DEVELOPMENT OF A SOFTWARE DESIGN TOOL FOR HYBRID SOLAR-GEOTHERMAL HEAT PUMP SYSTEMS IN HEATING- AND COOLING-DOMINATED BUILDINGS

FINAL REPORT

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EXECUTIVE SUMMARY

This project provides an easy-to-use, menu-driven, software tool for designing hybrid solar-geothermal heat pump systems (GHP) for both heating- and cooling-dominated buildings. No such design tool currently exists. In heating-dominated buildings, the design approach takes advantage of glazed solar collectors to effectively balance the annual thermal loads on the ground with renewable solar energy. In cooling-dominated climates, the design approach takes advantage of relatively low-cost, unglazed solar collectors as the heat rejecting component.

The primary benefit of hybrid GHPs is the reduced initial cost of the ground heat exchanger (GHX). Furthermore, solar thermal collectors can be used to balance the ground loads over the annual cycle, thus making the GHX fully sustainable; 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; 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, and hybrid GHPs can expand the market by allowing reduced GHX footprint in both heating- and cooling-dominated climates.

The design tool allows for the straight-forward design of innovative GHP systems that currently pose a significant design challenge. The project lays the foundations for proper and reliable design of hybrid GHP systems, overcoming a series of difficult and cumbersome steps without the use of a system simulation approach, and without an automated optimization scheme. As new technologies and design concepts emerge, sophisticated design tools and methodologies must accompany them and be made usable for practitioners. Lack of reliable design tools results in reluctance of practitioners to implement more complex systems.

A menu-driven software tool for the design of hybrid solar GHP systems is provided that is based on mathematically robust, validated models. An automated optimization tool is used to balance ground loads and incorporated into the simulation engine. With knowledge of the building loads, thermal properties of the ground, the borehole heat exchanger configuration, the heat pump peak hourly and seasonal COP for heating and cooling, the critical heat pump design entering fluid temperature, and the thermal performance of a solar collector, the total GHX length can be calculated along with the area of a supplemental solar collector array and the corresponding reduced GHX length. An economic analysis module allows for the calculation of the lowest capital cost combination of solar collector area and GHX length.

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INTRODUCTION AND BACKGROUND

The hybridization of geothermal heat pump systems (also known as ground-coupled or ground source heat pump systems) is accomplished by incorporating supplemental heat rejection or generation equipment with the ground heat exchanger (GHE) loop. Typically such equipment includes cooling towers, fluid coolers, boilers, and solar collectors, and generally, hybridization of geothermal heat pump systems could conceivably include the coupling of any heat source or sink to a GHE loop. Hybridization thus allows for part of the building thermal load to be exchanged via the supplemental equipment before heat transfer with the ground takes place.

In non-hybridized geothermal heat pump (GHP) systems that serve heating- or cooling-dominated building thermal loads, an annual thermal imbalance of the ground thermal loads will occur (Figure 1). For instance, in heating-dominated buildings a non-hybridized geothermal heat pump system will on an annual basis extract more energy from the ground than reject to it, causing the average temperature of the ground volume to decrease over time.

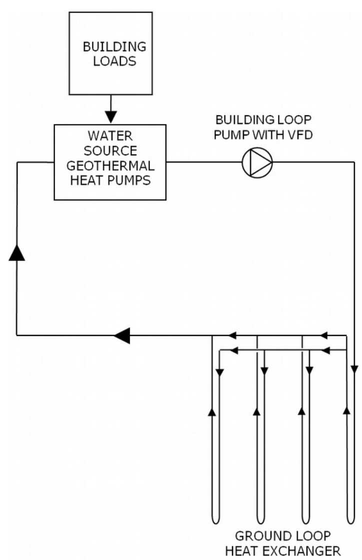

Figure 1. *Example of a configuration of non-hybridized GHP systems.*

As the average ground temperature decreases, the thermal quality of the heat source for the heat pump cycle is degraded (a heat source at a progressively lower temperature), causing the coefficient of performance (COP) of the heat pump to deteriorate. Similarly, in cooling-dominated buildings more energy is rejected to the ground than extracted from it, and on an annual basis the average ground temperature will increase, resulting in a thermally degraded heat sink (a heat sink at a progressively higher temperature) for the heat pump cycle. Thermal imbalance conditions in the ground will cause the GHP system to operate at increasingly reduced capacities, and may ultimately result in system failures due to continuously deteriorating heat pump COP. In order to avoid failure without hybridization in heating- or cooling-dominated buildings, ground heat exchanger loops must be sized to satisfy annual peak heating and cooling loads for the entire life span of the system, which requires excessively large and costly ground heat exchanger loops and borehole fields.

The significance of hybridization lies in the fact that it may be used to completely balance ground thermal loads on an annual basis, thus preventing sink/source thermal degradation of the heat pump cycle to occur. Furthermore, balancing ground loads annually by shifting the unbalanced portion to a supplemental heat transfer unit removes an implicitly built-in limitation in life span. A thermal balance in the loading of the ground volume via ground loop heat exchangers is achieved so that on an annual basis the magnitude of energy extracted equals the magnitude of energy rejected, ensuring maximum and minimum heat pump entering fluid temperatures (temperature of the heat transfer fluid returning to the heat pump from the ground) to remain constant within an acceptable range for the operation of the heat pump cycle at designed efficiencies. Thermal balancing of the ground loads implicitly 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 hybrid systems permit the use of smaller, lower-cost borehole fields.

However, 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. For example, as building loads display a time-dependent behavior, 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 of weather conditions, solar availability and ground loop temperature. 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. An example system component inter-connect diagram for a hybrid GHP is shown is Figure 2.

The accurate design of hybrid GHP systems is essentially an optimization problem as sizing of the supplemental components and the GHE loop 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. Clearly, proper, 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.

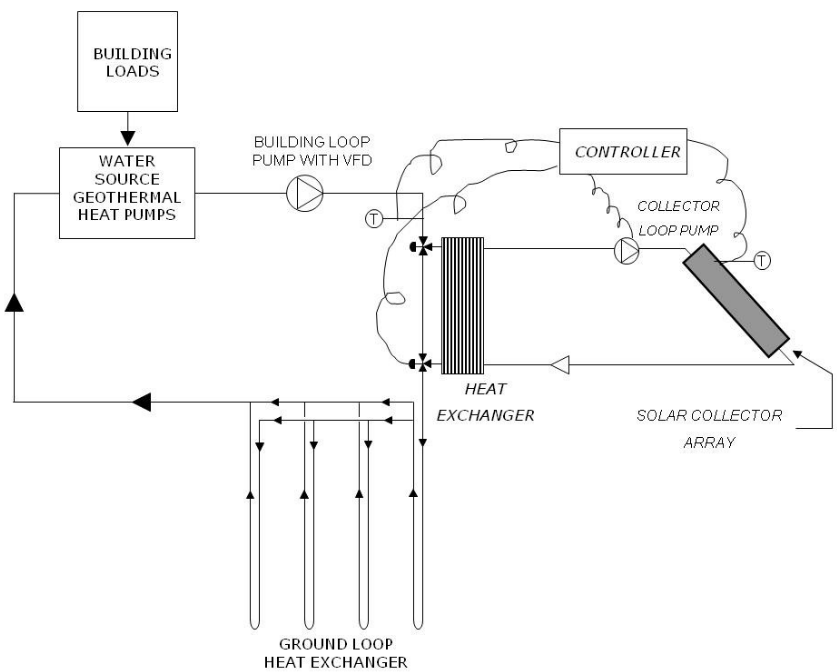

Figure 2. *Example of a system configuration for a hybrid geothermal heat pump application.*

The main benefit of hybrid geothermal heat pump systems relative to non-hybrid systems is the significantly reduced initial cost of the ground heat exchanger. 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.

PROJECT OBJECTIVES

This project comprises the development and integration of algorithms cast in a stand-alone software tool developed using the TRNSYS (SEL, 2000) computing environment that employs solar collectors for both heating- and cooling-dominated applications. For heating-dominated buildings, glazed solar collectors are used as supplemental heat transfer devices for the thermal recharge of the ground volume where ground borehole heat exchangers are installed. With proper system control and operating strategies, this hybridization ensures sustainable operation of the system through balancing of the annual ground loads. 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 before it is allowed to re-circulate to the ground. Again, with proper system control and operating strategies, hybridization with unglazed collectors ensures long-term sustainable operation. The overall approach in this project is ‘solar-centric’ with respect to the choice of supplemental heat transfer devices as solar collectors are utilized for ground source heat pump system hybridization in both heating- and cooling-dominated buildings.

The project uses a validated optimization algorithm along with validated system components and sub-components in developing an integrated system simulation and design model for hybrid GHP systems in heating- and cooling-dominated buildings that effectively balances ground thermal loads (Chiasson et al. 2009). Furthermore, the model 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 model is cast as a stand-alone software tool in the TRNSYS (SEL

2000) computing environment with an easy-to-use, menu-driven, graphical user interface for designing hybrid solar-geothermal heat pump systems. In heating-dominated buildings, the design approach takes advantage of glazed solar collectors to effectively balance the annual thermal loads on the ground with renewable solar energy. In cooling-dominated climates, the design approach takes advantage of unglazed solar collectors as the heat rejecting component.

An economic analysis module is included in the software tool 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 software tool aids the design engineer in comparative analyses and serves as a supplemental decision-making tool in addition to being a design tool.

Ultimately, the main endeavor of the project has been to bring ‘state-of-the-art’ and proven system design, simulation and optimization algorithms to the GHP design engineers in an easy-to-use, reliable, and accurate software tool. Currently, no such comprehensive tool exists that allows the use of solar collectors for the design of hybrid GHPs for both heating- and cooling-dominated buildings. Coupled with the economic analysis and decision-making tool, the final product of the project fills a significant gap in hybrid GHP design.

