Techno-Economic Modeling and Monitoring of Hybrid Ground-Source Heat Pump System with Borehole Heat Exchangers for Cooling-Dominated Cellular Tower Application

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Abstract: The technical and economic performance of a hybrid ground-source heat pump system satisfying the cooling requirements of a cooling-dominated cellular tower shelter were investigated. An experimental full-scale ground-coupled heat pump system is described that is designed to meet an annual cooling demand of approximately 60 MWh. The system is equipped with a dry-cooler for reservoir recharging, an air-economizer for cooling with cold ambient air, and an extensive data acquisition and monitoring system to assess the behavior of the geothermal reservoir and surface components. The reservoir consists of 4 single-U and 2 double-U borehole heat exchangers, an open-hole water monitoring well and several temperature monitoring wells. Further, a simplified techno-economic model is presented to simulate the performance of these systems and to explore their potential to replace traditional wall-mounted air-source air conditioning units. Preliminary results show that the ground-source heat pump with air-economizer but without dry-cooler has the lowest life cycle cost of 5 cases analyzed, although closely followed by the air-source unit with air-economizer.

Key Words: hybrid ground-source heat pump, geothermal cooling, techno-economic simulation, cooling-dominated application, borehole heat exchangers, cellular towers

1 INTRODUCTION

Geothermal or ground-source heat pumps (GSHP) utilize the relatively shallow ground as a thermal source or sink at moderate temperatures to efficiently provide space and water heating and/or cooling. Depending on many factors, including the local climate, the electricity, natural gas and fuel oil prices, and the efficiency and CO_2 emissions intensity of power plants, GSHP are often superior in terms of energy-efficiency, cost-effectiveness and CO_2 emissions to conventional systems including natural gas or oil furnaces, electrical heaters and traditional air-source space conditioning (HVAC) units (Omer, 2008; Self et al., 2013).

GSHP are mainly used for climate control in residential and commercial buildings. However, several other applications that require heating and/or cooling at moderate temperatures could be served by GSHP, e.g. snow melting of parking lots, heating of swimming pools, fermentation and pasteurization in the food industry, and heating and cooling of greenhouses (Gudmundsson et al., 1985; Lund, 2010). Furthermore, GSHP systems may be considered for climate control of cellular tower shelters which is discussed in this paper.

The equipment at a cellular site other than the antennas are typically housed in a shelter for protection against environmental conditions and vandalism. The equipment comprise batte-

ries, cabling, and telecommunication electronics and generates roughly 8 kW_{th} of internal heat that remains fairly constant year-round. Given the construction specifications and space use characteristics, the thermal load inside the shelter is usually cooling-dominated, even in colder climates, with wall-mounted air-source HVAC units being the standard cooling option.

In a recent "proof-of-concept" study conducted in our group in collaboration with Verizon Wireless, Labrozzi et al. (2010) have shown that a GSHP in combination with air-economizers presents a cost-effective and energy-efficient alternative to conventional air conditioning units. An experimental system with a full-scale hybrid GSHP was recently developed to provide the climate control of a cellular shelter at a new tower site on the grounds of the Cornell University campus. The set-up includes 6 borehole heat exchangers (BHEs), 3 ground-coupled heat pump units, an air-economizer, a dry-cooler for geothermal reservoir recharging and a data monitoring and logging system to closely observe the performance of the geothermal reservoir and hybrid cooling system.

In Section 2, the experimental hybrid GSHP system is discussed in more detail, along with a diagram of the set-up and a full list of the sensors installed. Section 3 develops a preliminary techno-economic model to perform hourly simulations of the system. All relevant equations governing the heat pump system, dry-cooler, reservoir and borehole heat transfer, and the economic model are provided. The model has been applied to several simplified cases to assess the technical and economic potential of the hybrid GSHP system for use in cooling-dominated cellular tower shelters. The simulation results are provided in Section 4. Finally, Section 5 provides concluding remarks and discusses the future work on this project.

2 EXPERIMENTAL HYBRID GEOTHERMAL HEAT PUMP SYSTEM

After the promising study of Labrozzi et al. in 2010, design of a full-scale experimental hybrid GSHP system started in the Fall of 2011. The permitting process delayed the project during 2012, however, construction eventually started in the Spring of 2013. The system start-up phase was completed by the end of 2013 and currently all telecommunication, heat pump and data acquisition equipment are in full operation. The main objective of this research project is to monitor the technical and economic performance of the hybrid GSHP system providing the climate control of the cellular tower shelter. In addition, operational data on the geothermal reservoir, BHEs and heat pumps are collected to validate models that describe the heat transfer in the underground system and the performance of the heat pump units. Figure 1 shows the set-up during construction in September 2013.

