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Quantifying the Long-Term Performance of a District-Scale Geothermal Exchange Field

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ABSTRACT

This study investigates the long-term performance of a cooling-dominated, district-scale geothermal heat exchange (GHX) field in the Midwest of the United States. The district-scale system includes multiple borefields, heat sink ponds, and central energy plants that provide heating and cooling to a 13,000-plus-employee campus. We work to isolate and analyze the performance of the largest borefield (2596 152-m deep exchange wells in 0.1-km^2 area). Conventionally, the coefficient of performance (COP) is the metric used to analyze GHX system performance. However, district-scale GHX systems can be too complex to simply characterize using COP alone; in part, due to the centralized heat exchange between building systems and external exchanges between multiple earth-exchange systems. In this study, the largest borefield (out of four) has been isolated, and we discretize the performance of this borefield using parameters including field power, energy exchanged with the ground, change in temperature of exchanger fluid, fluid flow rate, distributed ground temperature data, and others. By analyzing combinations of these parameters, relationships and trends are compiled to understand the long-term response of the field. These relationships can then be used to inform the standard-of-practice for field management. After an initial conditioning of the field, the average field temperature increased from approximately 14 °C to 17 °C over the past seven years. This increase has led to a decrease in field efficiency for heat dissipation and a corresponding enhancement in efficiency for heat extraction. Both the power exchange in the field and temperature difference between supply and return fluid have experienced decreases over time under heat dissipation conditions. The reduction in cooling efficiency is of concern as the campus is cooling-dominated. Many factors influence the performance of GHX systems; therefore, we must understand how long-term temperature changes in the ground and operation of the centralized energy plants affect the performance and energy efficiency of a district-scale GHX network, such as the one evaluated in this study.

1. INTRODUCTION

Geothermal heat exchange (GHX) fields send or receive energy from the ground to heat and cool buildings, provide domestic hot water heating, and other ancillary services (such as snow melt). An exchange fluid (often water) circulates through the ground in high-density polyethylene (HDPE) pipes. The temperature difference between the ground and the exchanger fluid results in heat transfer. Depending on the campus demand and temperature differentials, the field either transfers to or receives heat from the exchanger fluid. The exchanger fluid is then circulated to heat pumps, where it is used to heat and cool buildings or to heat domestic hot water. While heat pumps and fluid circulation pumps require electrical energy input, GHX systems provide efficient heating and cooling due to the use of steady ground temperature to facilitate heat transfer (Bloom and Tinjum 2016).

GHX systems are commonly portrayed as having increased energy efficiency compared to traditional space conditioning systems such as natural gas heating systems (Bloom and Tinjum 2016, Reddy et al. 2020). However, GHX systems can only continue to provide that increased energy efficiency if sustainably managed (and, from an industry perspective, if that efficiency is systematically documented, critically examined, and disseminated). Suboptimal design and management can render a GHX system functionally ineffective or underutilized (Florea et al. 2017, Herrera et al. 2018). Therefore, it is important to understand the nuanced management of these systems and the resulting responses of the geothermal exchange fields. This understanding can help to improve energy efficiency and long-term field sustainability. In this study, we observe, analyze, and provide management considerations for a district-scale GHX field in the Midwest of the United States.

The studied district-scale GHX system is large and complex with many components comprising the earth loop and space conditioning sides. The earth loop side of the system includes four separate GHX fields and additional cooling ponds that all provide heat dissipation and extraction. On the space conditioning side of the system, dozens of buildings are all conditioned by the geothermal exchange system.

The buildings are split up into sub-campuses. On some sub-campuses, each building has its own set of heat pumps. Meanwhile, other sub-campuses have a centralized energy plant where the heat pumps are located. In this system, water from different exchange sources can be mixed and sent to multiple locations. Through active management and experience, the field managers have improved the system's efficiency since it was constructed. However, we hope to continue to inform the sustainable management of the system through a better understanding of the behavior of the geothermal exchange field.

Coefficient of performance (COP) is a common metric used to measure the efficiency of geothermal exchange systems. COP is the useful energy produced by the system divided by the electrical energy needed to run it. Due to its complex nature, it is difficult to analyze and calculate performance metrics such as COP for integrated components of the holistic system. Therefore, to simplify our analysis, we look at the geothermal field performance exclusively using metrics other than COP. We use measured and calculated data such as ground temperature, power into and out of the field, energy exchanged within the field, and others to create informative graphs and observe key relationships between important variables.

We focus our analysis on Borefield 4, which is the largest of the four exchange fields and contains 2596 exchange wells at 152-m depth over an area of 0.1 km^2. Borefield 4 is cooling-dominated, meaning that more heat is dissipated into the field than is extracted over the course of a year. The field imbalance is documented in Figure 1. The orange color indicates heat dissipation, while the blue indicates heat extraction. From 2015 through 2022, 523 TJ of heat was dissipated into the field while 237 TJ was extracted from the field. That is, 79% was energy dissipation while 21% was energy extraction. For 2022 exclusively, 76 TJ (82% of the total energy exchanged) was dissipated into the field, while 17 TJ (18%) was extracted from the field. Note that the years 2020 through 2022 were particularly imbalanced compared to previous years.

