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FY20 Third Milestone Report for Advanced Techno-Economic Modeling for Geothermal Heat Pump Applications in Residential, Commercial, and Industry Buildings

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OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division

FY20 THIRD MILESTONE REPORT FOR ADVANCED TECHNO-ECONOMIC MODELING FOR GEOTHERMAL HEAT PUMP APPLICATIONS IN RESIDENTIAL, COMMERCIAL, AND INDUSTRY BUILDINGS

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EXECUTIVE SUMMARY

This report summarizes the developments of an integrated simulation program for enabling simulation, auto-sizing, and optimization of geothermal heat pump systems. This work fulfills the following FY20 third milestone for WBS 2.5.5.3: Advanced Techno-Economic Modeling for Geothermal Heat Pump Applications in Residential, Commercial, and Industry Building.

M3. A report covering verification of the model and architectural design of a web-based techno-economic analysis tool for geothermal heat pump (GHP) systems (Due by 6/30/2020)

Criteria: Capacity and performance of the new ground heat exchanger (GHE) modeling tool meet all the requirements. A platform to create and perform building energy simulations for GHP systems.

The highlights of the work covered in this report include the following:

- Implemented an accurate g-function calculation method to provide an enhanced library of g-functions in a standalone tool for modeling vertical bore ground heat exchangers (VBGHEs). Python scripts were developed to auto-size VBGHEs based on given thermal loads, ground thermal properties, and relevant g-functions.

- Developed several OpenStudio (OS) measures and Python scripts to automate the entire process of sizing VBGHEs and simulating GHP systems for assessing the techno-economic viability of potential GHP applications. A spreadsheet-based screening tool was developed as a prototype for the web-based tool to be developed.

- Conducted a case study with the screening tool to demonstrate how the tool can facilitate a holistic simulation-based design to improve the cost-effectiveness of a GHP system while maintaining thermal comfortable condition in a built environment.

1. INTRODUCTION AND BACKGROUND

Building owners are not usually familiar with geothermal heat pump (GHP) technologies and most people make decisions on whether to install a GHP system based on economics. A public-facing tool that can accurately analyze the costs and benefits of investing in GHPs will be able to help identify GHP projects with favorable economics. This tool will help implement cost-effective GHP systems in more homes and businesses and, as a result, fossil fuel consumption and the associated carbon emissions can be reduced.

However, the needed tool does not yet exist. Most existing tools are dedicated to sizing the ground heat exchanger (GHE), which is the most unique and critical component of a GHP system. These GHE sizing tools rely on inputs of the thermal loads of the GHE, which must be estimated or calculated with other methods or programs. Also, the dedicated GHE sizing tools do not account for the interactions among various components of a GHP system [e.g., pumping control or outdoor air (OA) ventilation system can affect the thermal loads and efficiency of a GHP system], so that they cannot accurately predict the performance of a GHP system. The lack of a tool possessing such functionality presents a major hurdle preventing GHP market penetration and novel financing models, such as third-party ownership of GHP systems. The feasibility of installing a GHP system for a specific project is usually assessed based on “rules of thumb” to estimate the equipment capacity required to meet the heating and cooling loads of the building and the size of the GHE. This rough estimation often results in a GHP system that does not meet the economic expectations of the owner or a GHP system that does not perform as efficiently as it could.

The size and cost of a GHE are sensitive to the amount of energy rejected to the ground when cooling compared with the amount of energy extracted when heating. Given the large thermal mass of the ground, the heat transfer process of a GHE is almost completely transient and thus both the peak and the total thermal loads of a GHE need to be accounted for when sizing a GHE. The thermal loads are affected by the design and operation of the building and its mechanical system. As buildings become more complex due to the increasing diversity in functions and efforts to reduce the environmental footprint of buildings, building energy simulation (BES) is more commonly used to predict the thermal loads of a building. Integrating BES with the GHE design tool not only provides a seamless transition between building’s thermal loads and the GHE sizing, but, more importantly, it allows the user to assess the impacts on the GHE size and the GHP system performance resulting from variations in the design and operation of the building and its mechanical system. With a side-by-side comparison between the GHP system and a conventional HVAC system for serving the same building, the energy savings and carbon emission reductions resulting from using the GHP system can be evaluated. Furthermore, an integrated tool enables a simulation-based holistic design approach for driving down the overall cost and energy consumption of the building by improving the design and controls of the building and the GHP system.

The bottleneck of the simulation-based design approach is building a detailed and accurate hourly BES model. It is time-consuming and requires many inputs. Having access to a software package that can estimate hourly energy loads with minimal user input will be beneficial. Additionally, GHE sizing tools should be improved to allow highly customizable designs of the GHE so that the GHE performance can be optimized based on the given thermal loads and the constraints of the available land area for installing the GHE.

The goal of this project is to develop a web-based and user-friendly techno-economic analysis tool for quickly assessing the techno-economic viability of applying GHP for a given building, or a cluster of buildings (e.g., a university campus). This tool is based on EnergyPlus and OpenStudio, the US Department of Energy’s (DOE’s) flagship program in BES, and the latest development in GHE modeling, which can quickly simulate the performance of highly customized GHE designs with satisfactory accuracy.

This report reviews the implementation of an automated simulation tool for performing a techno-economic analysis of the GHP system using VBGHE. Section 2 of this report reviews the literature on existing screening and design tools for GSHP. Section 3 gives an overview of the software developed to create GHP system simulation, auto-size GHE, and perform performance analysis. Section 4 demonstrates the use of the tool through a case study. Section 5 discusses the plan for developing a web-based tool based on current work. Section 6 provides conclusions and recommendations.

2. REVIEW EXISTING GHP SCREENING AND DESIGN TOOLS

An extensive review was conducted for the existing design and simulation tools for GHEs and GHP systems. Although most of the existing tools are dedicated to sizing GHEs, a few software programs integrate BES with GHE modeling and thus can simulate GHP system performance. Table 2-1 compares the existing standalone GHE sizing tools and software programs with integrated BES and GHE modeling.

Spitler and Bernier (2016) gave an overview of existing design tools and the sizing methods for VBGHEs. These GHE sizing tools are used to find the minimum size of VBGHE that can maintain the supply temperature of the VBGHE within the desired range based on user inputs of thermal loads, ground thermal properties, and in-borehole design parameters, including heat exchanger type and grout material thermal properties. Some early design tools (Bose et al. 1985, OSU 1988, and Kavanaugh 1995) use just a few pulses of thermal loads to determine the VBGHE size, which is later proved not as accurate as using monthly or hourly thermal loads (Cullin et al. 2015). The design methodologies for VBGHE are categorized in two groups: one is the method described in the ASHRAE Handbook (ASHRAE 2015), which requires six pulses of thermal loads (Kavanaugh 1995), and the other is based on simulation of VBGHEs using pre-calculated g-functions developed by Eskilson (1986), the ground heat storage model (usually called the duct storage model [DST]) developed by Hellström (1991), or other models of VBGHE (e.g., VGHEADS described by Leong et al. 2010 and Rad 2016). The GHE sizing tools can be used to determine the required depth and the number of boreholes, which usually are arranged in regular patterns (e.g., rectangular, L- or U-shaped) with uniform spacing among the boreholes.

As discussed in the second milestone report (Spitler et al. 2020), GHEs with irregular borefield patterns may reduce the thermal interaction among the boreholes and thus could use fewer boreholes to achieve the desired performance. A couple of existing tools approximate irregular borefields by applying some correction factors to regular borefields (Park et al. (2018) for DST and BLOCON (2017) for Earth Energy Designer [EED]). One existing GHE sizing tool, Geothermal Loop Designer (GLD), models irregular borefields using response factors developed with an approach similar to that used to generate the original g-functions. However, it is not clear from the documentation of GLD how these new response factors are compared with the original g-functions and whether they are valid for modeling irregular borefields. As introduced in the previous two milestone reports, the newly developed pygfunction (Cimmino 2018) can be used to generate g-functions for almost any borefields (with regular or irregular arrangement) if enough computation power and memory are available for performing the required computations.

The dedicated GHE sizing tools can size a GHE quickly (on the order of a second to a minute) and offer some flexibility in adjusting GHE design parameters. However, they rely on users to provide thermal loads of the GHE. Because the thermal loads can be significantly affected by the design of the building and its mechanical system, rerunning the GHE sizing tool is necessary to update the GHE size after a change is made in the building design. It usually requires manually transferring new thermal loads resulting from the design change to the GHE sizing tool. This procedure is not convenient, and more importantly, it cannot satisfactorily account for the impact of GHE design on the efficiency of the heat pump, especially for distributed GHP systems that include multiple independently operated heat pumps, and subsequently, the thermal loads of the GHE.

On the other hand, the integrated building and GHE simulation programs, including TRNSYS, EnergyPlus, eQUEST/DOE-2, can account for the interaction between the size and the thermal loads of the GHE and thus enable a truly simulation-based design approach for the GHE in one platform. However, these integrated programs currently have limited capability in modeling GHE. For example, EnergyPlus relies on user inputs of GHE design (i.e., number and depth of boreholes) and the associated g-functions to simulate a VBGHE. These inputs need to be determined based on the building's thermal loads predicted by EnergyPlus using some external programs such as GLHEPro. TRNSYS uses DST to model GHE, which is limited to modeling regular borefields in a circular shape. Some rough methods (e.g., a rule of thumb proposed by Bertagnolio et al. (2012), and the regression-based modification proposed by Park et al. (2018)) were used to approximately model irregular borefields with DST by adjusting the effective borehole spacing of the circular borefields. These modifications are not self-contained because other methods, such as g-functions, must be used to find the rule of thumb or the coefficients of the regression. A better approach would be to model directly the irregular borefields with the associated g-functions in the integrated programs.

Table 2-1. A comparison of existing tools for sizing or simulating GHE.

	GLHEPro (GHLEPro 2016)	**GLD (Gaia Geothermal 2016)**	**GSHPCal (Kavanaugh 2012)**	**EED (BLOCON 2017)**	**TRNSYS (Ahmadfard 2018; Park et al. 2019; Kim et al. 2013)**	**eQUEST (Liu and Hellström 2010; Wang et al. 2012)**	**EnergyPlus (Sankaranarayanan 2005; Murugappan 2002)**
Integrates with building model	No	No	No	No	Yes	Yes	Yes
Methodology	g-function	• ASHRAE method • Infinite cylindrical source • Customized g-function[1]	Infinite cylindrical source	g-function	DST model, modified DST variants, or other user-created models[2]	g-function	g-function
Thermal loads	Monthly total and peak	• Annual average and peak • Monthly total and peak • Hourly	• Three pulses for heating and three for cooling—an annual pulse, a monthly pulse, and a peak pulse of user-selected duration	Monthly or hourly heating and cooling loads	Hourly heating and cooling loads	Hourly heating and cooling loads	Hourly heating and cooling loads
GHE type	• Predefined vertical borefields with single or double U-tube and concentric • Horizontal bore: straight and slinky	• Vertical bore: predefined or custom-configured borefields with single or double U-tube • Regular or customer-build borefield • Horizontal bore: straight and slinky	• Vertical bore with single or double U-tube • Groundwater open loop • Surface water closed loop	Predefined vertical borefields with single or double U-tube and concentric	Multiple boreholes (with single, double, and coaxial U-tube) uniformly positioned in a cylindrical volume	Predefined vertical borefields with single U-tube	Predefined vertical borefields with single U-tube

Table 2-1. A comparison of existing tools for sizing or simulating GHE (continued).

	GLHEPro (GHLEPro 2016)	**GLD (Gaia 2016)**	**GSHPCal (Kavanaugh 2012)**	**EED (BLOCON 2017)**	**TRNSYS (Ahmadfard 2018; Park et al. 2019; Kim et al. 2013)**	**eQUEST (Liu and Hellström 2006; Wang et al. 2015)**	**EnergyPlus (Sankaranarayanan 2005; Murugappan 2002)**
Hybrid with other heat sink/source	Yes (GHE with cooling tower)	Yes (GHE with cooling tower and boiler)	Unknown	Unknown	Yes	Yes (GHE with cooling tower and boiler)	Yes (GHE with cooling tower and boiler)
Maximum borehole number	400 (expanded to 900 with curve fit)	Unknown	Unknown	1,200	Unknown	32 (can be approximately expended for larger borefield with a multiplier)	Need user to provide g-function calculated with an external program
Irregular borefields with non-uniform bore spacing	No	Yes	No	Approximation	Approximation	No	No
Time for sizing GHE	Seconds to minutes	Seconds to hours	Seconds to minutes	Seconds to minutes	Minutes to hours	Minutes through manual iterations	GHE has to be sized by an external program
Cost	$450 to $750	$550 (residential) to $4,300 (complete) and annual licensing fee	Free	$600 per year	$5,060 for single user license	Free	Free

[1] It is not clear from the documentation of the GLD how these new response factors are compared with the original g-functions and whether they are valid for modeling irregular borefields.
[2]Some rough methods (e.g., a rule of thumb proposed by Bertagnolio et al. (2012) and the regression-based modification proposed by Park et al. (2018)) were used to approximately model irregular borefields with DST by adjusting the effective borehole spacing of the circular borefields.

3. SOFTWARE DEVELOPMENT

The given review indicates that the design tool for GHE needs to be improved so that it can more accurately size GHE and enable a holistic simulation-based design approach for the GHP system. The new design tool would integrate building and GHE simulations and be able to model both regular and irregular borefields. Furthermore, the new tool would be user-friendly and ideally be free to the public so that it can be used by ordinary building owners in addition to professionals/researchers who design or study HVAC or thermal energy systems for residential, commercial, and governmental use.

The three components of the new tool include (1) an advanced VBGHE sizing tool, which allows highly customized borefield patterns and can automatically determine the size of the GHE in a timely fashion; (2) a seamless approach to integrate the state-of-the-art of the BES programs, EnergyPlus and OS, with the advanced VBGHE sizing tool; and (3) a user-friendly interface to accept user inputs, display key simulation results, and perform economic analysis based on the latest and localized cost data of HVAC equipment and energy prices. The new tool will model a building, size a GHE, and simulate the performance of a GHP system in real-time. It will allow users to do what-if analyses to evaluate alternative designs of the building and the GHP system. Furthermore, it will also be used to develop a screening tool to provide a quick answer on the techno-economic viability of a GHP system. In this case, simulations of DOE's prototype models for existing residential and commercial buildings will be performed with the conventional HVAC system and the GHP system, respectively. The simulation results will be stored and managed through a database. The pre-simulated results will be searched based on user inputs and the best-match simulation results will be displayed on the interface. The current development of the three components of the new tool is described in this section.

3.1 AUTO-SIZING TOOL FOR VBGHES

The auto-sizing tool for VBGHE (Figure 3-1) is called by OS and passed the hourly GHE heat rejection/extraction loads calculated with EnergyPlus. It has two major functions, demarcated in Figure 3-1 by the dashed-line boxes. First, it determines a suitable borehole configuration from the library. Once the configuration search has been completed, it sizes the specific configuration—that is, it finds the required borehole depth (BHD) for the selected configuration.

Each item in the flowchart is numbered and the following discussion gives a brief explanation of each item. Section 3.1.6 covers the verification of the auto-sizing tool.

1. Open Studio uses EnergyPlus to determine the hourly heat rejection/extraction to/from the GHE. This information is passed in a CSV file to the design tool. Other information related to the borehole design is passed in a JSON file:
   - Ground thermal properties
   - In-borehole design parameters (U-tube size and thermal properties of grouting material)
   - Design temperature limits (maximum and minimum heat pump entering fluid temperatures)
   - Maximum and minimum acceptable BHD
   - Design life for sizing purposes

2. The borehole configuration search is a unimodal search that determines which borehole configuration can meet the design temperature limits with the lowest number of boreholes. It is described in Section 3.1.1.