Due to relatively cold winters in Upstate New York, a hybrid system was designed that includes an air economizer (AE) and dry-cooler (DC). The AE provides cold outside air into the shelter when the ambient temperature drops below a certain set-point, which allows the geothermal reservoir to thermally recover as no heat rejection from the shelter to the ground is then taking place. When the ambient temperature drops even further, the DC actively cools down the reservoir ("recharging") to offset the imbalance in heat exchange and enhance the long-term performance of the GSHP. The projected annual cooling demand of the shelter is about 60 MWh (200 million BTU) of which 30 MWh is covered by the AE, mainly during the winter, and 30 MWh by the GSHP, mainly during the summer (see Section 3). The peak hourly load is estimated at 7.8 kW_{th} (26,700 Btu/hour).

The BHE field consists of 4 single-U heat exchangers (117 m depth each) and 2 double-U heat exchangers (87 m depth each) with each set of supply and return pipes individually controlled by a valve. The BHEs are located relatively close to each other (5.5 to 7.8 m) so that significant thermal interference is expected. The total BHE length is almost 650 m, about three times larger than the recommended length by the International Ground Source Heat Pump Association (IGSHPA, 2009) for these conditions. The reasons for this surplus of BHE



Figure 1: Picture taking during construction in September 2013, showing the equipment shelter in the middle and the monopole cellular tower on the right.

length are (1) a potential future expansion of cellular equipment which will increase the rate of heat generation, (2) to allow collecting experimental data on both single-U and double-U BHEs, and (3) to allow investigating different BHE field management options, e.g. rotating between BHEs or making strategic use of the anticipated groundwater flow in the reservoir. The three heat pump units are identical two-stage 7 kW_{th} water-to-air heat pumps which operate rotationally in lead, lag, and standby mode. Figure 2 shows the lay-out of the cellular site with the location of the BHEs.

The monitoring system logs the ambient temperature and humidity, the inside temperature, the fluid flow rate of each BHE, the fluid supply and return temperatures of the BHE field, the fluid supply and return temperature and fluid flow rate of each heat pump, the power consumption of different components, and the reservoir temperature at 30 different locations. These reservoir temperature sensors are distributed over 1 single-U BHE, 1 double-U BHE, and 3 monitoring wells (see Figure 2). In each well, the sensors are equally spaced at 5 different depths and are installed in duplicate for a total of 60 field temperature measurements. Since groundwater flow was observed during drilling and the in-situ thermal response test (TRT), an open-hole water monitoring well was also installed. This well is not permanently equipped with sensors but allows lowering a tool at regular times to assess groundwater presence. Moreover, it is anticipated that the large number of reservoir temperature sensors will reveal information on groundwater flow as well. In order to capture short-term heat pump and BHE behavior along with long-term reservoir and system performance, the data acquisition frequency is set at once per minute. In addition, a fully-equipped weather station is located about 300 m away from the cellular site. This weather station collects hourly data on ambient temperature, humidity, solar radiation, rain and snow fall, wind speed, wind direction and soil temperature at 4 and 8 inch (10 and 20 cm) depths.

A characterization of the geology, hydrogeology and stratigraphy of the geothermal reservoir at the cell tower location was also performed. Drilling revealed groundwater flow is present in a reservoir consisting mainly of shale with a 36 m thick layer of unconsolidated glacial and alluvial sediments on top. From a 96-hour TRT, the average effective reservoir thermal conductivity was estimated to be 3.5 W/mK. This relatively high value in combination with the highly fluctuating TRT average temperature is most likely explained by groundwater flow. Furthermore, rock samples from a nearby shale outcrop were taken, drill cuttings from one well were collected every 6 m (20 ft), and a seismic survey with 64 geophones spaced 0.9 m (3 ft) apart was conducted.