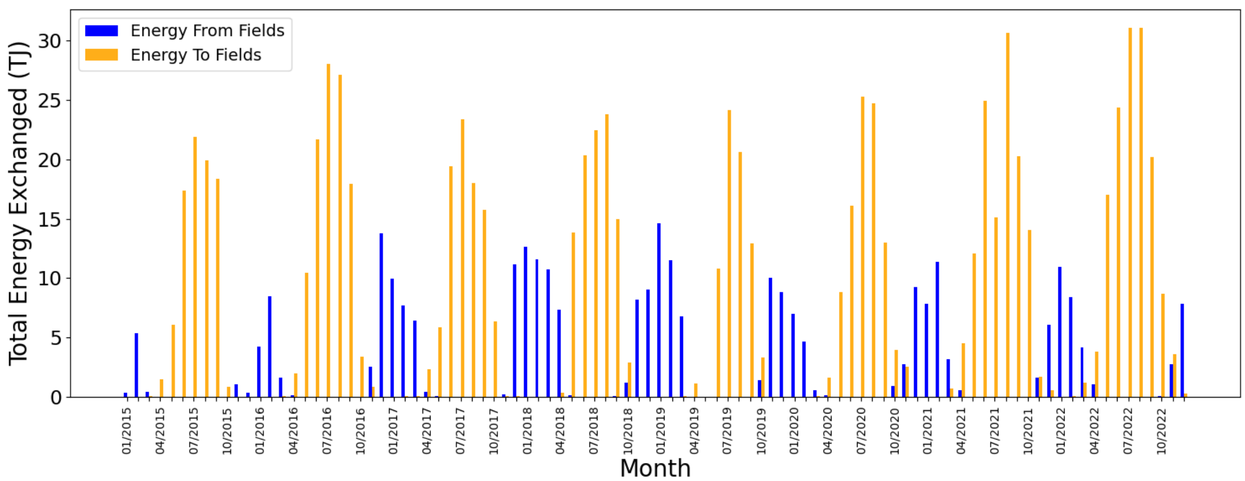

Figure 1. Heat dissipated and extracted from Borefield 4 (BF4) from 2015 through 2022.

A significant energy imbalance could lead to a ground temperature change in the field, especially if this pattern continues over long periods. In this district-scale field, we hypothesize that the significant energy imbalance increases the field's temperature leading to a decrease in heat dissipation efficiency and a corresponding increase in heat extraction efficiency (Hart et al. 2022). Our objective is to better understand how many years of a significant energy imbalance such as the one seen in Borefield 4 affects the properties and abilities of a geothermal field of this size. A better understanding of the field behavior can inform field management and design practices not only for this specific system but for other GHX networks with unbalanced loads, especially of similar district-scale systems in like climates. Due to the complexity of the system in this study, we do not use COP to evaluate system performance and instead present new findings regarding the performance of the geothermal field itself without respect to a heat pump or exchanger.

2. BACKGROUND

Borefield 4 is instrumented and monitored by both our research group and the owner of the GHX network. Our group oversaw the installation and monitors the eight temperature monitoring wells (TMWs) in Borefield 4 that measure ground temperature using fiber-optic distributed temperature sensing, while the owner of the GHX network monitors flows and temperatures of the exchange fluid at different key points throughout the system. The collection of these different datasets allows for the evaluation of the performance and efficiency of Borefield 4.

Much research has been conducted on GHX systems. However, a system and borefield at this scale have not been, to our knowledge, reported on in depth. Many papers evaluate GHX system performance using COP or a similar metric (Zhang et al. 2016, Bloom and Tinium 2016, Qiao et al. 2020, Han et al. 2021). Bloom and Tinium (2016) evaluate the performance of a residential system in the upper Midwest of the U.S. by measuring COP. Zhang et al. (2016) looked at COP for five residential systems in China while Han et al. (2021) observed COP across a few days in January for a GHX system providing heating and cooling to a university library. Qiao et al. (2020) evaluated the performance of 28 different GHX systems across China including groundwater-source, soil-source, and surface water-source heat pumps. The authors find that of those three types of heat pumps, the soil-source heat pumps have the best year-round efficiency based on the results of their study. Naicker and Rees (2018) provide a thorough performance evaluation of a moderately large GHX system providing heating and cooling to a large university building at De Montfort University in Leicester, England. This system includes 56 boreholes at 100-m depth each. The study looked at performance of the system over three years and found the system performance to be satisfactory, but that the cooling and heating equipment was oversized for the loads being experienced in the building, leading to diminished efficiencies. The authors stress the importance of proper design and recommend certain improvements to the system such as buffer tanks or variable speed compressors that would assist in dealing with variable load sizes.

Zhao et al. (2018) modeled the thermal imbalance of a theoretical GHX system for a hotel in Shanghai, China using TRNSYS modeling software. The authors looked at a cooling-dominated thermal imbalance, similar to the situation in the field in this study. They found through the modeling that a greater thermal imbalance led to a greater temperature increase in the ground, but that the temperature increase slowed with time. The authors also found that adding heat recovery to the GHX system for domestic hot water heating significantly improved the thermal imbalance based on the model. Other previous research regarding the performance of geothermal exchange fields includes Noorollahi et al. (2018), in which the authors evaluate how different design parameters affect the performance of a GHX system. The parameters include items such as grout material, pipe parameters, borehole depth, and others. Dehkordi and Schincariol (2014) and Zhao et al. (2022) both look at how the movement of groundwater affects the performance of GHX systems. Groundwater flow is of interest in our GHX field as Özdoğan Dölçek et al. (2017) and Hart et al. (2022) note how high-permeability (hydraulic) layers contribute to reduced heat buildup in those layers.

2. METHODS

To evaluate the thermal response of Borefield 4, we use several data streams. We monitored the ground temperature within the field using fiber-optic distributed temperature sensing (DTS) (McDaniel et al. 2018a). In 2015, fiber-optic cables were routed through wells located inside and outside the field to measure the ground temperature over time. In addition, campus facilities measure key parameters of the exchanger fluid in Borefield 4: incoming and outgoing temperature and volumetric flow rate. An Onicon F-3200 Series Inline Electromagnetic Flow Meter is the instrument used to measure the exchanger fluid volumetric flow rate in Borefield 4. The supply and return temperatures are measured using Rosemount™ 3144P Temperature Transmitters. The measurements of fluid temperature and flow are collected every 15 min. Both the ground temperature data and the fluid measurements started in 2015. There is a significant gap in the ground temperature data from mid-2019 to the end of 2020 due to maintenance issues with the measurement system and the COVID-19 pandemic.

