Proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE), and 2nd Latin-American Regional Conference of the International Association for Engineering Geology and the Environment (IAEG), La Serena Chile, 2024.

Seasonal Performance Evaluation for a District-Scale Geothermal Exchange System

Impacto de la Temperatura del Terreno en el Rendimiento de un Sistema Geotermal de Escala Distrital

Evan Heeg, **James Tinjum**, Dante Fratta
Department of Civil and Environmental Engineering, Geological Engineering Program, University of Wisconsin–Madison, USA, jmtinjum@wisc.edu

Shubham Attri
Biological Systems Engineering, University of Wisconsin–Madison, USA

David Hart
Wisconsin Geological and Natural History Survey, University of Wisconsin–Madison, USA

ABSTRACT: This study quantifies the performance of a cooling-dominated, district-scale geothermal heat exchange (GHX) field in the Midwest of the United States. The system includes multiple borefields, heat sink ponds, and central energy plants (CEPs) that provide heating and cooling to campus buildings. Previous research endeavors have found that for the largest borefield (2596 exchange wells 152-m deep over an area of 0.1 km^2), the temperature profile of the borefield has increased due to an energy imbalance in the field usage (the system is cooling-dominated). As many factors influence the performance of GHX systems, we seek to understand how long-term temperature changes on the ground affect the performance and energy efficiency of campus-scale GHX systems. We analyzed monitoring data from one of the primary CEPs. Results show that the Coefficient of Performance (COP) is around 3-4 in the winter and 7-8 in the summer, with the fall and spring seasons being transitional periods. The overall COP for all of 2022 was 4.66.This study helps to provide a benchmark for the COP that a district-scale GHX system is capable of achieving.

KEYWORDS: Coefficient of Performance (COP), Geothermal Heat Exchange, Heat Pumps

1 INTRODUCTION.

Geothermal heat exchange (GHX) systems utilize the relatively constant temperature of the subsurface to provide space conditioning to buildings and domestic hot water heating. A fluid (often water) is circulated underground through high-density polyethylene (HDPE) pipes, and the temperature difference between the ground and the exchanger fluid allows the energy exchange. After the energy transfer, the exchanger fluid is sent to heat pumps for space conditioning and domestic hot water heating. These heat pumps use refrigerants and the vapor-compression cycle to heat and cool. The exchanger fluid is then sent back to the ground or 'source-side' of the system for further energy exchange, and the cycle continues.

While GHX systems are often advertised as more environmentally friendly than traditional space heating and cooling methods, they must be designed and appropriately managed to achieve significant energy savings. GHX systems are considered a sustainable method of space conditioning and hot water heating that can significantly reduce energy compared to more common heating and cooling methods. Although heat and fluid circulation pumps require energy input, GHX systems can be much more energy efficient than conventional space conditioning systems (Bloom & Tinjum 2016, Reddy et al. 2020). Another advantage of GHX systems is that they can be applied at any scale, from residential homes to campus-scale systems. However, analyzing and evaluating whether GHX systems provide increased energy efficiency and, if so, by how much is essential. Additionally, it is important to properly design and manage these systems because inattention to design and management details can significantly reduce the effectiveness of these systems (Herrera et al. 2018).

In this study, we examine a district-scale GHX system located in the upper Midwest of the United States on a 13,000-employee campus. This system includes four geothermal bore fields and multiple cooling ponds for energy exchange and conditions dozens of buildings across the campus. The GHX network is interconnected, and the facility managers work to operate the system as efficiently as possible. The first building-scale components were constructed 15 years before this study, and the district system has changed and evolved as the campus has significantly expanded. The overall campus is split into sub-campuses. Parts of the original campus have a distributed approach for heating and cooling, where each building has its own set of heat pumps. Meanwhile, other sub-campuses have a centralized approach with a centralized energy plant (CEP) for the campus that houses all the heat pumps for that sub-campus. This study focuses on the CEP for two sub-campuses housed in a utility building (Figure 1).

Coefficient of Performance (COP) is defined as the heating or cooling energy that is provided by the heat pumps divided by energy used to run the system, which is a direct measure of system efficiency. In our case, we use all the energy usage of a specific utility building for the calculation, as it is assumed that much of that energy usage is required for heat exchange and circulation pumping. Therefore, the COP calculation includes the energy used for the system's heating and circulation pumps on the building conditioning side. This calculation does not include the energy circulation pumps used on the system's source side. It is important to note that the COP of the utility building does not represent the

COP of the entire system, as it is simply one part of a large and complex GHX structure; thus, it is difficult to calculate a COP for the system as a whole. Therefore, analyzing parts of the system rather than the whole is more approachable.

