A FEASIBILITY STUDY OF A MULTI-SOURCE HYBRID DISTRICT GEOTHERMAL HEAT PUMP SYSTEM

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INTRODUCTION

Accurate calculation of transient subsurface heat transfer is critically important in sizing ground heat exchangers (GHX) in geothermal heat pump (GHP) systems. The size of the GHX is a complicated function of a number of design variables that include the thermal properties of the subsurface, and the dynamics of short- and long-term building heating and cooling loads. So-called hybrid GHPs have received considerable attention in recent years (eg., Hackel, 2008) because they have been show to significantly improve the economics and energy use of GHP systems. Hybrid GHP systems couple a supplemental heat extraction or rejection subsystem to a conventional GHP system to handle some portion of the building or the ground loads, and as such, permit the use of a smaller, lower-cost GHX. Hybrid GHPs are especially effective in applications that have large peak loads and/or have highly imbalanced loads over the year (i.e. heavily heating or heavily cooling-dominated buildings).

Hybrid GHP systems are more complex in their design than conventional GHP systems due to the transient nature of the supplemental component. Further, recent research on hybrid GHPs identifies more than one method to design a hybrid GHP. For example, Chiasson and Yavuzturk (2009a, 2009b) describe a method for designing hybrid GHP systems based on annual ground load balancing. Xu (2007) and Hackel et al. (2009) describe hybrid GHP system design based on lowest life-cycle cost, while Kavanaugh (1998) describes a method based on designing the GHX for the non-dominant load, and the hybrid component for the balance of the load. Cullin and Spitler (2010) describe yet another method based on minimizing first cost of the system, while designing the GHX to supply both the minimum and maximum design entering heat pump fluid temperature over the life-cycle of the system.

Recent research on hybrid GHP systems highlights the complexity of their design. Published research mainly deals with single building applications with one hybrid component. Much less research, if any, has dealt with hybrid GHP