The measured data collected by the system owner is used for some key calculations of power exchanged in the field. The power (heat exchange rate) in the field can be calculated as:

$$Power = \rho\, C_p\, \Delta T\, q \tag{1}$$

where ρ is density of the exchanger fluid (kg m^{-3}), c is the specific heat capacity of the exchange fluid (J kg^{-1} K^{-1}), ΔT is the supply temperature minus the return temperature of the exchanger fluid (K), and q is the flow rate of the exchange fluid (m^3 s^{-1}). Since the measurements of exchanger fluid flow and supply (to the field) and return (from the field) exchanger fluid temperatures are all taken at a frequency of 15 minutes, this heat exchange rate change can be calculated in intervals of 15 minutes. Then, if those heat exchange rates are integrated over 15-minute time periods, the energy exchanged with the ground can also be approximated.

3. RESULTS

Figure 3 shows the ground temperature at 80 m below ground surface for six temperature monitoring wells (TMWs) in Borefield 4 (TMW-1 through TMW-6 as seen in Figure 2). These temperature-monitoring wells are located across the field, and the measurements from the wells are indicative of somewhat different extents of warming. The temperature at 80-m depth of all the wells initially increases from ~11 °C to ~14 °C as the field is first being conditioned. As operation time progresses, the ground temperature oscillates seasonally, increasing in the summer as heat is added to the field and decreasing in the winter when heat is extracted from the ground.

TMW-1 indicates the weakest overall warming trend, measuring ~15 °C at the end of 2022. The largest increase has occurred at TMW-5 which indicates a temperature of ~18 °C at the end of 2022. Most of the other wells show ~17 °C at the end of 2022. Much of the difference in temperature change between wells may be due to the presence of layered, heterogeneous geology throughout the field and groundwater flow across the field (Hart et al. 2022). Field performance can be significantly affected if conservative or incorrect thermo-physical properties are used in the design phase (Walker et al. 2015). A strong warming trend in the ground is indicated by the TMWs.

Having observed the ground temperature changes from 2015 through 2022, we analyze how those temperatures affect the field's performance. Figures 4 and 5 graphs show year-over-year relationships between several key parameters. Years 2015 and 2019 have been omitted from these plots due to dataset inconsistencies. These years presented challenges as a significant portion of the data comprised values that lacked an interpretation that could be validated, suggesting potential issues with the instrumentation. In 2019, a significant portion of the fluid exchanger flow measurements were negative, indicating an issue with the instrumentation and not allowing for a complete year-round dataset for 2019. A similar issue was encountered with the 2015 data as much of the flow data indicated a value of 0, even when significant temperature changes were seen in exchanger fluid across the field, suggesting that the instrumentation was incorrectly measuring flow. Therefore, a complete, year-round dataset was not achieved for 2015.

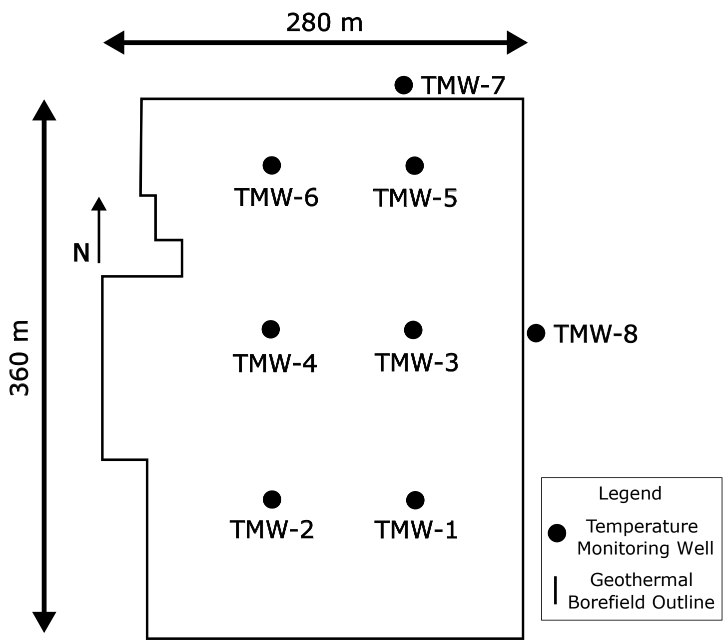

Figure 2. Map of Borefield 4 (2596 GHX wells) showing fiber-optic temperature monitoring well locations.

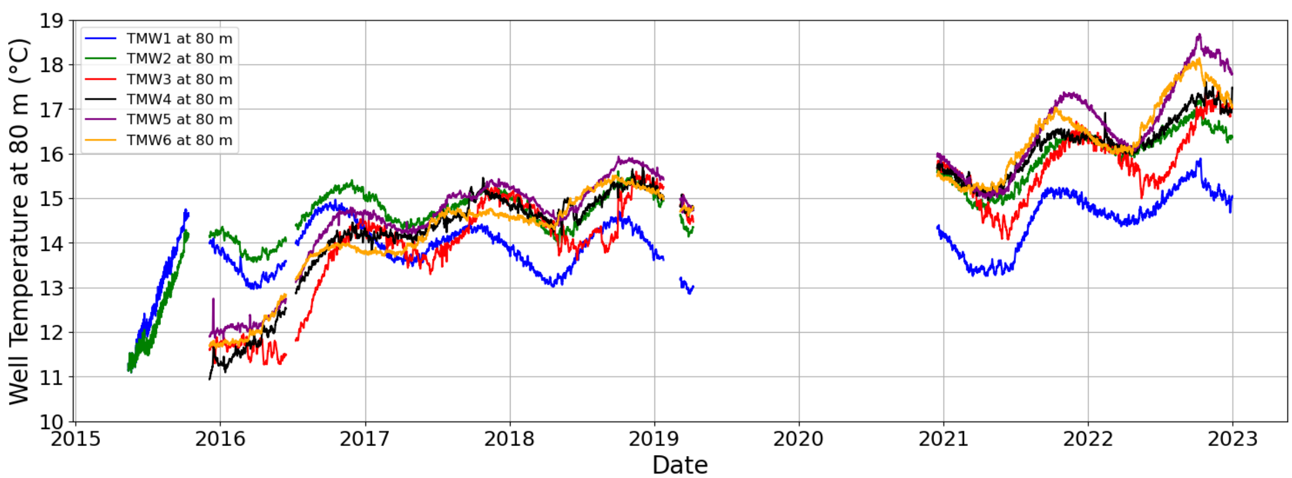

Figure 3. Moving average of ground temperature in temperature monitoring wells 1-6 at a depth of 80 m from mid-2015 through 2022.

