, as opposed to the continuous use of fuel-fired generators (Raymond et al., 2015). As these tests do not require a heat exchanger to be installed within the borehole, this also enables the use of existing wells to provide information about ground thermal properties, such as groundwater and environmental monitoring wells.

The use of solar energy for field applications mirrors the challenges faced by remote off-grid communities in that the energy produced must be aligned to the energy demand using a storage medium (typically a battery). Solar is flexible and versatile in many ways, and when appropriately sized, it can reduce the need for gas or diesel for electricity generation. This is convenient when sites are remote, and access is difficult and expensive. Common applications of solar energy include their use in weather stations, or Wireless Smart Sensor Networks for monitoring operations (Malek et al., 2023). The development of self-made solar powered sensors is enabling their integration into a variety of fields and applications (Malek et al., 2023). However, there is a lack of data on long term experiments and particularly using the larger loads that TRTs require (Malek et al., 2023). Unlike typical small-sensor photovoltaic (PV) applications, TRTs require sustained power on the order of hundreds of watts instantaneously over several days, what is referred to as a continuous load (Sağlam, 2010). This scale introduces new challenges for PV-battery sizing, energy storage management, and integration with a backup generator. The use of solar energy for ground source heat applications has been more thoroughly considered in the use of solar thermal energy for recharge and borehole thermal energy storage (Georgiev et al., 2006; Maranghi et al., 2023), which occurs in the context of system operation.

A typical solar energy system has the following components: PV panels, an inverter to convert alternating and direct current, and a storage system that is typically a battery (Malek et al., 2023; Mohanty et al., 2016). The critical factors that impact the size of a system include the load size, operation time, location of the system, and a safety margin to ensure adequate energy is available when required (Malek et al., 2023). The optimal sizing of a system is critical to maximize environmental benefits (Aberilla et al., 2020). The ideal placement of solar panels is perpendicular to the midday sun (Mohanty et al., 2016).

While PV systems are well established for small-scale sensing and monitoring, their application to higher-load experiments such as TRTs remains underexplored. This study builds this emerging area by assessing a solar-powered TRT setup under real northern field conditions.

3 METHODS

The power supply for the TRTs described below was provided by a custom-built and portable solar energy system (Figure 1 and Figure 2). The 3 kW Phocus Any-Grid ™ hybrid inverter requires a minimum of 90 volts (Phocus, 2023) to operate, so at least 3 * 360 W (34 V) panels strung in series meet that requirement. The battery is a Fortress Power E-flex Tier 1 EV Grade 5 kWh Lithium Iron Phosphate battery with a built-in battery management system (charge controller). The solar panels are mounted on a portable rack, and the entire electrical system is mounted in and transportable to site in 2.44 m by 3.66 m (8 by 12 foot) trailer. The panel racks originally accommodated three PV panels, however a more elegant two panel rack was designed and now fully implemented in the trailer. Two racks are connected in series (four panels total) to meet the minimum voltage requirements, with two additional racks available to be connected in parallel. In total, four racks have been constructed to date allowing for configurations between 720 to 1440 W of total capacity. These portable panels allow for maneuverability on the site to access the best solar energy for each time of day. PV systems that can track the sun are more efficient due to their ability to maximize available solar energy (Khan et al., 2016). The Phocus inverter provides a digital readout of the instantaneous PV energy which was recorded during site visits every 4 – 6 hours during the TRTs. Ambient weather conditions such as temperature and cloud cover were also recorded.

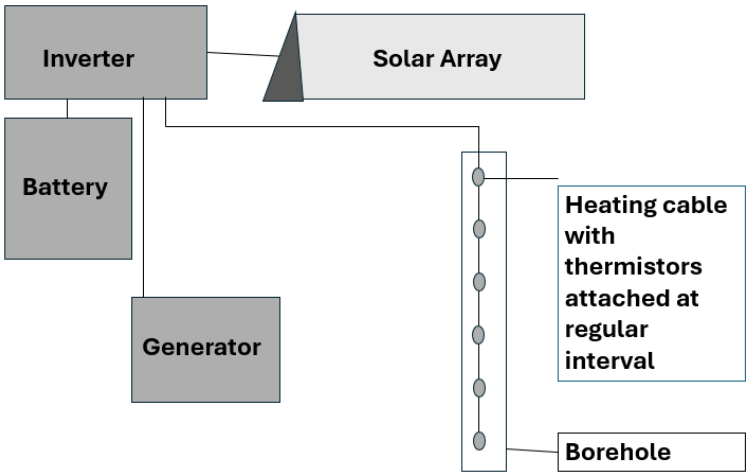


Figure 1. Technical diagram of solar energy system, borehole, heating cable and thermistors