Specific project objectives are summarized and listed below:

i. Identification of appropriate and field-validated mathematical simulation models for system components and sub-components (including various types of borehole heat exchanger configurations) of solar hybrid GHPs.
ii. Implementation the simulation models as TRNSYS component models, including any necessary modifications for operational suitability in the TRNSYS computing environment.
iii. Identification, selection and integration of appropriate optimization algorithms with the component simulation models for overall system simulation of solar hybrid GHPs.
iv. Development and integration of a synthetic load generator that allows for the computation of hourly building thermal loads using monthly and full load equivalent hours load profiles.

v. Development and integration of capabilities for user-selected weather and solar data into TRNSYS.

vi. Identification, development and integration of a comprehensive solar collector database into TRNSYS, including comprehensive performance data on glazed and unglazed solar collectors.

vii. Development of a menu-driven, user-friendly graphical user interface for the software tool.

viii. Development of comprehensive and software integrated help files, users' manuals and guided tutorials.

STRUCTURE AND CAPABILITIES

The software tool is developed in the TRNSYS computing environment and cast as a stand-alone package that runs under Microsoft Windows without the need for TRNSYS to be separately installed. The software tool was developed using Microsoft Windows version 7, however, it is backwards compatible to also operate under Microsoft Windows XP.

Mathematical models that describe the thermal performance and energy consumption of individual hybrid GHP system components were identified and coupled together (as shown in Figure 2 above) in the TRNSYS computing environment to ensure an accurate representation of the thermal behavior and operation of hybrid systems. Component models include the ground heat exchangers, isolation heat exchanger between the solar collector loop and the ground loop, solar collectors, heat pump unit, fluid circulation pumps, and tee-pieces/diverters. 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 recommendations of ASHRAE (2004), Yavuzturk and Spitler (2000) and Ramamoorthy et al. (2001).

TRNSYS computing environment allows for a series of optimization algorithms (LBNL –GenOpt 2004) to be coupled to mathematical component models so that various influence parameters can be optimized against each other, considering a defined objective function. The objective function under this task balances ground thermal loads (heat rejection to and heat extraction from the ground volume) 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.

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.

$$Z = \Sigma\left(T_{ann.\min.} - T_{design}\right)^2 \tag{1}$$

and

$$Z = \Sigma\left(T_{ann.\max.} - T_{design}\right)^2 \tag{2}$$

respectively for heating and cooling-dominated buildings.

The flowchart for the optimization algorithm coupled with the hybridized ground source heat pump system is given in Figure 3 below. The optimization algorithm is designed such that the system optimization model passes through the following stages:

i) Simulate the entire hybrid GHP system on an hourly basis for an initial set of Borehole Loop Length and Supplemental Equipment Size for the user-selected system life span, and store annual hourly minimum and maximum entering fluid temperatures to the heat pump (temperature of the fluid returning from the ground).

ii) Compare annual hourly minimum and maximum entering fluid temperatures to those values of desired design (and permissible to the heat pump), by computing the sum of the squares error Z.

iii) Compare Z to the pre-defined convergence criterion.

iv) If Z is less than the convergence criterion then the last values used for the Borehole Loop Length and the Supplemental Equipment Size represent optimized conditions (sizes) where ground loads will be annually balanced.

v) If Z is not less than the convergence criterion than values for the Borehole Loop Length and the Supplemental Equipment Size are updated using the Nelder and Mead Simplex optimization algorithm and passed to the beginning of the optimization algorithm to restart system hourly simulations.

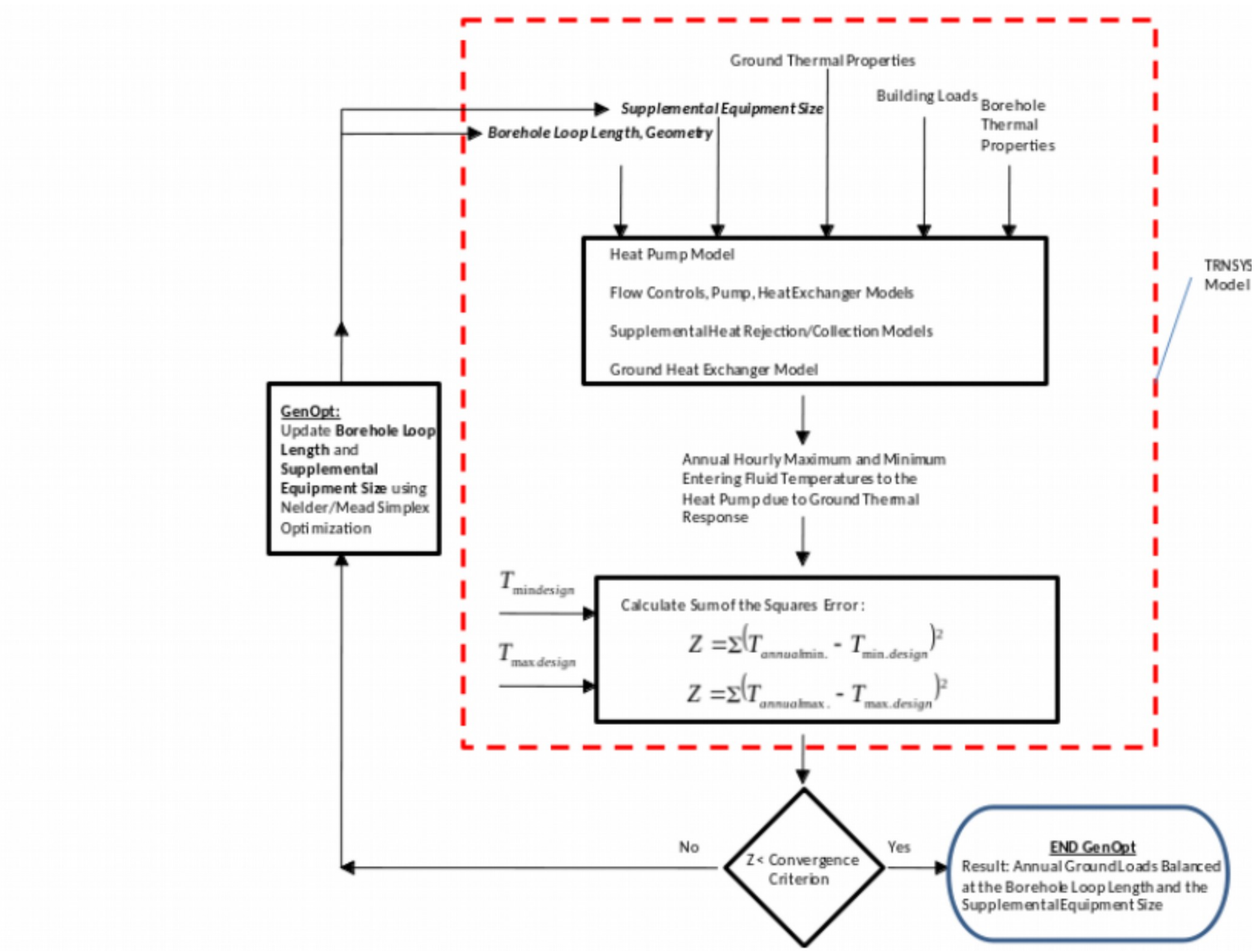

Figure 3. *Flowchart of the optimization algorithm.*

An example of the resulting objective function surface is illustrated in Figure 4 below where the sum of the squares error is computed as a function of the total borehole depth and the total size of the solar collector area.

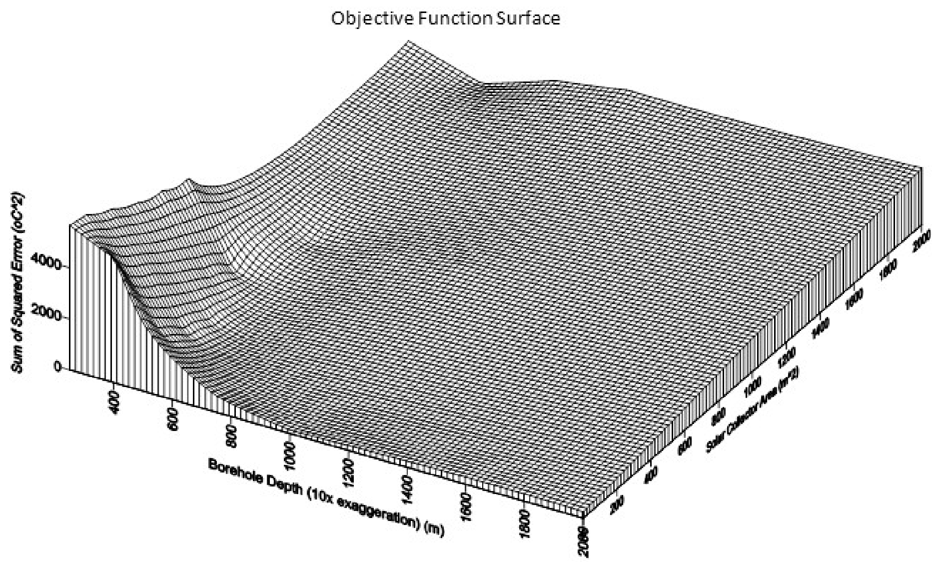

Figure 4. *Example optimization domain.*

Ground Heat Exchanger

In the design of GHP systems, the design engineer may select from among a number of different borehole ground heat exchanger types and configurations depending on thermal and physical characteristics of the ground formation. The software tool includes a significantly large percentage of borehole types that are commonly implemented in North American installations: i) single U-tube, ii) concentric tube, iii) standing column well type borehole (Figure 5). The model utilizes the duct storage approach for the calculation of the ground thermal response to heat rejection and extraction pulses (Claesson et al., 1981, Helstrom 1989, 1991, Mazzarella 1989, Pahud 1996). Previously field-validated component models for the computation of thermal resistance of various borehole types (Yavuzturk and Chiasson 2002) are incorporated into the software tools.