3. The three input files are provided by OS (Loads, System Description) and the borehole configuration search.

4. Long time-step g-functions are calculated from a library. The library is described in Section 3.1.2. Short time-step g-functions are calculated "on the fly" as described in Section 3.1.3.

5. Once the borehole configuration is determined, the sizing algorithm is used to determine the minimum BHD that meets the design temperature limits. The sizing algorithm is described in Section 3.1.4.

6. The simulator is designed for high computational efficiency and high accuracy. It is described in Section 3.1.5.

7. When the borehole configuration search and the sizing algorithm are complete, the results (configuration, depth and spacing of boreholes, and the associated g-function data pairs) are passed back in a JSON file to OS where EnergyPlus is used to predict the energy consumption of the simulated GHP system.

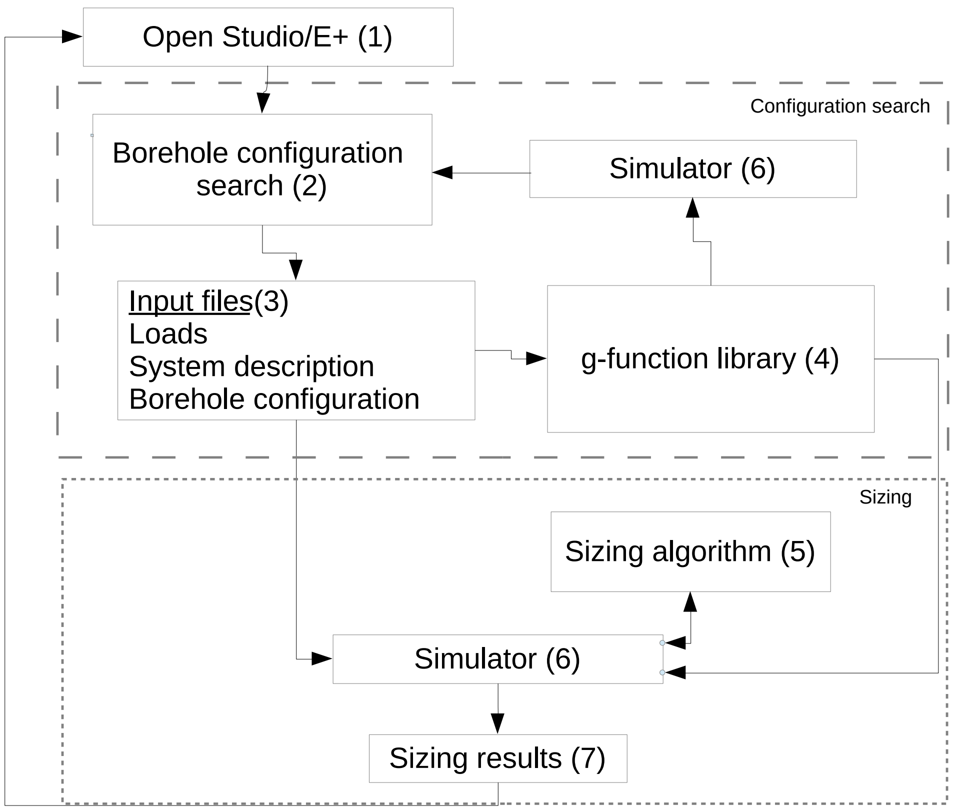


Figure 3-1. Flowchart for the automated sizing tool for VBGHE.

3.1.1 Borehole configuration search

The borehole configuration search uses a golden section search to find the borehole configuration that meets the design leaving fluid temperature (*DLFT* in Figure 3-2). For the work to date, the authors have not considered surface area constraints. By using rectangular configurations that are square or near-square (i.e., $N \times N$ or $N \times (N - 1)$) ordered as shown in Table 3-1, a unimodal search domain is defined.

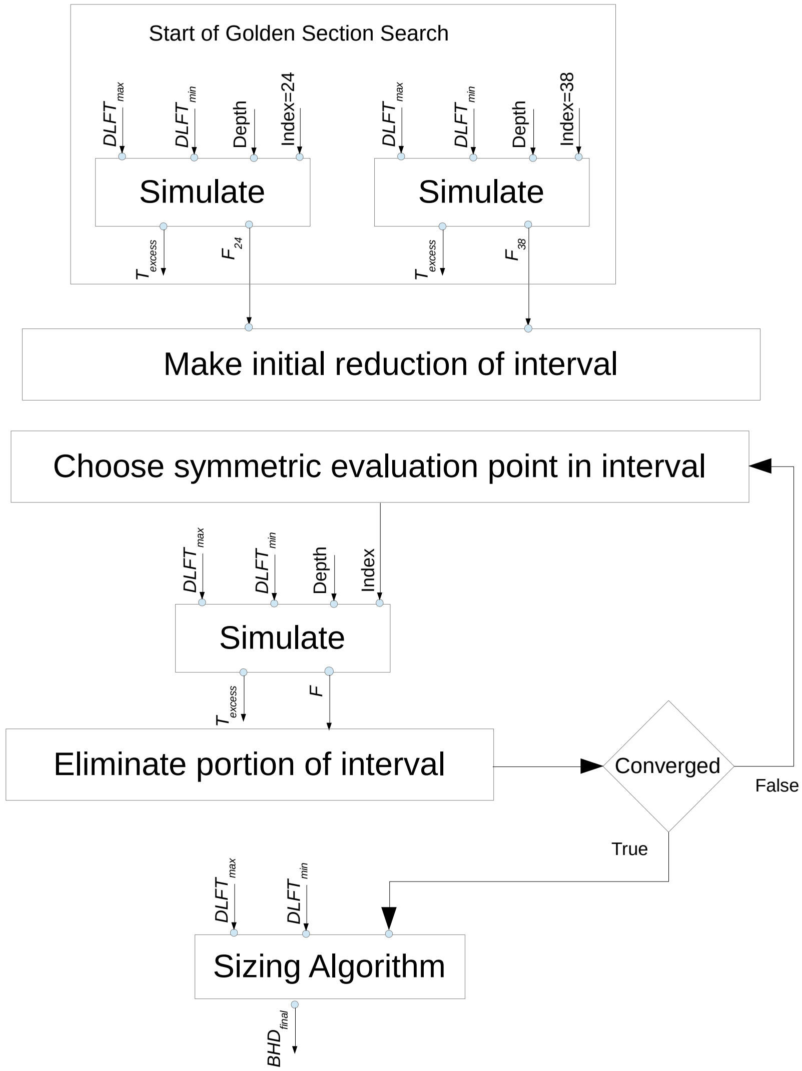


Figure 3-2. Golden section search used for selecting borehole configuration.

An objective function is defined based on the excess temperature:

$$T_{excess} = max[(SFLT_{max} - DFLT_{max}), (DFLT_{min} - SFLT_{min})] \tag{3.1}$$

Where

$DFLT_{max}$ = Design maximum leaving fluid temperature (°C)
$DFLT_{min}$ = Design minimum leaving fluid temperature (°C)
$SLFT_{max}$ = Simulated maximum leaving fluid temperature (°C)
$SLFT_{min}$ = Simulated minimum leaving fluid temperature (°C)

The goal of the search algorithm is to keep the excess temperature as near to zero as possible without exceeding zero. The objective function is defined with a penalty function:

$$f(DLFT_{max}, DLFT_{min}, index, loads, etc.) = (T_{excess})^2 + P_1 \cdot N_{BH} + P_2 \tag{3.2}$$

Where N_{BH} is the number of boreholes, and the values of the penalty coefficients are set:

P_1 = 0 and P_2 = 2048 if $T_{excess} > 0$;
P_1 = 1 and P_2 = 0 if $T_{excess} \leq 0$.

The resulting objective function is unimodal over the range of indices. The golden section search illustrated in Figure 3-2 can search the entire domain in about 10 iterations. To reduce the number of iterations, the range of configurations is reduced by estimating the minimum and maximum field sizes assuming 100 ft/ton and 1,000 ft/ton, respectively. These minimum and maximum field sizes determine the upper and lower boundaries of the searching domain. The "ton" here corresponds to the maximum of the heating and cooling loads, not the installed equipment capacity. A better algorithm could be developed that would reduce the search range further.

Once the borehole configuration search is completed, the results are passed to the sizing algorithm to determine the BHD as shown at the bottom of Figure 3-2. The indices of 24 and 38 (corresponding to Table 3-1) shown in Figure 3-2 are the starting points of the Golden Section searching scheme.

Table 3-1. Unimodal search domain.

Index	Nx	Ny	NBH[a]	% change[b]	Index	Nx	Ny	NBH	% change
1	2	2	4	NA	32	18	17	306	6
2	3	2	6	50	33	18	18	324	6
3	3	3	9	50	34	19	18	342	6
4	4	3	12	33	35	19	19	361	6
5	4	4	16	33	36	20	19	380	5
6	5	4	20	25	37	20	20	400	5

Table 3-1. Unimodal search domain (continued).

Index	Nx	Ny	NBH[a]	% change[b]	Index	Nx	Ny	NBH	% change
7	5	5	25	25	38	21	20	420	5
8	6	5	30	20	39	21	21	441	5
9	6	6	36	20	40	22	21	462	5
10	7	6	42	17	41	22	22	484	5
11	7	7	49	17	42	23	22	506	5
12	8	7	56	14	43	23	23	529	5
13	8	8	64	14	44	24	23	552	4
14	9	8	72	13	45	24	24	576	4
15	9	9	81	13	46	25	24	600	4
16	10	9	90	11	47	25	25	625	4
17	10	10	100	11	48	26	25	650	4
18	11	10	110	10	49	26	26	676	4
19	11	11	121	10	50	27	26	702	4
20	12	11	132	9	51	27	27	729	4
21	12	12	144	9	52	28	27	756	4
22	13	12	156	8	53	28	28	784	4
23	13	13	169	8	54	29	28	812	4
24	14	13	182	8	55	29	29	841	4
25	14	14	196	8	56	30	29	870	3
26	15	14	210	7	57	30	30	900	3
27	15	15	225	7	58	31	30	930	3
28	16	15	240	7	59	31	31	961	3
29	16	16	256	7	60	32	31	992	3
30	17	16	272	6	61	32	32	1,024	3
31	17	17	289	6	NA	NA	NA	NA	NA

a. NBH stands for number of boreholes; b. % change is the change of borehole numbers between a borefield to the immediate previous borefield in the list.

3.1.2 g-function library

The g-functions are thermal response functions that give the dimensionless temperature response of a GHE to heat inputs. By using temporal superposition, g-functions can predict the borehole wall temperatures of a VBGHE with a long history of heat rejection/extraction. g-functions are often divided into “short time-step” and “long time-step” portions—the former being where heat transfer in and very near the borehole dominates, and the latter being where borehole-to-borehole heat transfer dominates, along with heat transfer between the boreholes and the surface and deep earth. A common divider is at $\ln\left(\frac{t}{t_s}\right) = -8.5$, where t_s is the time-scale:

$$t_s = \frac{H^2}{9\alpha} \quad (3.3)$$

Where H is the borehole length (m) and α is the thermal diffusivity of the ground (m^2/s).

The concept of using thermal response functions, known as g-functions, was introduced by Claesson and Eskilson (1985). A numerical methodology, known as the superposition borehole method (SBM) for computing these was described by Eskilson and Claesson (1988). A 3,600-line FORTRAN 77 implementation is described in the paper. A more detailed explanation is given in a 95-page unpublished report by Eskilson (1986).

A thorough review of the state-of-the-art in g-function calculation is given in an earlier milestone report (Spitler et al. 2020) of this project. The earlier report also describes the reasoning for creation of a g-function library and selection of a method for calculating the g-functions. In this project, long time-step g-functions are computed for the g-function library with a modified version of recently developed tool called pygfunction (Cimmino 2018, 2019a, b). Short time-step g-functions are computed for each configuration on the fly.

The principal modification to the original pygfunction code involved recasting the code to use input and output files, rather than specifying all the inputs within the code itself and writing to the console. This allowed development of scripts that are capable of running large numbers of g-function calculations. Furthermore, because the authors quickly ran out of available memory and computing power on desktop computers, the authors transitioned to using two high-performance computing clusters available at Oklahoma State University. Further details on time and memory requirements, both of which are proportional to the total number of segments, are given in the earlier milestone report (Spitler et al. 2020).

Another modification to pygfunction was related to the dimensionless times for which g-values were computed. As originally distributed, pygfunction generated g-function values at times that were customized for a particular time-step (e.g., hourly) and load aggregation scheme. The VBGHE sizing tool developed in this project uses a computationally efficient hybrid time-step scheme (Cullin and Spitler 2011) for simulations. One consequence of the use of g-function libraries for part of this work is that the time-steps used in the simulation will depend on building loads, and so the actual time-steps are not known at the time the g-function is calculated. Therefore, pygfunction has been modified to use a fixed set of $\ln(\frac{t}{t_s})$ values suitable for interpolation. These values cover the LTS portion of the g-function.

The library was initially calculated for all rectangular configurations between 2 × 2 and 32 × 32—all combinations of 2 to 32 boreholes in each direction, with 12 segments per borehole. However, only the square and near-square combinations are used. When the number of segments was refined, as discussed in Section 3.1.2.4, with up to 32 segments per borehole, only the square and near-square combinations were re-calculated. Recalculation of the other configurations will be done in the future.

With the general methodology selected, there are still several important decisions required prior to computing library g-functions. These include the exact geometry, the boundary conditions used, and the number of segments used.

3.1.2.1 Geometry

As discussed by Cimmino and Bernier (2014) the dimensionless g-function values depend on four dimensionless parameters:

- $\frac{t}{t_s}$ = the dimensionless time
- $\frac{r_b}{H}$ = the ratio of the borehole radius to the length of the borehole

- $\frac{B}{H}$ = the ratio of the spacing between boreholes to the borehole length
- $\frac{D}{H}$ = the ratio of the depth of the top of the borehole to the borehole length

Claesson and Eskilson (1987) concluded that $\frac{D}{H}$ was relatively unimportant on the basis of varying the depth between 2 and 8 m and only finding a 0.1°C difference in extraction temperature. Presumably, for this reason, Eskilson (1987) does not specify the $\frac{D}{H}$ value for g-functions published in his thesis.

Nevertheless, $\frac{D}{H}$ is of some importance when calculating and comparing g-functions. Figure 3-3 shows g-functions computed with pygfunction, for different $\frac{D}{H}$ and one computed with SBM (labeled "Hellström") for a rectangular borehole field with 380 boreholes in a 19 × 20 configuration.

