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Simulation of Hybrid Solar-Geothermal Heat Pump Systems

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ABSTRACT

Hybridizing a geothermal heat pump system with solar thermal collectors is advantageous in realizing smaller, lower cost borehole heat exchanger arrays, in addition to achieving a more sustainable geothermal system over the long term. However, solar-geothermal heat pump system operation involves multiple, simultaneous physical processes, including building load dynamics, heat pump dynamics, heat transfer in the Earth, and solar thermal processes. Each of these processes occurs over various time scales on the order of minutes up to many decades. Lack of accurate design tools to accurately capture these effects leads to lack of confidence in further deployment of these systems. In this paper, we describe the development and use of a new, novel simulator for hybrid solar-geothermal heat pump systems. The simulator was developed using TRNSYS, a transient systems simulation environment with a modular structure, where the thermal performance of system components is described in the FORTRAN computing language. A controls and multi-variable optimization strategy has been implemented in to the simulator, where the result is the optimal depth and number of borehole heat exchangers and solar thermal collectors to achieve balanced thermal loads on the Earth over the annual cycle.

1. INTRODUCTION

Systems that couple heat pumps to vertical, closed-loop borehole ground heat exchangers (GHXs) are proving to be energy-efficient systems to heat and cool buildings. However, the cost associated with the borehole array remains relatively high, which inhibits more widespread application of the technology. Furthermore, when the heat pump operates predominantly in heating mode, it extracts heat from the ground, which reduces the ground temperature near the borehole. In turn, the lower ground temperature decreases the coefficient of performance (COP) of the heat pump. The opposite occurs in cooling mode. Thus, it can be advantageous to inject solar energy into the borehole array to increase the ground temperature and heat pump performance. Solar panels can also be used to reject thermal energy from the ground by radiation and convection to the atmosphere. An example system component inter-connect diagram for a hybrid solar-geothermal heat pump (GHP) is shown is Figure 1.

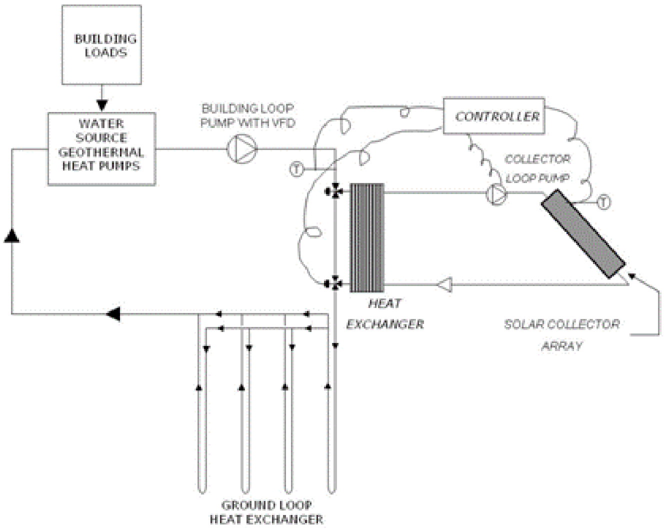

Figure 1: Example of a system configuration for a hybrid geothermal heat pump application.

The main benefit of hybrid geothermal heat pump systems relative to non-hybrid systems is the significantly reduced initial size (and cost) of the GHX. ASHRAE (2008) completed a research project that examined hybrid ground source heat pump systems, but the hybrid components considered were limited to conventional equipment such as boilers and cooling towers. Hybrid-solar GHPs have the following advantages: (i) solar thermal collectors can be used to balance the ground loads over the annual cycle, thus making the ground heat exchangers fully sustainable, (ii) in heating-dominated buildings, the hybrid energy source (i.e., solar) is renewable, in contrast to a typical fossil fuel boiler or electric resistance as the hybrid component, (iii) in cooling-dominated buildings, use of unglazed solar collectors as a heat rejecter allows for passive heat rejection, in contrast to a cooling tower that consumes a significant amount of energy to operate with stringent maintenance needs, and (iv) they can potentially expand the residential ground source heat pump market by allowing reduced ground heat exchanger footprint in both heating- and cooling-dominated climates.