Figure 2. Photo of setup with three panel solar rack and trailer visible. The borehole is indicated by a red arrow.

Four TRTs were conducted using the Yukon Observation Well Network, a series of groundwater monitoring wells located in Whitehorse (Yukon) and operated by the Yukon Government – Water Resources Branch. Additionally, three wells were tested on private property, City of Whitehorse and Yukon Government- Highways and Public Works sites respectively. These tests were conducted between 2023 and 2025. These wells were chosen based on depth and ability to access the diverse bedrock formations to characterize ground thermal properties throughout the Whitehorse area.

Two snow melting heating cables, 25.7 m and 72 m respectively, were used for this research to disrupt the subsurface temperature at different depths in existing wells. Star Oddi temperature data loggers with a temperature measurement resolution of 0.032 °C and an accuracy of 0.1 °C were attached to these cables at a regular interval being 1, 2, 5 or 10 m depending on the length of the well and the number of available data loggers. These loggers measured temperature development over time at 5 min intervals over the maximum possible portion of the borehole depth. A Hoboware Plug Load data logger measured the heat injection rate to 10mW of resolution with 5% accuracy over the course of the test. The tests were analyzed using the slope method described by Velez et al. (2018). Additionally, where power interruptions occurred, the superposition principle was applied to the analysis made with the infinite line-source equation as described by Raymond et al. (2011). Heat injections occurred over 72 h, and the recovery period was at least 96 h. Only the recovery period of the test is analyzed because it better reflects the assumptions of the infinite line source model and the temperature measurements or independent of the cable position.

4 RESULTS

4.1 Benefits of Solar Panels

The two cables, being different lengths, require vastly different amounts of energy to conduct the TRTs (Table 1). The heat injection rate and the total energy required for the short cable are about 30% that of the long cable. The

resulting percentage of site visits where the photovoltaic panels were able to meet or exceed the instantaneous load of the TRT is therefore higher for the short cable. The PV system was appropriately sized to meet the energy requirements of the 25.5 m cable tests; however, it was not adequately sized in both PV capacity and storage to meet the energy requirements for the 72 m cable.

Table 1. Chart of specifications for instantaneous and total power required, heat injection rate and the percentage of site visits during 2025 where the instantaneous power need was met by solar PV.

Cable length	Q (W)	Heat Injection Duration (h)	Injection Rate (W/m)	Total Energy (Wh)	% of site visits met load with PV
25.5 m	250	72	10	18,000	20.6
72 m	830	72	11.5	59,760	5.9

A benefit in having PV panels that are portable and easily maneuverable was that they can be pivoted to take the best possible advantage of available solar energy at each site visit. In Northern Canada, during the summer, the sun essentially travels around the horizon in a circle, as opposed to rising and setting. This means if the panels were fixed in place, there would be long periods of time without optimal solar gain. During six site visits, the PV panels were pivoted which resulted in an increase of PV output (Figure 3).