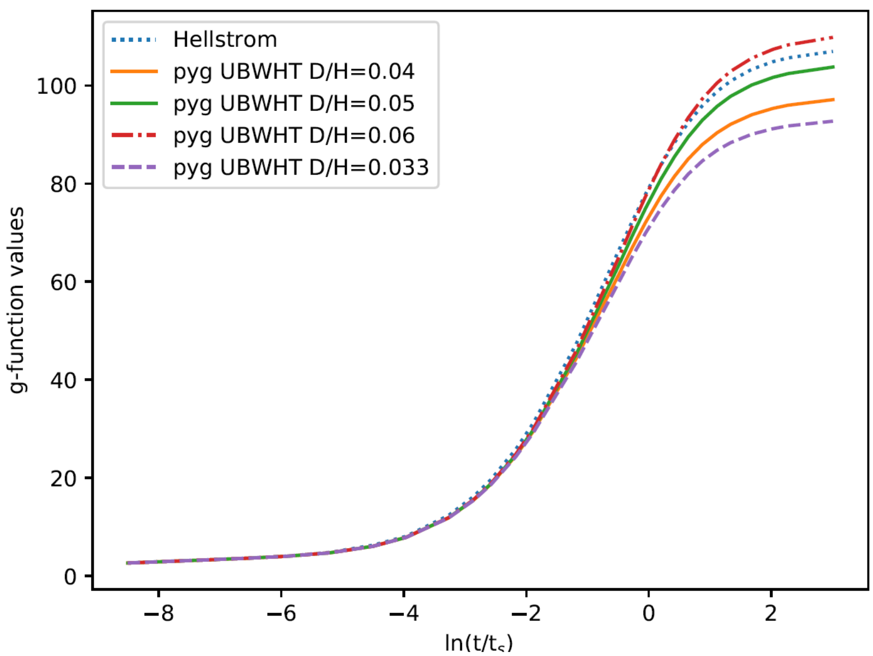


Figure 3-3. Comparison of g-functions computed with SBM (Hellström 2006) and pygfunction, at different values of D/H

The g-functions published by Ekilson (1987) and calculated with the SBM (Eskilson 1986) are often used as reference values and the authors do so here. Based on number of analyses similar to that shown in Figure 3-3, the authors used $\frac{D}{H} = 0.06$ with pygfunction when comparing with g-functions computed with the SBM. Up until about $\ln(t/t_s) = 1$, the SBM g-function matched most closely the $\frac{D}{H} = 0.06$ g-function. A value for $\ln(t/t_s)$ of one corresponded in dense rock to 18.5 years for H = 50 m, 74.1 years for H = 100 m, and longer durations for greater borehole lengths.

For computation of library g-functions, the authors computed all g-functions for a burial depth of 2 m, borehole spacing of 5 m, and borehole radius of 64 mm. For each borehole configuration, g-functions were calculated for depths of 50, 100, 175, 275, and 400 m. Table 3-2 summarizes the parameters for the g-functions calculated in the library.

Table 3-2. g-functions calculated for use in the library.

B(m)	***D***(m)	***H***(m)	$\frac{B}{H}$	$\frac{D}{H}$
5	2	50	0.1000	0.0400
5	2	100	0.0500	0.0200
5	2	175	0.0286	0.0114
5	2	275	0.0182	0.0073
5	2	400	0.0125	0.0050

For sizing purposes, Lagrangian interpolation (Spitler et al. 2020) is used between different g-functions (for the same borefield layout but with different BHDs). At any iteration in the sizing procedure, the borehole spacing, *B*, and length, *H*, are known. The interpolation is based on the $\frac{B}{H}$ ratio. As previously shown in the milestone report, the interpolation is highly accurate. As discussed by Claesson and Eskilson (1987), small variations in *D* have very little impact on the g-function.

The $\frac{r_b}{H}$ ratio also has an effect on the results, but as it is readily corrected with an algebraic equation [$g\left(\frac{t}{t_s}, \frac{r_b^*}{H}\right) = g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) - \ln\left(\frac{r_b^*}{r_b}\right)$, Eq. (12) in Eskilson (1987)], the authors simply make this correction as needed after interpolating the g-function.

3.1.2.2 Boundary conditions

One complicating but subtle feature of g-functions is that the thermal response has a significant dependence on how the heat rejected or extracted is distributed through the borefield. g-functions are computed with a fixed heat rejection rate, but how the heat is distributed through the borefield will vary with time. One can think of the situation for a large rectangular borefield with continuous heat rejection over many years. In this case, the inner boreholes get “saturated’ with heat and hence reject less heat over time. There are three approximations that have been used:

1. Uniform inlet fluid temperature (UIFT). Here, all of the boreholes receive fluid at the same temperature. The actual distribution is then calculated as part of the calculation of the g-function.

2. Uniform borehole wall temperature (UBHWT). With this approximation, the borehole wall temperatures have a time-varying but uniform temperature (i.e., same borehole wall temperature for all boreholes at any given time).

3. Uniform heat flux (UHF). With this approximation, the heat input is uniformly distributed and all boreholes have the same heat flux (i.e., the total heat input used to calculate the g-function is divided by the total borehole length).

Arguably, the UIFT approximation is the closest match to reality. The heat transfer fluid is generally returned to the GHE in a single pipe, which is then delivered to each borehole in parallel. Other than differences in the length of horizontal piping having a small effect on the delivery temperature to each borehole, the inlet fluid temperature should be uniform. The UBHWT approximation gives similar results to the UIFT approximation. Malayappan and Spitler (2013) investigated the UHF approximation and found that, while it works well for small numbers of boreholes, it can give significant sizing errors for large borefields where significant thermal interference between boreholes is present. Figure 3-4 shows an example comparison. As can be seen, the UBHWT g-function is slightly lower than the UIFT, but the difference is very small up to about $\ln(t/t_s) = 0$. A value for $\ln(t/t_s)$ of zero corresponds in dense rock to 6.8 years for *H* = 50 m, 27.3 years for *H* = 100 m, and longer durations for greater borehole lengths.

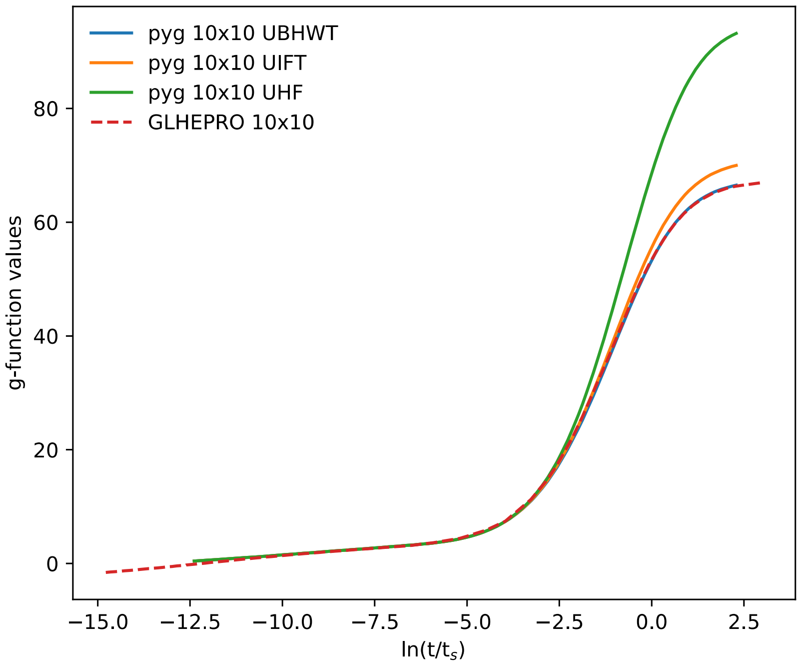


Figure 3-4. Comparison of g-functions for a 10 × 10 borefield computed with pygfunction under three different boundary conditions (UBWT, UIFT, and UHF).

Alhough the UIFT approximation is the closest match to reality, the results have some dependence on the borehole thermal resistance and fluid flow rates. Spitler et al. (2020) describe a sensitivity study; g-functions based on combinations of low and high borehole thermal resistance and low and high fluid flow rates are shown in Figure 3-5. For practical design lives, the difference in the g-functions is quite small, and rather than compute multiple library entries for different borehole resistances, typical values are used in the calculation. These values are summarized in Table 3-4. All the library g-functions are calculated with these parameters and approximately 13 segments/100 m. Where this does not result in an integer number of segments, the value is rounded up to the nearest integer (e.g., the 50 m case uses 7 segments).

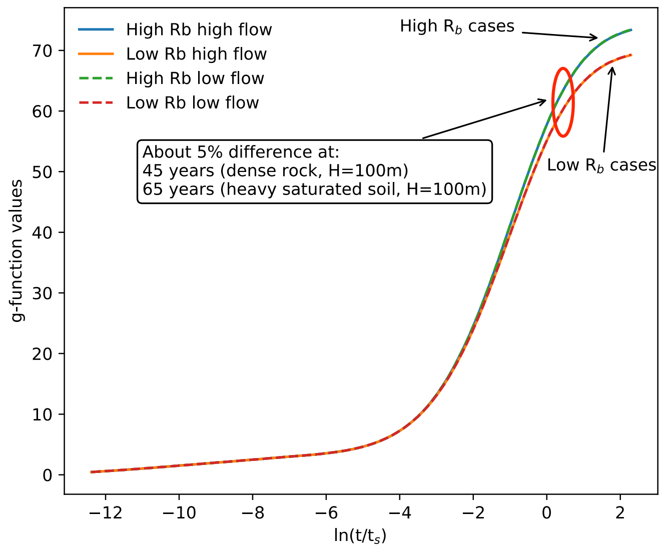


Figure 3-5. Comparison of g-functions based on combinations of low and high borehole thermal resistance and low and high fluid flow rates for a 10 × 10 borefield computed with pygfunction under the UIFT condition.

Table 3-4. Borehole parameters used in library g-function calculations.

Depth (m)	Depth (ft)	BH dia. (mm)	BH dia. (in.)	Flow rate (GPM)	Flow rate (L/s)	Nominal pipe size (in.)	Pipe ID (mm)	Pipe OD (mm)	Tube wall to tube wall shank spacing (mm)
50	164	150	5.9	2.0	0.13	0.75	21.5	26.7	58.9
100	328	150	5.9	4.0	0.25	0.75	21.5	26.7	58.9
175	574	150	5.9	6.9	0.44	1.25	34.0	42.2	64.1
275	902	175	6.9	10.9	0.69	1.5	29.0	48.3	74.4
400	1312	175	6.9	15.8	1.00	2	48.7	60.3	78.4

3.1.2.3 Number of segments

Finally, the number of segments used is also important. The time required to compute larger borehole fields, even on a high-performance computing cluster, can be quite substantial. Spitler et al. (2020) developed an equation fit that gives the time in seconds on either OSU cluster based on the total number of segments. To generate a g-function for a borefield with 8,000 segments, it will take about 2.3 h. The largest borefield in the library is a 32 × 32; with 32 segments per borehole, this takes about 42 h to compute. Therefore, it is desirable to use a minimum number of segments. However, the accuracy is lower with lower numbers of segments.

Two approaches can be used to investigate the accuracy. One approach is to compare with g-functions created with the SBM (Hellström 2006); as these were created with UBHWT boundary conditions, pygfunction is used to compute g-functions with UBHWT boundary conditions. It is then assumed that relationship between accuracy and number of segments is about the same with UBHWT and UIFT boundary conditions.

A second approach is analogous to a grid-independency study used with numerical (e.g., finite difference, finite volume, finite element) analyses. That is, the number of segments is increased until further increases in numbers of segments do not change the results. Cimmino and Bernier (2014) used this approach for a 7 × 7 borehole field with $\frac{B}{H}$ = 0.05 and 256 segments/borehole as the reference condition. For a fixed configuration, they characterized the error for 20 years and steady-state conditions. Errors for 20 years are much lower and generally more relevant for design use than steady-state conditions, which usually would take hundreds of years to reach. For 20 years, the error in the g-function with 12 segments is less than 2%. This should be quite adequate for design of GHEs.

In these investigations, the authors also found some sensitivity to the $\frac{B}{H}$ ratio and number of boreholes. Two examples, shown in Figures 3-6 (4 × 4) and 3-7 (10 × 10) illustrate this. These errors are calculated based on the reference cases, which have 100 segments/100 m. The errors are given at steady-state conditions; therefore, they are higher than would be expected for a 20- or 30-year design life. ($\ln(t/t_s) = 3.003$ corresponds in dense rock conditions to 137 years for 50 m borehole length, 549 years for 100 m borehole length, and so on). The results in Figures 3-6 and 3-7 are plotted as error vs. number of segments per 100 m of borehole length. A rough curve is formed, suggesting that the number of segments for a given error is related to the height or $\frac{B}{H}$ ratio. Looking at the circled points in Figure 3-6, one can see about the same error for a configuration with borehole length of 50 m and 10 segments as a borehole length of 400 m and 40 segments.

Also, comparing Figures 3-6 and 3-7, it also seems clear that the number of boreholes or perhaps the relative density of the boreholes also has an influence on the required number of segments as the error increases for the same number of segments between a 4 × 4 configuration and a 10 × 10 configuration.

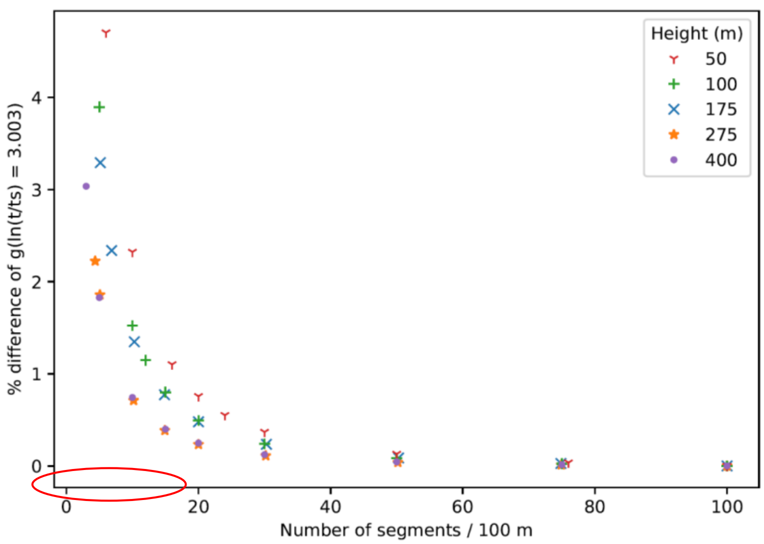


Figure 3-6. Steady-state error for a 4 × 4 borehole configuration with *B* = 5 m.

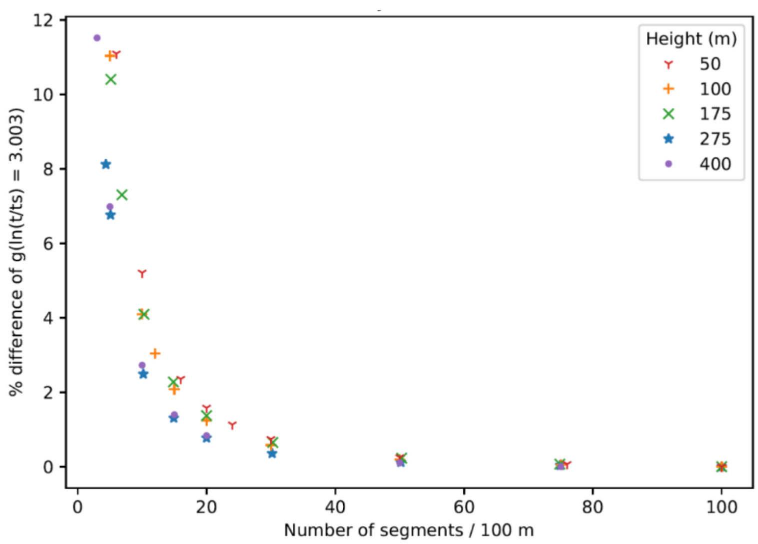


Figure 3-7. Steady-state error for a 10 × 10 borehole configuration with *B* = 5 m.

The grid independency approach has some limitations for GHEs with large numbers of borefields. Specifically, computation of a reference case for large borehole fields is either difficult (due to long run times) or impossible (due to exceeding the available memory on even the largest memory node on the cluster—1.5 TB). For example, calculating a reference g-function for a 32 × 32 borehole field with 120 segments would take 24 days, but the code would have to be modified to save intermediate results, because the computing center policy would not allow use of a single node for a continuous 24 day period. Therefore, determining the exact error in g-functions for very large borehole fields is currently out of reach.