Another main benefit of hybridizing a GHP system is that the system can be designed to balance ground thermal loads on an annual basis, thus preventing sink/source thermal degradation of the heat pump over time; balancing ground loads annually by shifting the unbalanced portion to a supplemental heat transfer unit removes an implicitly built-in degradation of the geothermal resource. Thermal balancing of the ground loads indirectly sizes the ground loop heat exchanger loop for the less dominant building load at the allowable heat pump entering fluid temperatures, and as a consequence the system runs sustainably.

The design of hybrid systems adds to the complexity of the overall GHP design process because of the addition of another transient component to the system. Since building thermal loads are highly transient, acceptable conditions for supplemental heat rejection to the atmosphere in a cooling-dominated building and for solar recharging of the ground in a heating-dominated building are also time-dependent functions driven by weather conditions, solar availability, and ground loop temperature history. Consequently, hybrid GHP systems are best analyzed on an hourly basis (as typical weather data are also available in hourly time-steps) for the accurate and reliable assessment of the overall system thermal behavior.

The accurate design of hybrid GHP systems is essentially an optimization problem; sizing of the supplemental components and the GHX length stipulate the management of multiple degrees of freedom on multiple system design parameters under constraint conditions of annual thermal load balance in the ground at a desired entering heat pump fluid temperature range. In addition, the design of hybrid GHP systems must use an appropriate control algorithm for system operation for load balancing in the ground. Accurate and reliable design of hybrid GHP systems is quite difficult and cumbersome without the use of a detailed system simulation approach. Furthermore, without an automated optimization scheme coupled to the system simulation program, the design activity itself can become tediously impractical and time-consuming.

Thus, the main objective of the work presented here has been to develop a novel simulator for hybrid solar-geothermal heat pump systems. The simulator construction involved the development and integration of algorithms cast in a stand-alone software tool using the TRNSYS computing environment. Stand-alone GHP systems, plus hybrids that employ solar collectors for both heating- and cooling-dominated applications are included in the simulator. A description of the development and example use of the simulator are described in what follows.

2. DEVELOPMENT OF THE SIMULATOR

For heating-dominated buildings, glazed solar collectors are used as supplemental heat transfer devices for the thermal recharge of the Earth volume where the borehole heat exchanger array is installed. Similarly, for cooling-dominated buildings, low-cost unglazed solar collectors are used to improve the thermal conditions in the ground volume (in this case the heat sink) by rejecting a portion of the building cooling load to the atmosphere. With proper system control and operating strategies, hybridization with solar collectors ensures long-term sustainable operation.

The simulator employs validated system component and sub-component models. It allows for the selection and simulation of different borehole heat exchanger configurations, such as the single U-tube, double U-tube, concentric pipe, groundwater filled, and the uncased standing column well without groundwater bleed, thus including nearly of all borehole types and configurations that are currently used. The simulator is cast as a stand-alone software tool in the TRNSYS computing environment with an easy-to-use, menu-driven, graphical user interface for designing hybrid solar-geothermal heat pump systems.

The simulator employs a validated optimization algorithm that effectively balances ground thermal loads in hybrid solar GHP systems (Chiasson et al. 2009). For hybrid GHP systems, the simulator employs a multi-variable optimizer that adjusts borehole depths and solar collector area to minimize an objective function based on desired heat pump entering fluid temperatures. In addition, for stand-alone GHP systems (i.e., non-hybridized systems), the simulator employs a single-variable optimization scheme to adjust borehole depths to meet the desired heat pump entering fluid temperatures.

An economic analysis module is included in the simulator that allows the computation of the lowest capital cost combinations of solar collector area and ground heat exchanger length based on user-input cost data. Thus, the simulator aids GHP system designers in comparative analyses, and serves as a supplemental decision-making tool in addition to being a design tool.