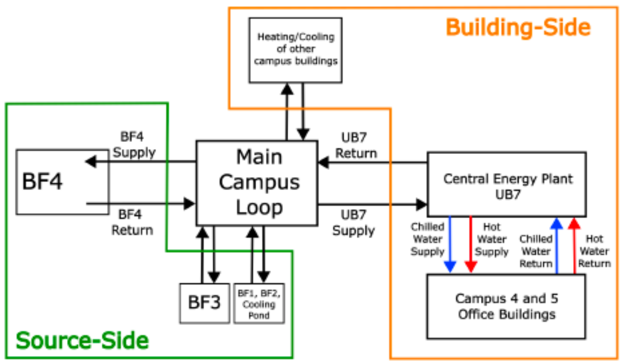

Figure 1. Schematic of the district-scale GHX system detailing how Bore Field 4 (BF4) and Utility Building 7 (UB7) fit into the larger system.

2 BACKGROUND

The effects of different GHX system factors on performance have been evaluated in many publications. For example, Noorallahi et al. (2017) assess several factors (e.g., pipe parameters, grout material, borehole depth) that affect the performance of a GHX system. Liu et al. (2020) presents a sensitivity analysis of different geologic parameters on the behavior of the GHX system and finds that geothermal gradient, ground thermal conductivity, and ground heat capacity are the three most important parameters in the thermal extraction capabilities of the system. Others have studied the effects of groundwater movement on the behavior of GHX systems (Fan et al. 2007, Wang et al. 2009, Dehkordi & Schincariol 2014, Zhao et al. 2022). Zhao et al. (2022) find that groundwater flow generally improves the performance of GHX borefields. These findings are also supported by Özdoğan Dölçek et al. (2017) & Hart et al. (2022), which show how highly permeable geologic layers allow for greater heat dissipation.

As mentioned before, many of these previous studies have evaluated the performance and seasonal variations of various sized and constructed GHX networks. However, a key issue is consistency between different studies in how COP and Seasonal Performance Factor (SPF; i.e., the ratio of heat supplied or rejected to total electrical input over the heating or cooling season, respectively) are calculated, especially related to what components are included as part of the GHX system energy usage. Nordman et al. (2012) establish a framework as part of the SEPEMO (SEasonal PErformance factor and MOnitoring for heat pump systems) project to help define different SPF values that include or exclude different components of the GHX system in the SPF calculation.

A study of a residential system in the upper Midwest of the US found an average system COP of 3.2 (Bloom & Tinjum 2016). Another study of five residential GHX systems in Yangzhou, China, revealed average weighted COPs that vary from 1.95 to 4.35 when both circulation and heat pump energy usage were considered (Zhang et al. 2016). Zhang et al. (2016) revealed that when more cooling capacity was used, the COP tended to be higher. However, it should be noted that this higher COP value was for heating-dominated systems with more extraction than dissipation. Han et al. (2020) conducted a study over four days in January on a GHX system for a university library in China. Over those four days, the system COP varied between 2.5 and 4.0. Michopoulos et al. (2013) evaluate a GHX system for a municipality hall in Greece over eight years. This GHX network comprises 21 vertical borehole heat exchangers at 80-m depth and 11 water-to-water heat pump units. The authors report a Seasonal Energy Efficiency Ratio (SEER) of 4.5-5.5 for heating and 3.6-4.5 for cooling. Zhai and Yang (2011) evaluate the performance of a GHX system for the Minhang Archives building in Shanghai, China. The system consists of 280 vertical borehole exchangers at 80-m depth. The system is cooling-dominated, and the authors report that the average COP in summer was 4.7, the average COP in winter was 4.6, and the average COP in transition season was 3.9.

Garber-Slaght & Peterson (2017) evaluate a heating-dominated GHX system located in Alaska (United States). Over three years, the authors note a 14% decrease in COP; however, the decrease from year two to year three was only 3%, which may represent some level of stabilization in the system performance. The COP values ranged from approximately 2.75 to 4.1 over a period of three years. Spitler & Gehlin (2019) also evaluate a building-scale GHX system serving a student center building at Stockholm University in Sweden. The authors report a heating SPF of 3.7±0.2 and a cooling SPF of 27±5 when the energy usage includes the heat pumps and circulation pumps/fans on the source-side of the system. It should be noted that the cooling SPF is particularly high because cooling comes directly from the boreholes in this system. Another key finding in this paper is that the authors review 55 previous GHX case studies and report that when energy usage includes the heat pumps and circulation pumps/fans on the source-side, the median cooling and heating SPF values are 6.4 and 3.6, respectively.