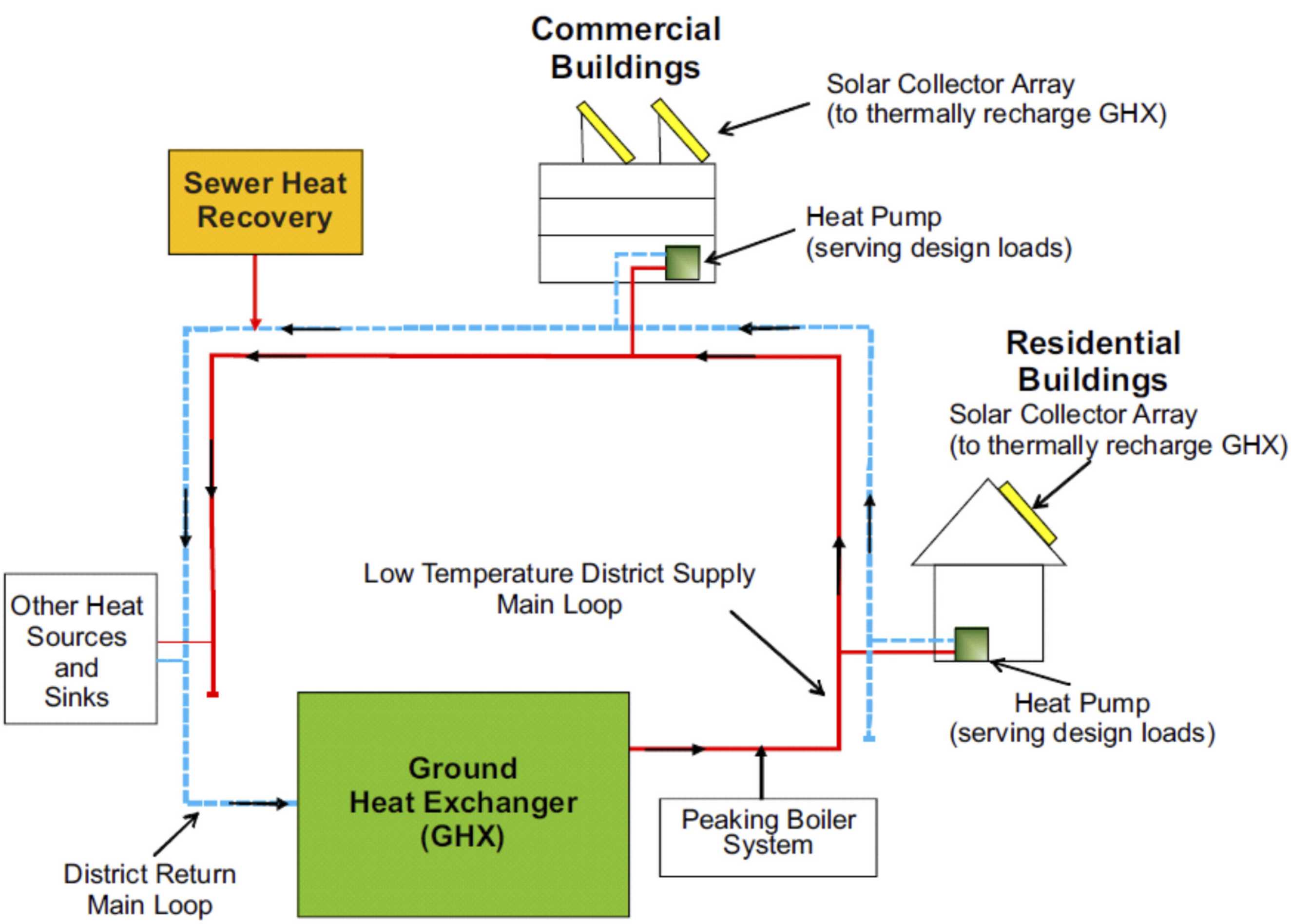

Figure 1. Concept schematic of a multi-source hybrid GHP system.

systems with more than one hybrid component in a district application. The objective of this article, therefore, is to describe a system simulation approach to examine the feasibility of a multi-source hybrid GHP system for an actual proposed district heating application in a cold climate, where conventional GHP systems were deemed to be infeasible and impractical.

THE MULTI-SOURCE HYBRID CONCEPT

Here, the term multi-source hybrid is used to describe a hybrid GHP system with multiple heat sources. The concept is shown schematically in Figure 1 for a cold climate with very little to no cooling load.

The basic design concept shown in Figure 1 takes advantage of a modular “plug-and-play” structure such that heat sources or sinks can be added as practical. The concept is centered around a common low-temperature supply pipeline that serves to distribute energy in the form of an aqueous antifreeze solution to the sources and sinks. A low-temperature distribution loop was conceived in this design so that lower-grade heat sources could be rejected to the loop. A lower temperature fluid distribution loop typically requires larger diameter pipe relative to that used in a high-temperature loop, but the added advantage of larger pipe diameter means more fluid volume in the loop and correspondingly more thermal mass (or thermal inertia) of fluid in the pipe, which helps to damp large fluid temperature excursions during peak load times. Amplification of the low-temperature source loop to useful temperatures for space heating is accomplished with water-to-air or water-to-water heat pumps distributed throughout the district in the buildings they serve. The minimum heat pump supply temperature of 0˚C was chosen because of the low ground temperatures in cold climates.

An integral component of the district energy system is the ground heat exchanger (GHX), which could consist of one central array or multiple de-centralized arrays. The GHX acts to provide a baseload heat source for heat pumps, supplemented by a peaking boiler during extreme cold periods. In addition, the GHX acts as a short-term and long-term (i.e., seasonal) storage medium for various waste and other available heat sources, which help to improve the GHX thermal performance during times when heat is needed. The waste and other heat sources considered in this study were limited to solar energy and heat recovered from sanitary sewers.

As noted in Figure 1, general options exist for “other heat sources and sinks”, which could conceivably include heat rejection from refrigeration systems (i.e., ice rinks) or any other source deemed practical. This box could also represent another modular GHX as the district system expands and/or additional GHX’s are incorporated at de-centralized locations.

Each of the individual components of the district GHP systems are described in further detail below.

THE GROUND HEAT EXCHANGER (GHX)

Two types of loads are important in sizing a GHX to meet intended loads: (i) the peak hour load and (ii) the annual load. Sizing a GHX therefore differs from sizing conventional heating and cooling equipment (i.e., boilers and chillers) because the earth does not respond instantaneously to heat rejected to and extracted from it; long-term temperature changes take place in the underground GHX storage volume if annual loads are not balanced (i.e., the same amount of energy added approximately equals the amount taken out). When annual loads are not balanced, the GHX must be increased in size to accommodate long-term underground temperature changes over years and decades. Annual loads are sometimes naturally balanced by a distinct heating and cooling season, but this is not the case in a sub-Arctic environment, and the size of the GHX to meet all of the intended loads is excessive and unnecessary, which led to this concept of a hybrid system. Supplemental systems are used to offset peak loads and annual loads on the ground.