Figure 4 uses trendlines of field power versus supply temperature (T_{supply}), and Figure 5 plots change in temperature ($\Delta T = T_{supply} - T_{return}$) versus supply temperature (T_{supply}) to compare field behavior and performance year-over-year. However, before examining the difference in these trendlines for different years, we will first look at how the trendline fits the data for a given year (2022). Figure 4 shows the fit of the trendline of ΔT versus T_{supply} for 2022, where the data points are color-coordinated by quarter of the year. The data point cloud is generally linear and linear regression trendlines are used to evaluate year-over-year patterns in ΔT versus T_{supply}. Figure 4 provides an example of what the data point cloud of ΔT versus T_{supply} looks like for a given year, before being simplified to a linear regression trendline. The r^2 value of ΔT versus T_{supply} for 2022 is 0.94.

Figure 5 shows the fit of the overall trendline of the power versus T_{supply} data for 2022, where the data points are color-coordinated by quarter of the year. Figure 5 provides an example of what the data point cloud of power versus T_{supply} looks like for a given year, before being simplified to a linear regression trendline. Note the position of the data points for different quarters of the year and the overall shape of the data points. The data points have a mostly linear trend, but the cloud of points tends to get steeper for the highest and lowest supply temperatures. At high supply temperatures, the data point cloud "curls" upward; at low supply temperatures, the data cloud "curls" downward. The curling at the extreme temperatures for the relationship between power and supply temperature is due to significant increases in flow values at extreme supply temperatures. Therefore, the absolute power exchanged increases exponentially at the temperature extremes of the exchanger fluid. For our purposes, we will still use linear trendlines to observe differences from year-to-year in power versus T_{supply}. However, it is important to recognize that the linear trendline does leave out some information regarding the behavior of the data point cloud. The r^2 value of power versus T_{supply} for 2022 is 0.90.

Figure 6 plots year-over-year linear regression for change in temperature in exchanger fluid across the field ($\Delta T = T_{supply} - T_{return}$) against supply temperature (T_{supply}). The trendlines generally have a high r^2 value as they vary between 0.83 to 0.95. These values indicate over 80% of the observed variation in ΔT can be explained by T_{supply}. The slope for the year 2016 is significantly lower than the slopes for the other years. Another note is that the trendlines' position varies yearly. The trendlines for 2017 and 2018 sit the highest on the graph, with 2020 below, then 2021 slightly further down, and 2022 significantly lower than the other trendlines. We will leave 2016 out of this part of the discussion as the slope is markedly different than the other years due to field 'conditioning' that occurred in 2016. Notice that, except for 2016, the trendlines diverge more with higher T_{supply} values. The graphs indicate that for higher supply temperatures (that correspond to a heat dissipation and positive ΔT) the corresponding ΔT for a given supply temperature has decreased over time.

Figures 6B and 6C 'zoom in' on sections of the ΔT versus T_{supply} plot (as indicated in Figure 6) to better illustrate the shifting of the trendlines year-over-year. In Figure 6B, the shifting indicates a decrease in heat dissipation efficiency as the corresponding ΔT value for a given T_{supply} value shows a decreasing trend year-over-year (in other words, there is less of a temperature change). Meanwhile, Figure 6C helps illustrate the trend of increasing efficiency for heat extraction. In Figure 6C, the shifting of the trendlines year-over-year shows that the corresponding ΔT value for a given T_{supply} value becomes more negative over time (in other words, there is a greater temperature change).

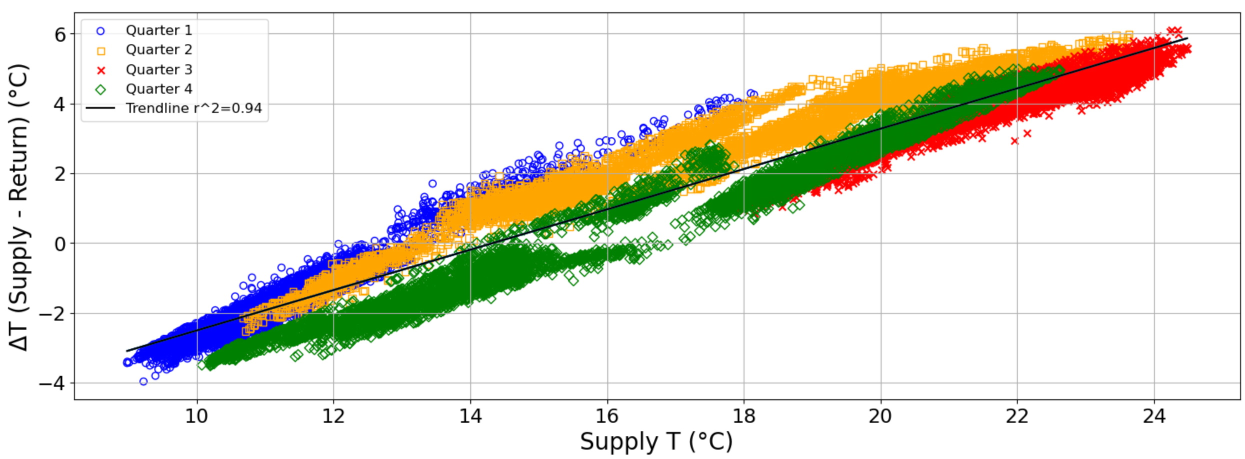

Figure 4. Change in temperature of exchanger fluid (Tsupply – Treturn) versus exchanger fluid supply temperature for 2022 separated by quarter of the year with a linear regression trendline plotted over the data points. Quarter 1 begins on January 1st.

