PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

Hybrid Geothermal Heat Pumps for Cooling Telecommunications Data Centers

David P. Zurmuhl[1], Maciej Z. Lukawski[1], Gloria A. Aguirre[1], George P. Schnaars[1], Koenraad F. Beckers[1,2], C. Lindsay Anderson[1], and Jefferson W. Tester[1]*

[1]Cornell University: Cornell Energy Institute, Sibley School of Mechanical and Aerospace Engineering, Smith School of Chemical and Biomolecular Engineering, Earth & Atmospheric Sciences, Biological and Environmental Engineering, Ithaca NY 14853, USA

[2]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

*corresponding author: jwt54@cornell.edu

Keywords: geothermal heat pump (GHP), ground-source heat pump (GSHP), data center cooling, computer room air conditioning (CRAC), air-source heat pump (ASHP), techno-economic modeling, TRNSYS

ABSTRACT

The technical and economic performance of geothermal heat pump (GHP) systems supplying year-round cooling to representative small data centers with cooling loads less than 500 kW_{th} were analyzed and compared to air-source heat pumps (ASHPs). A numerical model was developed in TRNSYS software to simulate the operation of air-source and geothermal heat pumps with and without supplementary air cooled heat exchangers – dry coolers (DCs). The model was validated using data measured at an experimental geothermal system installed in Ithaca, NY, USA. The coefficient of performance (COP) and cooling capacity of the GHPs were calculated over a 20-year lifetime and compared to the performance of ASHPs. The total cost of ownership (TCO) of each of the cooling systems was calculated to assess its economic performance. Both the length of the geothermal borehole heat exchangers (BHEs) and the dry cooler temperature set point were optimized to minimize the TCO of the geothermal systems. Lastly, a preliminary analysis of the performance of geothermal heat pumps for cooling dominated systems was performed for other locations including Dallas, TX, Sacramento, CA, and Minneapolis, MN.

1. INTRODUCTION

Geothermal or ground-source heat pumps (GHPs) utilize the relatively shallow ground as a heat source or sink to provide space or water heating and/or cooling. Depending on factors such as climate, particularly ambient air temperature and humidity, and price of electricity, GHPs are often the most energy efficient and cost-effective systems for space cooling.

The IT equipment in data centers produces large amounts of heat and typically requires year-round cooling. About 40% of the energy consumed by a data center is typically used for cooling the IT equipment, which corresponds to 0.5% of the world's electricity demand (Song, et al., 2015). The most commonly used data center cooling technologies rely on air-source heat pumps (ASHPs), which use the atmosphere as a heat sink. An alternative solution is to use GHPs utilizing a set of vertical boreholes which are typically more efficient because the ground remains at a moderate temperature year-round, whereas the ambient air temperature fluctuates throughout the year. Although the initial cost of GHP systems can be significantly higher than the cost of ASHPs, the reduced electricity consumption of geothermal systems over the course of their lifetimes can allow the initial cost to be recovered within a reasonable timeframe, while reducing the carbon footprint of data centers.

Unlike GHP systems used in residential buildings for both space heating and cooling, a system used for data center cooling needs to transfer heat to the subsurface year-round. One of the main concerns of such systems is the potential increase in temperature of the geothermal well field over the lifetime of the system, resulting in diminished efficiency and cooling capacity of the heat pumps. In order to mitigate the expected temperature increase, an air-cooled heat exchanger – a dry cooler (DC) – can be added to the system to transfer heat generated by the IT equipment and stored in the subsurface to the atmosphere when ambient temperatures are low.

An earlier study comparing the performance and economics of different cooling systems for cellular tower shelters with cooling loads of approximately 8 kW_{th} (including ASHPs and GHPs equipped with DCs and/or air economizers) was conducted in our group and is documented in Beckers et al. (2014), Beckers (2016), and Aguirre et al. (2017). The study utilized computer models validated against data from a cellular tower demonstration site in Varna, NY. The main outcome of the study was that in most cases, an ASHP combined with an air economizer provided the lowest total cost of ownership while a GHP combined with an air economizer provided the lowest lifetime electricity consumption. A nationwide analysis of the cooling systems was then conducted using climate and hydrogeological data to produce maps of the total cost of ownership of the GHP and ASHP systems. An experimental study comparing the performance of GHPs and ASHPs over a one year period was conducted by Urchueguía et al. (2008). Although the studied systems were used for both heating and cooling, the experimental site was located in the warm climate of Valencia, Spain, making for a cooling-dominated application. The study concluded that GHPs compared to ASHPs save 43±17% of energy in heating mode and 37±18% of energy in cooling mode.

2. OBJECTIVE

This paper provides a comparison of the technical and economic performance of GHP, GHP with dry cooler (GHP+DC), and ASHP systems used for year-round cooling of a data center located in Ithaca, NY, USA. The analysis was conducted using TRNSYS models of GHP and ASHP systems for a lifetime period of 20 years. The numerical models were calibrated using data from a hybrid GHP system installed at a small telecommunications data center in Ithaca, NY. Section 3 of this paper discusses the methods of experimental data collection, computer simulation of the heat pump systems, and validation of these simulations. In Section 4, technical and economic performance of the three cooling systems is evaluated based on the simulations for the Ithaca data center. The results of the optimization of the borehole length and DC control set point are also presented. In Section 5, the sensitivity of the results to climate, cost of electricity, and hydrogeology are illustrated based on the results for Sacramento, CA, Minneapolis, MN, and Dallas, TX.