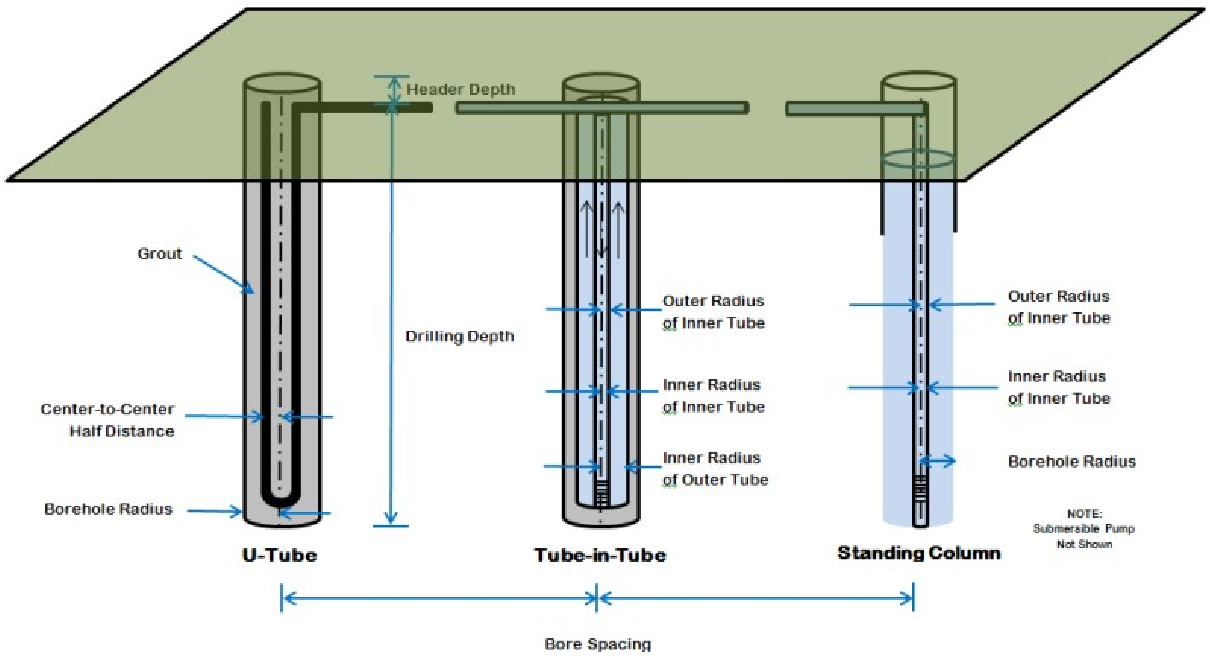

Figure 5. *Borehole configurations.*

For borehole configurations that utilize U-tubes, the software tool is capable of differentiating three different borehole completion cases where U-tube legs may be in contact with the borehole wall, the U-tube legs may be evenly spaced inside the borehole or where the U-tube legs are in contact with each other. The borehole completion configuration, although relatively difficult to control on the field, can have significant impact on the computation of the overall borehole thermal resistance that directly influences the magnitude of heat transfer between the borehole and the surrounding ground formation. Figure 6 below illustrates the three configurations built into the software tool.

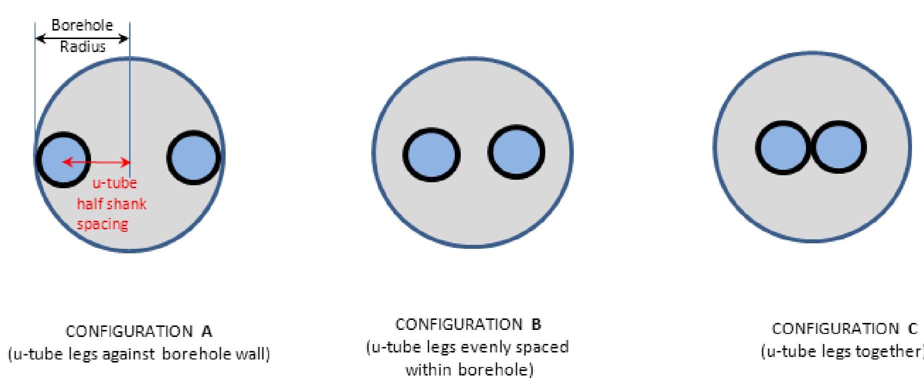

Figure 6. *Borehole completion cases for U-tube configuration.*

Building Loads

The level of detail for reliable design of hybrid solar geothermal heat pump systems necessitates hourly simulation. Since most practitioners and field engineers do not use hourly building loads a synthetic loads generator, based on peak building heating and cooling loads scaled based on the particular space use characteristics of different building types, are pre-calculated and incorporated into the software tool. The methodology involves developing hourly load profiles for reference buildings for all DOE climate zones (Figure 7).

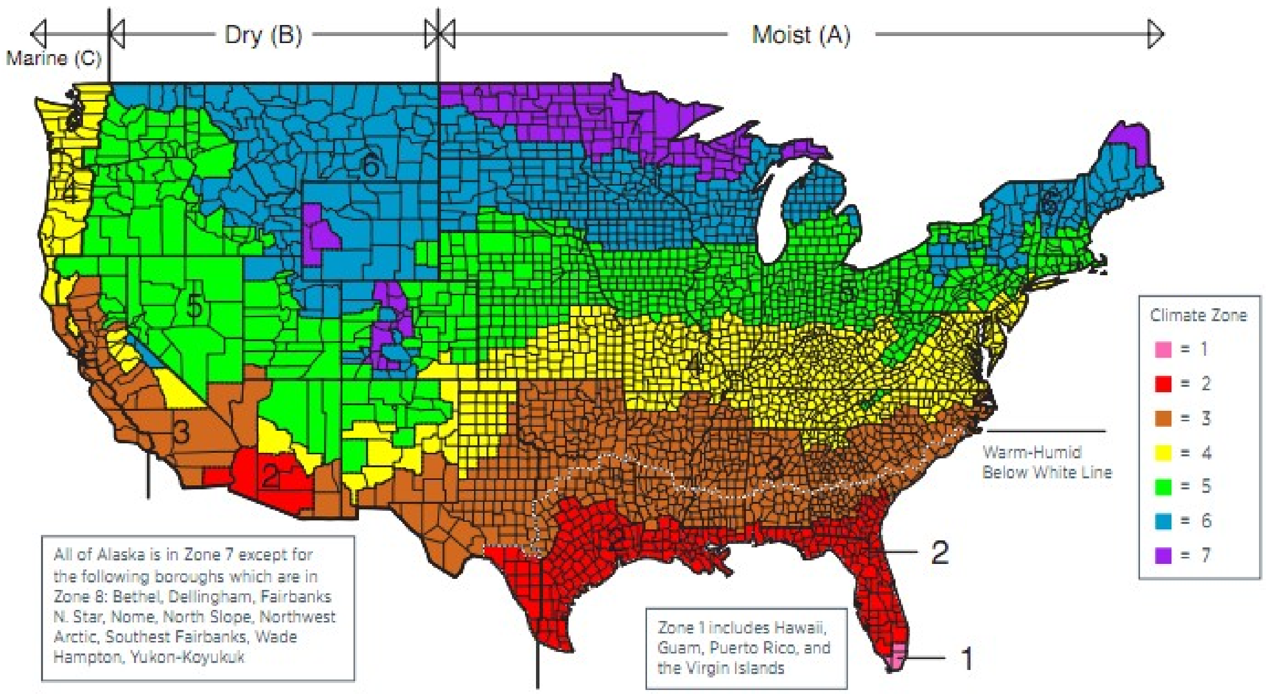

Figure 7. *United States climate zones.*

Reference loads are 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. Hourly loads are scaled internally within the program to match user-entered peak and annual loads. As the synthetic load generator model internally calculates hourly loads by multiplying the normalized load by the user-entered peak heating and cooling loads, the approach of using reference loads does not model a building as accurately as it would be calculated if the building hourly loads were known beforehand. Nevertheless, the approach provides an excellent means for modeling buildings in pre-design stages.

The reference loads approach can also be used to model buildings outside the United States with the following parallels to US climate regions:

Hot-Humid (portions zones 1, 2, and 3 that are in the moist category (A)): A region that receives more than 20 inches (50 cm) of annual precipitation and where one or both of the following occur:

• A 67°F (19.5°C) or higher wet bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year; or

• A 73°F (23°C) or higher wet bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year.

Mixed-Humid (zones 4 and 3 in category A): A region that receives more than 20 inches (50 cm) of annual precipitation, has approximately 5,400 heating degree days (65°F basis) or fewer, and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.

Hot-Dry (zones 2 and 3 in the dry category): A region that receives less than 20 inches (50 cm) of annual precipitation and where the monthly average outdoor temperature remains above 45°F (7°C) throughout the year.

Mixed-Dry (zone 4 B (dry)): A region that receives less than 20 inches (50 cm) of annual precipitation, has approximately 5,400 heating degree days (50°F basis) or less, and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.

Cold (zones 5 and 6): A region with between 5,400 e and 9,000 heating degree days (65°F basis).

Very-Cold (zone 7): A region with between 9,000 and 12,600 heating degree days (65°F basis).

Subarctic (zone 8): A region with 12,600 heating degree days (65° basis) or more. The only subarctic regions in the United States are found in Alaska, which is not shown on the map.

Marine (zones 3 and 4 located in the "C" moisture category): A region that meets all of the following criteria:

- A coldest month mean temperature between 27°F (-3°C) and 65°F (18°C)
- A warmest month mean of less than 72°F (22°C)
- At least 4 months with mean temperatures higher than 50°F (10°C)
- A dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

In addition to the option of using reference loads, the software tools allows for the use of pre-calculated building heating and cooling loads directly via an external file input.