Naicker & Rees (2018) provide a detailed performance evaluation of a 56-boreholes, 100-m depth GHX system providing heating and cooling for a building at De Montfort University in Leicester, England. The system size is significantly smaller than the size of the system in this study but still a relatively large GHX system. The authors used an SPF metric, which is similar to the COP in that they both involve the valuable energy transfer divided by the energy used. The authors define a few different SPF calculations depending on what is described as 'energy usage.' For example, they provide one SPF calculation that does not include circulation pump energy usage and another that does. Naicker & Rees (2018) use data collected over three years to evaluate the performance of the GHX system. They found that the system's performance was diminished because the loads experienced by the building were much smaller than expected and that the heating and cooling equipment was oversized. This is another case of partial loads reducing the performance of the system. The authors stress proper initial design to allow for the greatest efficiencies by a GHX system. The authors also suggest improvements such as using heat pumps with variable-speed compressors or buffer tanks.

An important study is by Pater & Ciesielczyk (2017), which compares the COP values reported by heat pump manufacturers with experimental values (all in heating mode) and finds that the manufacturer's coefficient does not give full information about the heat pump's performance in real conditions during the heating season.' The authors assert that the COP value given by the manufacturer should only be used to compare specifications between heat pumps. In another study, Qiao et al. (2020) evaluated groundwater-source, soil-source, and surface water-source heat pump systems across China. After evaluating the performance of 28 of these systems, the authors determine that soil-source heat pumps have the best year-round efficiency.

Many of these studies also evaluate the energy savings using a GHX system. Bloom & Tinjum (2016) found a 45% reduction in energy usage compared to conventional systems for using a residential GHX system in the upper Midwest of the United States. Urcheguia et al. (2008) found primary energy consumption savings of 43 ± 17% for heating and 37 ± 18% for cooling for the studied building at the Universidad Politécnica de Valencia. Michopoulos et al. (2013) report primary energy savings of 25.7% and CO_2 and NO_x reductions of 22.7% and 99.6%, respectively, for the studied GHX system of a municipality hall in Greece. However, these authors also report an increase in SO_2 emissions of 18.4%. Carvalho et al. (2014) use the results of an evaluation of a GHX system to analyze energy savings provided by replacing natural gas-powered heating in the European Union (EU) with heat pump systems, including GHX systems. The authors find that by replacing natural gas heating with heat pumps, the EU would experience a 60% reduction in primary energy usage and a 90% reduction in CO_2 emissions associated with heating.

To our knowledge, the system in this study is significantly larger than any GHX system that has had its performance analyzed. As such, we do not use any of a number of existing frameworks for a small system but rather fully describe what is included and excluded in our COP calculations, and we clearly separate heating and cooling seasons. Further, our COP is unitless according to the following equation:

$$COP = \frac{\sum Energy\ Exchanged}{\sum Energy\ Usage} \tag{1}$$

whereas many studies, particularly in the United States, use unbalanced, non-SI units such as British Thermal Units (BTUs) as an expression of total heat in the numerator and kW in the denominator.

3 METHODS

The owner of the campus facilitates the data collection. The campus has instrumentation that measures the supply and return temperatures, volumetric flow rates, and energy usage for the central energy plant housed in Utility Building 7, UB7. In terms of instrumentation, an Onicon F-3200 Series Inline Electromagnetic Flow Meter is used to measure the exchanger fluid volumetric flow rate, and the supply and return temperatures are measured using Rosemount™ 3144P Temperature Transmitters for UB7. Specific parameters, such as COP, are calculated from the collected data. To calculate COP, we divide the useful energy exchanged by the heat pumps divided by the energy used by the central energy plant in the utility building. The energy usage includes both the energy usage of the heat pumps and the energy usage of the circulation pumps in UB7. However, recall that this utility building is a portion of a much larger system, so certain circulation pumps—such as circulation pumps on the source side—are not included in this calculation of COP.

The energy exchanged is calculated for both hot and chilled water and summed. If the absolute value is taken, the same equation can be used for the energy exchange on both the hot and chilled water sides. The equation is as follows:

$$Energy\ Exchanged = \rho \cdot C_p \cdot \Delta T \cdot q \cdot t \tag{2}$$

where ρ is the density of the exchanger fluid, C_p is the specific heat capacity of the exchange fluid, ΔT is the temperature difference across the heat pump, q is the flow rate of the exchanger fluid, and t is the time elapsed between measurements. We can then calculate COP for UB7 with Equation 1. Here, the energy exchanged and the energy usage are summed over the same period. During data *cleaning*, rows with missing data or unrealistic values (indicating an issue with the measurement device) were dropped for this analysis.