The GHX design consists of a closed network of vertical boreholes drilled to approximately 100 m deep. Each borehole would be completed with a HDPE plastic u-tube heat exchanger grouted in place with standard bentonite-based grout. The heat transfer fluid consists of an aqueous solution of 20% propylene glycol.

GEOTHERMAL HEAT PUMPS

The district energy concept presented here involves heat pumps distributed throughout the district, located in the buildings they serve. GHPs would simply replace conventional furnaces or boilers in buildings, and would be installed during construction of each individual building. Individual heat pumps would be sized to meet the intended loads of the building; the hybrid components are only designed to assist the GHX in providing source energy to the heat pumps. Therefore, no supplemental heating is necessary within individual buildings, and emergency back-up heating in buildings would be up to the preference of the individual building owner. The concept of providing low-temperature source water to customer buildings allows for customer flexibility to choose their preferred type of heating system, either ducted forced air or radiant floor heating.

PEAKING BOILER

For consistent delivery temperature of source fluid from which thermal energy can be extracted by heat pumps, a peaking boiler is added to the district system concept. A peaking boiler system serves to offset peak loads on the ground, thus reducing unnecessary GHX size and cost. The optimum size of the boiler depends on the economic trade-off between the avoided GHX cost and the annual operating cost of the boiler. The fuel source for the boiler could be natural gas, biomass, heating oil, or combined fuel.

The design concept involves only operating the boiler during times when the fluid temperature exiting the GHX falls below 0˚C, which will occur during peak heating load hours. The boiler will therefore contribute very little to operational costs. The boiler operates on a temperature control, set to maintain a minimum supply temperature of 0˚C to the district loop. An additional benefit of a peaking boiler system is that it could be used as a backup in the event of sewage heat recovery interruption (sewer heat exchanger maintenance) or GHX maintenance.

SOLAR THERMAL RECHARGE AND SEWER HEAT RECOVERY

The role of solar thermal and sewer heat recovery is to offset annually imbalanced loads on the ground by recharging the GHX with thermal energy. Balancing ground loads allows for further reductions in the GHX size and cost. As with a peaking system, the optimum size of the solar collector array and sewer heat recovery system depends on the economic trade-off between the avoided GHX cost and the capital and operating cost of the load balancing systems.

As shown in the district schematic concept (Figure 1), solar energy would be the "first" energy source added to the district loop, mainly because the most strategic location for solar collector location is on customer roof tops. Solar energy would therefore be added to the district loop immediately downstream of the heat pumps. This would be accomplished with existing off-the-shelf, flat-plate solar technology. Solar collectors are typically operated using a differential set point control, meaning that the collector must be warmer than the district loop by a set amount (typically at least 5˚C) for useful heat transfer to occur. Thus, useful heat can be collected beginning at low solar collector temperatures (i.e., less than 5˚C).

Similar to the solar recharging concept, sewer heat would be added to the loop at a strategic location as the fluid returns to the GHX. This allows heat to be collected at any time during year and stored underground in the GHX to improve its thermal performance. Useful heat could only be transferred to the district loop when the wastewater temperature exceeds the district loop temperature

METHOD OF FEASIBILITY ANALYSIS

Heating Load

The hybrid district GHP system described here is intended to serve approximately 124,000 m2 of mixed residential and commercial floor space in a new subdivision in Whitehorse, Yukon, Canada. Weather conditions at the subject site are sub-arctic, with a heating design temperature of -37oF, and 12,447 oF-day (6,915 ˚C-day) heating degree days. The underground earth temperature is approximately 3˚C (37.4oF).

The peak heating load is estimated at 5,840 kW (19.9 million Btu/hr), and the annual heating energy load is estimated at 9.4 MWh.

Parametric Analysis with Optimization.

"Parametric analysis with optimization", in general, refers to a systematic investigation aimed at finding the maximum or minimum value of a particular parameter of interest. Here, the optimization procedure seeks the minimum life-cycle cost of the hybrid GHP district energy system.