Heat Pump

Geothermal heat pump performance is modeled using performance data from major US 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). The following approximate heating and cooling coefficients of performance are used considering heat pump entering fluid temperatures:

Standard Efficiency Heat Pump:

Approximate heating COP@ 0ºC entering fluid temperature = 3.4
Approximate heating COP@10ºC entering fluid temperature = 4.0
Approximate cooling COP@25ºC entering fluid temperature = 4.8
Approximate cooling COP@35ºC entering fluid temperature = 3.8

High Efficiency Heat Pump:

Approximate heating COP@ 0ºC entering fluid temperature = 3.8
Approximate heating COP@10ºC entering fluid temperature = 4.5
Approximate cooling COP@25ºC entering fluid temperature = 5.7
Approximate cooling COP@35ºC entering fluid temperature = 4.4

Integration of Weather Data and Solar Collector Product Database

The software tool 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 software tool 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.

Domestic Hot Water Supply

The software allows for the modeling, design and optimization of domestic hot water supply in three distinct configurations (system component interconnect diagram is shown in Figure 8):

i) 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 model input parameters are as follows:

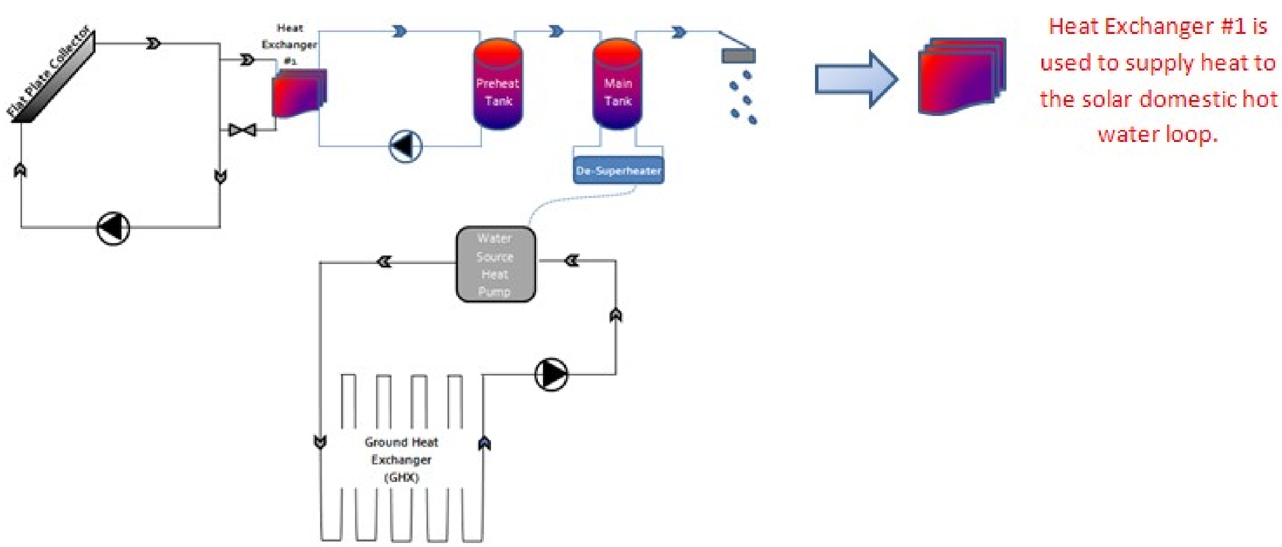

Figure 8. *Component interconnect diagram for solar domestic hot water configuration.*

Number of Residents: The number of people in the building using hot water.

Daily Hot Water Draw: The daily quantity of hot water consumption per capita. A typical value for residential buildings is about 60 L/day/person or 16 gal/day/person. The model stipulates usage schedules via a forcing function that is typical of the selected building type.

Tank Storage Temperature: The desired water temperature in the main storage tank. Most building codes limit this storage temperature to 60°C or 140°F.

Main Tank Volume: The volume of water in the main storage tank.

Main Tank Loss Coefficient: The heat loss coefficient (i.e., the "U-value") per unit surface area of the tank. This parameter is used to calculate the heat losses from the tank to the ambient environment.

Heat Exchanger Effectiveness: The effectiveness of the heat exchanger. The effectiveness is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate.

Preheat Tank Volume: The volume of water in the preheat storage tank.

Preheat Tank Loss Coefficient: The heat loss coefficient (i.e., the "U-value") per unit surface area of the tank. This parameter is used to calculate the heat losses from the tank to the ambient environment,

Pump Power Consumption at Maximum Flow: The hot water loop pump power delivered at maximum flow. The actual power is calculated by the model as a function of the pump control signal.

ii) 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.

iii) In the third configuration the auxiliary heating is 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.

Economics

An economics analysis module is incorporated into the software tool 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).

$$LCC = P_1F + P_2E \tag{3}$$

The parameters that are used for the specification of the life-cycle cost analyses include:

<u>Life of project</u>: This parameter is specified in years, and the selection should correspond to the amount of data in the hourly results output file.

<u>Seasonal and Time-of-Day Electricity Rate Schedules</u>: Utility companies can have many different types of electricity rate structures, and not all of them could be accommodated in the software tool. However, some common elements of utility rate structures are included in the module, such as the time-of-day rates and seasonal rates. Block rate structures are not included.

Input parameters here include the beginning and ending time of day that peak rates apply, in units of hours. The software tool expects the starting and ending date to which seasonal electric rates apply.

Electricity Rates: Rates corresponding to the above schedules must be specified. The module allows for energy rates, demand charges, and monthly connection fee. In addition, the module includes an annual ratchet fee if applicable.

Total capital cost of system: The total cost of the system under consideration.

Down payment fraction: The down payment on the system expressed as a fraction of the capital cost.

Installation cost fraction: The installation cost of the system expressed as a fraction of the capital cost.

Rebate/incentive fraction: Rebates and incentives expressed as a fraction of the capital cost.

Loan period: The number of years that borrowed money will be paid back.

Interest rate on loan: The interest rate paid on the loan or mortgage.

Annual escalation rate of electricity: The annual rate at which electricity costs are expected to increase. A default value of 0.05 is assumed.

Discount rate: The rate used to discount future cash flows in order to obtain their present value. The default value is 0.08. This rate is generally viewed as being most appropriate for an organization's weighted average cost of capital. An organization's cost of capital is not simply the interest rate that it must pay for long-term debt, but it is rather a broad concept involving a blending of the costs of all sources of investment funds, both debt and equity. The discount rate used to assess the financial viability of a given project is sometimes called the "hurdle rate," the "cut-off rate," or the "required rate of return."

Income tax rate: The rate at which income is taxed.

Property tax rate: The rate at which property is taxed.

Depreciation life: The equipment depreciation life.

Salvage fraction: The salvage price of the equipment at the end of its life time expressed as a fraction of the capital cost.

Annual maintenance cost (as fraction of capital cost): Annual maintenance costs expresses as a fraction of the capital cost.

The module supplies analysis results in terms of the net present value of the life-cycle cost of the simulated project, the annualized cost of electricity, and the maximum and minimum heat pump entering fluid temperatures. It should be noted that the life-cycle cost analysis module only provides a first-cut approximation based on the assumptions entered and more detailed economic studies may be appropriate in order to obtain a more accurate assessment.

Output

The software tool provides three forms of selectable output:

(i) Online Results display a time-series graph of the hourly heat pump entering fluid temperature as the simulation is progressing. This selection is highly useful in tracking progress of the simulation, both in terms of execution time and "reality-checking" of the results. If the results are unacceptable, the simulation can be terminated and then re-started with revised input parameters as necessary.

(ii) Monthly Summaries can be printed to a user-named file following simulation results on a monthly basis. The file headers and corresponding units are listed below:

Column 1: Time the end of the month (hours)
Column 2: Monthly minimum heat pump entering fluid temperature (ºC)
Column 3: Monthly maximum heat pump entering fluid temperature (ºC)

Column 4: Heat pump monthly energy consumption (kWh)

Column 5: GHX fluid circulating pump monthly energy consumption (kJ)

Column 6: Solar loop circulating pump monthly energy consumption (kJ)

Column 7: Hot water loop circulating pump monthly energy consumption (kJ)

Column 8: Hot water tank auxiliary heating element monthly energy consumption (kJ)

Column 9: Monthly total solar energy collected (kJ)

Column 10: Monthly average solar preheat tank temperature (ºC)

Column 11: Monthly average main storage tank temperature (ºC)

(iii) Hourly Output can be printed to a user-named file e following simulation results on an hourly basis. The file headers and corresponding units are listed below:

Column 1: Time of the simulation (hours)

Column 2: Heat pump entering fluid temperature (ºC)

Column 3: Fluid mass flow rate through the heat pump(s) (kg/hr)

Column 4: Heat pump power (kW)

Column 5: GHX fluid circulating pump power (kJ/hr)

Column 6: Solar loop circulating pump power (kJ/hr)

Column 7: Hot water loop circulating pump power (kJ/hr)

Column 8: Hot water tank auxiliary heating element power (kJ/hr)

Column 9: Solar power collected (kJ/hr)

Column 10: Solar preheat tank temperature (ºC)

Column 11: Main storage tank temperature (ºC)

INSTALLATION OF THE SOFTWARE TOOL

The install package of the software tool contains installation setup and support files. The software tool has been extensively tested to run under Microsoft Windows version 7, and is backward compatible including Microsoft Windows XP.

Figure 9. *Hybrid Solar-GHP simulation tool installation screen.*

The software tool is installed by double-clicking the executable 'setup' file that activates the installer package. The splash screen of the installer package is shown in Figure 9. At this window, clicking 'Install' will install the software tool with default options using the default directory structure. Clicking 'Next' allows user to be able to choose a variety of install options with respect to the location of the installation files, directory structure, and shortcuts (Figure 10).