4 RESULTS

4.1 *Coefficient of Performance*

A moving average has been applied to most of the plots to remove noise and better determine trends in the data. A window size of 288 was selected as the initial data points are five minutes apart—a window size of 288 corresponds to averaging over a day. It should be noted that plots of energy versus time are presenting the energy exchanged every five minutes which is also due to the initial data points being five minutes apart. COP has only been calculated for 2022, while other data sets presented herein vary from 2019 to 2022. Figure 2 presents the calculated COP and a moving average of the calculated COP, showing that the COP stays around 4 during winter and increases to about 7 during summer. During the spring and fall months, the COP is in a transitional phase. The COP for all of 2022 is 4.66.

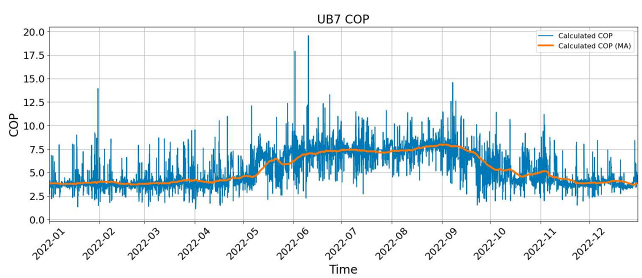

Figure 2. Calculated COP in blue and the daily moving average in orange, plotted for 2022.

4.2 *Energy Exchange versus Energy Usage*

Figure 3 illustrates the patterns in energy usage and total energy exchange. Observe that the energy exchange remains higher throughout the year than the energy usage. The energy exchange peaks twice in the year, once in the summer and once in the winter. However, the energy exchange peak is higher in winter than in summer. Conversely, the energy usage remains relatively low and relatively constant during the summer months, while the energy usage increases for the winter months and oscillates more. Note that energy usage and exchange increase during the winter months, but during the summer months, the energy exchange increases while the energy usage remains relatively low and constant. We want to evaluate and analyze why COP tends to be higher in the summer when energy usage is low and energy exchange is relatively high. Figure 4 shows the differences in energy exchanged for hot and chilled water. The hot water energy exchange reaches a maximum in the winter and a minimum in the summer. Conversely, the chilled water energy exchange reaches a maximum in the summer and a minimum in the winter months. Generally, the hot water energy exchange maximum is higher than the chilled water energy exchange peak. Additionally, some energy is exchanged for domestic hot water during the cooling season. Meanwhile, the chilled water energy exchange is approximately zero for the winter heating season. In other words, the minimum energy exchanged for chilled water is lower than the minimum for hot water.

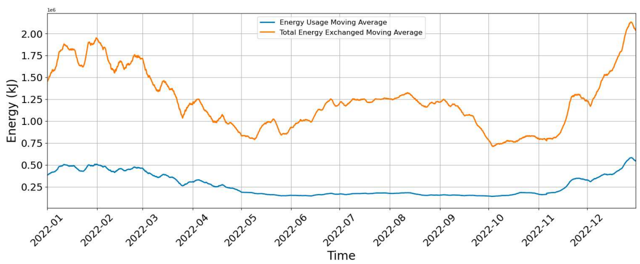

Figure 3. Energy usage and total energy exchanged for UB7 across 2022. Both plots use a daily moving average, and the y-axis is in unit of x10^6 kJ.

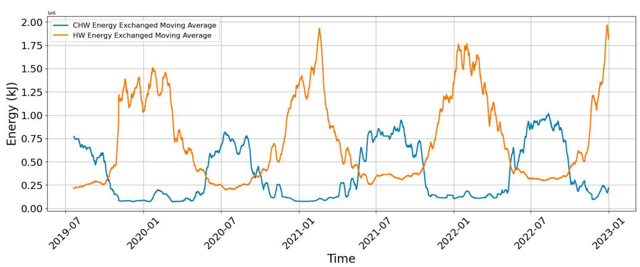

Figure 4. On a daily moving average, absolute energy (unit of x10^6 kJ) was exchanged for hot and chilled water in UB7 from July 2019 to the end of 2022.

Another critical feature to evaluate is the temperature of the water across the system and the water flow rates. Water enters UB7, which is heated or cooled to a desired temperature. The water entering UB7 is called 'UB7 Supply' in the figures. The heated and cooled water is then sent to the buildings on the campus, where it moves through heat exchangers that use the hot and cold water for heating and cooling purposes. The heated and cooled water leaving UB7 is the 'HW Supply' and 'CHW Supply'. After crossing the heat exchangers, the water is sent back to UB7, which is the 'HW Return' and 'CHW Return' data. The supply and return temperatures (to and from the campus buildings) for the hot water are shown in Figure 5. The dramatic shift in temperatures in mid-2020 was due to system operational changes during the COVID-19 pandemic. After this offset in temperature values, the supply temperature has remained relatively constant at around 54 ºC. Conversely, the return temperature oscillates to some degree. Overall, the return temperature increases in the summer and decreases in the winter.