In absence of absolute certainty about the error, the authors chose the number of segments for each depth as shown in Table 3-5, along with the estimated error at 30 years for each depth.

Table 3-5. Number of segments used for library g-function calculation.

Borehole length (m)	Number of segments	Estimated % error at 30 years
50	7	2.4
100	13	1.9
175	21	2.2
275	25	1.7
400	32	1.8

3.1.3 Short time-step g-function calculation

Short time-step g-function values were calculated using the Xu and Spitler (2006) model. Three verification test cases were described by (Spitler et al. 2020) and shown to match nearly very well with both GLHEPro and EnergyPlus. Both GLHEPro and EnergyPlus use the Xu and Spitler model, so this confirms that the implementation works correctly in the design tool.

3.1.4 Sizing algorithm

The sizing algorithm determines the required depth of the boreholes for a given VBGHE configuration. The sizing algorithm adjusts the size of the VBGHE to be the minimum that meets both the design minimum and maximum heat pump entering fluid temperature. This is characterized by the excess temperature (Eq. 3.1). In the sizing algorithm, Brent's root-finding method is used to find the depth at which $T_{excess} = 0$. A sample for a specific VBGHE is shown in Figure 3-8; the root is found at 78.1 m; this is the design depth.

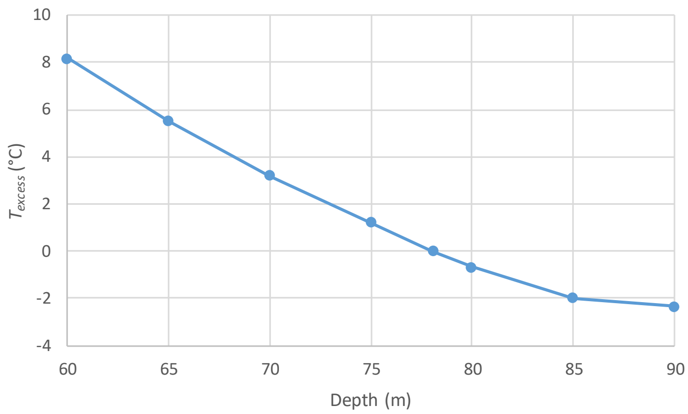


Figure 3-8. Illustration of root-finding used for sizing BHD.

3.1.5 GHE simulator

The design tool uses the VBGHE simulator both for purposes of selecting the borehole configuration and sizing the depth of boreholes of the selected VBGHE. Both purposes are iterative in nature. Iterative approaches rely on a simulation of the VBGHE to predict heat pump entering fluid temperatures over time. The simulation inputs (usually the depth) are adjusted to determine the required size of the VBGHE. In this project, the authors adjusted both the borehole configuration (number and arrangement of boreholes) and BHD to determine the required size of VBGHE.

For reasons of accuracy and computational speed, response factor (g-function) simulation methods are preferred. However, even with use of a response factor method, hourly simulations over the design life of the GSHP system are computation-time prohibitive in an iterative design context. Because at each hour of the simulation, the response factor formulation takes account of all past hours, the simulation time is proportional to the square of the number of hours, and 20- or 30-year simulations can take multiple hours or more on a desktop PC. Because of this, load aggregation methods are used to reduce the computational time while maintaining high accuracy. A comprehensive study of load aggregation methods (Mitchell and Spitler 2019) recommended the dynamic method proposed by Claesson and Javed (2012) with different parameters. This method gives a 73-fold increase in speed over an hourly 10-year simulation with RMSE less than 0.1°C. Nevertheless, in a design context where approximately 20 iterations may be needed, the speed of an hourly simulation for design lives of 20-years or more is still insufficient.

Specifically, the goal of determining a GHE design and analyzing its performance in 5 min or less would set an absolute maximum time of around 15 s/simulation so that 20 iterations could be performed in 5 min. Even with load aggregation, this time would commonly be exceeded by two orders of magnitude. Ergo, an hourly simulation cannot be used to size the GHE.

To further increase the computational speed, an alternative representation of the building loads is used. This representation is referred to as a hybrid time-step scheme (Cullin and Spitler 2011). Instead of using an hourly time step, the hybrid time-step scheme uses a monthly time step combined with a monthly peak time step. Cullin and Spitler (2011) described the scheme implemented in GLHEPro. For each month, the monthly heating and cooling loads are specified, as are the monthly peak heating and cooling loads. The monthly peak loads were assumed to occur at the end of the month and two durations were used—one for heating peaks and one for cooling peaks.

Cullin and Spitler (2011) described a method for obtaining the peak load durations. Prior to this, users of GLHEPro and other programs had to "guesstimate" the peak load duration that would give approximately the same peak temperatures as a detailed simulation using continuously varying hourly loads. This may be harder than it sounds; as discussed by Young (2004), load profiles for different types of buildings with different occupancies and controls can be different, requiring significantly different durations of peak loads.

The method developed by Cullin and Spitler (2011) uses a very simple numerical simulation of a single borehole upon which the hourly heating and cooling loads of the building are imposed. For the days on which the annual peak heating load and annual peak cooling load occur, the simulation is used to predict the responses to the actual 24 hourly loads on those days. The responses of various durations of the peak loads are visually compared to the response of the actual 24-h days. Because these durations impose the peak load for the entire duration, the load forms a "rectangular pulse." This comparison is facilitated by plotting dimensionless temperature responses ($\Delta T/\Delta T_{max}$).

For example, Figure 3-9 shows the hourly cooling load on a peak day for a hotel in Oklahoma. Calculating the response and normalizing the temperatures, the dimensionless temperature response (hourly heat pump entering fluid temperature) is shown in Figure 3-10. On Figure 3-11, the dimensionless temperature responses of three rectangular pulses have been superimposed, for 11, 13, and 15-h durations. The 13-h duration here gives the best match. Because of the shape of the actual load profile, the peak load duration is quite high and the peak temperature is relatively insensitive to the exact duration.

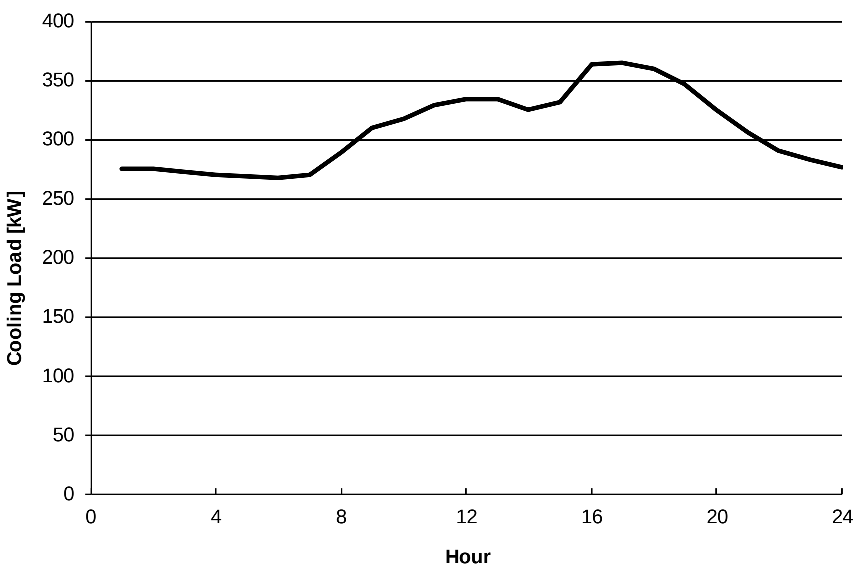


Figure 3-9. Hourly cooling loads on peak cooling load day for a hotel in Oklahoma.

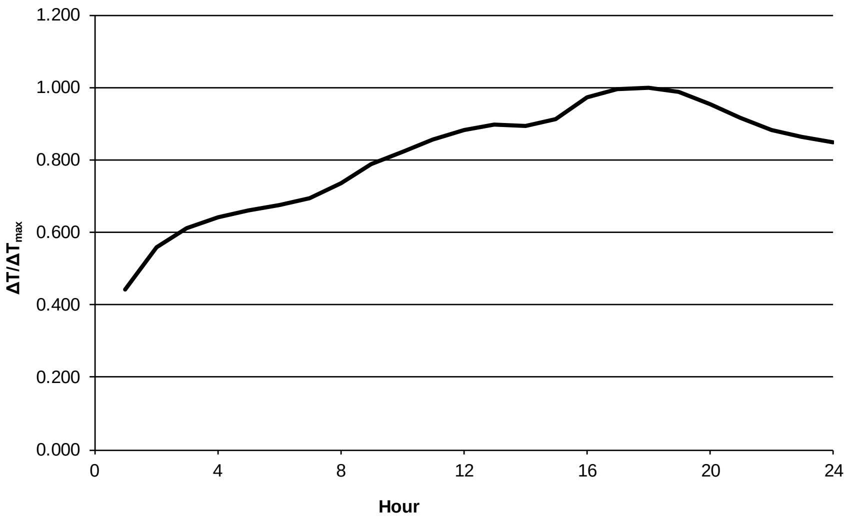


Figure 3-10. Dimensionless temperature response to actual hourly loads.

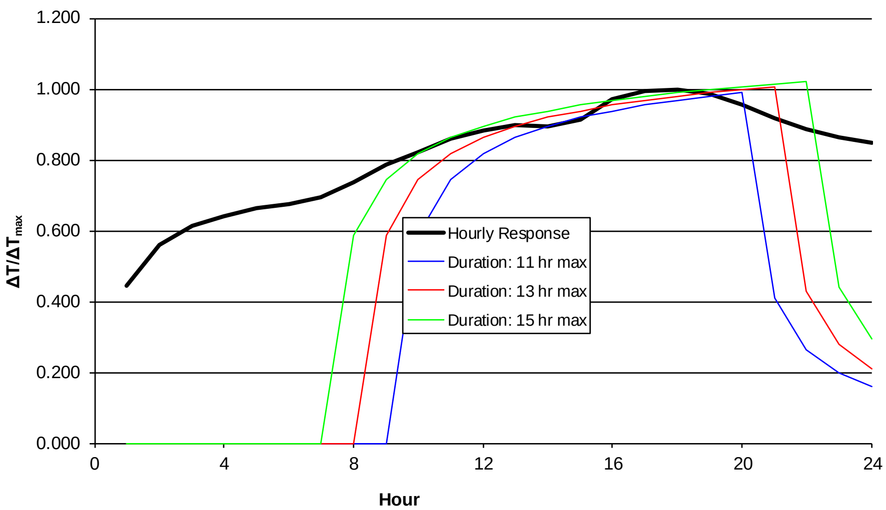


Figure 3-11. Dimensionless temperature responses to actual hourly loads and rectangular load pulses.

However, the heating load profile, shown in Figure 3-12, results in a much shorter duration, 5 h, as shown in Figure 3-13.

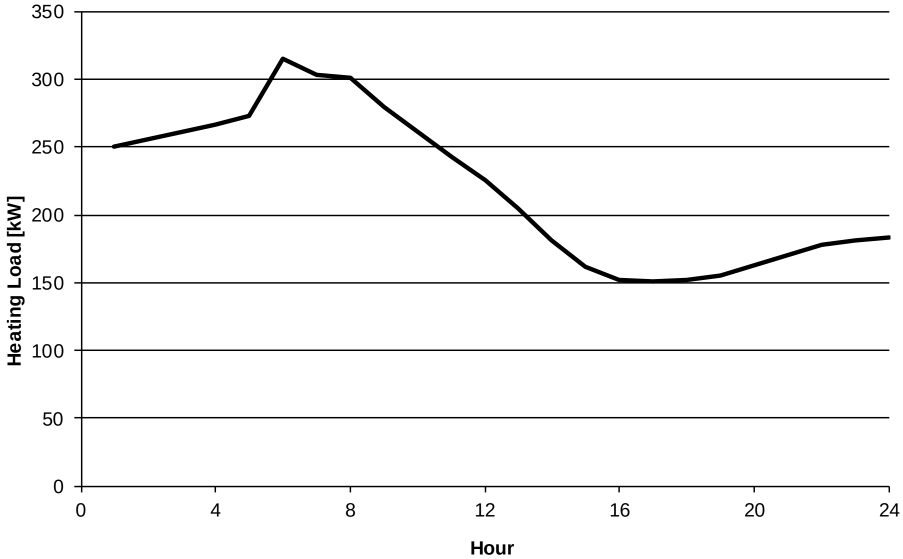


Figure 3-12. Hourly heating loads on peak heating load day for a hotel in Oklahoma.

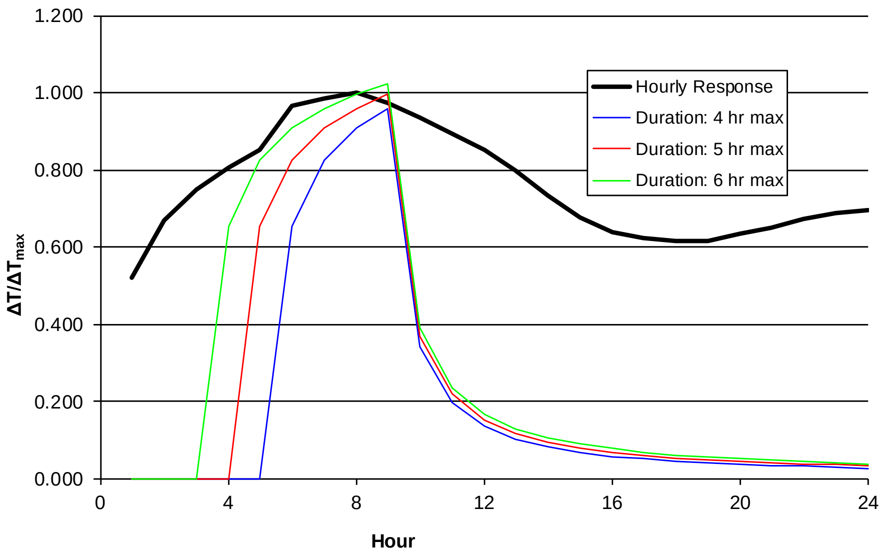


Figure 3-13. Dimensionless temperature responses to actual hourly loads and rectangular load pulses.

Cullin and Spitler (2011) investigated the accuracy of the hybrid time step scheme for sizing GHE. For three buildings in 16 locations, the designs using the hybrid time step simulation averaged 2.4% oversized compared to designs using an hourly simulation. Maximum errors using the hybrid time step simulation were 7.8% oversizing and 5.7% undersizing. When the GHE sized with the hybrid time step simulation were simulated with the hourly simulation, the design peak temperature was never exceeded by more than 1.3°C. The sources of error were identified as

1. An inherent limitation in representing an hourly profile with a rectangular pulse
2. The peak temperature day not being the peak load day
3. The peak load does not occur at the end of the month
4. There is an effect of the previous day that may not be reflected properly in the above analysis

Additionally, the peak load analysis tool developed by Cullin and Spitler (2011) is not automated—the user has to look at plots like those above and choose the best representation. Development of a new, automated peak load analysis tool is described below.

To remove the need for users to visually identify the required peak load durations, an automated peak load analysis tool was developed in Python. The accuracy of the tool was improved by addressing the sources of error identified by Cullin and Spitler (2011), summarized above. The modifications made are the following:

1. Cullin and Spitler (2011) surmised that there may be an inherent limitation in representing an hourly profile with a rectangular pulse. This is not explicitly addressed, but one minor improvement made is to allow non-integer peak load durations.