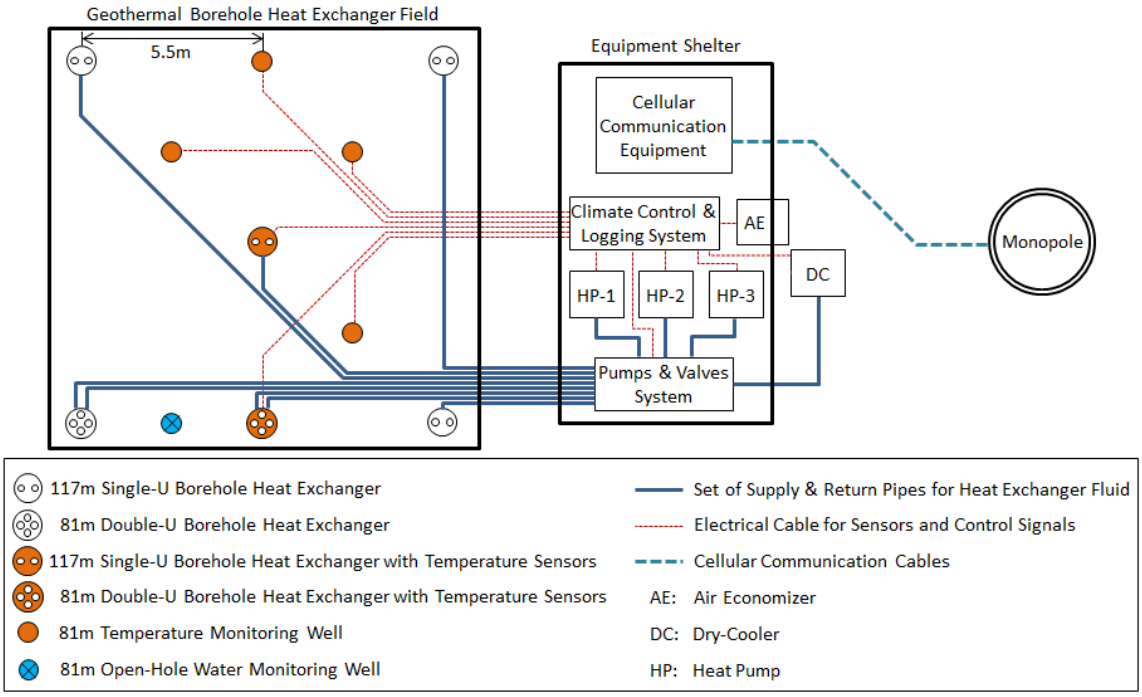


Figure 2: Lay-out of borehole heat exchanger field, equipment shelter and cellular tower.

3 THERMO-ECONOMIC MODEL OF SYSTEM

A simplified hourly techno-economic model has been developed to make preliminary long-term cost and performance predictions of a hybrid GSHP system and to compare with other shelter climate control options. This section provides the relevant equations to predict the cooling demand, the heat transfer in the geothermal reservoir and the performance of the heat pump, air economizer and dry-cooler. Also the equations to simulate a wall-mounted HVAC unit (based on the manufacturer's data sheet) and the economic model are included.

3.1 Ambient Temperature and Shelter Cooling Demand

The Typical Meteorological Year version 3 (TMY3) dataset for Syracuse, NY developed by NREL (Wilcox and Marion, 2008) is used to represent the hourly ambient temperature T_{amb} at the cellular site each year. Figure 3 shows T_{amb} in addition to the shelter set-point temperature T_{set} (21.1°C or 70°F), the set-point temperature below which the air economizer is activated T_{AE} (10°C or 50°F) and the set-point temperature below which the dry-cooler is activated T_{DC} (4.4°C or 40°F).

The shelter has a total wall and ceiling area of 66.9 m^2 with an R-value of 2.3 Km^2/W which results in a thermal conductance UA of 29.2 W/K with UA defined as the product of the overall heat transfer coefficient and surface area. Neglecting the thermal capacitance of the shelter and the heat losses through the floor, and assuming 1-dimensional heat exchange with the environment, the hourly cooling demand of the shelter Q_s is estimated as:

$$Q_s = 7500 + 29.2 \times (T_{amb} - 21.1) \quad (1)$$

Equation (1) represents a steady state heat balance with a constant heat generation of 7.5 kW$_{th}$ by the telecommunication equipment. For short time-scales, this model is not expected to be highly accurate, however, for multi-year simulations, as is the scope in this study, it is stipulated this approach will yield on average sufficiently accurate cooling demand predictions.

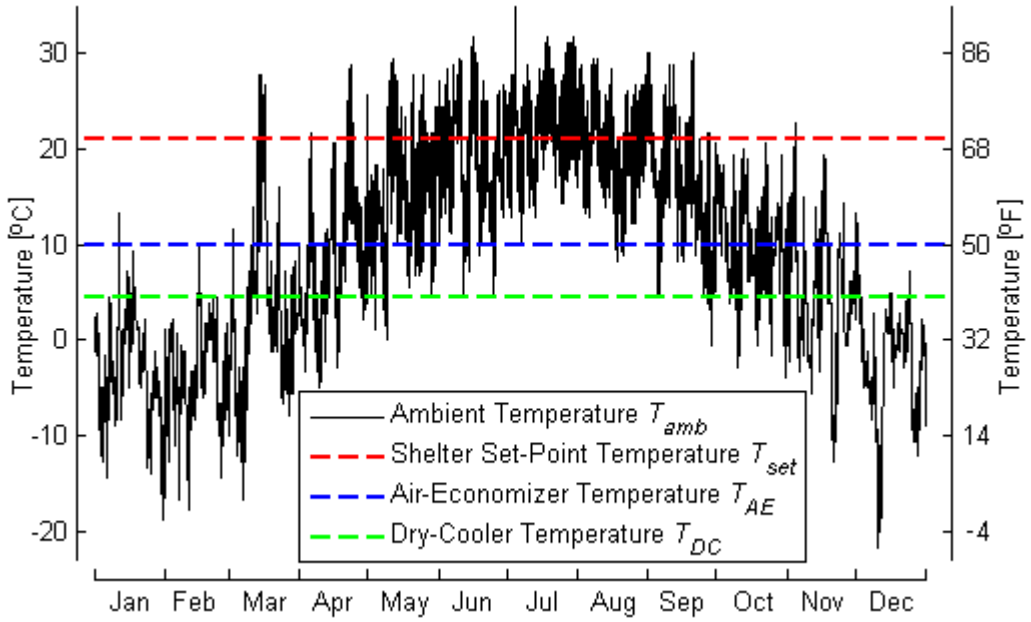


Figure 3: Test site ambient air temperature from TMY3 data and shelter, air-economizer, and dry-cooler set-point temperatures taken at the experimental site.