An optimization analysis is needed in hybrid GHP system design because a multitude of combinations of hybrid component sizes is possible (i.e., combinations of GHX size, number of solar collectors, sewer heat recovery, and peaking boiler size). There is a trade-off in cost savings in reducing the size of a GHX in favor of adding initial and operating cost of a hybrid component. Therefore, the objective of the optimization analysis presented here is to find workable combinations of hybrid GHP system components (i.e., the GHX, solar collectors, sewer heat recovery, and peaking boiler) that result in minimum life-cycle cost. It is emphasized that the goal of this optimization analysis is not to find the precise combination of hybrid system component sizes, but to provide a first approximation of whether feasible combinations exist. Precise sizing of hybrid components is an analysis left for later stages of the design process.

The methodology in conducting the optimization analysis involved examining numerous combinations of hybrid system component sizes. The thermal performance of 25 hybrid GHP cases with various combinations of GHX size, number of solar collectors, and peaking boiler fraction were simulated with and without sewer heat recovery. Therefore, a total number of 50 combinations were examined. Hybrid GHP energy simulations were conducted using TRNSYS (SEL, 2000), which is a state-of-the-art transient energy simulation software tool. Computer models were configured similar to the concept diagram shown in Figure 1. Once constructed, the use of TRNSYS computer models allowed examination of several "what-if" alternatives. The GHX configuration and thermal properties were modeled as described above. Glazed flat plate solar thermal collectors were modeled with properties similar to those described by Numerical Logics (2008). Solar collector glycol-based loops were separated from the main district loop with isolation heat exchangers. The peaking boiler was controlled to maintain a minimum fluid supply temperature to building heat pumps of 0˚C. The sewer heat recovery heat exchanger was modeled with a heat exchanger effectiveness of 0.80, controlled to shut off when the wastewater temperature dropped to 2˚C. Energy simulations were conducted for fifty years.

LIFE-CYCLE ECONOMIC ANALYSIS

Fifty-year life-cycle cost analyses were conducted for each parametric case using the energy simulation results, along with capital cost and other economic data. The rate-of-return (ROR) method was used as the economic indicator to evaluate options. The ROR represents the true interest yield provided by the project equity over its life before income tax. It is calculated using the pre-tax yearly cash flows and the project life. It is also referred to as the internal rate of return (IRR). It is calculated by finding the discount rate that causes the net present value of the equity to be equal to zero. Therefore, it is not necessary to establish the discount rate of an organization to use this indicator, as it is for use of the net present value method. The ROR obtained is specific to the project and applies to all investors in the project.

Capital costs assumptions in the economic analysis are as follows:

- GHX costs are estimated at $100/m, based on professional judgement, discussions with installers, and lack of local contractors,
- Solar collector costs are based on a correlating equation from Hackel (2008), where solar collector array cost = $5096(0.135N + 0.865), where N is the number of glazed flat plate collectors,
- Peaking boiler costs are based on a correlating equation from Hackel (2008), where boiler cost = $3825(-0.00430f2 + 0.411f + 0.692) for f<=31.2 or boiler bost = $3825(0.118f + 5.64) for f>31.3, where f = ratio of boiler size to a nominal reference 122 MBH boiler,
- Distribution piping system = $600/m. This estimated cost include piping material, installation, pumping system, and customer connections expressed per meter of street length. Street lengths are multiplied by 10% to account for branch lines to customer buildings. Piping costs are for pre-insulated HDPE pipe per vendor quote. The total distribution system cost is estimated from NRCan (2008), at a proportion of 45% for pipe material, 45% for installation and connections, and 10% for the pumping system,
- Mechanical building cost = $1,600/m2,
- Sewer heat recovery cost = $0.78 million,
- Engineering and design fees = 10% of capital cost,
- Arctic cost multiplier = 1.3,
- Contingency = 30%, and
- Grants and incentives: none.
- Annual operating and maintenance costs assumptions in the economic analysis are as follows:
- Maintenance costs on the distribution system are estimated at 1% of capital cost,
- District system administrative, management, and billing costs are estimated at $1/ m2of floor space,
- Boiler system maintenance costs are based on a correlating equation from Hackel (2008), where boiler maintenance cost = $759(-0.0009f2 + 0.0648f + 0.952) for f<=11, or boiler maintenance cost $759(0.0196f + 1.367) for f>11, where f = ratio of boiler size to a nominal reference 122 MBH boiler, and
- Sewer heat recovery system maintenance costs are estimated at $1,000.

Additional assumptions in the economic analysis are shown in Table 1.