2. Cullin and Spitler (2011) showed that the peak temperature day many not occur on the peak load day. The case where the peak temperature day occurs on a monthly peak load day, but not the annual peak load day, is addressed by calculating the required durations (heating and cooling) for all monthly peak load days.

3. The peak load does not necessarily occur at the end of the month; this issue has been corrected by using the correct day for the monthly peak load.

4. The effects of the previous day are now accounted for by using a 48-h sequence of loads for the peak day and the day before the peak day.

The automation is done by using a short time-step simulation to find $\Delta T/\Delta T_{max}$ for a 1-h rectangular pulse, a 2-h rectangular pulse, etc. When the value of $\Delta T/\Delta T_{max}$ for the rectangular pulse exceeds 1, an interpolation is used to estimate the precise, non-integer duration that will give the correct peak temperature, corresponding to $\Delta T/\Delta T_{max} = 1$.

A sample representation of the improved hybrid time step scheme is shown for the first two months of the simulation. For purposes of illustration, the peak heating loads have been placed near the middle of each month and peak cooling loads have been placed near the end of the month. Also, for illustration purposes, the durations of peak heating loads and peak cooling loads have been set at 13 and 8 h, respectively. With two peak loads occurring during each month, the authors have five different load periods during each month. The different load periods shown in Figure 3-14 can be labeled as follows:

- ①, ③, ⑤ represent January average monthly heat rejection
- ② represents the January peak heating load
- ④ represents the January peak cooling load

- ⑥, ⑧, ⑩ represent February average monthly heat rejection
- ⑦ represents the February peak heating load
- ⑨ represents the February peak cooling load

The response can be estimated by summing the responses to a series of step functions devolved from these monthly loads. Although it hasn't been done yet, computational time for this scheme can readily be reduced by, first, neglecting peak loads for all years but the last year, and second, aggregating monthly loads for all years but the last two or three.

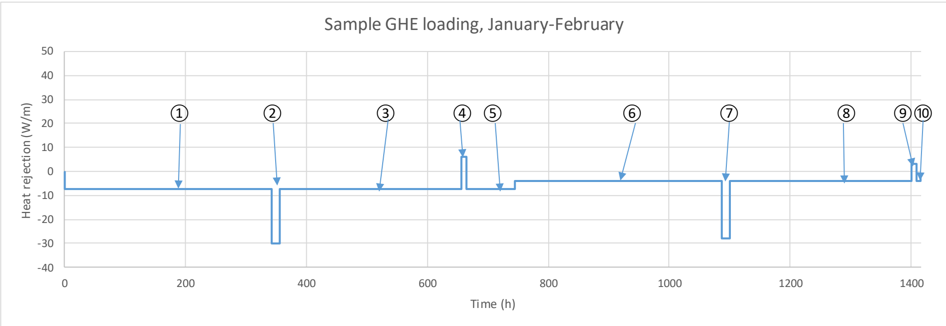


Figure 3-14. GHE loading represented with hybrid time step scheme.

A standard formulation for the g-function simulation is given by Grundmann (2016):

$$T_{BHW,n} = T_{ground} + \sum_{i=1}^{n} \frac{Q_i - Q_{i-1}}{2\pi k_g} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right) \tag{3.4}$$

Where

$T_{BHW,n}$ = Temperature at the borehole wall at the end of the n^{th} period (°C)
T_{ground} = Average undisturbed ground temperature over the length of the borehole (°C)
Q_i = heat rejection to the ground per unit length of borehole (W/m)
k_g = ground thermal conductivity (W m^{-1} K^{-1})
$g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right)$ = g-function, dimensionless temperature response

Prior to evaluating Eq. 3.3, the compact representation of loads developed by the peak load analysis tool must be converted to a series of step heat inputs, as shown in Figure 3-14. One important change to save computational time is a feature that can ignore peak loads during the middle of the simulation. Peak temperatures usually occur in the last year of the simulation (e.g., as the ground surrounding the GHE heats up or cools down over time, the maximum heat pump EFT or minimum heat pump EFT will occur in the last year). Occasionally, peak temperatures can occur in the first year of the simulation—the most common example is the minimum heat pump EFT occurring during the first winter of operation, for a system with substantial summertime heat rejection. Therefore, the design is always constrained by a peak temperature in the first year or last year of operation. Because of the nature of Eq. 3.3, the time required for a simulation is roughly proportional to n^2. By neglecting the peaks in the middle years, the number of steps can be reduced substantially, speeding the calculation. This is an option in the input file to specify how many months to consider peak loads at the beginning and end of the simulation.

Once the borehole wall temperatures ($T_{BHW,n}$) are computed for each time step, the mean fluid temperature ($T_{f,n}$) is computed for each period as

$$T_{f,n} = T_{BHW,n} + Q_n R_b^* \tag{3.5}$$

Where

L = Total length of the VBGHE (m)
R_b^* = Effective borehole thermal resistance (K/(W/m))
Q_n = Heat transfer rate along a borehole (W/m)

And the temperature exiting the VBGHE (entering the heat pump) is given by

$$T_{entering,n} = T_{f,n} - \frac{L \cdot Q_n}{2\dot{m}c_p} \tag{3.6}$$

Equation 3.5 assumes that the simple mean fluid temperature is an adequate approximation to the true mean fluid temperature. More sophisticated models are available (Rees 2015, Beier et al. 2018), but this sophistication is mainly important at short times, below an hour, when transit time effects are predominant. A comparison of experimental measurements presented by Beier et al. (2018) to a conventional borehole model using the simple mean fluid temperature approximation gives quite good results over a wide range of flow rates as long as the thermal short-circuiting is accounted for. That is, to obtain good accuracy, the effective borehole thermal resistance (R_b^*) should be used as shown in Figure 14 of Beier et al. (2018) rather than the local borehole thermal resistance (R_b). When the local borehole thermal resistance is used with the simple mean fluid temperature approximation (labeled "1D model with f = 0.5"" in Figures 9 and 11 of Beier et al. (2018)) errors exceed 1°C at Reynolds numbers below about 6,500.

3.1.6 Verification of design tool

Cullin and Spitler (2011) validated the original hybrid time step method against sizes determined with hourly simulation of VBGHEs for three buildings in 16 climates. To verify the overall performance of the design tool, the original loads, borehole design, ground thermal properties and design temperature limits from the Cullin and Spitler study were used. To make a fair comparison, the following modifications to the design tool were made:

- The borehole configuration was specified to be the same as that in the Cullin and Spitler study rather than having the design tool pick the configuration. This was done because the Cullin and Spitler study used, in a number of cases, GHE that were not square or near-square.

- The g-functions used were computed with pygfunction, using the 30 segments/100 m and the UIFT boundary condition. $\frac{D}{H}$ was held at 0.06 to match the geometries for which the Hellström (2006) g-functions were computed, and which were used to calculate the hourly time step sizes in the Cullin and Spitler (2011) work.

As expected, the revisions to the hybrid time step scheme described in Section 3.1.4, generally improved the accuracy. In Table 3-6 and Figures 3-15 through 3-17, the original hybrid time step scheme presented in Cullin and Spitler (2011) is referred to as "HyTS 2011." The new design tool using the improved hybrid time step scheme is referred to as "HyTS 2020."

As can be seen in all three figures, for most cases the magnitude of the oversizing is significantly reduced. There are a few exceptions, but overall, the results as summarized in Table 3-6, show significantly better matches to the results obtained with the hourly time step simulation. The RMSE (Root Mean Square Error) shown in Table 3-6 is an indicator of "goodness of fit"—smaller numbers indicate better match between the VBGHE size determined with simulations using hybrid time steps and hourly simulations. Furthermore, this confirms the overall "correctness" of the design tool—it found sizes for all 48 cases, and they are all reasonably close to the design obtained with an hourly time step simulation. Whereas a single hourly timestep simulation for a period of 10 years takes about 15 min to run on a desktop PC, each simulation using the hybrid time step scheme takes less than a second. This makes it possible to design a VBGHE in around 30 to 40 s.

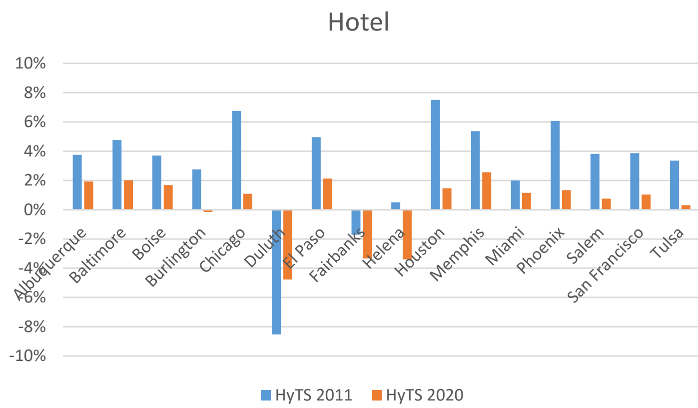


Figure 3-15. Comparison of oversizing relative to design based on an hourly time step simulation—hotel.

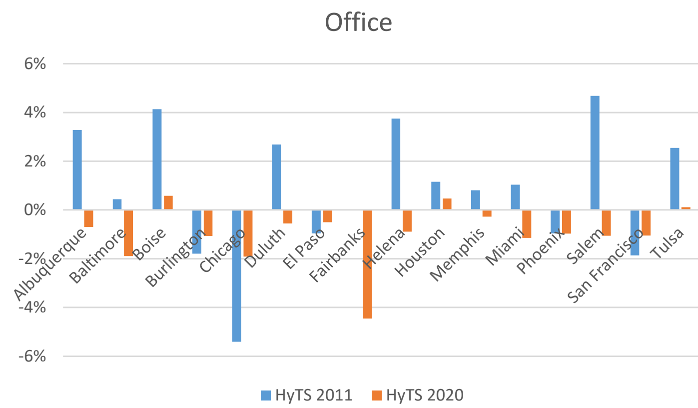


Figure 3-16. Comparison of oversizing relative to design based on an hourly time step simulation—office.

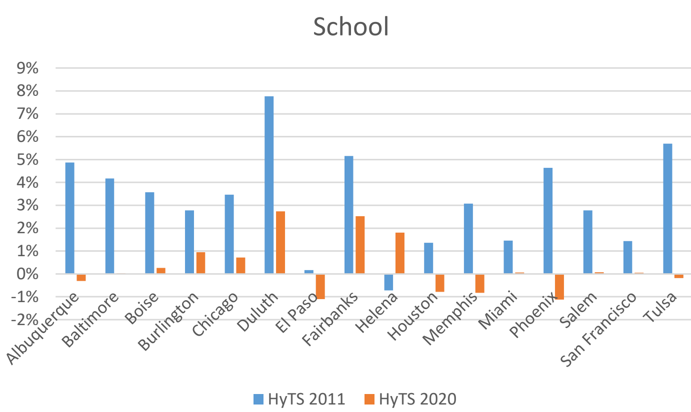


Figure 3-17. Comparison of oversizing relative to design based on an hourly time step simulation—school.

Table 3-6. Overview statistics.

	RMSE (%)		Maximum oversizing (%)		Minimum oversizing (%)	
	HyTS 2011	HyTS 2020	HyTS 2011	HyTS 2020	HyTS 2011	HyTS 2020
Hotel	4.8	2.2	7.5	2.6	−8.5	−4.8
Office	2.7	1.5	4.7	0.6	−5.4	−4.5
School	3.9	1.2	7.8	2.7	−0.7	−1.1

3.2 INTEGRATION BETWEEN BES AND THE VBGHE SIZING TOOL

OS is an open-source, cross-platform (Windows, Mac, and Linux) collection of software tools to support EnergyPlus and other tools for performing the whole-building energy simulation. OS has several graphical applications including the OS SketchUp Plug-in, OS Application, ResultsViewer, and the Parametric Analysis Tool. The OS SketchUp Plug-in allows users to quickly create geometry needed for EnergyPlus. Additionally, OS supports the import of gbXML and IFC for geometry creation. The OS Application is a fully featured graphical interface to OS models including envelope, loads, schedules, and HVAC systems. ResultsViewer enables browsing, plotting, and comparing simulation output data, especially time series. The Parametric Analysis Tool enables studying the impact of applying multiple changes to a base model as well as the export of the analysis results (DOE 2020). The core component library of OS is a continuously increasing collection of various types of building components, including but not limited to, building construction, materials, and HVAC system components (NREL 2020a).

The auto-sizing tool of VBGHE is seamlessly integrated with OS to establish a fully automated process for replacing an existing HVAC system in a BES model with a GHP system, sizing each component of the system, including the VBGHE, and simulating the performance of the GHP system. Inputs and procedure of the automated process consist of the following steps, as numbered and shown in Figure 3-18.

1. Replace the existing HVAC system with a GHP system. Currently, the program takes in building type and climate zone as the initial input then loads the corresponding prototype building model. The

prototype model was modified with an OS measure to replace the existing HVAC system in the prototype model with a GHP system that uses a VBGHE;

2. Simulate the initial design of the GHP system to get the thermal loads and design parameters of the VBGHE. In this initial simulation, the borehole number is estimated based on the floor space of the building and default values for the BHD (200 ft or 61 m), the g-functions, and the in-borehole design parameters are used;

3. Size VBGHE to determine the borefield arrangement, number and depth of the borehole, and the associated g-functions;

4. Update the input of the prototype model with the above sizing results of VBGHE;

5. Perform simulation of the updated GSHP system to predict its performance; and

6. Report key performance metrics and pass them to the interface and a database.

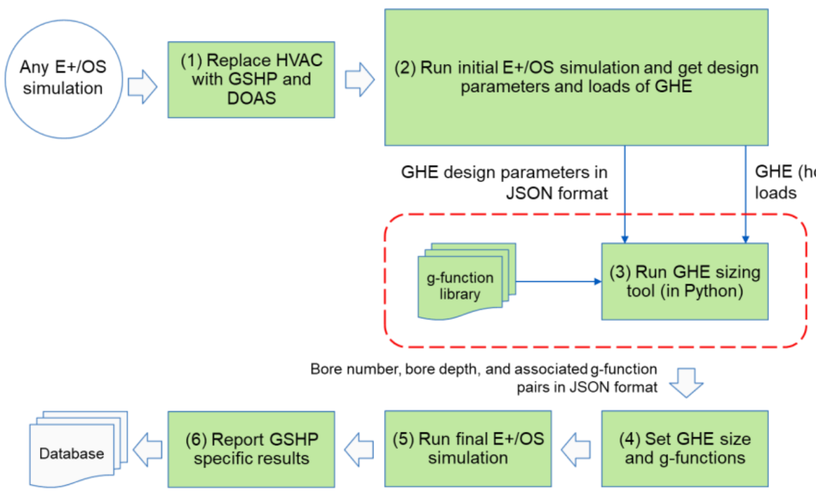


Figure 3-18. Flowchart of the automated process for modifying existing building model, sizing VBGHE, and simulating the sized GHP system

As shown in Fig. 3-18, the thermal loads of the building are calculated first and used to size the VBGHE. Ideally, the GHE would be sized based on the simulation results of the GHP system. However, it will require multiple full-year BESs in an iterative sizing process. Given the lengthy time requirement for performing a BES with OS (could be several minutes depending on the complexity of the simulated building), it would take more than an hour to size a VBGHE. The current approach was implemented to reduce the computation time for automated sizing and simulation. The automated process could be modified to be based on the simulation results of the GHP system if the BES with OS could be accelerated.

In parallel to the above described GHP system simulation, the original prototype building model with an existing HVAC system is also simulated to establish a baseline for comparing with the GHP system. Both the baseline and the GHP system simulations are performed with OS. Given that OS measures are callable through command line scripts and the VBGHE sizing is implemented with Python (Section 3.1), the automation process was implemented with Python. Compared with Ruby (the programming language of OS), Python has better capability in data processing and analysis, which makes it handy for post-processing output data. Furthermore, the Python code can be easily incorporated into an existing python-based framework for developing a web-based interface for the GHP screening tool.