3. STRUCTURE OF THE SIMULATOR

3.1 Individual Component Models

Mathematical models that describe the thermal performance and energy consumption of individual hybrid GHP system components were modified and/or developed, and coupled together (as shown in Figure 1 above) in the TRNSYS computing environment. Component models include the ground heat exchangers, isolation heat exchanger between the solar collector loop and the ground loop, solar thermal collectors, heat pump unit, fluid circulation pumps, tee-pieces/diverters, and controllers. The selection and implementation of mathematical models were based on models that were field-validated and/or available in the TRNSYS components library. A control algorithm was developed and refined for the integrated system model that uses a differential scheme based on Yavuzturk and Spitler (2000) and Ramamoorthy et al. (2001).

3.1.1 Ground Heat Exchanger (GHX) Model

A number of different borehole heat exchanger configurations are possible, and the simulator allows selection of the most common types: (i) single U-tube, (ii) concentric tube, (iii) standing column well type borehole (Figure 2). The simulator employs the duct storage model (Claesson et al., 1981, Helström 1989, 1991, Mazzarella 1989, Pahud 1996) for the calculation of the ground thermal response to heat rejection and extraction pulses. Computation of thermal resistance of various borehole types (Yavuzturk and Chiasson 2002) is incorporated into the simulator.

A full description of the DST model is not warranted here, but to summarize, the DST model is able to predict the amount of heat transferred from a fluid circulating in a borehole array to the Earth. Boreholes are assumed to be uniformly placed in a volume of soil/rock. The heat transfer problem is solved by splitting the problem into simpler problems. Then, using the linearity of the heat conduction equation, various solutions are superimposed to obtain the final solution. Central to the DST model is the superposition of two numerical solutions: the so-called local and global solutions, both of which are linked by sub-regions. Heat transfer between the circulating fluid and the ground is given by an analytical solution applied over borehole segments which is then used as a boundary condition in the local problem. Finally, a steady-flux analytical solution redistributes the energy into the soil/rock storage volume.

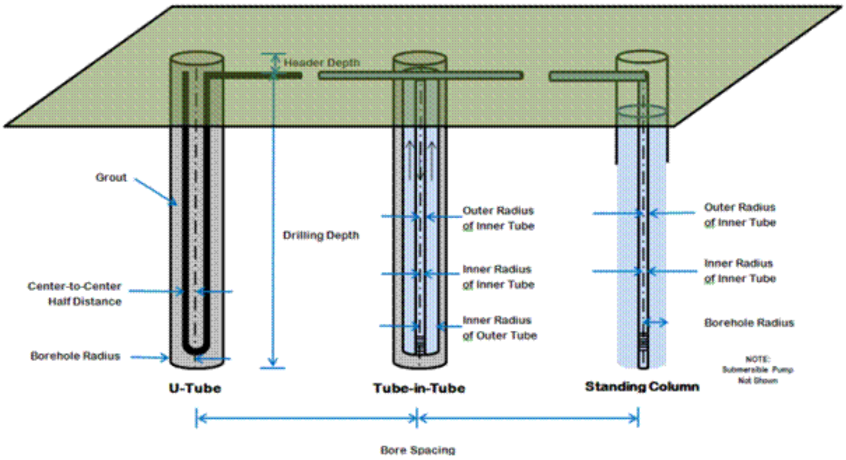

Figure 2: Borehole heat exchanger configurations available in the simulator.

3.1.2 Thermal Loads of the Building

The level of detail for reliable design of hybrid solar geothermal heat pump systems necessitates hourly simulation. The simulator allows two options: (i) user-supplied hourly loads or (ii) hourly building loads determined by a synthetic loads generator, based on peak building heating and cooling loads. The loads generator contains a set of stored reference loads for all U.S. Department of Energy climate zones. These climate zones also have descriptions for extrapolation to other locations worldwide. Reference loads have been developed for a typical bank building, department store, multi-family dwelling, elementary school, middle school, high school, mid-rise and two-story office buildings, service station/convenience store building and a stand-alone structure. The approach of using reference loads does not model a building as accurately as it would if the building hourly loads were known beforehand. Nevertheless, the approach provides an excellent means for modeling buildings in pre-design stages.