Figure 4 shows for each month the contribution of the AE and GSHP to the shelter cooling.

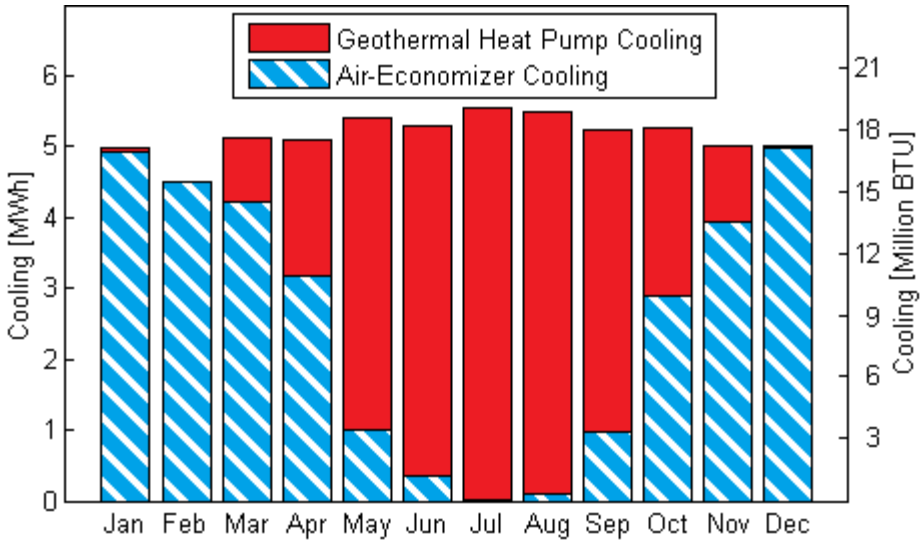


Figure 4: Shelter cooling demand covered by AE (striped blue bars) and GSHP (solid red bars)

3.2 Mathematical Model of Hybrid Geothermal Heat Pump System

The two-region model by Yang et al. (2009) is applied to simulate the geothermal reservoir and BHEs. The datasheets provided by the manufacturers are utilized to develop curve-fit correlations to simulate the dry-cooler, air-economizer and heat pump units.

3.2.1 Geothermal heat pump unit model

A simple steady-state energy balance is applied to the heat pump units. Their coefficient of performance *COP* is represented by an empirically fitted equation as a function of the reservoir return temperature T_{out} (in °C). The heat exchange rate with the reservoir Q_r can then be estimated as:

$$Q_r = Q_s + Q_s/COP = Q_s + Q_s \times (0.000116 \times T_{out}^2 + 0.000229 \times T_{out} + 0.08727) \quad (2)$$

3.2.2 Heat transfer modeling inside BHE

The heat transfer inside the BHEs is simulated by a counterflow heat balance model (Hellström, 1991; Yang et al., 2009), which is also called the quasi-3D model (Zeng et al., 2003). This model relies on the Delta-circuit which takes thermal short circuiting into account (Hellström, 1991). The BHE heat transfer in this counterflow model is assumed steady-state, which is considered a reasonable assumption for long-term simulations (Yang et al., 2009). The equations for a single-U BHE are provided below. For a double-U BHE, they can be found in the work by Zeng et al. (2003). For each single-U BHE, the relation between the BHE supply temperature (T_{in}) and return temperature (T_{out}) is given by:

$$(T_{out} - T_b)/(T_{in} - T_b) = \big(\cosh(\beta) - K \times \sinh(\beta)\big)/\big(\cosh(\beta) + K \times \sinh(\beta)\big) \quad (3)$$

with K and β calculated as:

$$K = \sqrt{(R_{11} - R_{12})/(R_{11} + R_{12})}, \quad (4)$$

$$\beta = L_{BHE}/\Big(\dot{m}_{BHE} c_{p,fluid} \sqrt{(R_{11} + R_{12})(R_{11} - R_{12})}\Big) \quad (5)$$

In these equations, L_{BHE}, $\dot{m}_{BHE}$, $c_{p,fluid}$ *and* T_b are the length, fluid mass flow rate, fluid heat capacity and wall temperature (see Section 3.2.3) of the BHE, respectively. R_{11} and R_{12} are thermal resistances which are calculated using a 10th order multipole method presented by Bennet et al. (1987).