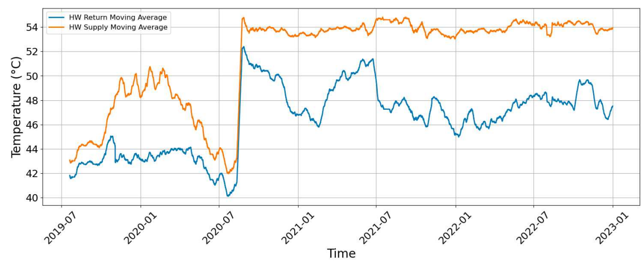

Figure 5. Hot water return and supply temperatures with a moving average from July 2019 to the end of 2022. The moving average covers a 24-h period. Initial measurements were every five min. The dramatic change in temperature recorded in mid-2020 was due to system operational changes during the COVID-19 pandemic.

Figure 6 shows plots of the supply and return temperatures (to and from the campus buildings) for the chilled water. Chilled water results differ from hot water results (Figure 5). First, the supply temperature is lower than the return temperature for the chilled water, and the reverse is true for the hot water, which is as expected. The chilled water supply temperature tends to vary between 6 ºC and 8 ºC. The chilled water return temperature differs substantially. The return temperature peaks in the summer at ~16 ºC and reaches a low in the winter, generally around 7–8 ºC.

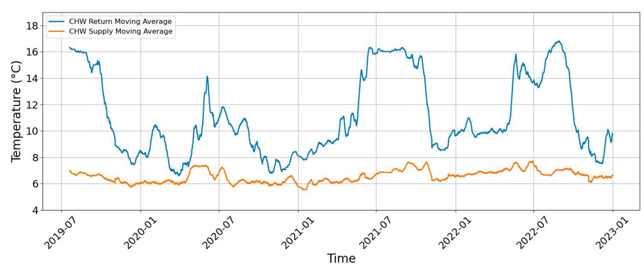

Figure 6. Chilled water return and supply temperatures with a moving average from July 2019 to the end of 2022. The moving average covers a 24-hour period. Initial measurements were every five minutes.

Flow rate is also an essential parameter in determining the amount of useful energy exchanged, as the energy exchanged is directly proportional to the flow and ΔT. Figure 7 shows the volumetric flow rate for hot and chilled water. The hot water flow rate reaches a maximum in the winter and a minimum in the summer. Meanwhile, the chilled water flow reaches a maximum in the summer and a minimum in the winter. The hot water flow is generally higher than the chilled water flow. Although the hot and chilled water flow rates peak at different times of the year, the hot water maximum is higher than the chilled water maximum, and the hot water minimum is higher than the chilled water minimum.

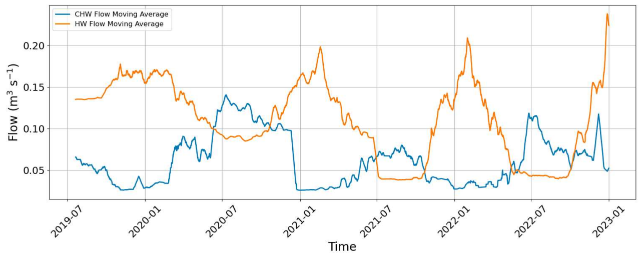

Figure 7. The 24-hour moving average of the flow for hot and chilled water in UB7 from July 2019 to the end of 2022.

The temperature change (ΔT) and flow rate across the energy exchangers in the campus buildings are the parameters used to calculate the useful energy exchanged because this energy is directly used for heating and cooling. However, the energy input takes place in UB7, where the heat pumps are located. These heat pumps heat and cool the incoming water from the borefields. Once heated and cooled, the water is sent to the campus buildings for heating and cooling.

Figure 8 shows moving averages on the incoming UB7 temperature (UB7 Supply), the chilled water leaving UB7 and heading to the campus buildings (CHW Supply), and the hot water leaving UB7 and heading to the campus buildings (HW Supply). The heat pumps raise or lower the temperature of the UB7 supply water to the desired temperatures of the hot water and chilled water, leaving UB7. Note the significant difference in temperature between the UB7 supply and chilled water supply versus the UB7 supply and hot water supply. Generally, the chilled water supply temperature ranges between 0 ºC and 10 ºC lower than the UB7 supply temperature. Meanwhile, the hot water supply temperature is about 25–35 ºC higher than the UB7 supply temperature. Therefore, the heat pumps must do much more work to heat water than to chill it.