3.1.3 Heat Pump Model

Geothermal heat pump performance is modeled using performance data from major U.S. brand manufacturers as of 2010. The heat pump coefficient of performance (COP) is calculated using a curve fit to two variables: (1) the heat pump entering fluid temperature and (2) the fluid mass flow rate. The power consumption is determined by an energy balance on the heat pump. De-superheat is also modeled from manufacturers performance data. A general categorization is developed for the heat pump performance based on system efficiency (standard efficiency and high efficiency).

3.1.4 Integration of Weather Data and Solar Collector Product Database

The simulator uses weather data for the calculation of solar collector performance and to calculate the water main temperature when modeling domestic hot water supply, and is designed to accept weather data in the *.epw format (EnergyPlus weather file format). Weather data for more than 2,100 locations are available in EnergyPlus weather format, which consists of 1,042 locations in the USA, 71 locations in Canada, and more than 1,000 locations in 100 other countries throughout the world, and are arranged by World Meteorological Organization region and Country.

The software tool utilizes standard component models from the TRNSYS library for the calculations of the thermal performance of glazed and unglazed solar collectors. An extensive solar collector database is integrated into the simulator, and for each solar collector the model is designed to accept input solar collector performance parameters that are typically available from ASHRAE-standardized collector tests as published by the Solar Rating Certification Corporation (SRCC). Other input parameters that are required to fully describe and specify a solar collector array system in the software tool include: local weather files in *.epw format, collector geometry and orientation, collector heat transfer fluid properties, circulating pump power consumption at maximum heat transfer fluid flow, fluid flow rate, collector emissivity, intercept efficiency, efficiency slope and curvature, and first and second order incidence angle modifiers.

3.1.5 Flow Controls, Pump, and Heat Exchanger Models

The simulator models hybrid GHP systems as a primary/secondary loop system. The primary circuit is the building loop plus ground loop heat exchanger and the secondary circuit is the hybrid component loop. The flow circuits are separated by a plate type heat exchanger (TRNSYS component type 5) modeled with a constant effectiveness. The system is modeled in this way to mimic design practices and to allow different fluids to be placed in each loop. For example, the solar collector fluid is typically an aqueous solution of 50% propylene glycol to avoid extreme freezing conditions.

Tee pieces, diverters, and pumps were modeled using TRNSYS standard library component models. Differential temperature control schemes are specified with the differential controller model, which was used to activate pumps and valves. A simple control scheme was used to simulate a variable frequency drive on the primary building loop pump; the flow rate for the current hour of the simulation is scaled to the peak flow rate according to the ratio of the current hourly load to the peak building load. A maximum pump turn-down speed of 30% was assumed.

3.1.6 Domestic Hot Water Modeling

Domestic hot water is modeled (when applicable) using three possible options. The first option is an indirect solar loop with separate fluid circulating pump, an isolation heat exchanger (Heat Exchanger #1), and a hot water loop with preheat and main storage tanks, and a circulating pump between the preheat tank and isolation heat exchanger. In this configuration, the only source of auxiliary heating supplied to the main tank is by an electric heating element as necessary to maintain the specified storage temperature.

The second configuration is essentially identical to the first one above except that the auxiliary heating is supplied to the main tank by a heat pump de-superheater in addition to an electric heating element as necessary to maintain the specified storage temperature. The available heat pump superheat is calculated from curve-fits to manufacturers catalog data.

The third configuration models the auxiliary heat supplied to the main tank by a heat pump de-superheater, and there is no electric heating element to maintain the specified storage temperature. Again, the available heat pump superheat is calculated from curve-fits to manufacturers catalog data.

3.1.7 Control of the Hybrid Solar Component

Previous work by Yavuzturk and Spitler (2000) and Ramamoorthy et al. (2001) concluded that the most effective control strategy for hybrid GHPs was a differential temperature control, where the monitored temperatures were the exiting heat pump fluid temperature and the source/sink temperature used by the supplemental component. Thus, this was the control strategy selected for this work. With regard to solar collectors, the monitored temperature is that of collector absorber plate. The differential control temperature selected was 5.0^{o}C.

3.2 GHP System Simulation

Three types of GHP systems may be simulated as described in the following.