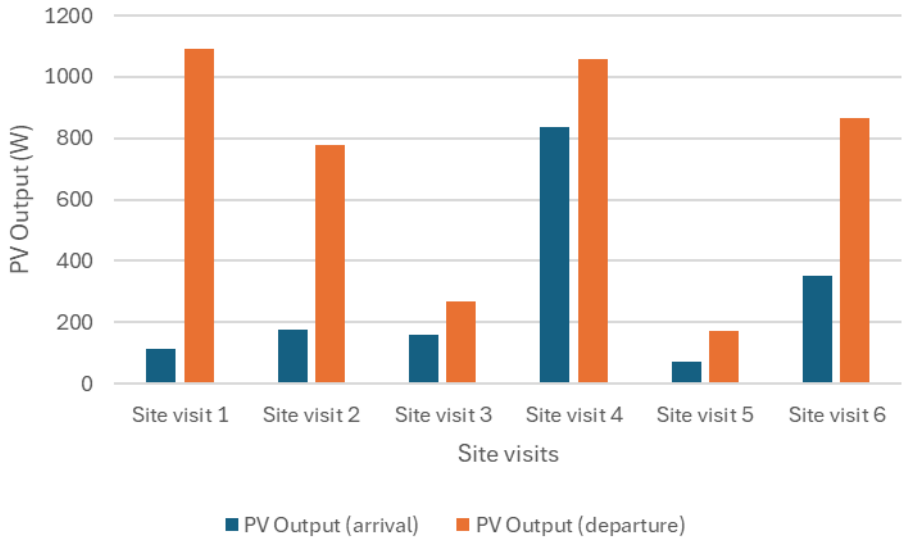


Figure 3. The amount of solar energy produced on arrival and upon departure after the panels were directed to maximize solar exposure.

During TRTs with the shorter cable, running the backup gas generator was able to power the test and charge the battery. This allowed the operator to extend the time between site visits to six hours and reduce the number of hours and frequency of generator running time. However, during the TRT with the longer cable, running the available generator could power the test but had no additional energy to charge the battery, negating the benefit of having that storage available. Additionally, the test would discharge the fully charged battery in less than 4 h, which was less than the time between site visits.

Each site visit that required the filling of the generator consumed approximately 6.7 L of gasoline. Site visits occurred at 4 – 6 h intervals and when the generator ran out of gasoline, the battery backup system met the energy loads of the test until the following site visit. When the system was running the smaller cable and the sun was shining, it was not uncommon for the generator to not be needed at all. However, it was always needed to recharge the battery during the overnight periods when the sun was low in the sky, behind trees or for the period it is below the horizon.

Conventional TRTs require the use of a 1.75 kW pump to circulate fluid with an additional heating load of between 3 – 12 kW (Gehlin, 2002) operating over 50-100 hours. The continuous operation at minimum using 4.75 kW

requires a large generator of at least 7 kW to protect against overheating or other system failure. The lower power requirements of a heating cable TRT require small generators being a 2.2 kW generator as the solar backup, and a 5 kW for generator powered tests, again as protection for overheating. The different sizes of generator have unique efficiencies and therefore GHG emissions. Using a comparison chart for Champion generators from the specifications reported on their website, the fuel consumption per Watt hour can be normalized and used to estimate the total gasoline required for the different configurations of TRT. For the solar powered TRT and backup generator, a total run time of 60 hours is estimated representing the conservative intermittent use of the generator over the course of the 72-hour heat injection period. The standard ratio of litres of gasoline to kg of CO_2 equivalent emissions is 2.3 (Environment and Climate Change Canada, 2023). To assess the environmental benefits of the solar-assisted setup, the total fuel use and corresponding GHG emissions were estimated for each TRT configuration (Table 2).

Table 2. Comparative analysis of energy and fuel consumption, and GHG emissions from different TRT configurations.

TRT type	Instantaneous load (W)	Champion Generator Model	Gasoline (L)	GHG emissions (kg CO_2 eq)
Conventional (3kW heating load)	4750	8000 W Electric Start	249.5	573.88
Heating cable (25 m) with generator	250	5500W Generator	17.3	39.94
Heating cable (25 m) with solar and generator backup	250	2500W Inverter	11.7	27.04

4.2 TRT Analysis

For consistency, all sites were analyzed based on the infinite line source model and using the curve fitting method applying the superposition principle to account for short power disruptions when it occurred during testing. Local lithology was incorporated by assigning laboratory-measured volumetric heat capacities corresponding to the sediment or bedrock units described in the drilling logs. The calculated temperature response was fitted to the measured data using Microsoft Excel's Solver to minimize the squared error between modeled and observed temperatures. Final TC values were derived from the late recovery period fit where the temperature-time relationship is most stable.