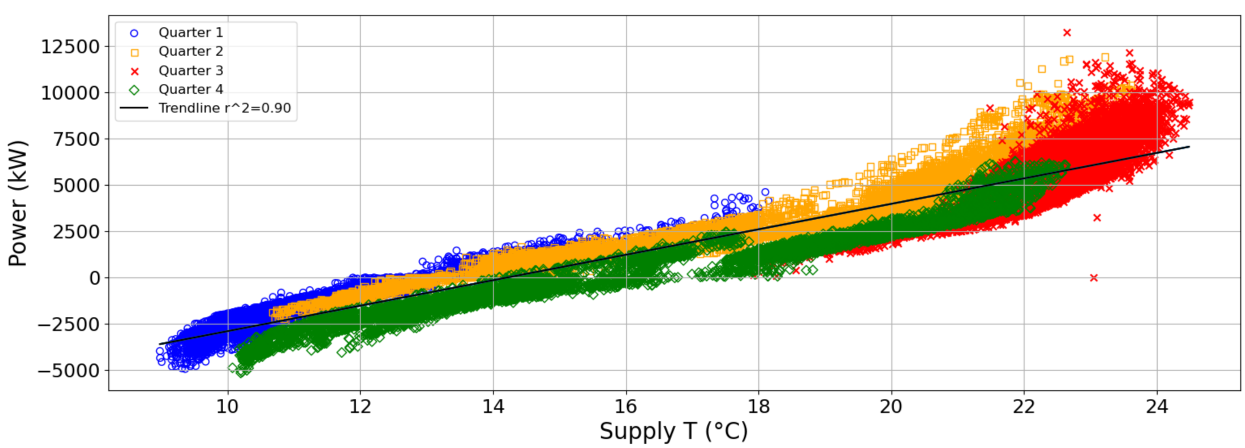

Figure 5. Geothermal field power versus exchanger fluid supply temperature for 2022 separated by quarter of the year with a linear regression trendline plotted over the data points. Quarter 1 begins on January 1st.

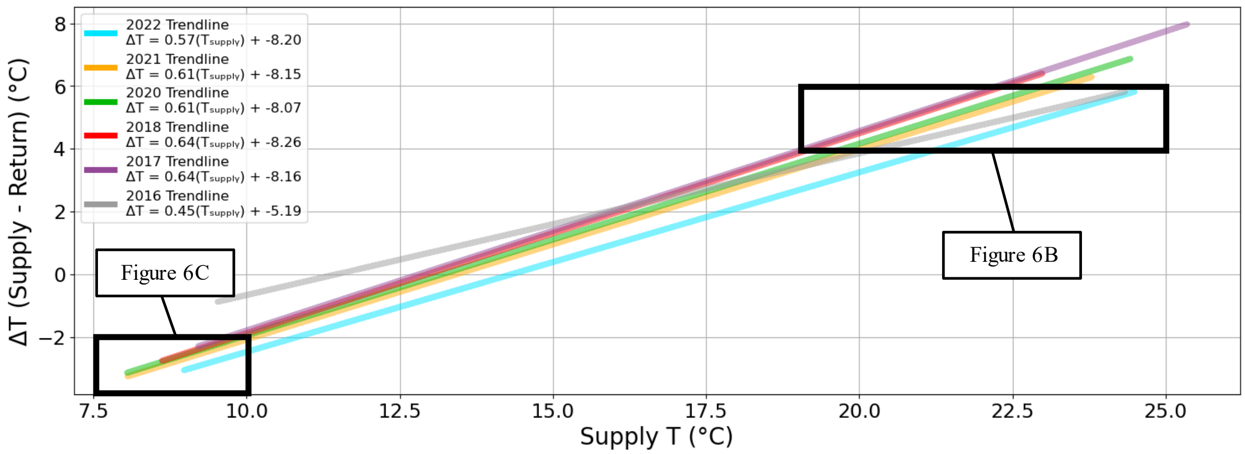

Figure 6A. Linear regression trendlines by year for ΔT versus T_{supply} in Borefield 4.

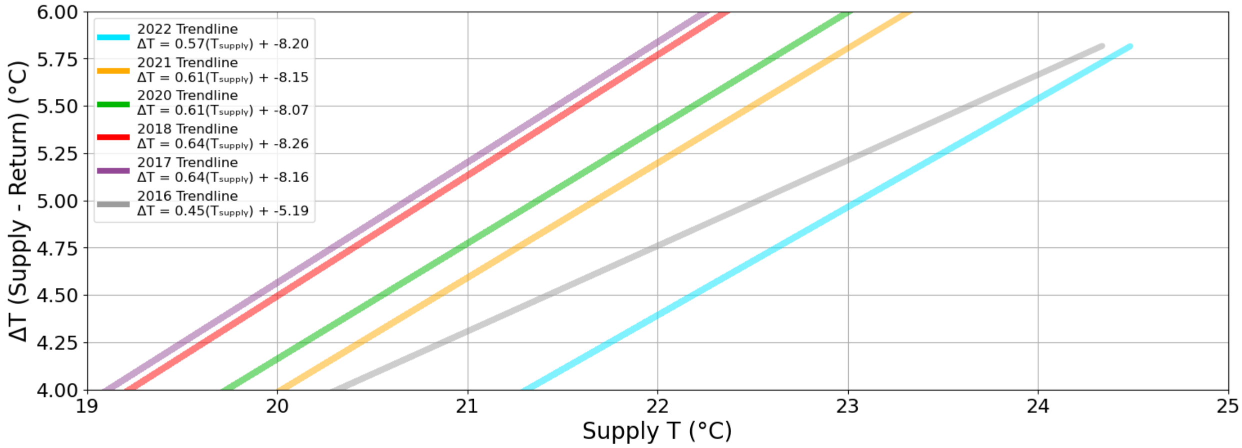

Figure 6B. 'Zoomed in' section of Figure 6A showing linear regression trendlines by year for field power versus T_{supply} in Borefield 4 at high T_{supply} values.