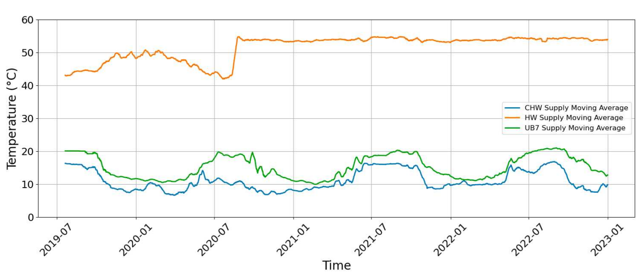

Figure 8. The 24-h moving average of UB7 supply, chilled water supply, and hot water supply temperatures from July 2019 to the end of 2022.

5 DISCUSSION

COP is a vital metric in evaluating GHX systems as it is used to assess the energy efficiency of these systems, which are portrayed as significantly more energy efficient than conventional systems if designed and managed correctly (Bloom & Tinjum 2016, Zhang et al. 2016, Naicker & Rees 2018). However, GHX systems also require more energy to install, so they must offset the initial energy input with energy savings compared to conventional systems (Tinjum et al. 2023). Then, after the initial extra energy input is 'paid back,' the GHX network provides additional energy savings compared to conventional heating and cooling systems. Previous research has shown that proper design and management are paramount in using GHX systems, as the performance can be significantly reduced otherwise (Florea et al. 2017, Herrera et al. 2018).

In this study, we evaluated a portion of a district-scale GHX operation, as analyzing the whole system at once would be an overwhelming and complicated task. We assessed the performance of one central energy plant in the system that provides heating and cooling to two sub-campuses, noting that the entire GHX system is cooling-dominated. For example, previous research on this system has shown that in the largest borefield of the system, cooling accounts for ~80% of the energy exchange with the ground, while heating accounts for ~20% of the energy exchange with the ground (Hart et al. 2022, Heeg et al. 2024). Additionally, the field has heated ~2 ºC to 3 ºC over the past decade (Heeg et al. 2024).

Based on the cooling-dominated nature of the whole system and the cooling-dominated nature of the primary borefield, it is instructive to note that the COP is significantly higher for UB7 when cooling is dominant in the summer than when heating is dominant in the winter. For 2022, the COP ranged between 7 and 8 for the summer and approximately between 3 and 4 for the winter. This difference is further explained by looking at the energy usage and exchange. The energy usage stays relatively low in the summer months while the energy exchange increases. In the winter, both the energy exchange and the energy usage increase. Therefore, the COP is higher in the summer. Next, we explore what allows the energy exchanged to increase in the summer while the energy usage remains relatively low.

One hypothesis to explain the difference in COP is that the temperature change across the heat pumps or 'lift' required is much greater for hot water than chilled water. 'Lift' refers to the work a heat pump must do to heat or cool the water to the desired temperature. In our case, water enters UB7 from the field, where it is heated and cooled by heat pumps to the desired temperature. The energy input happens here in UB7, where the water is brought to a desired temperature. Then, the water is sent to buildings on the campus, where it moves across heat exchangers that use the heated and cooled water for space conditioning. The campus buildings are where the useful energy exchange for heating and cooling occurs.

The temperature difference across the heat exchangers in the campus buildings (where the useful energy exchange takes place) is of similar magnitude for both hot water (heating) and chilled water (cooling), as seen in Figures 5 and 6, respectively. However, as observed in Figure 7, the flow tends to generally be higher for hot water than chilled water, considering seasonal variations. The higher flow rates for the hot water drive the higher useful energy exchange values for the hot water compared to the chilled water, as seen in Figure 4.

However, the energy usage values are also much higher for hot water, causing the COP to be lower in the winter (when heating is dominant) than the summer (when cooling is dominant). The difference in energy usage is driven by the 'lift' required by the heat pumps in UB7. Figure 8 illustrates this difference in lift, as the temperature difference between the water entering UB7 and the desired temperature of the hot water is much greater than the temperature difference between the water entering UB7 and the desired temperature of the chilled water. The hot water requires an approximately 25–35 ºC increase to the desired temperature, while the chilled water requires only an approximately 0 – 10 ºC decrease in temperature.