3. METHODOLOGY

3.1 Experimental GHP Cooling System

An experimental hybrid GHP cooling system was installed in a telecommunications data center in Ithaca, NY with an approximate equipment cooling load of 14.5 kW_{th}. The system was equipped with a comprehensive data acquisition system to record relevant temperature, flowrate, control, and power consumption data at 5-minute intervals. The cooling system presented in Figure 1 consists of two loops, each with a pump circulating propylene glycol solution. The two loops are connected by a heat exchanger that transfers heat from the building loop to the subsurface loop. The building loop circulates fluid between two 35.2 kW_{th} (10 tons of cooling each) GHPs (ClimateMaster TCV120), a DC, and the heat exchanger. The subsurface loop circulates fluid between the heat exchanger and the geothermal well field. The geothermal well field consists of three sets of boreholes connected in parallel, each set consisting of three 139 m (455 ft.) boreholes connected in series. The nine borehole heat exchangers (BHEs) have a total length of 1248 m (4095 ft.).

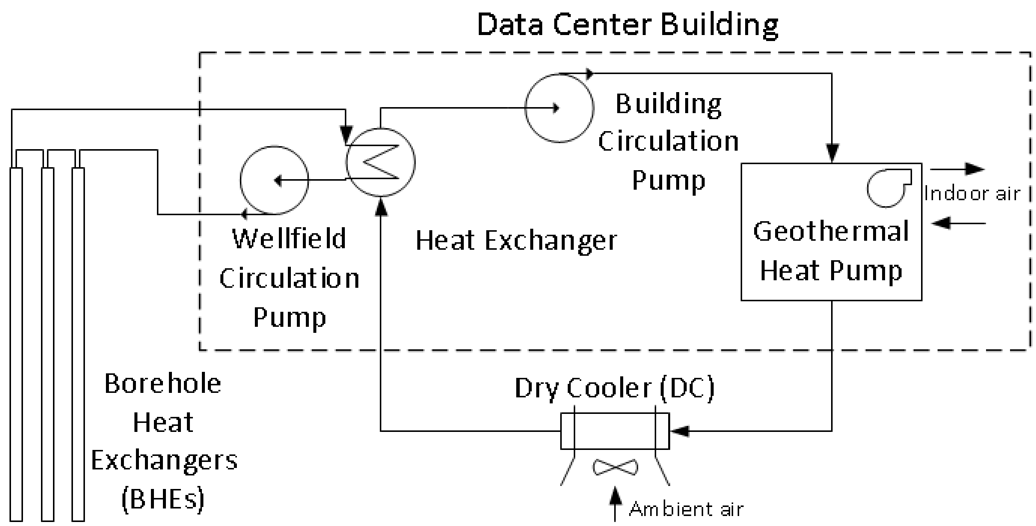

Figure 1: Simplified schematic of the hybrid geothermal heat pump (GHP) system at the experimental site.

The cooling system is designed to maintain the server room temperature between 25.6°C and 27.8°C (78°F to 82°F) and the two GHPs can each operate in part load or full load. The combined cooling capacity of the heat pumps (70.4 kW_{th}) is almost five times higher than the current cooling load (14.5 kW_{th}) to provide backup capacity and to facilitate possible future expansion of the data center. The DC operates at full capacity when the temperature difference between the glycol entering the DC and the ambient air ΔT_{DC} is greater than 4.4°C (8°F) and the temperature of the glycol leaving the DC is greater than 1.7°C (35°F). Otherwise the DC is bypassed and its fan is switched off.

3.2 Numerical TRNSYS Model

Long-term operation of the GHP system was modeled using TRNSYS – Transient System Simulation Tool, a software environment developed to simulate performance of thermal and electrical energy systems (Klein, et al., 2014). TRNSYS includes an extensive library of components that can be used to model the performance of each part of the system of interest. Operation of the data center cooling systems was simulated for 20 years with a 10-minute time step.

Performance of the ClimateMaster TCV120 heat pumps was modeled using performance tables provided by the manufacturer, which were implemented in the TRNSYS model (ClimateMaster, 2017). The tables provide cooling and electricity consumption data for discrete input values of temperature and flowrate of the entering glycol-water mixture as well as the temperature, humidity, and flowrate of the entering indoor air. The TRNSYS *conditioning equipment component* (type 42) interpolates between these values to determine heat pump performance at each time step. Only full load operation was modeled due to a lack of performance tables for a part load operation. The DC was modeled using the *counter flow heat exchanger component* (type 5). The model uses the specified heat exchanger coefficient as input to calculate the heat exchanger effectiveness. The server room was modeled using the *lumped capacitance building component* (type 88) which simulates the building as a single zone. The model assumes constant heat gains from equipment, neglects solar heat gains, and lumps heat transfer through the building envelope and ventilation into an overall heat loss coefficient. The annual ambient temperature inputs to this model came from a TMY3 file for the Elmira Regional Airport which is located about 30 miles from Ithaca (NREL, 2005). TMY3 files represent the hourly weather conditions for a typical meteorological year based on multiple years of recorded data (Wilcox & Marion, 2008). The glycol heat exchanger was modeled using the *effectiveness heat exchanger component* (type 91). This model uses a specified value of heat exchanger effectiveness to calculate the heat transfer rate between the two circulation loops (Klein, et al., 2014).