An example from the curve fitting analysis is provided in Figure 4, which compares measured temperatures to the fitted model for temperature logger 6 at 54 m below the top of casing at the St. Francis Assizi site. The sum of squared residuals (0.020) calculated for 15 points from hours 95.45 to 153.55 indicates a strong agreement between the calculated and observed temperatures.

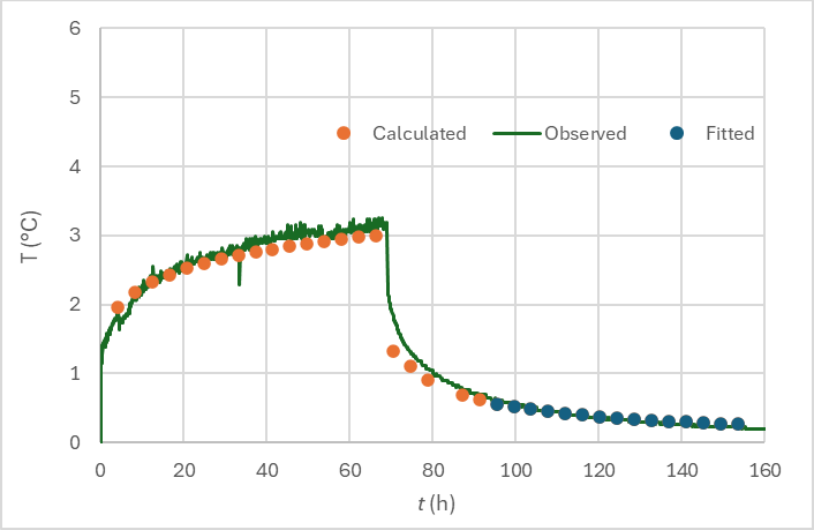


Figure 4. Measured and calculated temperature responses for temperature logger 6 (54 m BToC) at the St. Francis Assizi site, showing close agreement between observed and fitted data (sum of squared residuals = 0.020).

TC values measured at each site are presented in Figure 5 as a series of boxplots. The median TC values were very similar between sites, excluding Golden Horn, reflecting the relatively sediment dominated lithology intercepted by the shallow monitoring wells. This accessibility limited the available depth and lithological diversity for testing. The near surface sediments generally exhibit low TC values, and depending on the depth to bedrock, can have an important contribution to the average TC value at relevant sites.

Figure 6 summarizes the TC results by lithology. The high variability in the TC of the basalt likely reflects the differences in porosity and permeability between layers. The low TC values of the sandstone likely reflect the low quartz content of the tested sandstone sites. As the Golden Horn site is in granodiorite, the results of both categorizations reflect the higher TC value at that site and within that lithology. Results suggest that it may be possible to extrapolate the average TC value for shallow depth TRTs beyond the depth of the borehole when the stratigraphy is known. However, the bedrock lithology is expected to have a higher impact on the site effective TC especially for GCHPs that are installed at depths deeper than about 60 m.