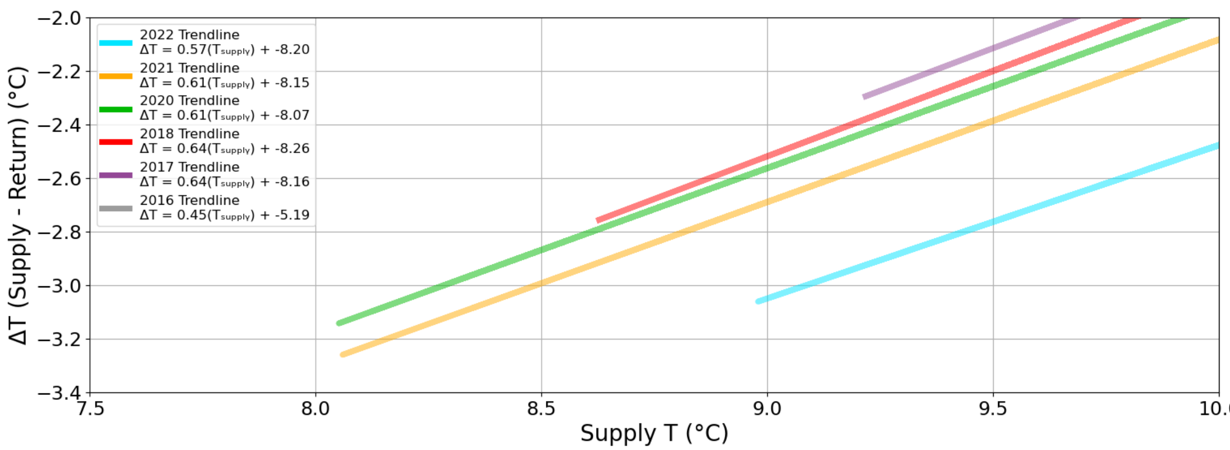

Figure 6C. 'Zoomed in' section of Figure 6A showing linear regression trendlines by year for field power versus T_{supply} in Borefield 4 at high T_{supply} values.

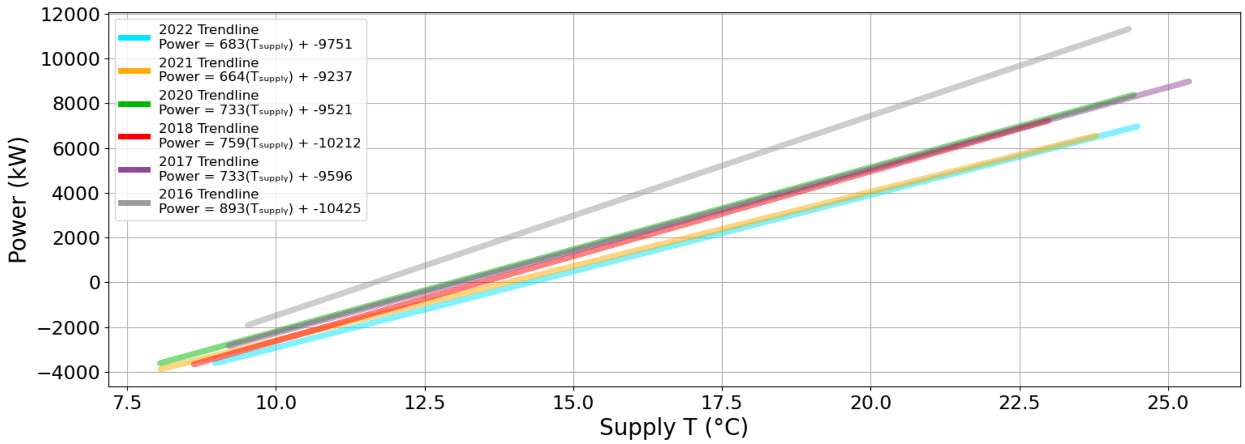

Figure 7. Linear regression trendlines by year for field power versus Tsupply in Borefield 4.

Figure 7 shows a similar relationship to Figures 6 as Figure 7 shows year-over-year trendlines for field power versus supply temperature (T_{supply}) of exchanger fluid. Again, 2015 and 2019 are omitted due to the challenges with the data sets for these years. The linear trendlines of Figure 7 have r^2 values that vary from 0.82 to 0.91. These values indicate that over 80% of the observed variation in field power can be explained by T_{supply}.

Figures 6 and 7 generally indicate that—for higher values of T_{supply} (which correspond to heat dissipation and positive ΔT)—the corresponding ΔT and power values have decreased year-over-year. On the other hand, the plots also show that—for lower supply temperatures (that correspond to a heat extraction and negative ΔT)—the corresponding absolute ΔT and absolute power have increased year-over-year. However, the decrease in ΔT and power at high values of T_{supply} is significantly more pronounced than the increase in absolute ΔT and absolute power at low values of T_{supply}.

Figures 8 and 9 further illustrate the patterns seen in Figures 6 and 7. Figure 8 shows the change in slope year-over-year for each trendline of ΔT and power versus T_{supply}. Figure 9 shows the change in x-intercept (where y = 0) for each trendline year-over-year. Again, 2015 and 2019 are excluded from these plots due to the issues with the datasets from these years. In Figure 8, the slope values generally show a decreasing trend, except for 2016 for ΔT versus T_{supply}. As discussed previously, 2016 was a year in which field conditioning was still taking place, and therefore we are not overly concerned with the results from 2016, but they are shown for completeness. Figure 9 illustrates the increasing trend of x-intercept values year-over-year. Figure 8 and Figure 9 help demonstrate the decreasing slopes and shifting of the trendlines for ΔT and power versus T_{supply} down and to the right over time.