The thermal behavior of the borehole heat exchangers (BHEs) was simulated in MATLAB using a semi-analytical slender-body heat transfer model (Beckers, 2016). The TRNSYS model called the MATLAB script at each time step to calculate the outlet temperature of the BHEs. The thermal conductivity and diffusivity of the soil were obtained from a BHE thermal response test performed at the site. The far-field temperature of the subsurface was assumed to be the average ambient temperature calculated from the TMY3 file.

Heat pump operation was controlled using the *five stage room thermostat component* (type 108). This component controls two stages of cooling and was set so that the first heat pump would begin operation if the indoor temperature went above 25.6°C (78°F) and the second heat pump would switch on if the indoor temperature exceeded 28.1°C (82.5°F). DC operation was controlled using the *differential controller component* (type 2). The controller used a specified temperature dead band to determine the fan control signal based on the difference between the temperatures of the entering glycol solution and the ambient air ΔT_{DC}. The circulation pumps were assumed to be in operation if either one of the heat pumps or the DC were operating (Klein, et al., 2014).

Component	Parameter	Value
BHE	Far-field formation temperature	9.0 [°C]
	Density of heat exchanger fluid	1017 [kg/m^2]
	Specific heat of heat exchanger fluid	4.019 [kJ/kg-K]
	Thermal conductivity of heat exchanger fluid	0.477 [W/m-K]
	Dynamic viscosity of heat exchanger fluid	0.00236 [Pa-s]
	Thermal conductivity of the soil	3.271 [W/m-K]
	Thermal diffusivity of the soil	0.903*10-6 [m^2/s]
	Thermal conductivity of the grout	1.5 [W/m-K]
	Pipe outer radius	0.0167 [m]
	Pipe inner radius	0.0134 [m]
	Thermal conductivity of the pipe	0.45 [W/m-K]
	Borehole radius	0.0762 [m]
	Total borehole length	1248 [m]
	Spacing between center of pipes	0.11 [m]
Building	Thermal Capacitance	70000 [kJ/K]
	Volume	918 [m^3]
Dry cooler	Air flowrate	1.89 [m^3/s]
GHP	Air flowrate	1.89 [m^3/s]
	Entering air relative humidity	50%

Table 1: Specifications of components used in the TRNSYS model.

The model of the hybrid system (GHP+DC) was modified to represent a GHP system without a DC by setting the DC permanently off. A model of an ASHP system was developed using the GHP+DC model with the glycol heat exchanger and subsurface loop components removed.

3.3 Validation of the TRNSYS Model

The numerical TRNSYS model was validated using data recorded at the experimental site between August 11, 2017 and September 27, 2017. The values of the TRNSYS parameters listed in Table 2 were selected based on the recorded data to better represent the performance of the actual system. Average flowrates were calculated for both the subsurface and the building loops and used in the TRNSYS model. An average value of heat gains from the IT equipment was determined based on the measurements of flowrate in the building loop and the temperatures at the inlet and outlet of the heat pumps. Only measurements at times when the difference between the indoor and ambient temperatures was less than 0.5°C were used so that heat transfer to or from the atmosphere was minimized. The inlet and outlet temperatures of the DC were used to determine its heat transfer coefficient. Similarly, the inlet and outlet temperatures of the glycol heat exchanger were used to determine its heat transfer effectiveness. It was not feasible to calculate the building heat loss coefficient from the data recorded at any single point in time due to the sensitivity of this parameter to the fluctuating cooling load. Therefore, the cooling load data was plotted and a value of the building heat loss coefficient was determined that aligned the TRNSYS results most closely with the cooling load recorded at the experimental site.

Component	**Parameter**	**Value**
Building	Heat gains from IT equipment	14.5 [kW]
	Building heat loss coefficient	0.193 [kW/K]
Building loop circulation pumps	Flowrate (1 heat pump running)	0.00132 [m^3/s]
	Flowrate (2 heat pumps running)	0.00240 [m^3/s]
	Power consumption	0.5 [kW]
Subsurface loop circulation pumps	Flowrate	0.00328 [m^3/s]
	Power consumption	0.6 [kW]
Glycol heat exchanger	Heat exchanger effectiveness	0.94
Dry cooler	Heat exchanger coefficient	3.61 [kW/K]
	Power consumption	3.7 [kW]

Table 2: TRNSYS model input values obtained from the experimental data.