DISCUSSION OF RESULTS

One challenge in the examination of feasibility of a multi-source hybrid GHP system is visualizing the numerous options. Here, the most economically favorable general combination of hybrid component sizes was found graphically by constructing optimization plots. The plots display the 50-yr rate of return as a function of GHX size, number of solar collectors, and annual energy fraction contributed by a peaking system (Figure 2). Optimization plots were constructed for cases with sewer heat recovery and for cases without sewer heat recovery.

Prior to discussion of the results, some explanation is necessary for interpretation of the plots. Contour lines represent the number of 100-m deep GHX boreholes required to provide all thermal source energy to the district heat pumps with assistance from various numbers of solar collectors (shown on the bottom or x-axis) and annual fractions of energy from a peaking boiler system (shown on the left axis or y-axis). Therefore, the lower left-hand corner of each plot represents the case of a GHX providing energy to heat pumps with no solar or boiler hybrid assistance. The annual fraction of energy provided by a boiler system on the left or y-axis is expressed relative to the total annual building heating load. Therefore, the maximum amount of annual

Table 1. Additional Assumptions in Economic Analysis.

Boiler life expectancy	25 yrs.	Estimate. With proper maintenance.
Sewer HX life expectancy	15 yrs.	Per manufacturer.
Fossil fuel combustion efficiency	80%	For peaking boiler and fuel oil furnace base case.
Fuel oil rates (residential)	$1/L	Based on Yukon Energy price tracking.
Fuel oil rates (commercial)	$0.8/L	Based on Yukon Energy price tracking.
Blended electricity rate	$0.13/kWh	Based on current Yukon Electric schedule.
Commercial Electric Demand Charge	$7.3/kW	Based on current Yukon Electric schedule.
Annual inflation rate	2%	Typical assumption.
Annual fuel oil inflation rate	4%	Conservative. Actual inflation rate ~ 7%.
Annual electricity inflation rate	2%	Conservative. Actual inflation rate over last 10 years is close to 0%.

District system income is presumed to be based on energy sales to building owners (customers). The energy charge to customers is based on cost savings of operating geothermal heat pumps over the conventional choice of fuel oil.

energy a boiler could supply, even with no GHX, is less than 100% due to heat pump thermodynamic principles. The source-side energy of a heat pump in heating mode is less than the load side energy by a factor equal to (COP-1)/COP. Finally, the colored areas of the plots represent the ROR of the particular combination of hybrid components. A ROR color legend is shown to the right of the optimization plot.

A non-hybrid GHX (i.e., one with no assistance from hybrid components) sized to provide all of the thermal energy to heat pumps in the district buildings with no sewer heat recovery (i.e., the lower left-hand corner of Figure 2) would require approximately 6,500 100-m deep boreholes and occupy a footprint area of about 65 ha, exceeding the land area available for potential drilling. The capital cost of a non-hybrid district GHP system is approximately $80 million with a 50-year ROR of about 1.2%.

With the inclusion of sewer heat recovery as the only hybrid component, the GHX size reduces to approximately 5,650 100-m deep boreholes, occupying a footprint area of about 56 ha. The reduction in the GHX size is due to extraction and underground storage of thermal energy from wastewater. The savings in GHX cost, with the addition of sewer heat recovery infrastructure, results in a lower overall capital cost of $71 million and a higher 50-year ROR of about 1.6%, relative to a non-hybrid district GHP system.

The optimization analysis reveals that the capital cost and ROR can be significantly improved with the integration of a solar collector array and peaking boiler system. The levelling off of the borehole curves beyond about 3,000 to 5,000 solar collectors means that there is diminishing benefit for the added cost of solar collectors exceeding this amount. The near optimum ROR with no sewer heat recovery is about 7.2% with a reduced GHX of 250 100-m deep boreholes, 3,000 solar thermal collectors, and a peaking boiler system that supplies only 9% of the annual heating load. The reduced GHX size would occupy a footprint area of about 2.5 ha. The capital cost of this case is about $15.2 million.

The near optimum ROR with sewer heat recovery is about 6.7% with a reduced GHX of 500 100-m deep boreholes, 3,000 solar thermal collectors, and a peaking boiler system that supplies only 1% of the annual heating load. The reduced GHX size would occupy a footprint area of about 5 ha. The capital cost of this case is about $18.8 million.