It is also useful to present data regarding the exchange fluid flow rates in Borefield 4 over time, as flow is a key parameter in determining the power exchange in the field. The campus has updated their flow management approach over time. As seen in Figure 10, in the earlier years of field usage (2015-2018), the flow would remain at a set flow rate for extended periods of time such as weeks or months. Since then, flow management controls have changed to a more dynamic approach.

Looking at 2020 onwards in the more dynamically varying flow regime in Figure 8, the flows peak twice in a year. The higher flow peak occurs in the summer and corresponds to positive peak values of ΔT. In contrast, the second flow rate peak in the year is generally lower and corresponds to negative peak values of ΔT and occurs in the winter.

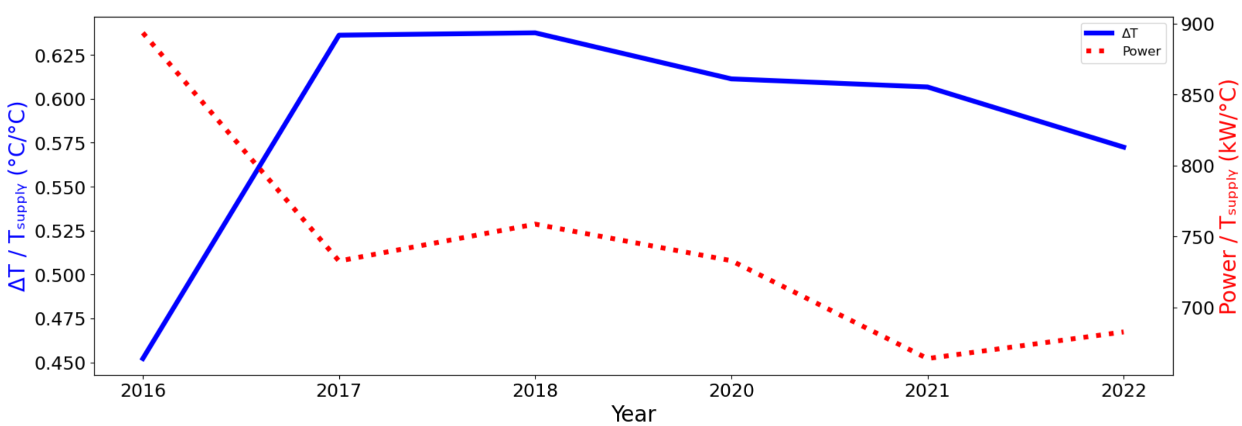

Figure 8. Year-over-year plot of linear regression trendline slopes for both ΔT and power versus T_{supply}.

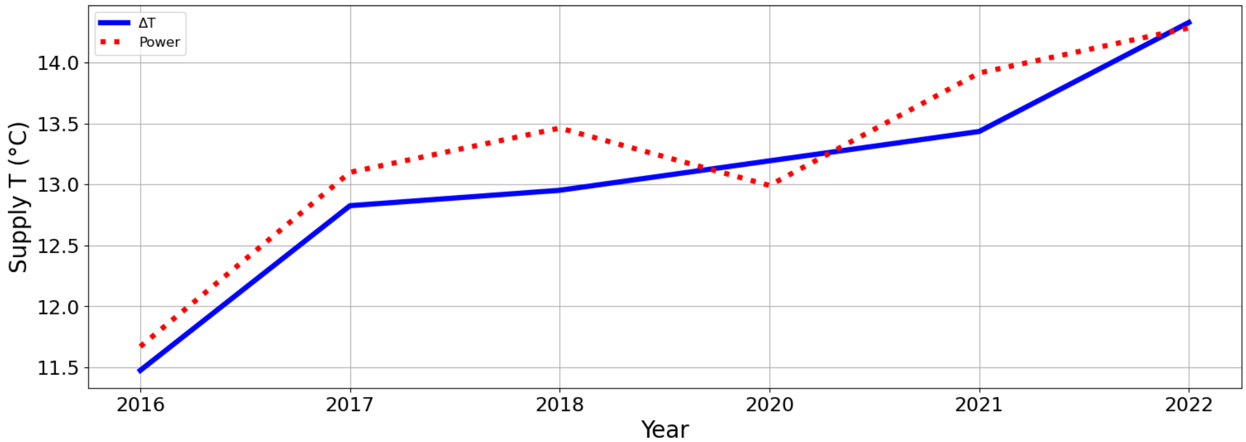

Figure 9. Year-over-year plot of linear regression trendline x-intercept (y = 0) values for both DT and power versus Tsupply.

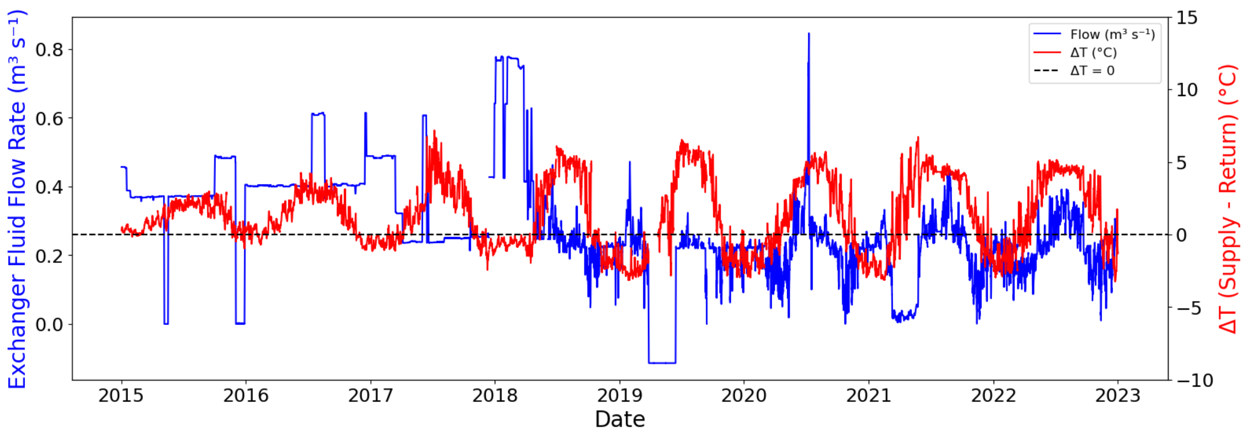

Figure 10. Moving averages of flow rate and DT over time from 2015 through 2022. Flow rate is in blue, while DT is in red.