The simulated behavior of the system was validated against the data recorded at the experimental site. For this purpose, the ambient temperature input to the TRNSYS model from the TMY3 file was replaced with the recorded local ambient temperature. The data from the experimental site was compared to the TRNSYS results for several important parameters including the BHE outlet temperature shown in Figure 2. The cooling system at the experimental site began operation before the data acquisition system was installed, which explains the lower simulated temperature in TRNSYS compared to the measured temperature at the site during the first 800 hours of operation. After approximately 800 hours, the short-term transient effects in the subsurface became less pronounced and the two sets of results achieved a good agreement.

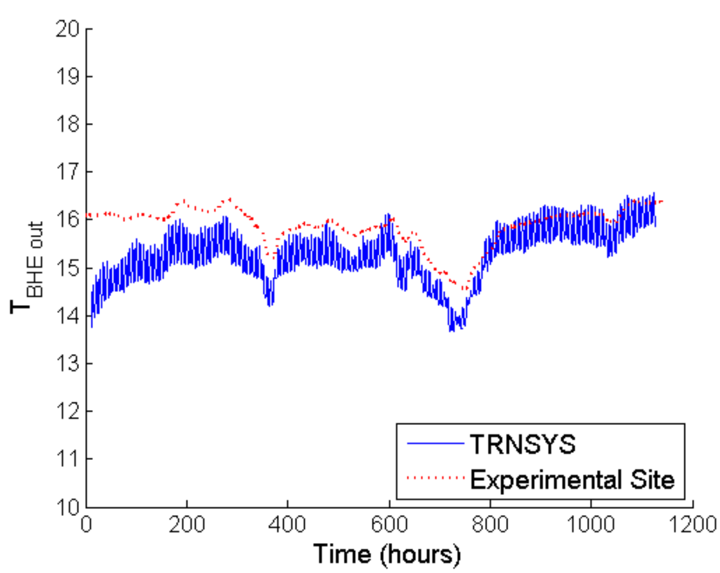

Figure 2: A one-day moving average of the measured temperature of the borehole heat exchanger outlet ($T_{BHE\ out}$) in the experimental system compared to a predicted value from the calibrated TRNSYS model.

3.4 Economic Analysis

The economic performance of the three cooling systems was compared using their total cost of ownership (TCO) defined as a sum of present values of the capital costs, operation costs (including electricity purchased), and maintenance costs of the system over its expected lifetime (20 years). The cost information used for the analysis is presented in Table 3. While the costs of ductwork and installation may vary from site to site, the main cost difference between the geothermal and air-source systems is due to the drilling and installation of the subsurface loop. The cost of the subsurface loop was estimated based on the average cost per foot of BHEs in the Northeast region of the U.S. (Battocletti & Glassley, 2013). The TCO was calculated assuming a real (i.e. inflation adjusted) discount rate of 5%. The electricity cost of 15¢/kWh represents an average rate for commercial customers in New York State (EIA, 2017). No tax incentives, carbon credits, or other environmental benefits as a result of the efficiency improvements of the GHP system were included in the economic analysis of the base case systems, however economic incentives were investigated for the optimized systems in Section 4.2.3.

<table>
<tr><th rowspan="2">Cost Component</th><th colspan="3">Cost for Each Case</th></tr>
<tr><th>GHP</th><th>GHP+DC</th><th>ASHP</th></tr>
<tr><td>Heat pump units (2)</td><td colspan="3">$30,000</td></tr>
<tr><td>Dry cooler</td><td></td><td colspan="2">$7,500</td></tr>
<tr><td>Circulation pumps and piping</td><td colspan="2">$10,000</td><td>$5,000</td></tr>
<tr><td>Ductwork and insulation</td><td colspan="3">$17,000</td></tr>
<tr><td>Control equipment</td><td colspan="2">$6,500</td><td>$5,000</td></tr>
<tr><td>Commissioning and air balance</td><td colspan="3">$2,500</td></tr>
<tr><td>Project management</td><td colspan="3">$4,000</td></tr>
<tr><td>Overhead and profit</td><td colspan="3">$11,000</td></tr>
<tr><td>Drilling and installation of subsurface loop</td><td colspan="2">$52.59/m</td><td></td></tr>
<tr><td>Heat pump maintenance</td><td colspan="3">$300/year</td></tr>
<tr><td>Dry cooler maintenance</td><td></td><td colspan="2">$500/year</td></tr>
<tr><td>Electricity</td><td colspan="3">15.0¢/kWh</td></tr>
</table>

Table 3: Cost data used in the economic analysis given in 2017 USD.

4. RESULTS AND DISCUSSION

4.1 Technical Performance Comparison for the Ithaca Site

Simulated performance of the GHP, GHP+DC, and ASHP systems at the Ithaca site were first analyzed based on coefficient of performance (COP), defined as the ratio of the heat removed from the building to the electricity consumed by the entire cooling system. The year-long averages of COP over the 20 year lifetimes are plotted in Figure 3. As expected, the COP of the GHP system decreased over the lifetime of the system due to the increase in temperature of the subsurface. However, the COP of the GHP system never dropped below that of either the GHP+DC or ASHP systems. The simulated COP of the GHP+DC was less than that of the ASHP due to the frequent operation of the DC fan. For the climate region corresponding to Ithaca, NY, the GHP+DC system would function more efficiently if the control set point for the DC, ΔT_{DC} was set above the 4.4°C value selected in the base case design.