This feasibility study has used a number of cost assumptions, typical at an early concept stage of a project, and a sensitivity analysis gives some insight into the effect of major cost items on the computed ROR. A sensitivity analysis is a standard method to vary input parameters to a computation individually and in a systematic way, to see the relative effect on the output (in this case ROR%). A sensitivity

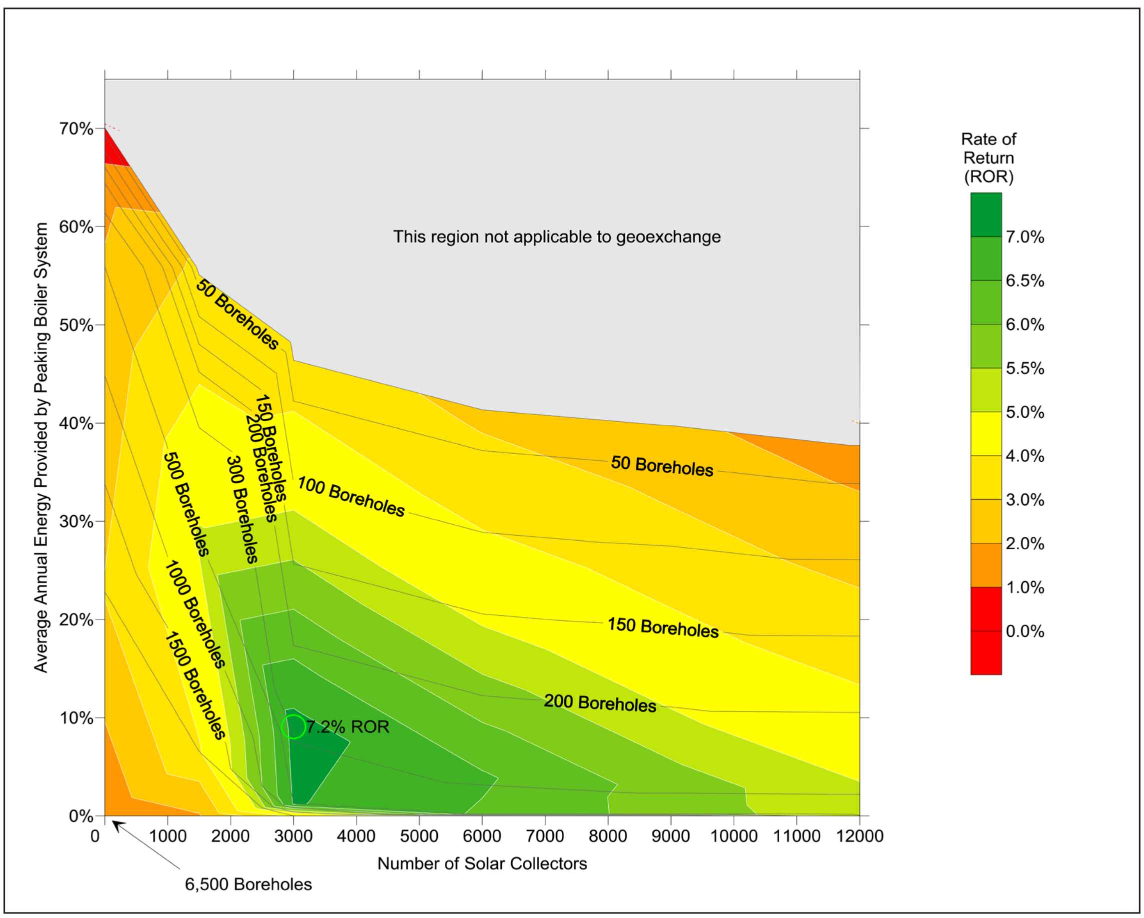

Figure 2. Optimization plot showing investment rate of return for number of GHX boreholes as a function of number of solar collectors, and average annual fraction of energy provided by a peaking boiler system.

analysis was conducted on the input parameters in order to quantify uncertainty in the cost estimates. Cost items of the hybrid GHP district system were varied from -50% to +50% of the assumptions used to calculate the ROR. The cost items varied included: annual fuel oil escalation rate, electricity escalation rate, GHX cost, solar thermal collector array cost, piping/distribution network cost, boiler costs, and sewer heat recovery system cost. The results of the sensitivity analysis are shown in Figure 3.