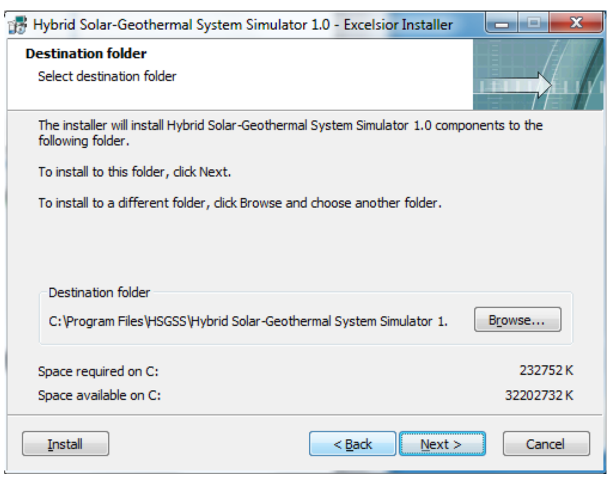

Figure 10. *Hybrid Solar-GHP simulation tool installation options.*

The software tool is run by selecting the executable file 'HybridSolarGHPSimulator.exe', which will be available under the Start Menu inside the HSGSS folder. When the software is first started the TRNSYS environment is activated as a stand-alone framework (TRNEdit). The TRNSYS software package is not required to be installed separately. The introduction screen for the Hybrid Solar-GHP Simulation Tool will appear on the screen as shown in Figure 11.

Figure 11. *Hybrid Solar-GHP simulation tool welcome screen.*

The software tool includes four distinct simulation options that allow for the thermal and economic assessment of stand-alone and hybrid geothermal heat pump systems. The optimization module is coupled and used with hybrid GHP system simulations, and not used for the stand-alone system simulations. The simulation options can be selected in the ensuing screen as shown in Figure 12. It should be noted that the optimization module should only be selected in conjunction with the hybrid solar-GHP system simulations for either heating or cooling dominated buildings.

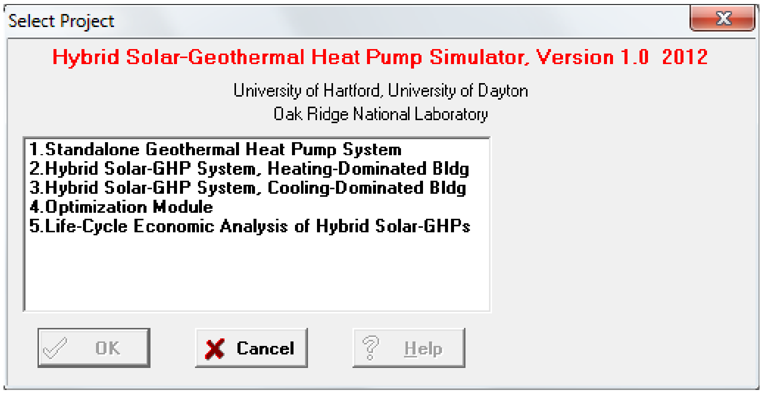

Figure 12. *Hybrid Solar-GHP Simulation tool project selection screen.*

SIMULATION OPTIONS

Stand-Alone Geothermal Heat Pump System

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. Although not part of the initially proposed project scope, this option is included in the software tool as it provides an additional important tool for final system design and analysis, and as a check for the non-hybridized system configuration. The software tool does provide the capability to add a solar domestic hot water system. The component interconnect diagram for the configuration inside the window screenshot is shown in Figure 13.

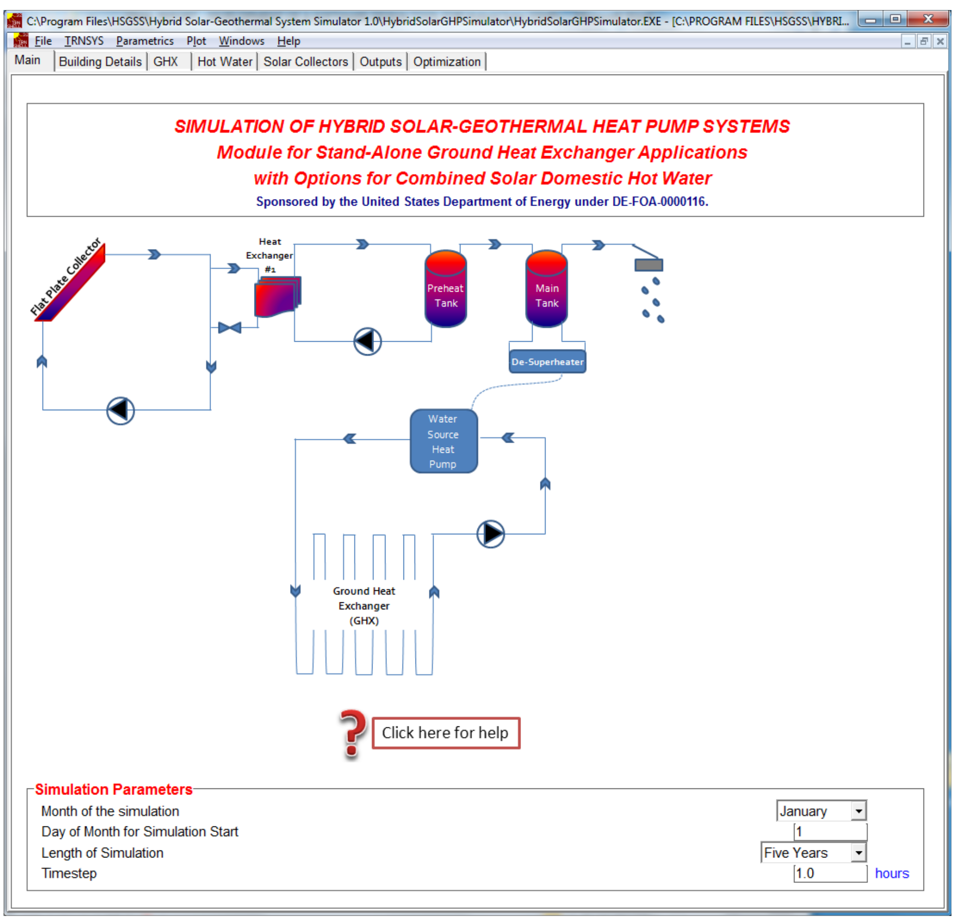

Figure 13. *Stand-alone geothermal heat pump system with optional domestic hot water supply.*

The stand-alone system configuration requires input via the ‘Main’, ‘Building Details’, ‘GHX’ and ‘Outputs’ tabs. The ‘Main’ tab requires the specification of the length of simulation and the simulation time steps, in addition providing a visual of the system configuration. The ‘Building Details’ tab requires the selection of heat pump efficiency, the appropriate DOE climate zone for the project, the building type and the building loads. If hourly building loads are already available via other means, the software tool is designed to read such loads in a predefined format. In case no pre-calculated building loads are available the software tool requires peak heating and cooling loads for the selected building type, and calculates hourly building loads based on estimates on space use requirements, building construction, and indoor and outdoor design conditions. The ‘GHX’ tab requires the input parameters that define the ground heat exchanger, specifically with respect to the type and geometry of the boreholes, ground thermal properties, circulating heat transfer amount and properties, and the operating characteristics of the circulating pumps for the heat transfer fluid in the ground heat exchangers.

If solar domestic hot water will be integrated into the system, inputs via the ‘Hot Water’ and ‘Solar Collector’ tabs are also needed (Figure 13). The ‘Hot Water’ tab requires the specification of energy supply to the hot water tank. It is possible to design the hot water supply without the solar collector loop, relying only on the de-superheater of the heat pump unit. The ‘Solar Collector’ tab requires input parameters for the solar collector type (selectable via a drop down menu), geometry, performance parameters and specifications of the circulating heat transfer fluid.

However, the optimization algorithm can also be used in conjunction with the stand-alone option for sizing ground heat exchanger lengths by specifying maximum and minimum entering fluid temperatures allowable to the heat pump via the ‘Optimization’ tab. In order to accomplish this, the Option 1 must be selected in the window shown in Figure 12, and all input parameters must be entered for a stand-alone simulation. At this point, the project file must be saved as a .trd file preferably in the root install directory, and the simulator must be restarted. At restart, the user must select Option 4 (Optimization Module) and specify the type of optimization (in this case ‘Conventional GHP System’), enter the full file name of the previously saved project .trd file, and desired maximum and minimum number of boreholes (Figure 14). The optimization routine, using the golden section search algorithm, will subsequently size the length of each borehole and the total number of boreholes for the ground heat exchanger.

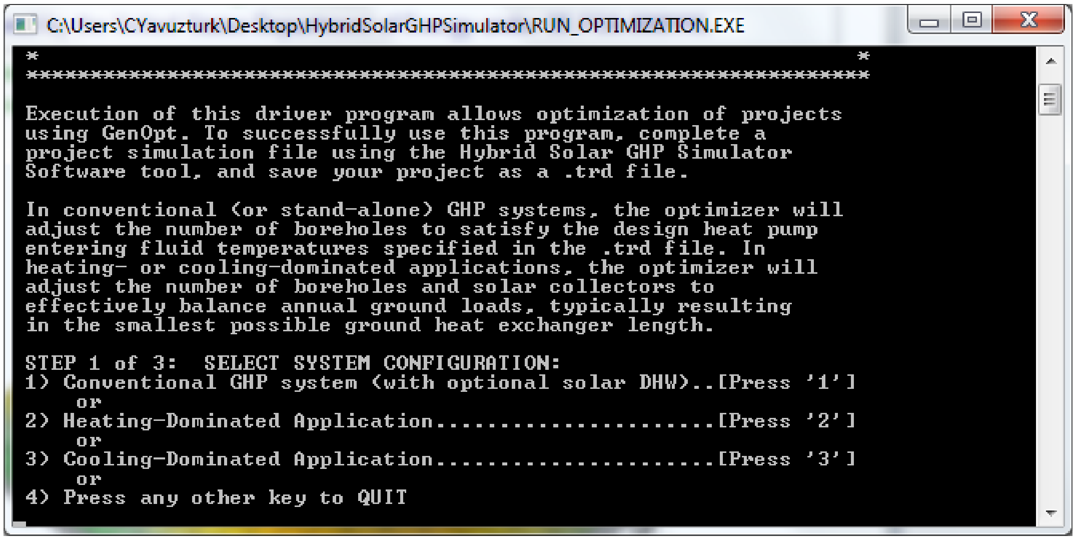

Figure 14. *Optimization project selection screen for a stand-alone system.*

The system simulations can be started by selecting TRNSYS and Calculate from the TRNSYS window menu, which will activate the on-line printer for the hourly simulation. A sample simulation result for slightly cooling-dominated building is shown in Figure 15 below.