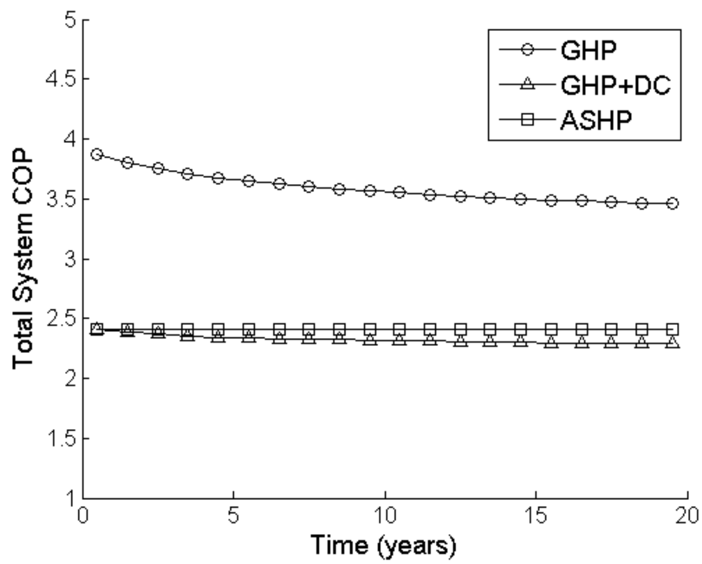

Figure 3: Average yearly system coefficient of performance (COP) over a 20 year lifetime of the geothermal heat pump (GHP), geothermal heat pump with dry cooler (GHP+DC), and air-source heat pump (ASHP) systems installed in Ithaca, NY.

Increases in subsurface temperatures are a potential concern for the cooling systems because higher heat pump inlet temperatures can diminish the total cooling capacity and decrease the overall system performance. The minimum cooling capacities of the GHP and GHP+DC systems achieved after 20 years of operation are presented in Table 4. For the geothermal well field configuration at the Ithaca site, the expected reductions in the cooling capacities of GHP and GHP+DC systems are 4.1% and 1.1%, respectively. It is unlikely that either of these reductions in cooling capacity would pose any significant threat to the data center and the lower performance deterioration of the GHP+DC system does not compensate for its lower COP as compared to the GHP system.

System	Year	Maximum temperature into heat pumps [°C]	Total cooling capacity at maximum temperature [kW]	Percent reduction in total cooling capacity after 20 years
GHP	1	21.8	73.2	4.1%
	20	26.5	70.2	
GHP+DC	1	20.9	73.8	1.1%
	20	22.1	73.0	

Table 4: Total cooling capacity of GHP and GHP+DC systems in the first and 20th year of operation.

4.2 Economic Comparison for the Ithaca Site

The capital cost and TCO of each of the three cooling systems are presented in Table 5. The cooling system installed at the Ithaca site has a total nominal capacity of 70.4 kW_{th}, which is nearly five times more than the average equipment cooling load of 14.5 kW_{th}. Other data center cooling systems would likely have an installed capacity that is about two times greater than the cooling load. The spare cooling capacity provides an added reliability and allows for future expansion of the data center. While the installed capacity impacts the TCO, the following analysis was kept consistent between all three cooling systems.

System	Capital Cost	TCO
GHP	$147,000	$201,000
GHP+DC	$154,000	$243,000
ASHP	$82,000	$169,000

Table 5: Capital cost and the total cost of ownership (TCO) of cooling systems for the Ithaca site.

The analyzed GHP configurations have higher TCO compared to the ASHP as a result of their higher capital cost. However, a more adequately sized subsurface loop, an optimized control scheme, or energy efficiency incentives could improve the economics of the GHP systems. The effects of such changes are analyzed in Sections 4.2.1-4.2.3.

4.2.1 Economic Optimization of the Total Borehole Length for the GHP System

The greatest capital cost component differentiating a GHP system from an ASHP system is the drilling and installation of the subsurface loop. The performance of GHP and GHP+DC systems was simulated for various lengths of the subsurface loop to determine the economically optimal total borehole length assuming no future increases in cooling load. Figure 4 shows the TCO of the GHP system plotted as a function of the total borehole length. The economically optimal value is approximately 760 m, nearly 500 m less than in the base case design. The optimized GHP system has a TCO of $189,000, which is $12,000 less than the TCO of the base case. The TCO of a GHP system with an optimized subsurface loop is $20,000 greater than the TCO of the ASHP system, meaning that the geothermal system requires additional incentives to be more economical than an ASHP.