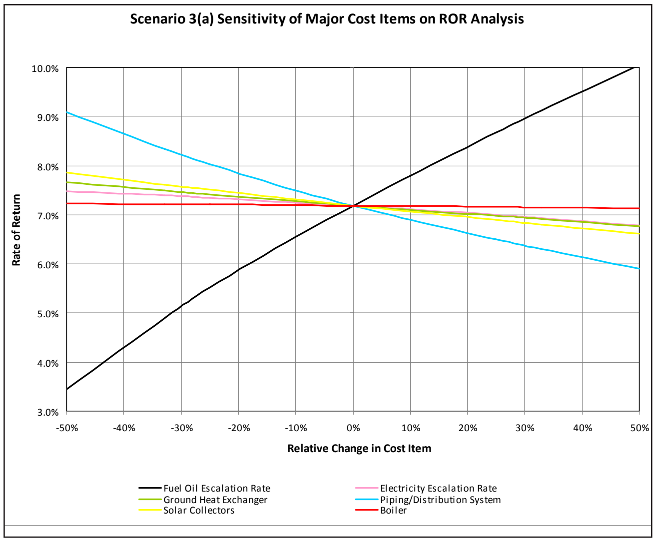

Figure 3. Sensitivity of major cost items on 50-year rate of return.

A review of Figure 3 reveals that the most sensitive cost item on the 50-year ROR of the hybrid GHP district system is the annual fuel oil escalation rate. The fuel oil price was used to project energy revenues from the district system, and deviation from this assumption affects the ROR. If the annual fuel oil escalation rate were to increase by 50% (i.e., closer to what it actually has been over the past 10 years), the ROR increases to 9 to 10%. On the other hand, if the annual fuel oil escalation were to decrease by 50%, the ROR would decrease to 3 to 4%.

Sensitivity of the ROR is next most sensitive to the cost of the piping/distribution system. A 50% decrease in the piping/distribution system cost increases the ROR to 8 to 9%. A 50% increase in the piping/distribution system cost decreases the ROR to 5.7 to 6%.

The ROR is not significantly sensitive to the GHX cost, solar collector array cost, or the annual electricity escalation rate. A ±50% change in these cost items changes the ROR by less than 0.7%. The ROR is relatively insensitive to boiler costs and sewer heat recovery system cost

CONCLUSIONS

This paper has presented a method of analyzing the practicality and feasibility of a multi-source hybrid geothermal heat pump system in a sub-arctic climate. This work has had two main outcomes: (i) without a system simulation approach, feasible design of a multi-source hybrid GHP system is extremely difficult to complete due to numerous transient design variables, and (ii) in an impractical situation for a conventional GHP system, practical and feasible designs can be found for multi-source hybrid GHP systems, where the GHX is used as a thermal storage medium.

REFERENCES

Chiasson, A.D., and Yavuzturk, C., 2009a, "A design tool for hybrid geothermal heat pump systems in heating-dominated buildings", *ASHRAE Transactions* 115(2): 60-73.

Chiasson, A.D., and Yavuzturk, C., 2009b, "A design tool for hybrid geothermal heat pump systems in cooling-dominated buildings", *ASHRAE Transactions* 115(2): 74-87.

Cullin, J and Spitler, J.D., 2010, "Comparison of Simulation-based Design Procedures for Hybrid Ground Source Heat Pump Systems", *Proceedings of the 8th International Conference on System Simulation in Buildings 2010.* Liege, Belgium.

Hackel, S, 2008, *Development of Design Guidelines for Hybrid Ground-Coupled Heat Pump Systems.* ASHRAE Technical Research Project 1384, American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), Atlanta, GA.

Hackel, S., Nellis, G. and Klein, S., 2009, "Optimization of cooling-dominated hybrid ground-coupled heat pump systems", *ASHRAE Transactions* 115(1): 565-580.

Kavanaugh, S.P., 1998, "A design method for hybrid ground-source heat pumps", *ASHRAE Transactions* 104(2): 691:698.

Numerical Logics, Inc., 2008, *Solar Domestic Hot Water System Sizing for Whitehorse, YT and Dawson, YT, Waterloo, ON.*

SEL, 2000, TRNSYS, *A Transient Systems Simulation Program*, Version 15. Solar Engineering Laboratory (SEL), University of Wisconsin-Madison, Madison, Wisconsin, USA.

Xu, X. 2007, *Simulation and optimal control of hybrid ground source heat pump systems*, Ph.D. Thesis, Oklahoma State University, Stillwater, Oklahoma.