3.2.1 Existing DOE prototype models

The U.S. Department of Energy prototype building models are developed by the Pacific Northwest National Laboratory (PNNL 2020) to describe different types of buildings in compliance with ASHRAE 90.1 (ASHRAE 2011) and IECC (ICC 2015). The prototype building model covers around 80% of the existing buildings in the United States in all climate zones. The Commercial Prototype Models suite has 1,360 EnergyPlus models—resulting from combinations of 5 vintages (90.1-2004, 2007, 2010, 2013, and 2016-compliant), 16 US locations, and 16 building types. Older buildings (pre-2004) will not be used since most of the old buildings may have been retrofitted and thus the old prototype model is not valid for representing the retrofitted buildings. The prototype models originally developed for EnergyPlus have been converted to OS models and are available from the OS standards library (NREL 2020c). HVAC systems of some OS models of the prototype buildings have been replaced with a GHP system using an existing OS measure, as discussed in more detail in Section 3.2.2.

3.2.2 OS measures

Parameters and inputs of an OS model can be modified through a graphical interface or with OS measures. An OS measure is a script written in OS's Ruby API (NREL 2020b). OS measures can be called via the OS graphical interface or from a command line in an OS workflow (OSW) file, which is essentially a JSON string storing the information of the seed model, weather file, measure names, and measure inputs. This project uses OSW files to call for various OS measures. A Python script is developed to manage the workflow and modify the inputs of each OS measure based on the user inputs to enable a fully automated process for creating, sizing, and simulating a GSHP system. The OS measures used in this process are described below.

3.2.2.1 Replace existing HVAC system with a GHP system

- There is an existing OS measure named "Convert to GSHP with DOAS" available from the OS Building Components Library (NREL 2020b). This measure replaces the existing HVAC system in a building energy model with a distributed GHP system, which consists of multiple zonal water-air heat pump (WAHP) units throughout a building. As shown in Figure 3-19, all the WAHPs are attached to a two-pipe water loop through a series of parallel branches of the water loop. A VBGHE is connected to the main supply and return of the water loop. A variable speed pump is used to circulate water (or an anti-freeze solution) through the VBGHE and the WAHPs. The variable speed pump is controlled to maintain a user-specified differential pressure across the supply and return of the water loop.

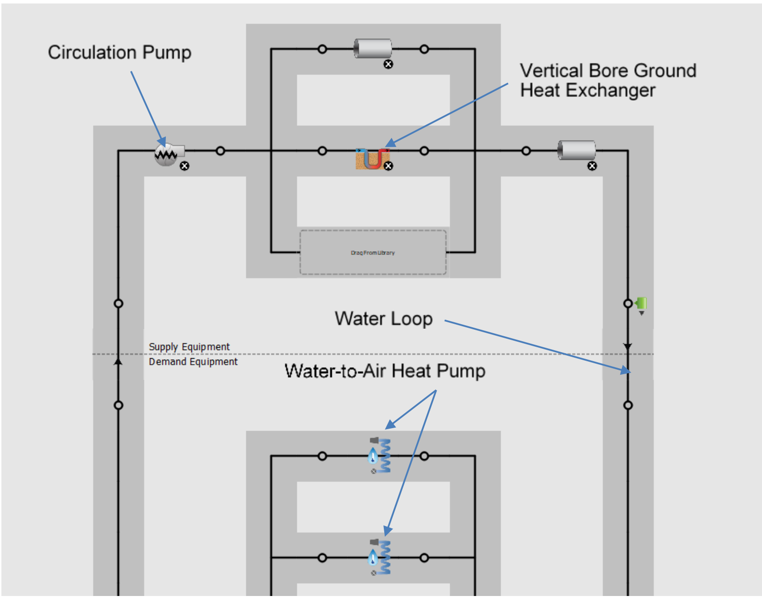


Figure 3-19. Structure of the simulated distributed GHP system.

- Following are the default specifications of the GHP system in the original measure:
- The WAHP has a rated cooling efficiency of 6.45 COP (coefficient of performance) and rated heating efficiency of 4 COP.
- The VBGHE is comprised of one or multiple vertical boreholes, each with a single U-shaped high-density polyethylene (HDPE) pipe in it;
- a fixed undisturbed ground temperature (not location-specific) is used;
- the borehole number is roughly estimated based on the total floor space of the simulated building and a set of fixed g-function values (independent to borehole numbers) were given;
- a dedicated OA system (DOAS) is used to distribute the conditioned OA to each thermal zone in the building. The DOAS uses a single-speed air-cooled direct expansion (DX) cooling system to cool the OA with a rated efficiency of 2.93 COP and a gas furnace to heat the OA with an 80% rated efficiency; and
- an electric resistance heater is added to each WAHP unit.
- This measure was modified in this project to more closely represent the real GHP systems by:
- removing the DX cooling and the gas furnace by zeroing their capacities while keeping the OA supply air and its operation schedule to ensure the code-compliant amount of OA is delivered into each zone. As an option, an Energy Recovery Ventilator (ERV) can be added to the DOAS;

- eliminating the electric resistance heaters by zeroing their capacities; and
- assigning all non-plenum zones to the GHP system.
- Implementing site-specific undisturbed ground temperature using a data set developed by Xing (2014).
- Currently, only 9 of the 16 prototype models can be successfully converted to a GHP system with the original and the modified OS measure. The convertible models include small office, medium office, retail stand-alone, strip mall, warehouse (non-refrigerated), quick-service restaurant, full-service restaurant, mid-rise apartment, and high-rise apartment, as listed in Table 3-7. The failure may be due to the complexity of the existing HVAC system. For example, if the existing HVAC system has hot water reheat coils in the terminals of a Variable Air Volume (VAV) system, it may not be removed by the measure and cause errors in the resulting modified OS model. Further review and modifications of the conversion measure are needed to solve this issue and successfully convert the existing HVAC system in the prototype models to a GHP system.

Table 3-7. A list of the 16 DOE prototype buildings and their main HVAC systems.

Building type	Energy distribution system	Cooling equipment	Heating equipment	Converted to GHP
Small office	Packaged single zone—Unitary HP	Single speed heat pump	Single speed heat pump	Yes
Medium office	Packaged VAV	Two speed DX	Gas	Yes
Large office	VAV	Chiller	Boiler	No
Stand-alone retail	Packaged single zone	Two speed DX	Gas furnace	Yes
Strip mall	Packaged single zone	Two speed DX	Gas furnace	Yes
Primary school	Packaged VAV	Two speed DX	Gas furnace	No
Secondary school	Packaged VAV	Two speed DX	Gas furnace	No
Outpatient healthcare	VAV	Two speed DX	Boiler	No
Hospital	VAV	Chiller	Boiler	No
Small hotel	Packaged terminal air conditioner	Single speed DX	Electric	No
Large hotel	Packaged terminal air conditioner	Single speed DX	Electric	No
Warehouse (non-refrigerated)	Packaged single zone	Two speed DX	Gas furnace	Yes
Quick-service restaurant	Packaged single zone	Two speed DX	Gas furnace	Yes
Full-service restaurant	Packaged single zone	Two speed DX	Gas furnace	Yes
Mid-rise apartment	Packaged single zone	Single speed DX	Gas furnace	Yes
High-rise apartment	Packaged single zone—Unitary HP	Water-to-air heat pump	Water-to-air heat pump	Yes

3.2.2.2 Obtain GHE Loads and Set VBGHE Design Parameters

This measure gets hourly thermal loads of GHE from the EnergyPlus simulation results of the initially converted GHP system. In EnergyPlus simulation results, the unit of ground heat transfer rate is in Watts and the heat extraction rates when the GHP system running in heating mode are expressed as positive values while negative values indicate heat rejection rates when the GHP system in cooling operation.

This measure also provides a list of VBGHE design parameters, as listed in Table 3-8. Both the hourly thermal loads and design parameters are used by the auto-sizing tool to size VBGHE.

Table 3-8. Design parameters used for sizing VBGHEs.

Parameter	Category	Default value	Note
Total installed capacity	GHP system	Obtained from the initial GHP system simulation	Sum of the nominal capacity of each WAHP auto-sized by EnergyPlus in the initial GHP system simulation
Design flow rate	GHP system	Calculated based on the total installed capacity of the GHP system using 3 GPM/ton	For the entire GHE consisting of one or multiple boreholes
Borehole radius (m)	In-borehole	0.055	
U-tube pipe thickness (m)	In-borehole	0.002	1-in. pipe with SDR-11 schedule
U-tube pipe outer diameter (m)	In-borehole	0.027	1-in. pipe with SDR-11 schedule
U-tube distance between two legs (m)	In-borehole	0.01887	Distance between the two legs of the U-tube
U-tube pipe thermal conductivity (W/m-K)	In-borehole	0.389	HDPE pipe
U-tube pipe volumetric heat capacity (J/m^3-K)	In-borehole	1,542	
Grout thermal conductivity (W/m-k)	In-borehole	0.744	Bentonite grout
Grout volumetric heat capacity (kJ/m^3-K)	In-borehole	3,901	Bentonite grout
Fluid type	In-borehole	1	Water
Anti-freeze concentration (%)	In-borehole	0	Water
Undisturbed ground temperature (°C)	Ground	Site-specific	Lookup table based on the location associated with user-specified weather data
Ground thermal conductivity (W/m-k)	Ground	2.423	Typical ground formation
Ground volumetric heat capacity (kJ/m^3-K)	Ground	2,343	Typical ground formation
Bore spacing (m)	Borefield	6.1	Uniform across the borefield. It can be overwritten with a custom-specified layout of the borefield.
Maximum BHD (m)	Borefield	120	
Minimum BHD (m)	Borefield	110	Currently is not used for sizing GHE
Maximum GHE supply temperature (°C)	Borefield	32	
Min. GHE supply temperature (°C)	Borefield	4	
Simulation period (Month)	Borefield	360	

Commented [LX1]: Shouldn't the unit be kJ/(m3K)? Also, the ground volumetric specific heat should also be included.

3.2.2.3 Update VBGHE Design Parameters and Perform Final GHP Simulation

This measure replaces the default values of the total number of boreholes, BHD, and the associated g-function data pairs, and the ratio between the borehole spacing and the BHD (i.e., the $\frac{B}{H}$ ratio) with the results from the auto-sizing tool (Section 3.1). It will then run a simulation using the updated GHE parameters to predict the performance of the GHP system. The simulation is only for 1 year for now, a multi-year simulation will be implemented in the next project year (see Section 5).

3.2.3 New Python codes for generating reports

Separated Python code was developed to extract key simulations results of both the GHP system and the baseline HVAC systems to enable technical and economic feasibility study. This Python code queries the output files of both simulations using Python's native sqlite3 library. The results of an OS simulation are stored in a SQL file inside a folder created for the simulation. The extracted data get displayed back to the corresponding location on the report pages of the Microsoft Excel-based interface discussed in Section 3.3.2. The displayed key simulation results include

- Hourly thermal loads of the GHE
- GHE design (arrangement, total number, and depth of boreholes)
- The capacity of the GHP system and the baseline HVAC system
- Monthly end uses of electricity and other fuels by the two systems
- Annual energy cost of the two systems
- Annual peak demand of electricity and other fuels of the two systems

3.2.4 Verification of the automated sizing and simulation program

As discussed in Section 3.1.1, with the current integration method, the thermal loads used for sizing the VBGHE are slightly different from that in the final simulation of the GHP system because of the difference between the initial and the final design of the VBGHE. Furthermore, the GHE simulator of the GHE sizing tool uses hybrid time steps instead of the hourly time step used in the E+/OS simulation. It is of interest to check whether the maximum supply temperature of the VBGHE predicted by the automated simulation is consistent with the criterion used for sizing the VBGHE (i.e., the maximum supply temperature is at or very close to the design temperature, e.g., 35°C). Because the current version of OS (2.9.1) only allows for 1-year simulation, the authors set up the automation program to size the VBGHE based on the criterion of having a 35°C maximum supply temperature in the first year of operation. The authors then compare the predicted maximum supply temperature with the design criterion. The authors found that the difference is less than 1°C, which will not result in any significant difference in the predicted GHP system performance. It indicates that the automated program can properly size the GHE and predict GHP system performance.

3.3 EXCEL-BASED USER INTERFACE

A preliminary Excel-based user interface was developed for taking inputs, performing automated simulations, and display key performance metrics. This front-end interface is designed and developed as a quick mockup for demonstrating the appearance of the GHP screening tool, as well as the input and output variables. This Excel-based interface will be used as a template for the future web-based interface. The interface includes a series of pages for collecting inputs and reporting performance metrics.

3.3.1 Input pages

The input pages guide a user to specify the location and prototype building model through dropdown menus. Alternatively, the building model and location can be determined using a Google map application as illustrated in the lower section of Figure 3-20. With this feature, a user can select a building from the map and draw out the area available for the GHE installation. It is also planned to automatically create a building model based on the footprint and images of the selected building using the AutoBEM program developed at Oak Ridge National Laboratory (New et al. 2018). The geometry of the user-specified land area will be used as the constraints for sizing the GHE. The above features will be implemented in the second year of this project as discussed in Section 5.

The interface also allows users to specify the building (e.g., floor space area, orientation, and window-to-wall ratio), and the parameters of the GHE, WAHP, and associated controls. New OS measures will be developed and used in the automation program to modify the prototype model and simulate both the baseline HVAC system and the GHP system based on the user inputs. Table 3-9 lists the allowed user inputs and the method to reflect each input in the simulation model.

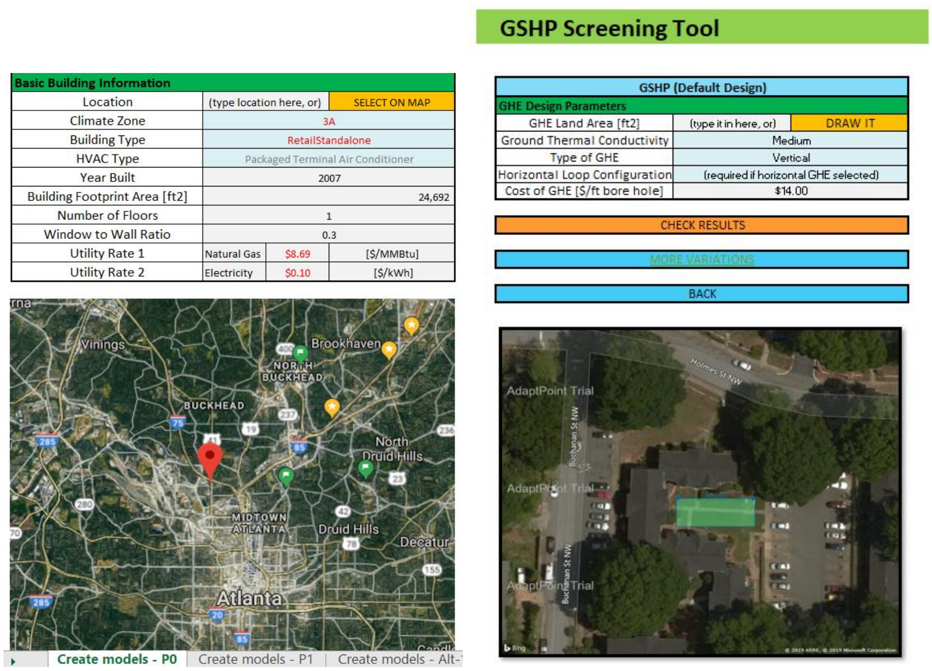


Figure 3-20. The input pages of the Excel-based interface.