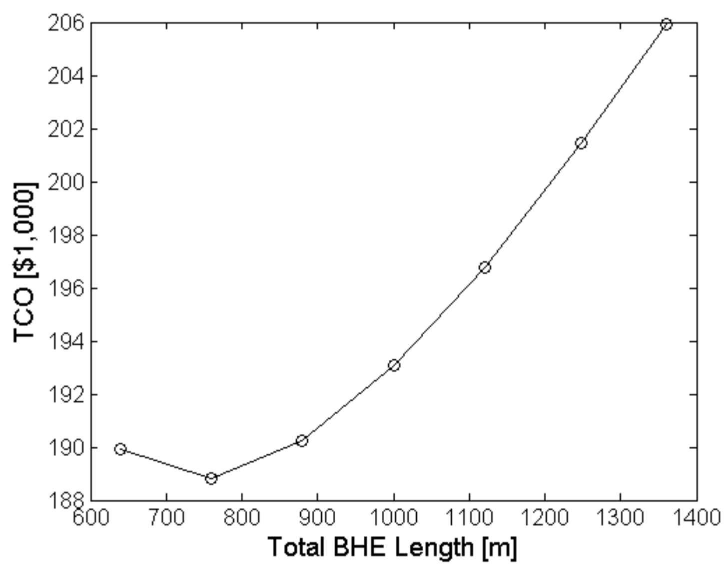

Figure 4: Total costs of ownership (TCO) of GHP systems with various total lengths of borehole heat exchangers (BHEs) for the Ithaca site.

4.2.2 Economic Optimization of Dry Cooler Control Set Point for GHP+DC

The base case results showed that the addition of a DC increased the TCO of a geothermal system. As a next step, the effect of varying the DC control set point was investigated for the previously optimized BHE length of 760 m. The optimal value of ΔT_{DC} (i.e. the minimum difference between the inlet temperatures of glycol and air at which the DC is activated) was approximately 22.2°C (40°F). The GHP+DC system with a ΔT_{DC} of 22.2°C yielded a much higher COP of 2.99 as compared to 2.29 for the ΔT_{DC} of 4.4°C used in the base case design. The optimized GHP+DC system provided slightly higher COP than the GHP system with a COP of 2.84. The reduced electricity consumption of the GHP+DC system was not enough, however, to cover the added capital cost of the DC compared to a GHP system. The COP and TCO of the systems with varying DC control set points are presented in Table 6.

System	COP	TCO
GHP+DC, ΔT_{DC} = 4.4°C (8°F)	2.29	$219,000
GHP+DC, ΔT_{DC} = 16.7°C (30°F)	2.96	$201,000
GHP+DC, ΔT_{DC} = 22.2°C (40°F)	2.99	$200,000
GHP+DC, ΔT_{DC} = 27.8°C (50°F)	2.98	$200,000
GHP	2.84	$189,000

Table 6: Coefficient of performance (COP) and the total cost of ownership (TCO) of GHP+DC systems for various dry cooler control set points (ΔT_{DC}) as compared to a GHP system. The total length of the borehole heat exchangers was set to 760 m for each case.

4.2.3 Economic Incentives

The effect of incentives on the TCO of the optimized GHP and GHP+DC systems were analyzed in two forms. The first was an investment tax credit which would effectively reduce the capital cost of the systems and the second was a utility rebate where a utilities company would incentivize more energy efficient systems with rebates on the saved electricity. The results are presented in Tables 7 and 8. The investment tax credit had a much greater impact on the TCO than the utility rebates. To break even with an ASHP system, the optimized GHP and GHP+DC systems would require investment tax credits of 18% and 24% of their respective capital costs if no utility rebates were provided. However, these results are heavily dependent on the configuration of the system and would differ if the total cooling capacity of the system were reduced.

TCO		Percent of capital cost granted in tax credits			
		0%	10%	20%	30%
Percent of electricity cost reimbursed per kWh saved	0%	$189,000	$177,000	$165,000	$153,000
	10%	$188,000	$175,000	$163,000	$151,000
	20%	$186,000	$174,000	$162,000	$150,000
	30%	$185,000	$173,000	$161,000	$149,000

Table 7: Total cost of ownership of an optimized GHP system for various investment tax credits and utility rebates.

TCO		Percent of capital cost granted in tax credits			
		0%	10%	20%	30%
Percent of electricity cost reimbursed per kWh saved	0%	$200,000	$187,000	$174,000	$161,000
	10%	$198,000	$185,000	$173,000	$160,000
	20%	$197,000	$184,000	$171,000	$158,000
	30%	$195,000	$182,000	$169,000	$157,000

Table 8: Total cost of ownership of an optimized GHP+DC system for various investment tax credits and utility rebates.

5. PRELIMINARY NATIONWIDE ANALYSIS

5.1 U.S. Representative Site Results

A preliminary analysis of the technical and economic performance of hybrid GHP systems for data center cooling was conducted for three other U.S. cities: Dallas, TX, Sacramento, CA, and Minneapolis, MN. The cities chosen for the preliminary analysis were intended to represent different climate zones in the U.S. and different prices of electricity. The ambient temperature inputs to the TRNSYS model were modified using TMY3 files for each respective city. The BHE models were modified using the average ambient temperature from the respective TMY3 files for the far-field soil temperature and the soil thermal conductivity values were estimated using hydrogeological data (Thomas, 1952; Heath, 1984; Schruben, et al., 1997; Soller, et al., 2009; USGS, 2014). The process of estimating soil thermal conductivities is outlined in further detail in Aguirre et al. (2017). The well field configuration was not optimized for each location. Instead, the total BHE length was adjusted for each site based on the prior study of geothermal cooling systems for cellular tower shelters (Aguirre, 2018). The values of total BHE length used for the nationwide cellular tower study were used to scale the optimized value of BHE length for the Ithaca site. The modified TRNSYS inputs for each city are presented in Table 9.