4. DISCUSSION

Measured ground temperatures from the fiber optic temperature monitoring wells clearly indicate a gradual warming of Borefield 4. After initial conditioning, the field has shown an increase from ~14 °C (in 2015-2016) to anywhere from 15 °C to 18 °C at the end of 2022 depending on the location of the monitoring well. Most wells show a temperature around 17 °C at the end of 2022. Varying thermophysical properties of the ground and groundwater flow may play a role in the differing levels of temperature increase (Hart et al. 2022) and this phenomenon should be explored further to better understand the reasons for significant temperature variation.

Figures 6 and 7 show the year-over-year trendlines for both ΔT and power versus T_{supply}. Figures 8 and 9 help further describe the movement of these trendlines year-over-year by showing the generally decreasing trend of the slope values with time and generally increasing trend of the x-intercept value (where y = 0) for both ΔT and power versus T_{supply}. The decrease in slope and general movement of the trendlines down and to the right on the plots reflects a decrease in efficiency for heat dissipation and increase in efficiency for heat extraction. For example, if we look at a T_{supply} value of 20 °C the 2017 trendline in Figures 6 and 7 shows that this corresponded to a ΔT of ~4.5 °C and ~5000 kW of power exchange. Meanwhile, the 2022 trendlines in Figures 6 and 7 show that the T_{supply} value of 20 °C corresponds to a ΔT of ~3.5 °C and ~4000 kW of power exchange. In other words, the ability to dissipate heat and affect a temperature decrease in the exchanger fluid has decreased over time due to the significant increase in field temperature. On the other hand, the ability to extract heat and affect a temperature increase has increased over time, also due to the increase in field temperature.

A decrease in heat dissipation (cooling) efficiency could pose significant problems as the field is cooling dominated. Although the heat extraction (heating) efficiency may have increased, it may not be enough to offset the decrease in heat dissipation efficiency as the system is used for heat dissipation significantly more than for heat extraction. Recall that approximately 80% of the energy exchanged with the ground in Borefield 4 is heat dissipation, while the other 20% is heat extraction. Additionally, if these usage patterns continue, the heat dissipation efficiency will continue to decrease. The primary concern is that a decrease in heat dissipation efficiency of Borefield 4 may lead to increased energy usage by the heat pumps and chillers that cool the campus buildings. Then the system uses more energy, is less sustainable, and has a greater environmental impact.

Field design and management measures can be taken to help deal with such an imbalanced field. Some measures have already been taken by the owners of the GHX network, including the incorporation of cooling ponds that are primarily used for heat dissipation. With regards to the design of the borefield, it is beneficial to consider the thermophysical properties of the geologic units encountered at the site and adjust the depth of boreholes make use of the geologic units with the greatest ability to move heat (Walker et al. 2015). The movement of groundwater can play a significant role in the movement of heat in a borefield (Hart et al. 2022) and adjusting the geometry of the field to make greatest use of the groundwater movement may be another potential design solution for most effectively moving heat. A final option would be to add supplementary cooling that does not require the use of the geothermal field. Supplementary cooling would likely require greater energy use than the GHX network but could help make the GHX network more sustainable by helping to manage the energy imbalance.

5. CONCLUSIONS

The fiber-optic temperature monitoring of a district-scale geothermal exchange system in the upper Midwest of the U.S. reveals that the ground temperature of the system is generally increasing due to the cooling-dominated nature of the system. However, the temperature increase is not the same across the field. Some temperature monitoring wells measure significantly more temperature increase than wells at other locations in the field, likely due to differences in geologic units and the presence of groundwater flow. The temperature increase varies from ~1 °C to ~4 °C.

The increase in field temperature has led to a change in field behavior over time. Specifically, the field is less efficient at dissipating heat and more efficient for extracting heat. However, the decreased efficiency in dissipating heat is of concern as this is a cooling-dominated field. Over the course of 2015 to 2022, of the total energy exchanged, 79% was energy dissipation while 21% was energy extraction. In 2022, specifically, the values were similar as energy dissipation accounted for 82% of the total energy exchanged while energy extraction accounted for 18%. This imbalance in dissipation versus extraction in the field is also what causes the ground temperature to increase and therefore decrease efficiency in heat dissipation.

The owners of the field have attempted to address the energy imbalance by adding cooling ponds for heat dissipation from the GHX network. Potential design improvements to deal with a significant energy imbalance is to consider thermophysical properties of different geologic units and groundwater flow to best facilitate heat movement in the borefield. The addition of supplementary cooling is another potential option that requires significant additional energy usage but can improve the sustainability of the field by reducing the energy imbalance of the field.

A logical next step is to study whether the change in field behavior has led to greater energy usage. We observe that the geothermal field itself is seeing significantly decreased efficiency for heat dissipation and improved efficiency for heat extraction, but the question remains whether these changes have had an impact on the actual energy usage needed to run the geothermal system. And if these changes in efficiency have not significantly impacted energy usage, will this pattern of usage eventually change the efficiencies such that there is an effect on energy usage.

Geothermal systems are often advertised as being “greener” options for heating and cooling as they can often be more energy efficient and last far longer than more common heating and cooling systems. This paper suggests that the sustainability of these systems and long-term performance depends on proper investigation, design, and experienced management coupled with consideration for a balanced reservoir to the extent possible.

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