Table 3-9. Variable parameters for GHP system simulation.

Parameters		Input method	Note
Building	Building type	Interface	Select from existing prototype building models

	Vintage (Year Built)	Interface	Select from existing prototype building models
	Location	Interface	Select from 16 climate zones in the US
	Building footprint area	Interface and OS measure	Use a new OS measure to accept this input. Simple scaling up/down the simulation results of a relevant prototype building model applies to some range only. For example, a small office will still be a “small” office so that the same conventional HVAC system will still be valid.
	Number of floors	Interface and OS measure	Use an OS measure to accept this input
	Window-wall ratio	Interface and OS measure	Use an OS measure to accept this input
	Window type	Interface and OS measure	Use an OS measure to accept this input
	Window shading	Interface and OS measure	Use an OS measure to accept this input
GHE	Heat exchanger type	Interface and the conversion measure	EnergyPlus needs to be improved to allow for other types of GHEs
	Borehole radius (m)	Interface and the conversion measure	Update the conversion measure to accept this parameter
	Ground thermal conductivity (W/m·K)	Interface and the conversion measure	Update the conversion measure to accept this parameter
	Grout thermal conductivity (W/m·K)	Interface and the conversion measure	Update the conversion measure to accept this parameter
	Pipe thermal conductivity (W/m·K)	Interface and the conversion measure	Update the conversion measure to accept this parameter
	Fluid mass flow rate per borehole (kg/s)	Interface and the conversion measure	Update the conversion measure to accept this parameter
Water-to-air heat pump	Cooling EER	Interface and the conversion measure	Update the conversion measure to accept this parameter
	Heating COP	Interface and the conversion measure	Update the conversion measure to accept this parameter
	Fan type	Interface and the conversion measure	Update the conversion measure to accept this parameter
Control and operation	Outdoor air (m^3/s)	Interface and the conversion measure	Use an OS measure to accept this input
	Temperature setpoint setback	Interface and the conversion measure	Use an OS measure to accept this input

If a user does not provide cost data of both the baseline HVAC system and the GHP systems, a set of built-in generic cost models will be used to estimate the initial costs of the two systems. Local energy prices will be provided by the user or obtained from the latest data provided by the Energy Information Agency of DOE (US EIA 2016a, 2016b, and 2016c). It is planned to obtain utility rates dynamically through an API from the utility companies serving the location specified by the user.

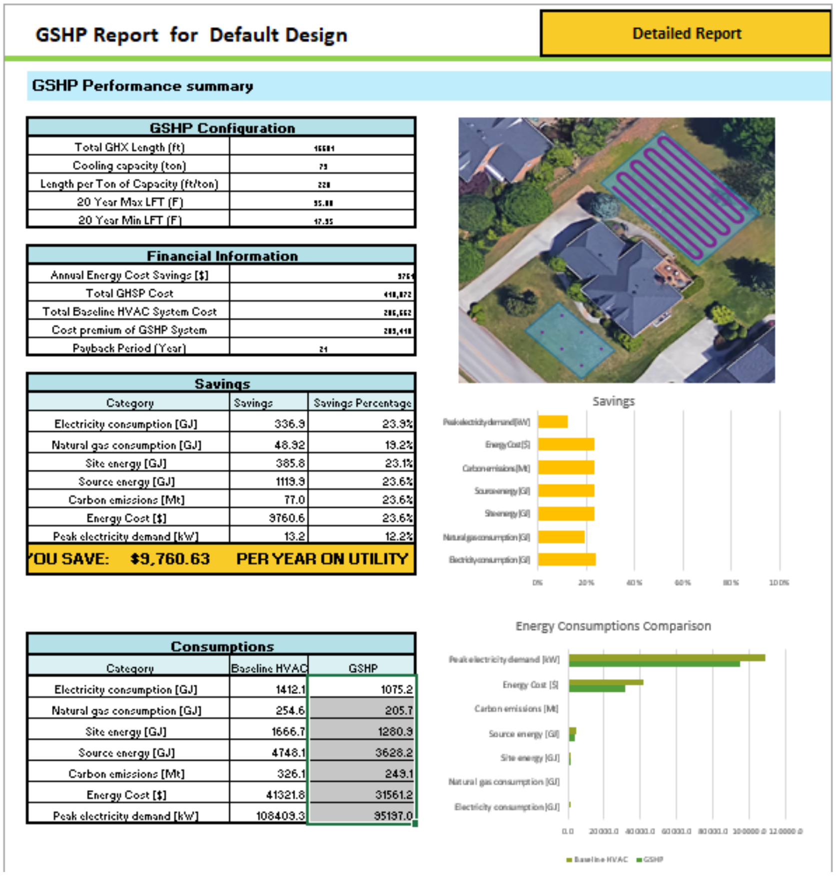
The Excel interface uses a VBA macro to call the automation program in a command-line based on the user inputs. Users can simply click on the ‘Run’ button to run the automated simulation. To get a quick answer may pre-simulate various combinations of the allowed design parameters. The key simulation results will be stored in a database and will be populated and displayed in the results page. To account for combinations of the following design variations, 9216 automated simulations would be performed.

- 16 prototype buildings
- 16 climate zones
- 6 variations in the design of the building and the HVAC system
- DOAS with ERV
- DOAS without heating and cooling capacity
- High-performance windows
- The efficiency of baseline HVAC equipment
- Increased OA ventilation
- Seasonal change of OA schedule
- 3 levels of ground thermal conductivities (low, medium, high)
- 2 types of GHEs: horizontal slinky and vertical closed loop

3.3.2 Report pages

The report pages contain two sections. The first section, shown in Figure 3-21 (a), lists key information of the simulated GHP system, including heating and cooling capacity, GHE size, and installation cost. Also presented on this page are the annual energy cost savings and associated carbon emission reduction, as well as the avoided peak electricity demand compared with the baseline HVAC system. Economic analysis results, including life cycle cost, the net present value of the investment, and the simple payback of the GHP system, are calculated with an economic analysis module (part of the interface) and displayed in this section. Furthermore, the borefield layout (based on the results of the VBGHE sizing tool) is illustrated in the top left corner of this section.

As shown in Figure 3-21 (b), the second section provides a side-by-side comparison on the predicted performance between the baseline HVAC system and the GHP systems with various user-specified design parameters, such as increased OA ventilation or larger borehole spacing. The comparison includes annual energy cost savings, monthly energy savings, as well as monthly thermal loads.



GSHP Report for Default Design

Detailed Report

GSHP Performance summary

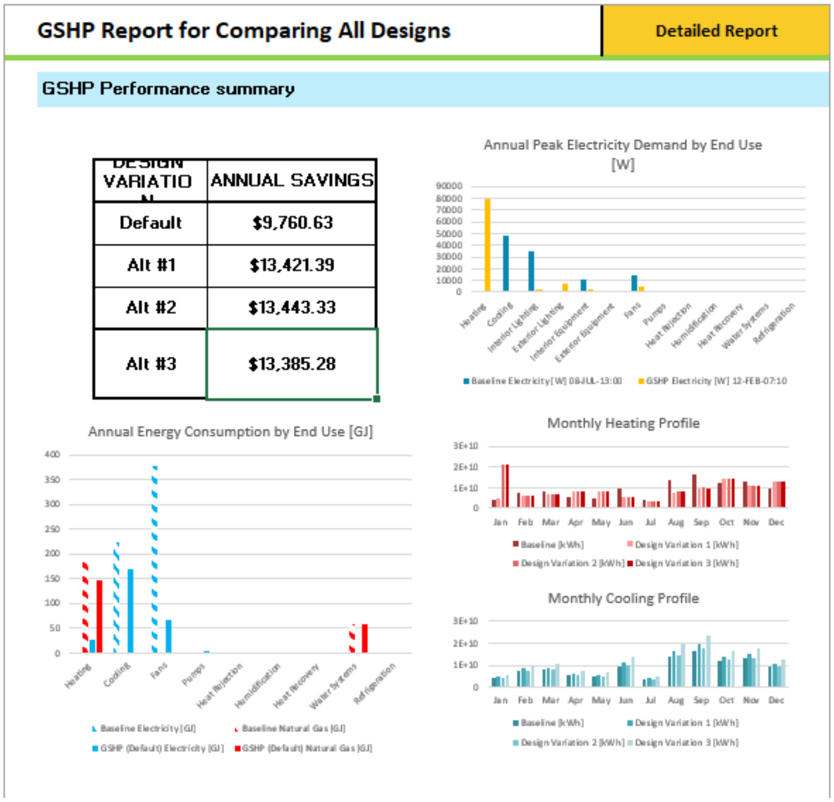
GSHP Configuration	
Total GHX Length (ft)	[illegible]
Cooling capacity (ton)	75
Length per Ton of Capacity (ft/ton)	[illegible]
20 Year Max LFT (F)	[illegible]
20 Year Min LFT (F)	[illegible]

Financial Information	
Annual Energy Cost Savings [$]	[illegible]
Total GHSP Cost	[illegible]
Total Baseline HVAC System Cost	[illegible]
Cost premium of GSHP System	[illegible]
Payback Period (Year)	21

Savings		
Category	Savings	Savings Percentage
Electricity consumption [GJ]	336.9	23.9%
Natural gas consumption [GJ]	48.92	19.2%
Site energy [GJ]	385.8	23.1%
Source energy [GJ]	1119.9	23.6%
Carbon emissions [Mt]	77.0	23.6%
Energy Cost [$]	9760.6	23.6%
Peak electricity demand [kW]	13.2	12.2%
'OU SAVE:	$9,760.63	PER YEAR ON UTILITY

Consumptions		
Category	Baseline HVAC	GSHP
Electricity consumption [GJ]	1412.1	1075.2
Natural gas consumption [GJ]	254.6	205.7
Site energy [GJ]	1666.7	1280.9
Source energy [GJ]	4748.1	3628.2
Carbon emissions [Mt]	326.1	249.1
Energy Cost [$]	41321.8	31561.2
Peak electricity demand [kW]	108409.3	95197.0

(a)

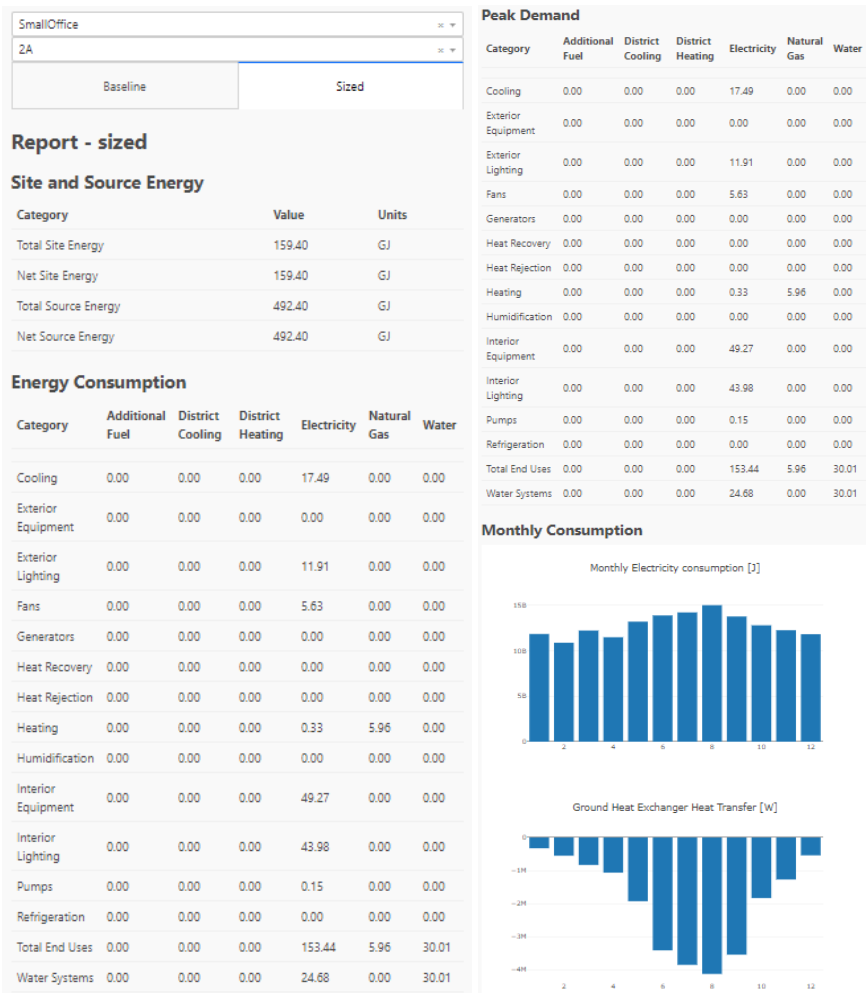


(b)

Figure 3-21. The report pages: (a) key performance metrics; and (b) side-by-side comparison between the baseline HVAC system and the GHP systems with alternative designs.

3.4 DEVELOPMENT OF A WEB-BASED INTERFACE

The second phase of the interface development is to create a web interface based on the Excel-based interface shown in Section 3.3. A simple web-based interface has been built to display key simulation results of both the baseline HVAC and the GHP system based on user-specified location and prototype building, as shown in Figure 3-22. Dash is a simple but powerful library written on top of web development framework Flask and web-based data analysis tools including plotly and D3.js (PDT 2020). An important benefit of using the Dash library is to keep all the web-app development in the Python environment, which will not only make it easier to integrate the web-interface with the automated simulation but also can use the powerful Python data analytics tools such as pandas.



SmallOffice

2A

Baseline | Sized

Report - sized

Site and Source Energy

Category	Value	Units
Total Site Energy	159.40	GJ
Net Site Energy	159.40	GJ
Total Source Energy	492.40	GJ
Net Source Energy	492.40	GJ

Energy Consumption

Category	Additional Fuel	District Cooling	District Heating	Electricity	Natural Gas	Water
Cooling	0.00	0.00	0.00	17.49	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	11.91	0.00	0.00
Fans	0.00	0.00	0.00	5.63	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Heating	0.00	0.00	0.00	0.33	5.96	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	0.00	0.00	0.00	49.27	0.00	0.00
Interior Lighting	0.00	0.00	0.00	43.98	0.00	0.00
Pumps	0.00	0.00	0.00	0.15	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	0.00	0.00	0.00	153.44	5.96	30.01
Water Systems	0.00	0.00	0.00	24.68	0.00	30.01

Peak Demand

Category	Additional Fuel	District Cooling	District Heating	Electricity	Natural Gas	Water
Cooling	0.00	0.00	0.00	17.49	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	11.91	0.00	0.00
Fans	0.00	0.00	0.00	5.63	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Heating	0.00	0.00	0.00	0.33	5.96	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	0.00	0.00	0.00	49.27	0.00	0.00
Interior Lighting	0.00	0.00	0.00	43.98	0.00	0.00
Pumps	0.00	0.00	0.00	0.15	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	0.00	0.00	0.00	153.44	5.96	30.01
Water Systems	0.00	0.00	0.00	24.68	0.00	30.01

Monthly Consumption

Figure 3-22. A simple web-based interface developed with Dash to display key simulation results of both the baseline HVAC and the GHP system based on user-specified location and prototype building.

3.5 BATCH RUN OF LARGE-SCALE SIMULATIONS

The batch simulation tool is a Python script created to automatically perform a series of operations (including creating, sizing, and simulating both a baseline HVAC and a GHP system) according to a list of building prototype models and the climate zones provided by a user. Once all the simulations are completed, the key simulation results will be displayed all together in the user interface described in Sections 3.3 and 3.4.