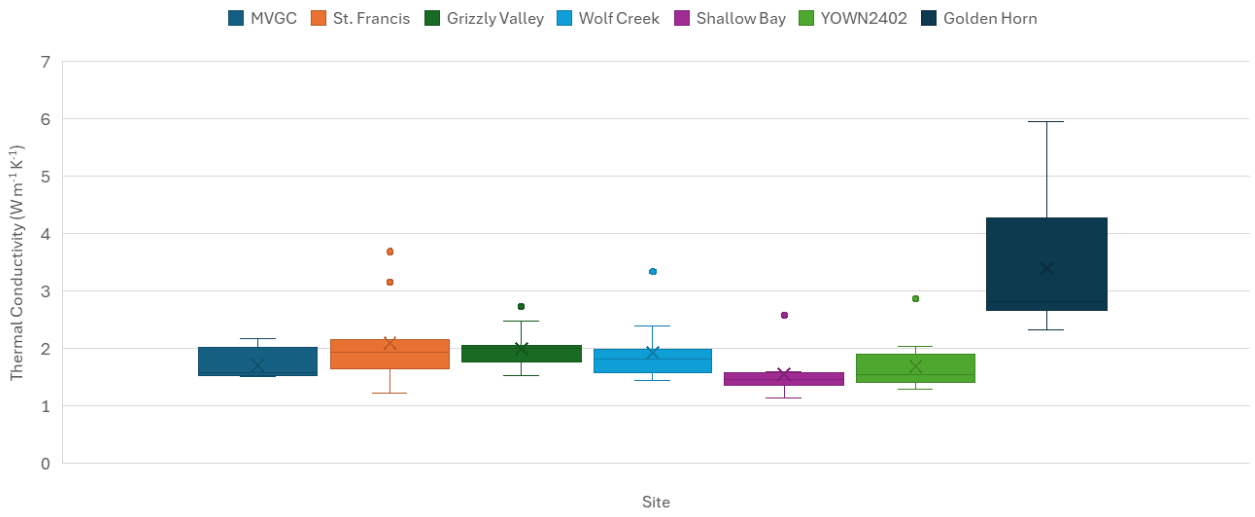


Figure 5. Thermal conductivity by site for TRTs conducted in the Whitehorse area. The Mountain View Golf Course (MVGC) and Yukon Observation Well Network (YOWN) sites are abbreviated.

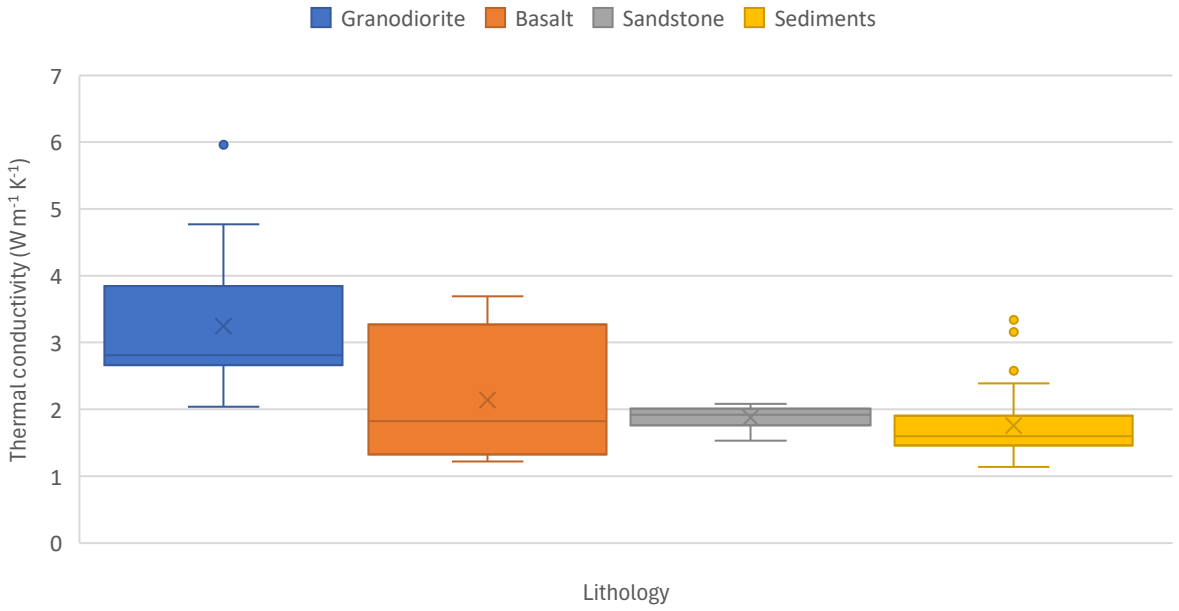


Figure 6. Thermal conductivity by lithology for TRT conducted in the Whitehorse area.