3.2.1 Stand-Alone GHP Systems

The stand-alone geothermal heat pump system option is designed to provide a single run simulation for the configured geothermal heat system with or without constraints on the entering and exiting fluid temperatures to the heat pump. This selection does not include any integrated supplemental heat rejection or extraction components in the system, and consequently optimization module is not activated during the simulations. The simulator does provide the capability to add a solar domestic hot water system.

3.2.2 Hybrid Solar-Geothermal Heat Pump System – Heating Dominated Application

This option allows for the simulation of a hybrid solar-geothermal heat pump system for heating-dominated buildings. A system schematic is shown in Figure 3.

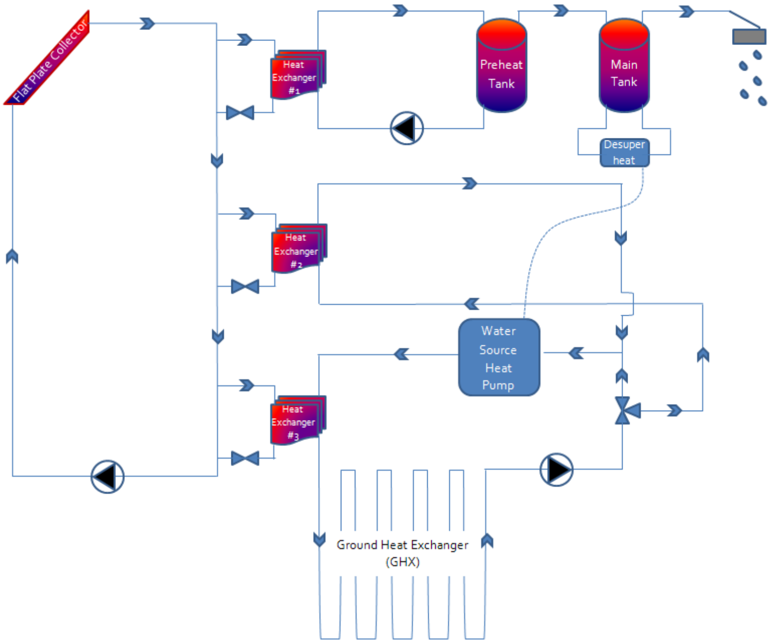

Figure 3: Borehole heat exchanger configurations available in the simulator.

The simulator allows for significant flexibility via the selection of *Heat Exchangers #2* and *#3* in the solar hybridization scheme. Implementation of *Heat Exchanger #2* allows solar thermal energy to be supplied to the evaporator side of the heat pump to "boost" the entering fluid temperature only when the heat pump is in heating mode. A control and operating strategy has been incorporated such that valves to *Heat Exchanger #2* are opened only when the solar loop temperature exceeds the heat pump entering fluid temperature by 5ºC. Similarly, the implementation of *Heat Exchanger #3* allows solar thermal energy to be either supplied to the ground for purposes of thermal recharge or unloaded from the ground, depending on a heating-dominated or a cooling-dominated building case. In a heating-dominated project, *Heat Exchanger #3* is used to recharge the ground with thermal energy, while in a cooling-dominated project, *Heat Exchanger #3* is used to unload thermal energy from the ground. Again, a control and operating strategy has been incorporated such that valves to *Heat Exchanger #3* are opened only when a differential temperature of 5ºC between the solar loop and the heat pump exiting fluid temperature is satisfied.

3.2.3 Hybrid Solar-Geothermal Heat Pump System – Cooling Dominated Application

This option allows for the simulation of a hybrid solar-geothermal heat pump system for cooling-dominated buildings. The component interconnect diagram is identical to the heating-dominated configuration as shown in Figure 3 above, but the system operation is the opposite of the heating-dominated case with respect to *Heat Exchanger #3* in that it is designed to reject thermal energy through unglazed solar collectors that essentially operate as radiant cooling panels. A system control and operating strategy is implemented that considers time-of-day and the direction of thermal potential between the ambient conditions and the thermal conditions of the heat transfer fluid circulating through the unglazed collectors.