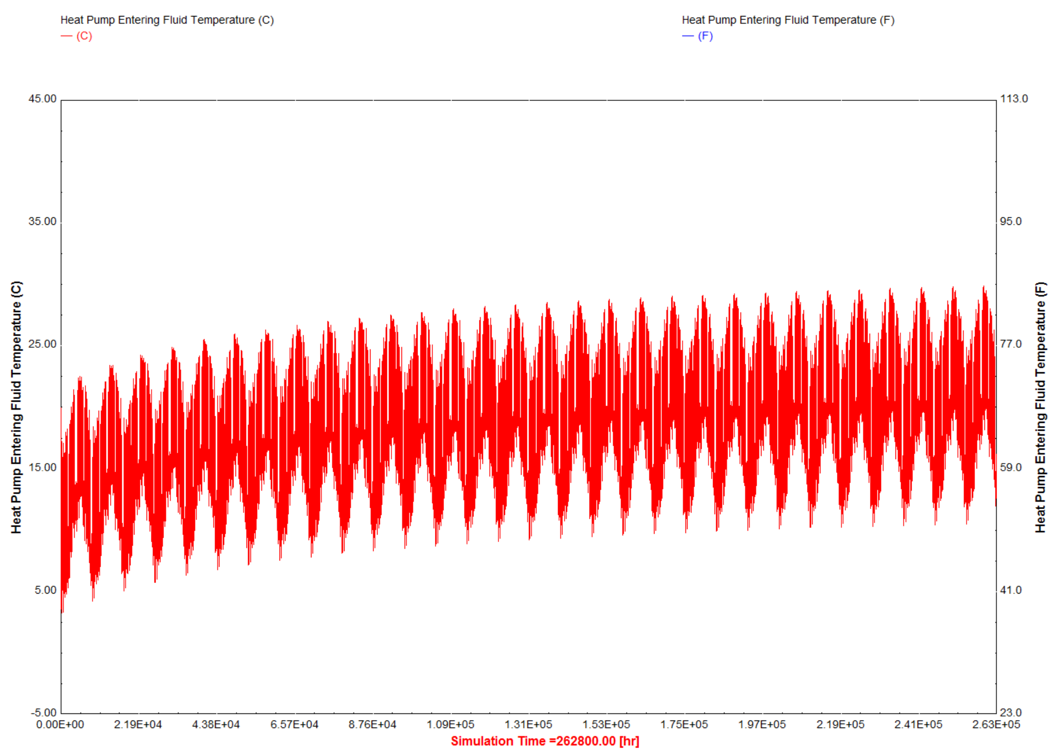

Figure 15. *A sample 30-year simulation run result as displayed on TRNSYS online plotter.*

Hybrid Solar-Geothermal Heat Pump System – Heating Dominated Building

This option (Option 2 of Figure 12) allows for the simulation as well as optimization of a hybrid solar-geothermal heat pump system for heating-dominated buildings by balancing the ground loads over the system life-cycle. The component interconnect diagram is shown in Figure 16.

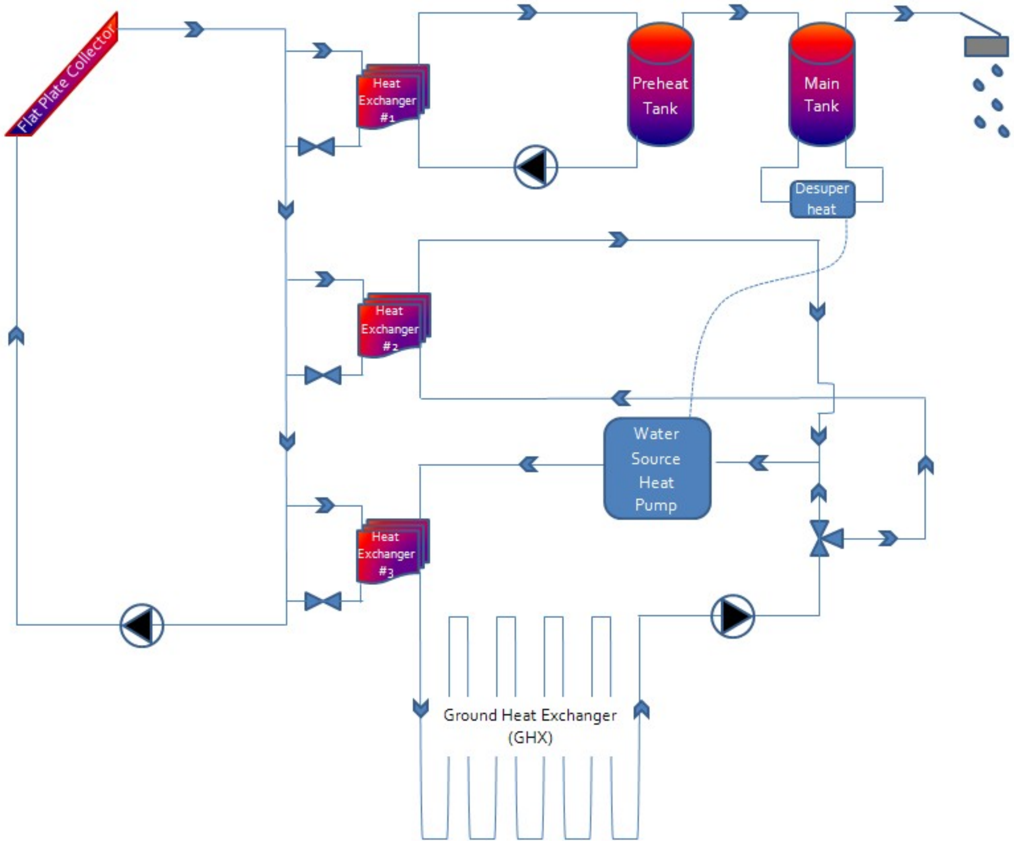

Figure 16. *Component interconnect diagram for hybrid solar-geothermal heat pump configuration for heating-dominated building applications including domestic hot water option*

Under this option, the software tool provides a new tab in the main window titled 'Hybrid Configuration'. It should be noted that this tab is only available for heating-dominated and cooling-dominated projects. The software tool 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. A screenshot of the 'Hybrid Configuration' tab is given in Figure 17.

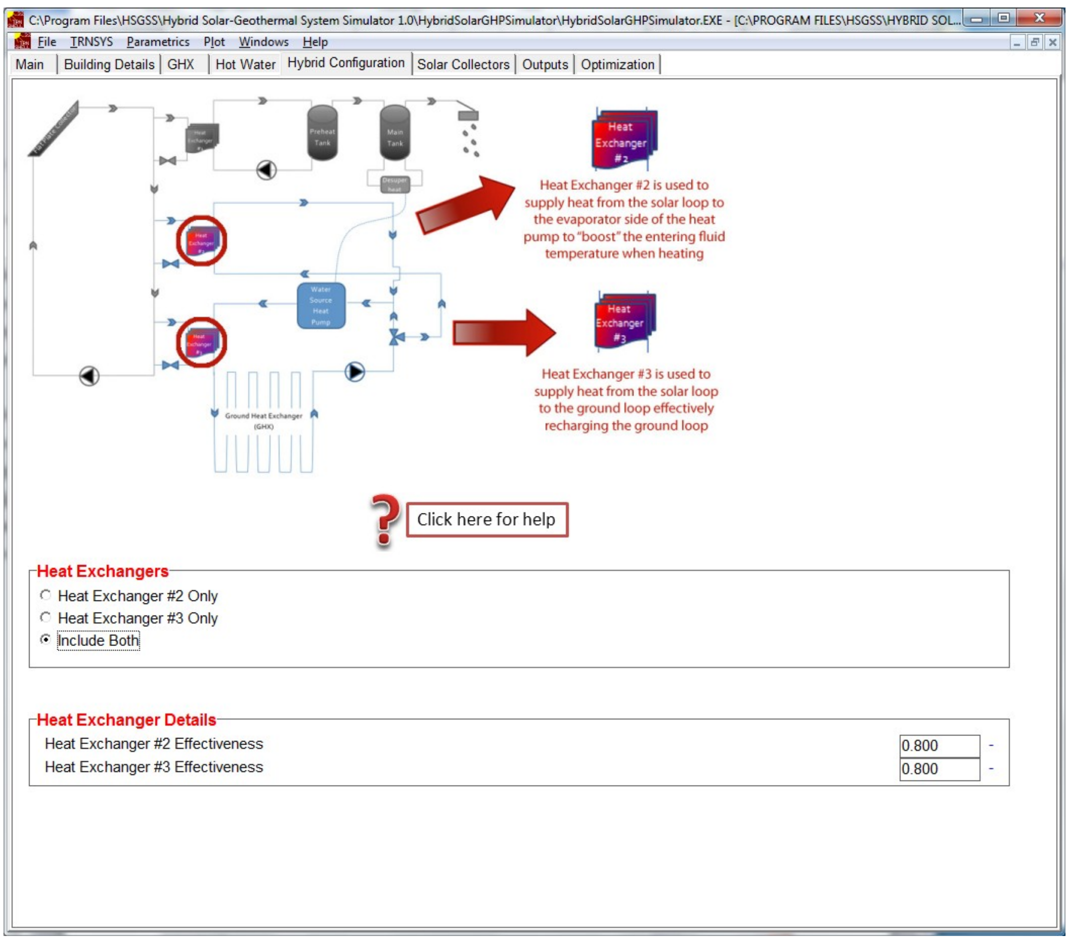

Figure 17. *Hybrid Configuration tab – Heating dominated buildings.*

The software tool is also configured 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.