5 DISCUSSION

Conventional TRTs require a continuous power supply to circulate a heat carrier fluid over several days. This energy is typically supplied by a diesel or gasoline generator operating for the full duration of the test. Although this energy use is small relative to the installation of a complete GCHP system—and reduced further when using heating cables (Vélez et al., 2018)—it remains important to minimize GHG emissions wherever possible. Solar power is increasingly used for long-term monitoring applications with low, intermittent electrical loads (Malek et al., 2023); however, TRTs involve a much higher and more continuous demand. This adds complexity to both battery storage requirements and the dependence on suitable weather conditions.

Because a battery storage system can supply energy during low solar output, its inclusion reduces the need for continuous generator operation during both conventional and heating-cable TRTs. This in turn mitigates the risk of generator overheating and unplanned shutdowns. Hybrid renewable–storage systems provide synergistic benefits by reducing overall component size requirements while improving system redundancy (Aberilla et al., 2020; Akikur et al., 2013). The partial substitution of generator power with solar and battery energy also reduces risks associated with fuel transport and storage, including potential spill events.

Using existing groundwater monitoring wells for TRTs eliminated the need for drilling new boreholes, further reducing total project GHG emissions. Wells tested were typically shallow (< 60 m), decreasing the energy required for testing compared to conventional GHE installations, which are commonly 150 m or deeper (Raymond et al., 2015). Both the use of existing wells and the integration of renewable power contribute to improved environmental performance and may enhance social acceptability for projects in northern and Indigenous communities, where stewardship of the land is a key consideration (YFNCAF, 2023).

The northern field setting of this study presented both opportunities and challenges. Extended daylight hours in summer provided long periods for solar generation, but dense forest cover at several sites created shading that reduced panel efficiency. These issues were generally mitigated using the backup generator (Akikur et al., 2013). However, the inverter required a stable sine wave input for proper operation, meaning some generators were compatible while others could not charge the battery effectively. One test conducted in early October was interrupted due to inverter control issues likely linked to low ambient temperatures outside the manufacturer's recommended range of –10 °C to 50 °C (Phocus, 2023). This interruption was accounted for in the data analysis using the superposition principle to represent variable heat input. Based on these findings, future solar-powered TRTs should be limited to the warmer months between May and September, when temperatures and daylight are sufficient for stable operation. This study contributes to the broader understanding of how solar energy can be applied to power field TRTs. More generally, hybrid renewable systems that combine solar, storage, and geothermal components show promise for reducing fossil fuel dependence in remote northern communities (Aberilla et al., 2020; Akikur et al., 2013; Langevin et al., 2024). For example, solar-assisted GCHP systems couple solar thermal energy with geothermal heat exchange (Kegel, 2016; Tian, 2013), using solar heat to recharge the subsurface and provide seasonal energy storage (Georgiev et al., 2006; Langevin et al., 2024; Maranghi et al., 2023). Such systems are particularly relevant in Arctic and sub-Arctic climates, where strong seasonal load imbalances occur. Solar-powered pumps may also be employed to circulate fluid within GCHP systems (Langevin et al., 2024). Collectively, these findings highlight the potential for integrating solar energy into geothermal research and operations and provide a foundation for optimizing hybrid system design and energy management in future work.

This research forms part of a larger effort to characterize the thermal properties of the subsurface in the Whitehorse region. Future work will involve comparing in situ TRT-derived thermal conductivities with laboratory measurements of rock and sediment samples and using these data to model ground heat exchanger performance for selected Yukon Government buildings based on real-world energy demand data.

6 CONCLUSION

The use of photovoltaic (PV) systems to operate heating cable thermal response tests (TRTs) is feasible when the system is properly sized, supported by adequate battery storage and backup generation, and operated under favorable environmental conditions, namely clear skies, minimal shading, and long daylight hours. Incorporating a battery storage system can reduce the required generator capacity and provide redundancy during power interruptions. Although PV power is increasingly used in scientific fieldwork, its application for high-load experiments such as TRTs remains sparsely documented. This study helps fill that gap by providing field-based evidence on the performance of a solar-powered TRT system in northern conditions. Continued documentation and testing will support broader integration of PV energy into off-grid scientific and engineering applications. By

enabling low-emission field testing and improving knowledge of subsurface thermal properties, this research contributes to the advancement and regional adaptation of geothermal energy solutions in remote northern communities.

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