City	Dallas, TX	Sacramento, CA	Minneapolis, MN
Far-field temperature [°C]	18.7	15.5	7.7
Thermal conductivity of the soil [W/m-K]	2.1	2.5	2.6
Total borehole length [m]	1552	1248	760

Table 9: Modified TRNSYS inputs for the analysis of other locations.

The COPs of the cooling systems for each city and the expected reduction in cooling capacity for the GHP and GHP+DC systems after 20 years are presented in Tables 10 and 11. The ASHP system in Dallas had the lowest COP due to the high average ambient temperature. Even though the total borehole length used for the simulations of the geothermal systems in Dallas was more than twice that of the length used in the optimized simulations for Ithaca, their COPs were lower.

City	System	COP
Dallas, TX	GHP	2.66
	GHP+DC	2.71
	ASHP	1.98
Sacramento, CA	GHP	2.80
	GHP+DC	2.84
	ASHP	2.15
Minneapolis, MN	GHP	2.72
	GHP+DC	2.97
	ASHP	2.34

Table 10: COP of cooling systems for Dallas, TX, Sacramento, CA, and Minneapolis, MN.

City	System	Total cooling capacity at maximum temperature [kW]		Percent reduction in total cooling capacity after 20 years
		Year 1	Year 20	
Dallas, TX	GHP	66.4	60.8	8.4%
	GHP+DC	66.6	62.8	5.7%
Sacramento, CA	GHP	67.6	62.2	8.0%
	GHP+DC	67.8	64.6	4.7%
Minneapolis, MN	GHP	67.0	60.4	9.9%
	GHP+DC	67.2	63.8	5.1%

Table 11: Reduction in total cooling capacity of GHP and GHP+DC systems in Dallas, TX, Sacramento, CA, and Minneapolis, MN resulting from increase in the subsurface temperature.

City	System	Price of electricity	Subsurface Loop Cost	Capital cost	TCO
Dallas, TX	GHP	8.2¢/kWh	$49.02/m	$157,000	$204,000
	GHP+DC			$165,000	$218,000
	ASHP			$82,000	$152,000
Sacramento, CA	GHP	17.0¢/kWh	$48.03/m	$141,000	$227,000
	GHP+DC			$148,000	$240,000
	ASHP			$82,000	$200,000
Minneapolis, MN	GHP	10.7¢/kWh	$42.62/m	$113,000	$164,000
	GHP+DC			$121,000	$174,000
	ASHP			$82,000	$147,000

Table 12: Results of the economic analysis for data center cooling systems in Dallas, TX, Sacramento, CA, and Minneapolis, MN.

The TCO for each location were evaluated using the cost information listed in Table 3. The price of electricity was modified to represent the average rate in each state (EIA, 2017) and the cost of drilling and installation of BHEs is a regional average (Battocletti & Glassley, 2013). Table 12 provides results of the economic analysis for all three locations without consideration of any economic incentives or tax credits. Of the cities analyzed, Minneapolis had the smallest difference in TCO between the GHP and ASHP systems at

$17,000, despite the fact that the difference in COPs between the two systems was the smallest for this city. This is likely due to the low cost per meter of the subsurface loop and moderate electricity price. Dallas had the greatest difference in TCO at $52,000 despite the largest difference in COPs. This is likely due to the low price of electricity for Dallas. Preliminary analysis suggests that economic parameters are typically a greater determinant of TCO than the relative efficiencies of the systems.

5.2 Future Work

Expanding on our preliminary analysis of three representative locations, future work will include a nationwide assessment of the technical and economic performance of geothermal and air-source heat pumps for cooling data centers. The results of this analysis should allow for the TCO of the systems to be expressed as a function of the climate, the thermal conductivity of the soil, the cost of installing BHEs, and the price of electricity. Additionally, other system components will be modeled including a waterside economizer used to provide low cost cooling at low ambient temperatures and a variable frequency drive used to reduce electricity consumption of the DC fan. The control scheme and placement of the DC may also be altered to allow the DC to exclusively cool the building loop or exclusively recharge the subsurface.