3.2.3 Heat transfer modeling in soil outside BHE

The transient heat transfer model for the soil, outside each BHE, relies on a combination of the Cylindrical Source Model (CSM) and the Kelvin line Source Model (KSM). Each BHE is modeled using the CSM as an infinitely long cylinder with borehole radius r_b and constant heat flux along the BHE (but not constant over time) (Yang et al., 2009). The thermal contribution at each BHE from the other BHEs (thermal interference) is included by applying the KSM to all other BHEs (Carslaw and Jaeger, 1947). The wall temperature $T_{b,j}$ for BHE j is calculated at time step t (in hours) as:

$$\begin{aligned} T_{b,j} = {} & T_0 + Q_{j,t} \times C(1) + \textstyle\sum_{i=1}^{t-1} Q_{j,i} \times [C(t-i+1) - C(t-i)] \\ & + \textstyle\sum_{n=2}^{N} Q_{n,t} \times K(s,1) + \sum_{n=2}^{N} \sum_{i=1}^{t-1} Q_{n,i} \times [K(s,t-i+1) - K(s,t-i)] \end{aligned} \quad (6)$$

The indices i and n are the time step and the BHE index, respectively. Further, T_0 is the initial or far-field reservoir temperature, $Q_{j,t}$ the total heat transfer from BHE j at time step t (in hours), N the total number of BHEs, s the spacing between BHE j and i, and C and K the CSM and KSM equations which are calculated as:

$$C(t) = 2/(k\pi^3 L_{BHE}) \int_0^\infty \Big(1 - \exp\big(-z^2 \times \alpha \times 3600 \times t/r_b^2\big)\Big)/\Big(z^3 \Big(J_1^2(z) + Y_1^2(z)\Big)\Big)\, dz \quad (7)$$

$$K(s,t) = 1/(4\pi k L_{BHE}) \times \mathrm{expint}(-s^2/(4 \times \alpha \times 3600 \times t)) \quad (8)$$

In equations (7) and (8), k, α, expint, J_1 and Y_1 are the soil thermal conductivity, soil thermal diffusivity, exponential integral function, 1st order Bessel function of the first kind and 1st order Bessel function of the second kind, respectively.

No experimental model validation is included in this paper; however, Yang et al. (2009) showed good agreement of the presented two-region model with experimental data for a long-term hourly simulation. Also, groundwater flow is omitted in this model but it could be accounted for by using e.g. the Moving Line Source Model (Molina-Giraldo et al., 2011).

3.2.4 Air-economizer (AE) model

When the AE is activated, the GSHP units are turned off and the geothermal reservoir can thermally recover. A fan (rated air flow capacity of 802 L/s at 1 atm and 21.1 ºC (70 ºF) and power consumption of 560 W (0.75 HP)) drawing cold outside air into the equipment shelter is the only cooling equipment running. The actual design allows for more complex operation such as simultaneous running of AE and heat pumps or active reservoir recharging by cooling the heat exchanger fluid with the AE; however, these modes have not been implemented in the model presented in this paper.

3.2.5 Dry-cooler (DC) model

When the DC is running, the geothermal reservoir will actively recharge (cool down) by using the cold outside air to cool down the heat exchanger fluid. The DC is equipped with a 0.66 m diameter outside fan having a power consumption of 560 W (0.75 HP) and rated air flow capacity of 3115 L/s. When assuming no heat losses from the DC to the reservoir, the heat extracted from the reservoir Q_r is calculated as (based on the manufacturer's datasheet):

$$Q_r = (T_{out} - T_{amb}) \times 501.2 \times (-0.291 \times \dot{m}^2 + 1.569 \times \dot{m} + 1.700) \quad (9)$$

with T_{out} the reservoir return temperature. This equation should only be used for a 40% ethylene – 60% water mixture with a mass flow rate $\dot{m}$ between 0.5 and 2.5 kg/s. Further, both during regular heat pump and DC operation, the ground loop circulation pump is assumed to consume 250 W.

3.2.6 Wall-mounted air-conditioning (HVAC) unit

The power consumption W of a traditional wall-mounted HVAC unit is estimated using an empirical equation for the *COP* based on the datasheet provided by the manufacturer:

$$W = Q_s / (-0.0367 \times T_{amb} + 3.9234) \quad (10)$$

3.2.7 Economic model

The economic comparison between each shelter cooling option is based on a Life Cycle Cost (LCC) model, with CF_y the cash flow in year y, lt the system lifetime (in years), dr the discount rate and ir the inflation rate:

$$LCC = \sum_{y=0}^{lt} CF_y / (1 + dr - ir)^y \quad (11)$$

For the hybrid GSHP system, the initial cost consists of the capital expenditures for the borehole field, heat pump units, dry-cooler and air economizer. Each following year, the cash flow consists of the cost for equipment maintenance (e.g. system check and filter replacement) and electricity consumption of heat pumps, fans and circulation pump.