It should be noted that, although the use of glazed solar collectors are relatively well-known and implemented in actual hybrid geothermal heat pump systems, the use of unglazed solar collectors for heat rejection is a highly novel system configuration. In industry practice evaporative cooling towers and fluid coolers are typically used as a supplemental hybridization component for cooling-dominated applications. Nevertheless, cooling towers and fluid coolers present significant disadvantages with respect to energy consumption requirements as well as maintenance needs. The use of unglazed solar collectors for hybridization of geothermal heat pump systems makes the hybridization solar-centric and allows for potentially significant cost reduction. Previous to this present work, no design and simulation tools had been available to incorporate the use of unglazed solar collectors for heat rejection in hybrid systems.

As in the heating-dominated system configuration, the simulator is designed to provide system simulations and optimization considering integrated solar domestic hot water heating via *Heat Exchanger #1*, with auxiliary heating that may include either heat pump de-superheating or supplemental electric heating or both.

3.3 Life-Cycle Economics

An economics analysis module is incorporated into the simulator to allow for the life-cycle cost analysis for a simulated system. It should be noted that in order to successfully use this module, a project simulation must have been completed and the simulation results printed as hourly outputs.

The economics module is based on calculations of the present worth of the sum of all costs associated with owning and operating the system over its estimated life. Fundamentally, it is the life-cycle cost (LCC), not the first costs or operating costs that dictate the selection of equipment for the hybrid solar-GHP systems. The life-cycle cost considers the time value of money by relating all future costs to present costs. In the economics module, the life cycle cost is calculated using the P1-P2 method presented in Duffie and Beckman (2006) where the life-cycle cost is considered to be the sum of two terms. The first term is proportional to the first year operating cost (F), and the second term is proportional to the first costs of the system (E).

$$LCC = P_1 F + P_2 E \tag{1}$$

3.6 GHP System Optimization

3.6.1 Implementation

In addition to straightforward simulation of GHP systems, the simulator incorporates an optimization module such that borehole depths and number of solar collectors (if applicable) can by systematically adjusted to meet design heat pump entering fluid criteria. The optimization algorithms used here are packaged in GenOpt (LBNL, 2004).

The objective function to be minimized (in hybrid GHP configurations) implicitly balances ground thermal loads (heat rejection to and heat extraction from the Earth) on an annual basis. At the conditions of ground thermal load balance, the annual minimum heat pump entering fluid temperature in heating-dominated buildings and the annual maximum heat pump entering fluid temperature in cooling-dominated buildings are set to be equivalent from year-to-year, rather than progressively reaching the maximum/minimum design temperature several years into the future. When the minimum (or maximum) temperatures are equivalent from year to year, the system is considered optimized with a thermal balance on the ground heat rejection/extraction loads, and the ground loop length is at a minimum.

3.6.2 Stand-Alone GHP Systems

For stand-alone GHP systems, the minimum and maximum heat pump entering fluid temperature limits are used in the objective function. The number of boreholes is automatically adjusted by the optimizer to just stay within the critical heat pump entering fluid temperature. The *Number of Boreholes* entered is the initial condition for the optimizer. This problem is one of single-variable optimization, and the Golden Section Search algorithm is used in the simulation to adjust the *Number of Boreholes* until the optimization constraints are satisfied.

3.6.3 Hybrid GHP Systems

For hybrid solar GHP systems, the minimum and maximum heat pump entering fluid temperature limits, in addition to the above, are used in the objective function. The number of boreholes and solar collectors are automatically adjusted by the optimizer to stay just within the critical heat pump entering fluid temperature limit each year. The *Number of Boreholes* and the *Number of Solar Collectors* entered are the initial conditions for the optimizer.

Several past studies have shown that a simplex-based optimization approach (Nelder and Mead, 1965) yields most accurate results in terms of the global maxima and minima, as well as with respect to computational speed (Chiasson et al. 2009, Chiasson and Yavuzturk 2009 and 2003). The objective function to be minimized is given by a sum of the squares between annual minimum heat pump entering fluid temperatures and the heat pump equipment dependent design entering fluid temperatures

The optimization algorithm implemented for hybrid heating- or cooling-dominated projects is the simplex method of Nelder and Mead (1965) with extensions by O'Neill (1971). Optimization runs of 20 or 30 year simulations can take several hours to complete. GenOpt will produce an output file summarizing results of each run, and will identify the best (optimized) result.