Hybrid Solar-Geothermal Heat Pump System – Cooling Dominated Building

This option (Option 3 of Figure 12) allows for the simulation as well as optimization of a hybrid solar-geothermal heat pump system for cooling-dominated buildings by balancing the ground loads over the system life-cycle. The component interconnect diagram is identical to the heating-dominated configuration as shown in Figure 16 above. Nevertheless, the system operation is the opposite of the heating-dominated case with respect to Heat Exchanger #3 that is designed to reject thermal energy through unglazed solar collectors. 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. A screenshot of the 'Hybrid Configuration' tab for cooling-dominated buildings is given in Figure 18 below.

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. Currently, no design and simulation tools are available that incorporate the use of unglazed solar collectors for heat rejection in hybrid systems, and the software tool developed within the scope of this project offers the first successful implementation.

As in the heating-dominated system configuration, the software tool 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.

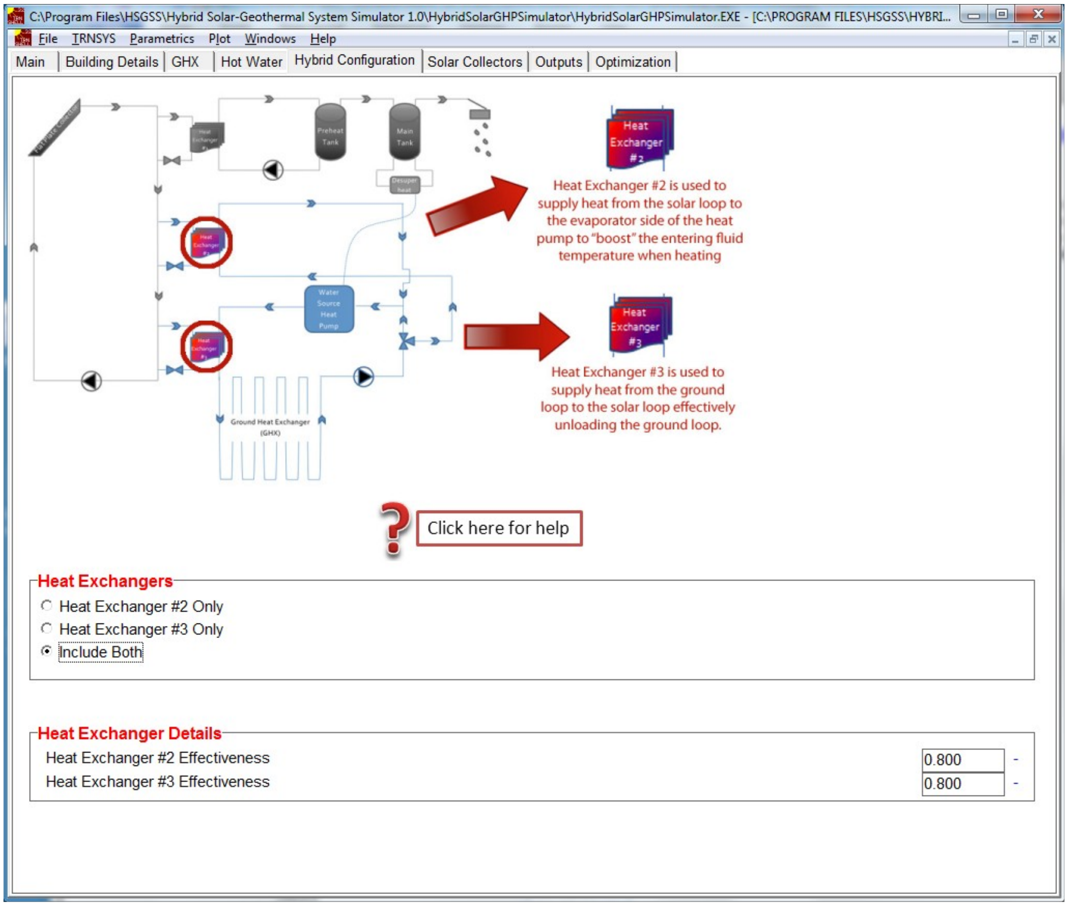

Figure 18. *Hybrid Configuration tab – Cooling dominated buildings.*

Optimization Module

This option (Option 4 in Figure 12) activates the optimization module either for the ground heat exchanger sizing for stand-alone GHP systems or for hybrid heating- or cooling dominated system configurations.

Stand-alone GHP Projects:

For Single-Run Simulations: The minimum and maximum heat pump entering fluid temperature limits are NOT USED. The *Number of Boreholes* entered is the actual number of boreholes simulated by the software tool.

For Optimization Runs: 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. The initial condition is modulated until the optimization constraints are satisfied.

Hybrid Heating- or Cooling-Dominated Projects:
For Single-Run Simulations: The minimum and maximum heat pump entering fluid temperature limits are used in the control of the solar collector loop. The numerical controllers will halt solar recharging or thermal unloading of the ground if heat pump entering fluid temperatures creep outside the acceptable limits. The *Number of Boreholes* and the *Number of Solar Collectors* entered are the actual number simulated.

For Optimization Runs: 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.

The following steps are recommended to initiate the optimization algorithm:

1) The .trd file must have been completed for the type of project of interest and saved when the input of all system configuration parameters finished. At this point, the user should restart the software tool.

2) The optimization module (Option 4 in Figure 12) must be selected once the software tool has been restarted.

3) From the optimization module, clicking on the figure will launch a console application prompting the user for further input data that will allow text files to be assembled for input to GenOpt, a generic optimization program. Full documentation of GenOpt is included in the *Optimization* subdirectory,

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. The file name of the summary file is titled *OutputListingAll.txt* and is found in the root HybridSolarGHPSimulator directory. A sample GenOpt optimization screen is shown in Figure 19. This window will open once the optimization algorithm is started along with the online printer for the entering fluid temperatures to the heat pump. Once the optimization is complete, the online printer will close, yet the optimization screen will remain open.

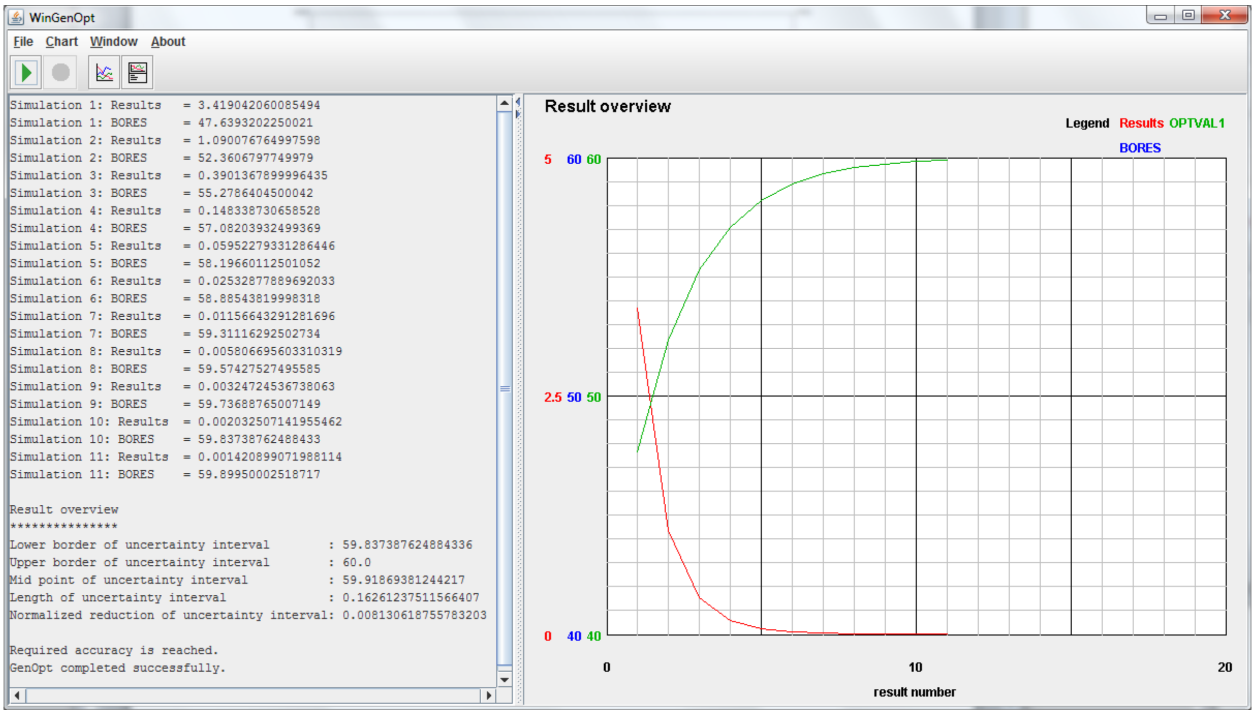

Figure 19. *Optimization module window showing a completed optimization run.*

Life-Cycle Economic Analysis

The life-cycle cost analysis module can be selected from the Hybrid Solar-GHP Simulation tool project selection screen (Option 5) as shown in Figure 12 above. The module is developed for companion use with the Hybrid Solar-Geothermal software tool and may not be activated as a stand-alone executable. The main window of the life-cycle cost analysis module is shown in Figure 20. The module requires the input of the project life cycle in years and the name of the file that contains the hourly results of a completed simulation. Additional data inputs are required with respect to seasonal and time-of-day electricity rate schedules, peak rates and utility fees.