3.2.8 Model coupling and computer implementation

The final equation is the energy balance that couples the geothermal reservoir supply temperature T_{in}, return temperature T_{out}, total heat exchange rate Q_r and total fluid mass flow rate $\dot{m}$:

$$Q_r = \dot{m} \times c_{p,fluid} \times (T_{in} - T_{out}) \quad (12)$$

In a symmetrical reservoir where each BHE performs identically, as will be the case in the scenarios investigated in Section 4, the supply and return temperature of each BHE equals the overall reservoir supply and return temperature. In addition, the heat exchange through each BHE is then equal to the total reservoir heat exchange rate (Q_r) divided by the number of boreholes (N). The same holds for the heat exchanger fluid flow rate. For non-symmetrical reservoirs, as is the case for the actual set-up, each BHE will have to be treated separately.

All equations have been implemented in the computer software MATLAB. For each hour during a simulation over the lifetime of the system, the cooling demand Q_s is first determined using Equation (1). Based on the ambient temperature, it is then decided whether the system is in normal GSHP mode, AE mode or DC mode. During normal GSHP mode, equations (2-8) and (12) are applied. This means for the symmetrical reservoirs studied in Section 4, each hour during GSHP mode, a closed system of 4 equations is solved for the 4 unknowns Q_r, T_{in}, T_{out}, and T_b. These 4 equations are equation (2) which gives a relation between Q_r and T_{out} based on the heat pump correlation, equation (3) which gives a relation between T_{in}, T_{out} and T_b using the quasi-3D BHE model, equation (6) which gives a relation between T_b and the current and historical Q_r using the Cylindrical and Kelvin Line Source Models, and finally equation (12) which couples Q_r with T_{in} and T_{out} using an overall energy balance. Note that thermal interference between the BHEs is accounted for, even though the equations for only 1 BHE are included since the reservoir is symmetrical and all BHEs perform identically. During DC mode, the same equations are solved for except equation (2) is now replaced by equation (9) which represents the DC unit. Eventually, the electricity consumption for each year can be calculated and, combined with the annual maintenance and initial capital cost, the LCC of the system is estimated using equation (11). For the traditional HVAC system, with or without AE, only equations (1), (10) and (11) are applicable.

4 SIMULATION CASES AND PARAMETERS, RESULTS AND DISCUSSION

4.1 Simulation Cases and System and Economic Parameters

An actual commercial hybrid GSHP system for climate control of a cellular shelter will most likely be simpler than the experimental set-up described in Section 2. Therefore, to make realistic predictions of the commercial potential, the techno-economic model presented in the previous section has been applied to a set-up with the same cooling demand but with no monitoring system, only 2 heat pump units (no 3rd standby unit), and a symmetrical geothermal reservoir with only 2 or 3 identical single-U BHE (instead of 4 single-U and 2 double-U BHE). Three different GSHP cases were investigated, one without AE and DC (case 1), one with AE but no DC (case 2) and one with both AE and DC (case 3). In addition, the climate control systems using wall-mounted HVAC units without AE (case 4) and with AE (case 5) were included in the analysis.

The borehole length was optimized in each GSHP case for minimum LCC. Other parameters such as flow rates and set-point temperatures were not optimized; instead their values were taken the same as at the experimental set-up. In terms of the cooling demand, Figure 4 applies directly to case 2 and 3 and indirectly to case 5 (the red solid bars represent the HVAC cooling in that case). For cases 1 and 4, the cooling demand covered by the GSHP and HVAC, respectively, are represented by the total height of the bars in Figure 4.

For the GSHP cases, the heat exchanger fluid is a 40% ethylene – 60% water mixture which has a freezing temperature around -25°C. Typical sedimentary rock thermo-physical properties were taken (Gehlin, 2002) and no groundwater flow was assumed. Since groundwater flow will enhance the diffusion of heat in the reservoir, a worse case is simulated in this study. Further, the same flow rate of the heat exchanger fluid was taken

both during normal GSHP and DC operation; in the actual set-up these can be different. Finally, the GSHP units have a 20 years lifetime while the outside, wall-mounted HVAC units are replaced every 10 years. Table 1 lists all system and economic parameters.

Table 1: System and economic parameter values for a design cooling load of 7.5 kW_{th}