4. EXAMPLE APPLICATION AND USE OF THE SIMULATOR

An hourly loads profile for an elementary school building in the Northern U.S. is shown in Figure 4.Note the heating dominant nature of the loads over the annual cycle.

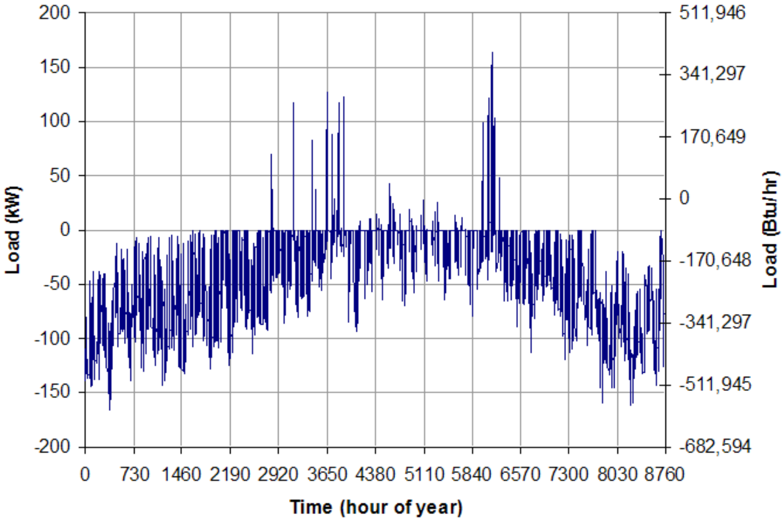

Figure 4: Hourly heating loads (negative) and cooling loads (positive) for a school building in the Northern U.S.

Performing an optimization on a stand-alone GHP system over a 30-year period yields heat pump entering fluid temperatures shown in Figure 5 for a minimum design temperature constraint of 2.5°C. The progressive decrease in Earth temperature from year to year is evident. Even after 30 years of operation, the temperature in the Earth storage volume has not quite reached steady-state. The optimized borehole configuration was 10 x 10 boreholes with 7 m spacing in a square pattern, with each borehole at a depth of 103 m.

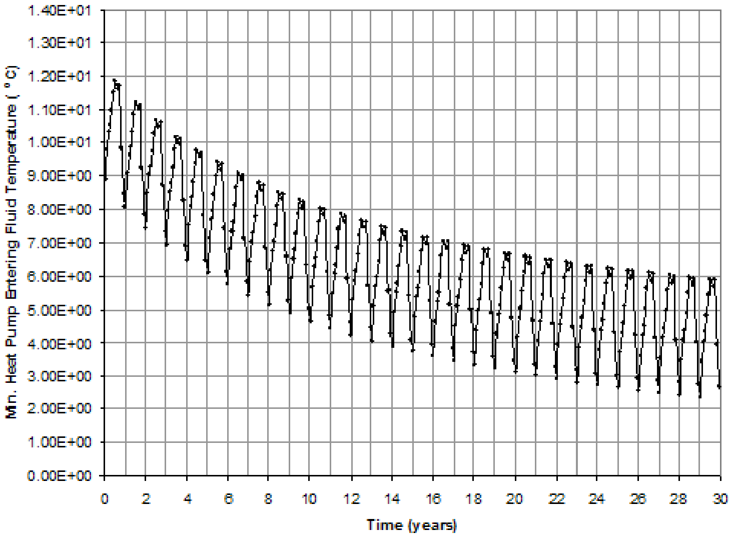

Figure 5: Heat pump entering fluid temperatures for a 30-year period for a school building in the Northern U.S.