6. CONCLUSIONS

This paper evaluated the thermodynamic and economic performance of heat pumps used for cooling small, regionally located data centers. Numerical models developed in TRNSYS software were validated using an experimental geothermal heat pump cooling system located in Ithaca, NY, USA. The simulated performance of geothermal heat pump (GHP) and geothermal heat pump with dry cooler (GHP+DC) cooling systems were compared to a traditional air-source heat pump (ASHP) using the validated models. Although the coefficient of performance of the base case GHP system was significantly higher than that of either the GHP+DC or ASHP systems, the electricity savings based on current electricity prices did not outweigh the added capital costs associated with the installation of borehole heat exchangers. However, economic optimization of the total borehole length and the dry cooler temperature set point ΔT_{DC} made the GHP and GHP+DC systems more competitive, lowering their total cost of ownership (TCO) to within 12% ($20,000) and 18% ($31,000) of the ASHP system respectively. These cost differences could reasonably be made up for through economic incentives, which may come in the form of investment tax credits or utility rebates based on the portion of electricity saved over an ASHP system. The GHP would require an investment tax credit of 18% of the capital cost and the GHP+DC system would require an investment tax credit of 24% of the capital cost to break even with the ASHP system. There are other advantages of GHP systems that are not fully quantified by the metrics of technical and economic performance used in this paper. One key environmental advantage that was not accounted for is that the higher COP of GHPs lowers the carbon footprint associated with cooling a specific data center in an amount that is directly proportional to the carbon emissions of the electric power generating system in the region. Additional advantages include the added security of a GHP system whose critical equipment would be located indoors or underground, less frequent maintenance, and the electric capacity freed up by using a more efficient cooling system which could have implications for data center capacity upgrades.

A preliminary analysis of three representative cities was conducted to gage the sensitivity of the technical and economic performance of the cooling systems to factors such as climate, thermal conductivity of the soil, price of electricity, and cost of drilling and installation of the subsurface loop. Our analysis suggests that the price of electricity and cost of the subsurface loop have a greater impact on the TCO than the relative efficiencies of the systems, which are dependent on the climate and soil properties.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge Verizon Communications for their major financial support of this work. The authors would also like to thank Charles Kellum, David Hampton, and Sean Clements from Verizon, Caren Rubin from Labella Associates, Rodney Scouten from Day Automation Systems, Chris Lesperance from Lono Mechanical, and Thomas Piekunka from RF Peck for their collaboration and continued advice on this project. The Cornell Energy Institute and the Atkinson Center for a Sustainable Future are also acknowledged for their partial support.

REFERENCES

Aguirre, G. A., Beckers, K. F., Lukawski, M. Z. & Tester, J. W., 2017. *Hybrid Ground-Source Heat Pumps for Cooling Cellular Tower Shelters : from Campus Living Laboratory to Nationwide Deployment.* Stanford, CA, s.n.

Aguirre, G. A., Cornell University, Earth and Atmospheric Sciences, personal communication, January 1, 2018

Battocletti, E. C. & Glassley, W. E., 2013. *Measuring the costs and benefits of nationwide geothermal heat pump deployment,* Davis, CA: U.S. Department of Energy, Geothermal Technologies Program under Award Number DE-EE0002741.

Beckers, K. F., Yavuzturk, C. C. & Tester, J. W., 2014. *Techno-Economic Modeling and Monitoring of Hybrid Ground-Source Heat Pump System with Borehole Heat Exchangers for Cooling-Dominated Cellular Tower Application.* Montréal (Québec) Canada, s.n.

Beckers, K. J. H. F., 2016. *Low-temperature geothermal energy: systems modeling, reservoir simulation, and economic analysis.* Ithaca, NY: Cornell University.

ClimateMaster, 2017. *ClimateMaster Tranquility Compact Belt Drive (TC) Series.* [Online] Available at: http://www.climatemaster.com/commercial/?cm_product=compact-belt-drive-heat-pump-tranquility-compact-tc-belt-drive-series [Accessed 2017].

EIA, 2017. *Electric Power Monthly with Data for October 2017.* [Online] Available at: https://www.eia.gov/electricity/monthly/archive/december2017.pdf [Accessed January 2018].

Heath, R. C., 1984. *Ground-Water Regions of the United States.* Washington, DC: United States Geological Survey.

Klein, S. et al., 2014. *TRNSYS 17.* [Online] Available at: http://www.trnsys.com/

NREL, 2005. *National Solar Radiation Data Base.* [Online] Available at: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html [Accessed 2017].

Thomas, H.E., 1952. *Ground-water Regions of the United States: Their Storage Facilities*.

Schruben, P.G., Arndt, R.E. and Bawiec, W.J., 1997. Geology of the conterminous United States at 1: 2,500,000 Scale–A Digital Representation of the 1974 PB King and HM Beikman Map: US Geol. *Survey Digital Data Series DDS–11 (Release 2), CD-ROM (available on World Wide Web at http://minerals. usgs. gov/kb/)*.

Soller, D. R., Reheis, M. C., Garrity, C. P. & Van Sistine, D. R., 2009. *Map Database for Surficial Materials in the Conterminous United States,* Reston, VA: United States Geological Survey.

Song, Z., Zhang, X. & Eriksson, C., 2015. Data Center Energy and Cost Saving Evaluation. *Energy Procedia,* pp. 1255-1260.

Urchueguía, J. F. et al., 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 Conversion and Management,* Volume 49, pp. 2917-2923.

USGS (United States Geological Survey), 2014. *Geologic Units Containing Earth Material, Mineral Resources On-Line Spatial Data.* [Online] Available at: http://mrdata.usgs.gov/geology/state/sgmc-lith.php?code=root

Wilcox, S. & Marion, W., 2008. *User's Manual for TMY3 Data Sets.* [Online] Available at: https://www.nrel.gov/docs/fy08osti/43156.pdf