Parameter	Symbol	Value
Soil thermal conductivity	k	2 W/mK
Soil thermal diffusivity	α	10^{-6} m^2/s
Grout thermal conductivity	k_{grout}	1.73 W/mK
Heat exchanger fluid thermal conductivity	k_{fluid}	0.34 W/mK
Heat exchanger fluid heat capacity	$c_{p,fluid}$	2864 J/kgK
Heat exchanger fluid density	ρ_{fluid}	1094 kg/m^3
Heat exchanger fluid dynamic viscosity	μ_{fluid}	0.0099 kg/ms
U-tube pipe thermal conductivity	k_{pipe}	0.6 W/mK
U-tube pipe outer radius	$r_{pipe,outer}$	0.02108 m
U-tube pipe inner radius	$r_{pipe,inner}$	0.01699 m
U-tube center-to-center distance	x	0.053 m
Borehole radius	r_b	0.0889 m
Borehole-to-borehole spacing	s	5.5 m
Total BHE fluid mass flow rate	$\dot{m}$	0.62 kg/s
Far-field soil temperature	T_0	9.2°C
Lifetime system	lt	20 years
Inflation rate	ir	2 %
Discount rate	dr	5 %
Electricity rate	el	14 ¢/kWh
GSHP unit capital cost	CAP_{GSHP}	$5000
Drilling capital cost	$CAP_{Drilling}$	$50/m
Dry-cooler capital cost	CAP_{DC}	$750
Air-economizer capital cost	CAP_{AE}	$500
HVAC unit capital cost	CAP_{HVAC}	$2500
HVAC unit with built-in AE capital cost	$CAP_{HVAC+AE}$	$3000
GSHP maintenance cost	MTN_{GSHP}	$200/year
HVAC maintenance cost	MTN_{HVAC}	$580/year

4.2 Simulation Results and Discussion

The results for the LCC and optimized borehole length are shown in Table 2. Case 2 (GSHP + AE) is the most cost-effective option but is closely followed by case 5 (HVAC + AE). Installing a DC (case 3) allows to save on drilling depth but the extra capital and electricity cost for the DC did not outweigh the electricity savings due to the overall increase in heat pump COP. A climate control system without AE (cases 1 and 4) is not recommended.

The maximum weekly reservoir return temperature T_{out} for the 3 GSHP cases are shown in Figure 5 (solid lines). T_{out} for case 1 (black line) is initially lower due to the longer total borehole length, but increases the fastest since the GSHP is permanently running. The increase in T_{out} for case 2 (blue line) is only modest since the reservoir can partially recover during the winter and thermal interference with only 2 BHEs is limited. With the additional DC in case 3 (red line) T_{out} levels off after about 5 years. The minimum weekly reservoir return temperature during recharging in case 3 is represented by the dashed blue line.

The monthly amount of reservoir heat exchange in case 3 during the first year is shown in Figure 6. The yearly amount of heat extracted (reservoir recharging) is 17 MWh, which is almost half of the yearly heat injected (36 MWh). Different DC set-point temperatures T_{DC} were analyzed with corresponding different levels of reservoir recharging but none resulted in a case with an LCC lower than case 2. Different DC fluid flow rates $\dot{m}$ were not investigated.

Table 2: Simulation optimized BHE length and economic results (7.5 kW_{th} cooling load)

Case ID	Case Description	Optimized Single BHE Length L_{BHE} and Number of Boreholes N	Life Cycle Cost LCC ($2013)
1	GSHP	L_{BHE} = 114 m & N = 3	$57,600
2	Hybrid GSHP with AE	L_{BHE} = 102 m & N = 2	$39,800
3	Hybrid GSHP with AE and DC	L_{BHE} = 93 m & N = 2	$44,100
4	Wall-Mounted HVAC	/	$54,000
5	Wall-Mounted HVAC with AE	/	$41,000

The results provided in Table 2 should be interpreted with care. Firstly, the techno-economic model includes several simplifications which can result in the actual LCC slightly different from the one presented in this study. Secondly, among the many system parameters, only the borehole length was optimized with respect to the LCC. Other parameters including flow rates and set-point temperatures were taken the same as in the experimental set-up (Section 2) and might not be at optimum values. Thirdly and most importantly, the results provided should not be extrapolated to other regions of the country. Different cooling requirements, climate conditions, and reservoir thermal conductivity will significantly impact the LCC. The same holds for the electricity rate and potential ground water flow. Finally, no federal, state or local incentives or tax credits were included in the analysis.

Table 2 only provides a comparison between different cases in terms of their LCC. Other factors to compare could be CO_2 emissions or energy consumption. The maximum outlet temperatures shown in Figure 5 might be fairly high, however, they are the result of optimizing with respect to LCC, not energy use. Larger L_{BHE} and correspondsing lower T_{out} would probably be obtained when optimizing with respect to energy consumption.