The overall COP for 2022 of 4.66 is comparable to the COP values found in previous studies evaluating the performance of GHX systems. However, these systems differ from the district-scale GHX network in this study. Bloom & Tinjum (2016) found a COP of 3.2 for a residential GHX system in the upper Midwest of the U.S., Zhang et al. (2016) found that COP varied from 1.95 to 4.35 for five residential systems in Yangzhou, China, and Han et al. (2020) evaluated the performance of a GHX system for a university library in China over a few days and found that the COP varied between 2.5 and 4.0. A 2014 review of COP standards in a variety of countries (such as the U.S., China, and New Zealand) found that "under standard rating conditions at full load operation, the minimum required COP ranges from 2.40 to 3.06 for air-cooled chillers and from 3.80 to 6.39 for water-cooled chillers" (Yu et al. 2014). Therefore, based on previous studies and industry standards, the central energy plant for the district-scale system studied here performs well, with its overall COP of 4.66 for 2022.

6 CONCLUSIONS

In this study, we calculate, analyze, and evaluate COP for a section of a district-scale GHX system. There needs to be more research regarding the performance of district-scale GHX systems. This research is important as GHX systems may provide sustainable, energy-efficient heating and cooling solutions for many campuses, neighborhoods, etc. Here, we look at the central energy plant for two sub-campuses on a much larger ~13,000-employee campus in the upper Midwest of the U.S. Overall, as of 2022, the utility building's central energy plant has a COP of 4.66. This COP includes heat and chilled water energy exchanges and energy usage.

However, over 2022, the COP peaked in the summer between 7 and 8 and reached a minimum between 3 and 4 through winter. Overall, this GHX system is cooling-dominated, so the higher COP for cooling than heating is somewhat unexpected. The temperature difference of 'lift' required by the heat pumps in UB7 is much higher for hot water than chilled water, meaning that more energy is required to heat water than to chill water. Therefore, despite the higher values of useful energy exchange for hot water versus chilled water, the significantly higher lift for hot water versus chilled water drives the lower heating COP during the winter compared to cooling COP during the summer.

Compared to the results of these previous studies, we find that an overall COP of 4.66, with peaks of between 7 and 8 in the summer months, is an efficient, well-performing well. This study helps to provide a benchmark for the COP that a district-scale GHX system may be capable of achieving. This study also proves that when designed and managed correctly, GHX systems can provide significantly increased energy efficiency over more conventional means. With heating, no system that involves burning something (such as natural gas) can have a COP higher than 1.

The next step is to evaluate the performance of this district-scale GHX system over a longer period, which was not possible in this study due to limitations in the data set. Another step is to evaluate the GHX system more, as this study only looks at one section of a much larger system. By considering more of the system over a more extended period, we can continue to understand better the performance of district-scale GHX systems and how to get the highest efficiency out of these systems.

7 ACKNOWLEDGEMENTS

The authors dedicate this paper in memory of Dr. Mehmet Yilmaz. Dr. Yilmaz was an important contributor in the early stages of the research that led to this paper. We dedicate this paper to him.

The authors acknowledge Epic Systems Corporation for their generous contributions of time, talent, and resources in the ongoing development of this research and for giving us access to a unique facility. The Morse Company, Hooper Corporation, Salas O'Brien, JP Cullen, and Teel Plastics all donated time, materials, and/or expertise, without which, this research would not have been possible. We thank Adam McDaniel (Westwood Professional Services) for preparing the initial Matlab code to process and calibrate FO DTS data. We acknowledge the National Science Foundation for sponsoring undergraduate research opportunities during the early phases of this project under Award # 1156674. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. 2137424. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding organizations.

8 REFERENCES

Bloom E.F. and Tinjum, J.M. 2016. Fully instrumented life-cycle analyses for a residential geo-exchange system. *Geo-Chicago 2016*.

Carvalho A.D., Mendrinos D., and De Almeida A.T. 2015. Ground source heat pump carbon emissions and primary energy reduction potential for heating in buildings in Europe-results of a case study in Portugal. *Renew. Sustain. Energy Rev.*, 45, 755–768.

Dehkordi S.E. and Schincariol R.A. 2013. Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems. *Hydrogeology Journal*, 22(1), 189–203.

Fan R., Jiang Y., Yao, Y., Shiming D., and Ma Z. 2007. A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection. *Energy*, 32(11), 2199–2209.

Garber-Slaght R. and Peterson R. 2017. Can ground source heat pumps perform well in Alaska? *In Proceedings of the IGSHPA Technical/Research Conference and Expo*, Denver, CO, USA, pp. 62–70.

Han J., Cui M., Chen J., and Lv W. 2021. Analysis of thermal performance and economy of ground source heat pump system: A case study of the large building. *Geothermics*, 89, 101929.