Performing an optimization on the hybridized version of the above case yields temperatures shown in Figure 6. For comparison purposes, the peak minimum and maximum monthly heat pump entering fluid temperatures are plotted for the corresponding base case shown in Figure 5. Review of Figures 5 and 6 shows that the system has been optimized as defined previously, since the minimum and maximum peak heat pump entering fluid temperatures are constant from year to year. The target minimum heat pump entering fluid temperature in the optimized case was set equal to the minimum heat pump entering fluid temperature of the corresponding base case so that total GHX size reduction could be assessed.

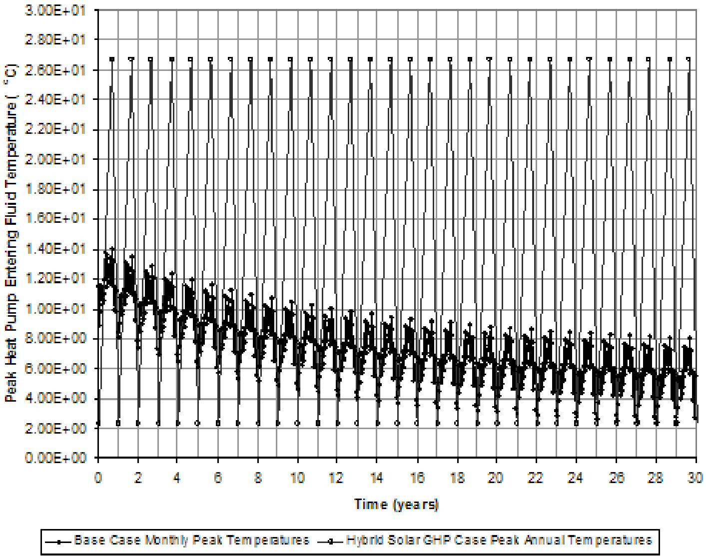

Figure 6: Heat pump entering fluid temperatures for the base GHP case and optimized hybrid solar GHP case for the school building in the Northern U.S.

The number of function evaluations to minimize the objective function in this case was 42. The optimized size of the GHX was reduced by 62%, with the addition of 219 m^2 of solar collector area. A review of Figure 6 shows the effect of balancing the annual ground loads on the "non-critical" design heat pump entering fluid temperatures (i.e., the maximum heat pump entering fluid temperature); thermal energy supplied by the solar array necessary to balance the annual ground loads does not result in the upper critical heat pump entering fluid temperatures to be exceeded.

In briefly considering the economics of hybridizing this building, the cost of the base case GHX would be on the order of $772,000, assuming an installed cost of $75/m of vertical borehole. The addition of the solar collector array trades off about $479,000 in GHX cost with about $263,000 on solar array costs, assuming $1200/m^2 installed cost of the collector array. Therefore, hybridizing this building with a solar array results in a capital cost savings of 28%.

In examination of additional cases, the total GHX size reduction is directly proportional to the annual loads ratio; the greater the imbalance of the annual ground loads, the greater the opportunity to reduce the total GHX size by balancing the annual ground loads. Generalized statements regarding reduction in GHX length are difficult to make; reductions in GHX length are case-specific and depend on the thermal properties of the subsurface materials, the design conditions of the project, spacing of the boreholes, and the life-cycle considered.

5. CONCLUSIONS

This paper has described the need for and development of a simulator for hybrid solar-geothermal heat pump systems. The simulator has been developed in the TRNSYS modeling environment as a freely distributable software package. A controls and multi-variable optimization strategy has been implemented in to the simulator, where the result is the optimal depth and number of borehole heat exchangers and solar thermal collectors to achieve balanced thermal loads on the Earth over the annual cycle. Both heating- and cooling-dominated applications can be modeled. In heating-dominated applications, the concept involves injecting solar energy into the ground via glazed solar collectors. In cooling-dominated applications, the concept involves rejecting thermal energy from the ground through unglazed solar collectors that behave as radiant cooling panels.

Based on a limited number of cases examined, the GHX size reduction with the tradeoff of additional solar collectors can result in significant economic advantages. However, generalized statements regarding reduction in GHX length are difficult to make; reductions in GHX length are case-specific and depend on the relative imbalance in the annual ground thermal loads, thermal properties of the subsurface materials, spacing of the boreholes, and the life-cycle considered

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