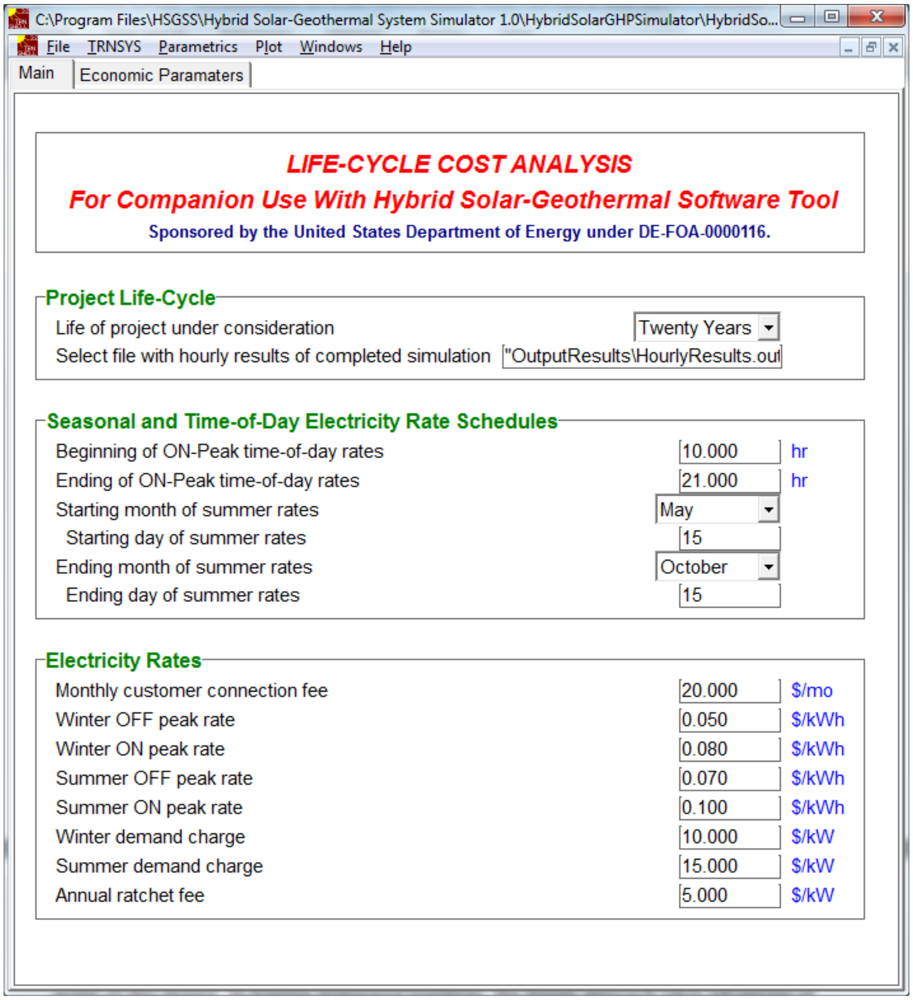

Figure 20. *Life-cycle cost analysis main window for companion use with Hybrid Solar-Geothermal software tool.*

Additional economic details including the total capital cost of the system, time value of money rates, depreciation life and salvage fraction along with estimates on annual system maintenance costs must be entered via the Economic Parameters window as shown in Figure 21. The software tool typically takes less than a minute to compute the net present value of the system life cycle cost, the annualized electricity cost, and the minimum and maximum entering fluid temperatures to the heat pump. The life cycle costs results window is shown in Figure 22.

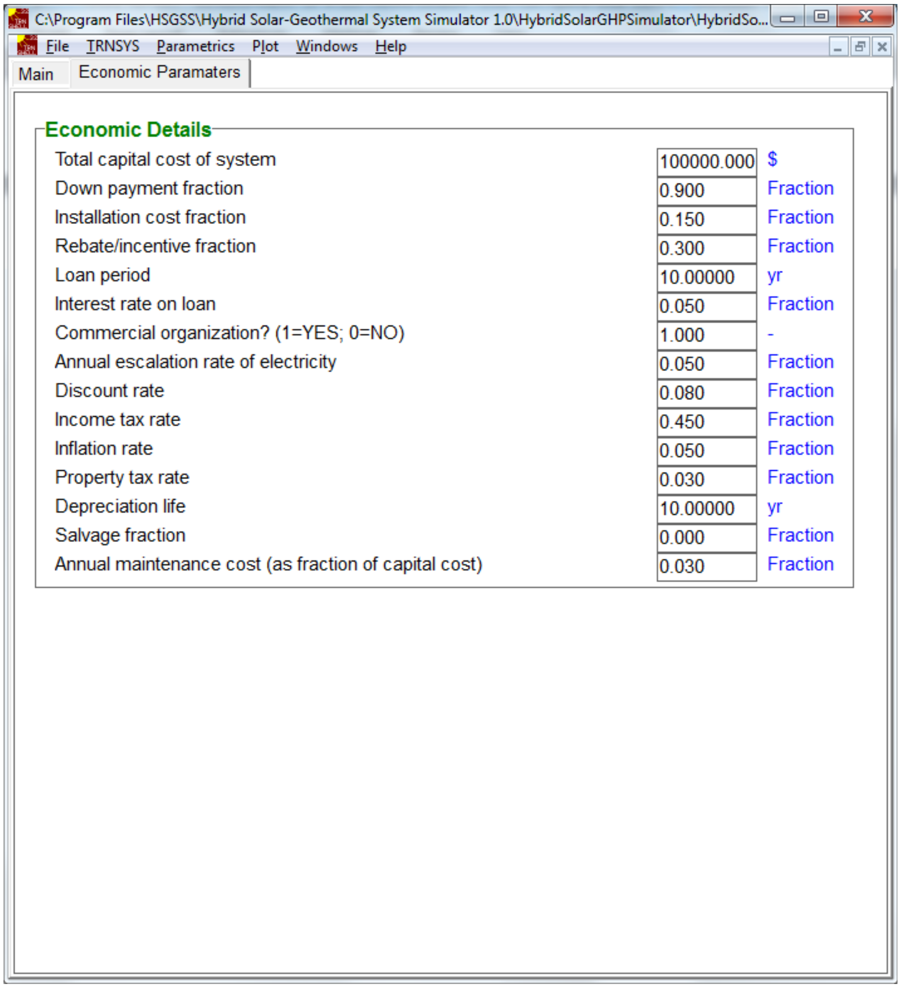

Figure 21. *Economic parameters data entry window*

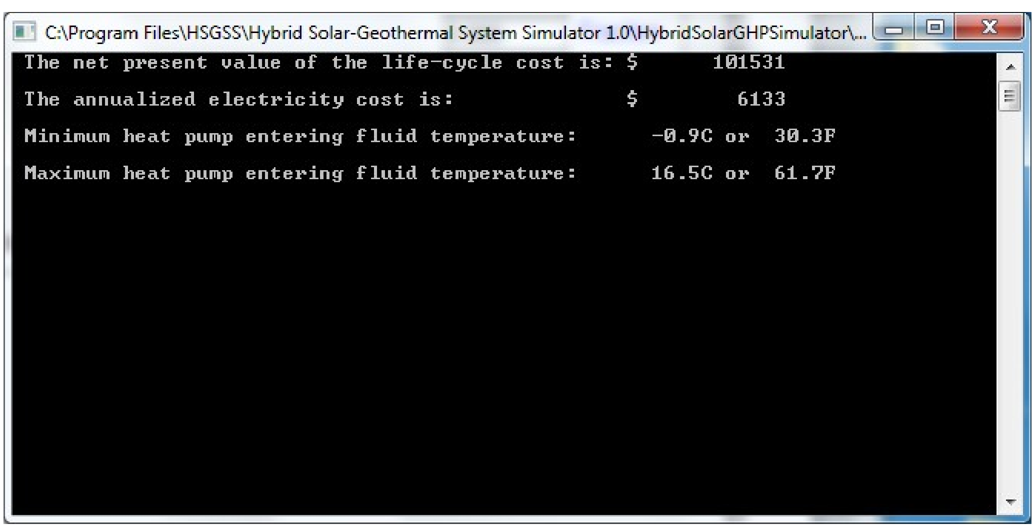

Figure 22. *Life-cycle cost analysis results window.*

CONCLUSIONS

An easy-to-use, menu-driven, software tool for designing hybrid solar-geothermal heat pump systems (GHP) for both heating- and cooling-dominated buildings is developed within the scope of this project. In heating-dominated buildings, the design approach takes advantage of glazed solar collectors to effectively balance the annual thermal loads on the ground with renewable solar energy. In cooling-dominated climates, the design approach takes advantage of relatively low-cost, unglazed solar collectors as the heat rejecting component.

The design tool allows for the design of innovative GHP systems that currently pose a significant design challenge. The project fills an important gap in availability of software tools that allow for proper and reliable design of hybrid GHP systems, overcoming a series of difficult and cumbersome steps without the use of a system simulation approach, and without an automated optimization scheme. As new technologies and design concepts emerge, sophisticated design tools and methodologies must accompany them and be made usable for practitioners. Lack of reliable design tools results in reluctance of practitioners to implement more complex systems.

A menu-driven software tool for the design of hybrid solar GHP systems is provided that is easy-to-use, but based on mathematically robust, and field-validated models. The method is based on current “state-of-the-art”, life-cycle system simulation tools for GHP systems. An automated optimization tool is used to balance ground loads and incorporated into the simulation engine. With knowledge of the building loads, thermal properties of the ground, the borehole heat exchanger configuration, the heat pump peak hourly and seasonal COP for heating and cooling, the critical heat pump design entering fluid temperature, and the thermal performance of a solar collector (selected from a product database), the total GHX length can be calculated along with the area of a supplemental solar collector array and the corresponding reduced GHX length. Furthermore, an economic analysis module is also integrated into the software tool that calculates the lowest capital cost combination of solar collector area and GHX length.

Furthermore, 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. Currently, no design and simulation tools are available that incorporate the use of unglazed solar collectors for heat rejection in hybrid systems, and the software tool developed within the scope of this project offers the first successful implementation.

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APPENDIX

1) Complete installation files of the software tool in an install package.