Hart D.J., Tinjum J.M., Fratta D., Thomas L.K., and Carew E.L. 2022. Radiators or reservoirs: heat budgets in district-scale ground-source geothermal exchange fields. *47th Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, CA, SGP-TR-223.

Heeg E.P., Tinjum J.M., Fratta D., Attri S.D., Hart D.J., and Luebbe A.K. 2024. Quantifying the long-term performance of a district-scale geothermal exchange field. *49th Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, CA, SGP-TR-227.

Herrera C., Nellis G., Reindl D., Klein S., Tinjum J.M., and McDaniel A. 2018. Use of a fiber optic distributed temperature sensing system for thermal response testing of ground-coupled heat exchangers. *Geothermics*, 71, 331–338.

Liu J., Wang F., Cai W., Wang Z., and Li C. 2020. Numerical investigation on the effects of geological parameters and layered subsurface on the thermal performance of medium-deep borehole heat exchanger. *Renewable Energy*, 149, 384–399.

Michopoulos A., Zachariadis T., and Kyriakis N. 2013. Operation characteristics and experience of a ground source heat pump system with a vertical ground heat exchanger. *Energy*, 51, 349–357

Naicker S.S. and Rees S.J. 2018. Performance Analysis of a Large Geothermal Heating and Cooling System. *Renewable Energy*, 122, 429–442.

Noorollahi Y., Saeidi R., Mohammadi M., Amiri A., and Hosseinzadeh M. 2018. The effects of ground heat exchanger parameters changes on geothermal heat pump performance – a review. *Applied Thermal Engineering*, 129, 1645–1658.

Nordman R., Kleefkens O., Riviere P., Nowak T., and Zottl A. 2012. Arzano-Daurelle C., Lehmann A., Polyzou O., Karytsas K., Riederer P. et al. SEPEMO—Seasonal Performance Factor and Monitoring for Heat Pump Systems in the Building Sector; SP Technical Research Institute of Sweden: Borås, Sweden.

Özdoğan Dölçek A., Atkins I., Harper M.K., Tinjum J.M., and Choi C.Y. 2017. Performance and sustainability of district-scale ground coupled heat pump systems. *Geotechnical and Geological Engineering*, 35(2), 843–856.

Pater S. and Ciesielczyk W. 2017. Real and Theoretical Energy Efficiency of Vapour Compression Heat Pumps. *Mechanics*, 5, 185–194.

Qiao Z., Long T., Li W., Zeng L., Li Y., Lu J., Cheng Y., Xie L., and Yang L. 2020. Performance assessment of ground-source heat pumps (GSHPs) in the Southwestern and Northwestern China: In situ measurement. *Renewable Energy*, 153, 214–227.

Reddy K.R., Ghimire S.N., Wemeyi E., Zanjani R., and Zhao L. 2020. Life cycle sustainability assessment of geothermal heating and cooling system: UIC Case Study. *E3S Web of Conferences*, 205, 07003.

Schibuola L. and Scarpa, M. 2016. Ground source heat pumps in high humidity soils: An experimental analysis. *Appl. Therm. Eng*, 99, 80–91.

Spitler J. and Gehlin, S. 2019. Measured performance of a mixed-use commercial-building ground source heat pump system in Sweden. *Energies*, 12(10), 2020.

Urchueguía J.F., Zacarés M., Corberán J.M., Montero Á., Martos J., and Witte H. 2008. Comparison between the energy performance of a ground coupled water to water heat pump system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast. *Energy Convers. Manag.*, 49, 2917–2923.

Wang H., Qi C., Du H., and Gu J. 2009. Thermal performance of borehole heat exchanger under groundwater flow: A case study from Baoding. *Energy and Buildings*, 41(12), 1368–1373.

Yu F.W., Chan K.T., Sit R.K.Y., and Yang J. 2014. Review of standards for energy performance of Chiller Systems serving commercial buildings, *Energy Procedia*, 61, 2778–2782.

Zhai X.Q. and Yang Y. Experience on the application of a ground source heat pump system in an archives building. 2011. *Energy Build*, 43, 3263–3270

Zhao Z., Lin Y.-F., Stumpf A., and Wang X. 2022. Assessing impacts of groundwater on geothermal heat exchangers: A Review of Methodology and Modeling. *Renewable Energy*, 190, 121–147.

Zhang S., Zhang L., Wei H., Jing J., Zhou X., and Zhang X. 2016. Field testing and performance analyses of ground source heat pump systems for residential applications in hot summer and cold winter area in China. *Energy and Buildings*, 133, 615–627.