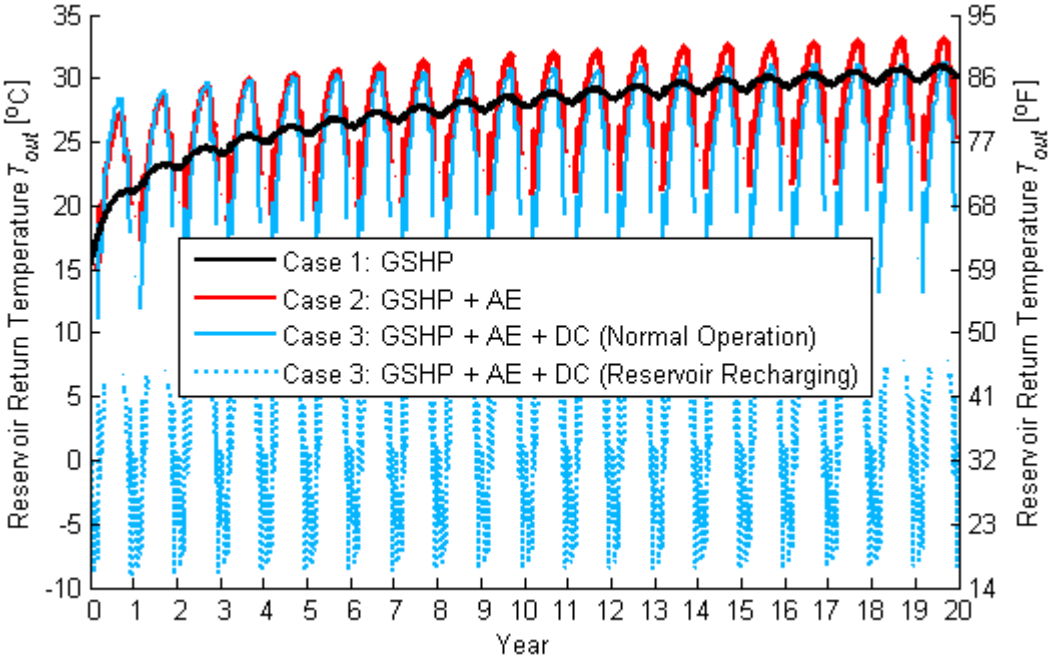


Figure 5: Reservoir return temperature for GSHP cases (cases 1, 2 and 3)

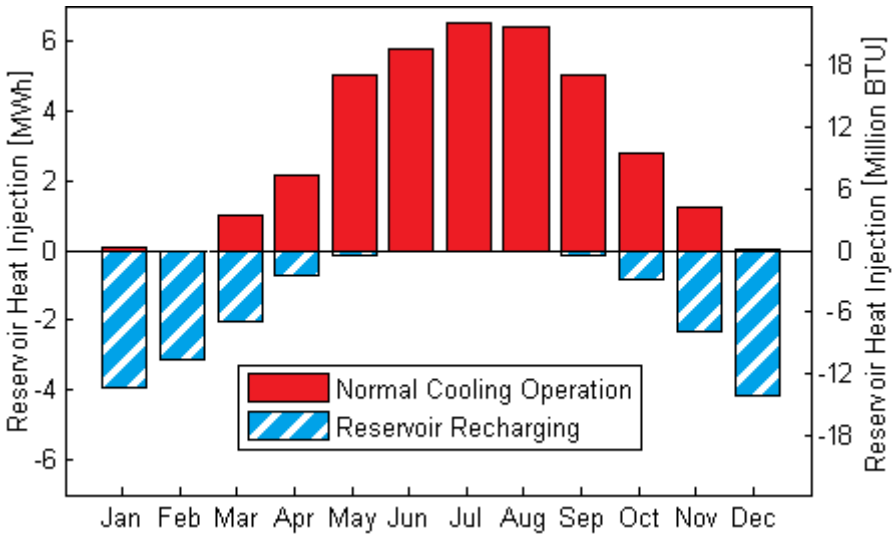


Figure 6: Reservoir heat injection (solid red bars) and extraction (striped blue bars) for case 3.

5 CONCLUSIONS AND FUTURE WORK

Thousands of cellular towers with accompanying shelter are installed across the US with most having a relatively constant cooling demand of about 8 kW_{th} year-round. Wall-mounted HVAC units are the traditional system for shelter climate control but hybrid GSHPs could be a more energy-efficient and cost-effective option. This paper described an experimental set-up of such a hybrid GSHP located in Ithaca, NY, USA that has an extensive monitoring and logging system to observe the behavior of the reservoir, shelter and heat pump units. A simplified techno-economic model was presented and applied to several cases to estimate the life cycle cost of the hybrid GSHP and compare with traditional HVAC systems. For typical Upstate NY conditions, preliminary results show that a hybrid GSHP with air-economizer (AE) is the most cost-effective option closely followed by an air-conditioning system with AE. Omitting an AE was not recommended and a dry-cooler (DC) was not necessary since the geothermal reservoir had enough time to recover during the winter months. Even though the model included several simplifications, the results for the GSHP cases treated in this study are considered conservative since the reservoir thermal conductivity was assumed modest, ground water flow was neglected, financial incentives were ignored and only limited parameter optimization was applied.

Future work on this project includes improving the techno-economic model by implementing more advanced reservoir models, considering the thermal capacitance of the shelter and incorporating tax credits, subsidies and other incentives in the life cycle cost calculation. In addition, a sensitivity analysis will be performed to explore the impact of system parameters such as the set-point temperatures and flow rates as well as the impact of several uncertain parameters including ambient temperature and ground thermal properties. Furthermore, the model will be applied to other locations to investigate the nationwide potential. Finally, real data will be collected from the experimental set-up which will be used to validate the reservoir, borehole heat exchanger and heat pump models.

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