This batch simulation tool will be expanded in the second year of this project to allow a batch run of hundreds of thousands automated sizing and simulations based on user-specified inputs on the design variations in the building, baseline HVAC, and the GHP system on top of the list of building prototype models and the climate zones, as discussed in Section 3.3.1. The key simulation results of the batch runs will be stored in a database linked to the interface. Based on the user's selections of the available inputs, the corresponding pre-simulated results will be fetched from the database and be promptly displayed on the interface.

4. CASE STUDY WITH THE GSHP SCREENING TOOL

A case study is presented in this section to demonstrate how the automated sizing and simulation program developed in this year can facilitate a holistic simulation-based design to improve the cost-effectiveness of the GHP system while maintaining thermal comfortable condition in a built environment. A standalone retail building, which is modeled with one of the DOE's prototype models is used in this case study.

4.1 TARGET BUILDING

The modeled standalone retail building is 1 story with 2,294 m^2 total floor space area. As shown in Figure 4-1, the modeled building has 5 zones. The HVAC system in the original prototype model is a package terminal unit with constant airflow in each of the thermal zones. Cooling equipment is an air-cooled direct expansion air-conditioner with a two-speed compressor. The rated efficiency is 3.58 COP at high speed. Heating equipment is a natural gas furnace with a 0.8 efficiency. OA is mixed with return air in each thermal zone. Percentage of OA in the total supply air ranges from 14% to 30% in various thermal zones (30% in the core zone and 14% to 20% in four perimeter zones). This system is used as the baseline HVAC system in this case study. The selected location for this case study is Atlanta, Georgia.

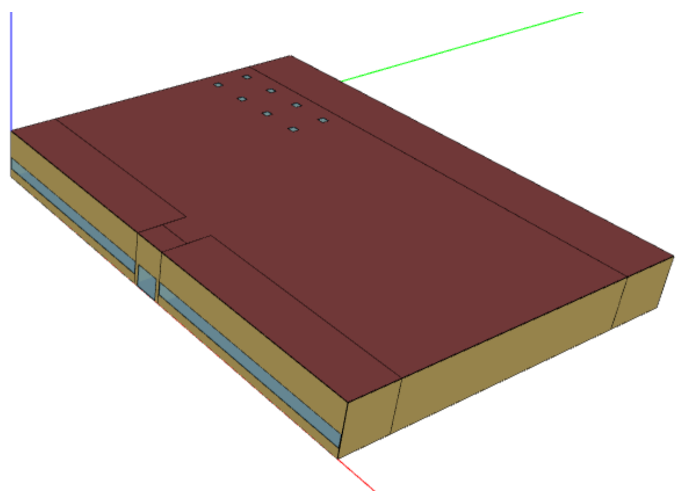


Figure 4-1. A 3D rendering of the prototype standalone retail building.

4.2 INVESTIGATED DESIGN PARAMETERS AND OTHER INPUTS

As discussed in Section 3.2.1, a distributed GHP system with a DOAS is created by the original OS measure (available from the Building Component Library of OS) to replace the existing HVAC system. Each thermal zone is served with a WAHP unit, which has a rated cooling efficiency of 6.45 COP and rated heating efficiency of 4 COP. The DOAS uses a single speed DX cooling with rated cooling efficiency of 2.93 COP and a gas furnace with 80% rated heating efficiency.

The first alternative design uses DOAS only to distribute OA to each thermal zone without cooling or heating it. The amount of the OA delivered to each zone is determined according to ASHRAE standard 62.1, and it is not changed in this alternative design. The unconditioned OA is delivered to a thermal zone and mixed with the room air. The WAHP is turned on and off to maintain the room air within the desired temperature range. The second alternative design is based on the first one but removes all the electric resistance heaters from each of the WAHPs. The third alternative design adds an ERV (a plate type for sensible heat recovery) in the DOAS to prevent cold or hot air from blowing directly into the zone when the WAHP is not called on (i.e., when the zone temperature is within the setpoints).

Because of the ongoing pandemic of COVID-19, increasing OA ventilation in buildings has been recommended by ASHRAE to dilute the indoor air where the virus may exist. This case study also evaluates how various OA ventilation schemes affect the cost and performance of the GHP system. The fourth alternative is built upon the third alternative design but with a 200% increase in the delivered OA in each zone all year long. The fifth design is like the fourth design but only increases OA in winter (and turn off the OA in summer). Descriptions of the alternative designs are listed below:

- Alternative #1: DOAS without heating and cooling capacity
- Alternative #2: Alternative #1 + No electric resistance heater at each WAHP
- Alternative #3: Alternative #2 + ERV in the DOAS
- Alternative #4: Alternative #3 + Increased OA ventilation by 200% all year long
- Alternative #5: Alternative #3 + Increased OA ventilation by 200% in winter and (without OA in summer)

The automated sizing and simulation program described in Section 3 is used to size GHE and predict the performance of both the baseline HVAC system and the GHP system. Economic analysis is also performed using the simulation results, the local prices of electricity and natural gas, and installation cost of both the baseline HVAC system and the GSHP system, which is based on a generic cost model described by Liu et al. (2019). The federal tax credits and other financial incentives offered by utility companies or heat pump manufacturers are not considered in the generic cost model.

4.3 RESULTS

The simulations results and the cost analysis of the baseline HVAC and the GHP system with various designs (the default GHP system and the first three alternative designs) are listed in Table 4-1. The compared results include energy consumption, carbon emission, peak electric demand, energy cost, and installed cost. The simple paybacks of the various GHP system are also calculated based on the cost premium of the annual energy cost savings achieved by each of the GHP systems.

Table 4-1. Simulation results of the baseline HVAC and the various GSHP systems.

Category	Baseline	GHP (Default)	Change from baseline (%)	GHP (Alt #1)	Change from baseline (%)	GHP (Alt #2)	Change from baseline (%)	GHP (Alt #3)	Change from baseline (%)
Electricity consumption (GJ)	1,412	1,075	−23.9	987	−30.1	986	−30.2	988	−30.0
Natural gas consumption (GJ)	255	206	−19.2	59	−77.0	59	−77.0	59	−77.0
Site energy (GJ)	1,667	1,281	−23.1	1,046	−37.3	1,045	−37.3	1,047	−37.2
Source energy (GJ)	4,748	3,628	−23.6	3,189	−32.8	3,187	−32.9	3,194	−32.7
Carbon emissions (Mt)	326	249	−23.6	220	−32.5	220	−32.5	220	−32.4
Energy cost ($)	41,322	31,561	−23.6	27,900	−32.5	27,878	−32.5	27,937	−32.4
Peak electricity demand (kW)	108	95	−12.2	98	−9.5	69	−35.7	67	−37.6
Total borehole length (m)	NA	5,060	NA	6,002	NA	5,998	NA	5,753	NA
Simply payback (year)	NA	21	NA	18	NA	18	NA	18	NA

The above results show that the GHP system with default design can shed 23.6% of the annual energy costs and 12.2% of the peak electric demand of the building by replacing the baseline HVAC system. However, the 21-year payback is too long. In the first alternative design, OA is conditioned with the GHP instead of the less efficient DX cooling and gas furnace in the DOAS. It increases the annual energy cost saving to 32.5% but the peak electric demand reduction is decreased to 9.5%. Although the increased thermal loads of the GHP system from conditioning the OA requires a larger GHE (the total borehole length increases from 5,060 m to 6,002 m), the increased cost of the larger GHE is offset by the increased energy cost savings. Therefore, the payback period is shortened from 21 years to 18 years. In the second alternative design, after removing the electric resistance heaters from the WAHPs, the electricity consumption of the GHP system only decrease slightly (from 987 GJ to 986 GJ). It indicates that the electric resistance heaters only run a very short period during a year so it will not significantly affect the indoor thermal comfort. However, by removing the electric resistance heaters, the peak electric demand is reduced drastically from 95 kW to 69 kW (a 35.7% reduction). Adding an ERV (alternative design 3) in the DOAS slightly increases the energy cost and slightly reduces the peak electric demand. Given the additional cost of the ERV, it may increase the simple payback. These results indicate that the alternative design 2 is more cost effective than other alternative designs. Figure 4-2 shows a side-by-side comparison of the energy end uses (electricity and natural gas) between the baseline HVAC, the default GHP system, and the second alternative GHP system. This figure shows that the energy savings of the GHP systems come from lower electricity consumption for space heating, space cooling, and fan. The alternative GHP design completely eliminates the natural gas consumption for space heating. The simulation results show very little pumping power consumption, which is not even visible in Figure 4-2. Previous case studies of real GHP systems usually show higher pumping power consumption. Further debug of the OS/E+ model is needed to verify or correct the simulation predicted pumping power consumption.

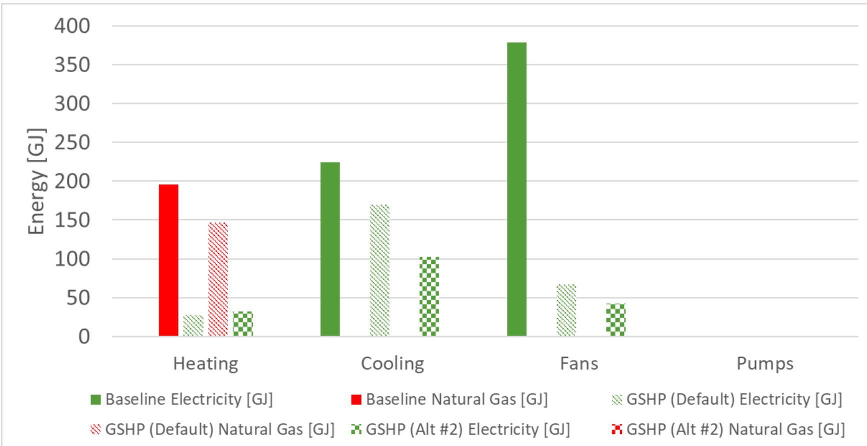


Figure 4-2. A side-by-side comparison of the energy end uses (electricity and natural gas) between the baseline HVAC, the default GHP system, and the second alternative GHP system.

Simulation results of both the baseline HVAC system and the GHP system (with the second alternative design) under the scenario of 200% increased OA ventilation are summarized in Table 4-2. These results show that increasing OA by 200% will slightly increase the electricity consumption and more than double the natural gas consumption of the baseline HVAC system. It results in a 7.2% increase in annual carbon emission and annual energy cost. Even with 200% increase in OA, the GHP system still consumes 31.3% less source energy than the baseline system without increasing OA. With 200% increase in OA, the difference in energy consumption between the baseline and the GHP system becomes bigger—the GHP system consumes 36.4% less source energy (a 35.5% reduction in annual carbon emission and annual energy cost) than the baseline system. It thus shortens the payback period from 18 years to 17 years.

Another simulation (Alternative #5) was performed to investigate how the control of OA can affect the size of the GHE. In this case, the OA was turned off on each workday from April through October, but 200% of OA required per ASHRAE Standard 62.1 was provide to the building on each workday and statuary in rest of the year. Resulting from this OA supply schedule, the cooling load is reduced slightly, but the heating loads is increased by 20%. It helps balance the thermal loads of the GHE, as shown in Figure 4-3, which in turn reduce the size of the VBGHE. Therefore, the payback of the GHP system is reduced down to 14 years. The simulation result show that, by manipulating OA supply in different seasons at a cooling dominant building (such as the simulated retail store at Atlanta, Georgia), the thermal imbalance of the GHE can be mitigated and thus the GHE size can be reduced.

Table 4-2. Simulation results of the baseline HVAC and the GHP systems with 200% increased OA.

Category	Baseline	Baseline with 200% increase in OA	Change from baseline (%)	GHP with 200% increase in OA ventilation	Change from baseline (%)	Change from baseline with 200% increase in OA (%)	GHP with 200% increase in OA ventilation in Winter
Electricity consumption (GJ)	1,412	1,430	1.3	1,011	−28.4	−29.3	983
Natural gas consumption (GJ)	255	557	118.7	59	−77.0	−89.5	59
Site energy (GJ)	1,667	1,987	19.2	1,069	−35.8	−46.2	1,041
Source energy (GJ)	4,748	5,132	8.1	3,264	−31.3	−36.4	3,176
Carbon emissions (Mt)	326	350	7.2	225	−30.9	−35.5	219
Energy Cost ($)	41,322	44,304	7.2	28,557	−30.9	−35.5	27,783
Peak electricity demand (kW)	108,409	122,624	13.1	77,301	−28.7	−37.0	77,404
Total borehole length (m)	NA	NA	NA	6,440	NA	NA	5,594
Simply payback (year)	NA	NA	NA	17	NA	NA	14

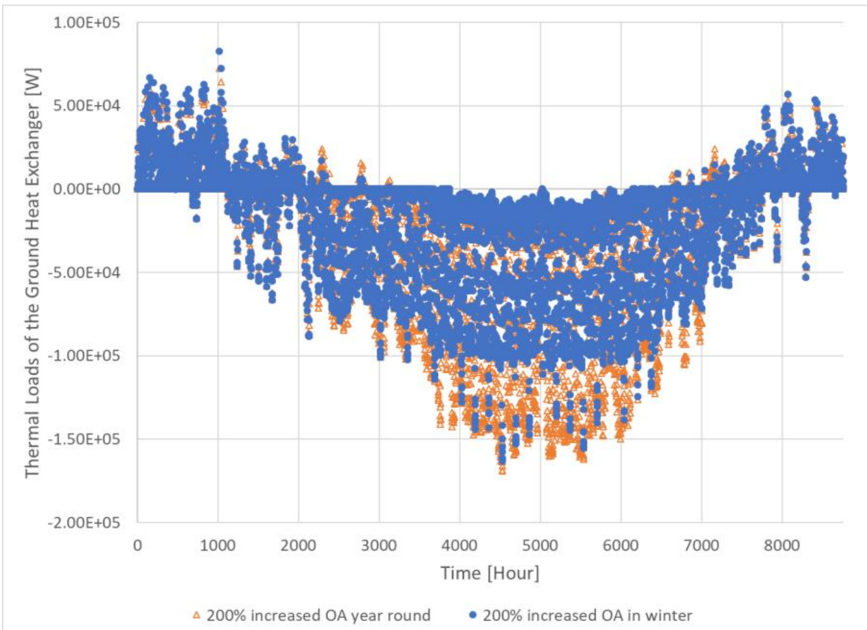


Figure 4-3. Thermal loads of GHE resulting from two different OA controls.

5. PLAN FOR THE NEXT TWO YEARS

The simple interface made with Excel is for demonstration purposes and it runs the full automated sizing and simulation in real-time. For many potential users of the screening tool, a few minutes may be too long to wait for seeing the results. The planned web-based screening tool will use pre-simulated results and fetch results associated with the user inputs so that the results can be displayed almost instantaneously. To enable this fast response web-based screening tool, the following work needs to be done in the next two years:

1. Improve existing OS measures or develop new OS measures for converting existing HVAC systems in all the prototype building models to GHP systems. In some cases, a central GHP system may be more appropriate, such as in big box supermarkets or lobby areas of large hotels. New OS measures should allow conversion to the central GHP system for certain buildings or certain zones in a building. Also, new OS measures or improved existing OS measures will enable multi-year simulation of the GHP system.

2. Integrate the GHP screening tool with ORNL's AutoBEM to automatically create a building model based on available information of the building, such as the footprint, Google Earth views, and principal function of the building. Currently, AutoBEM approximates each floor of a building as one zone and models the building with information of the DOE prototype building with the same principle function, such as office or hotel. It may be needed to have multiple zones on each floor for some buildings to account for the diversity of different zones.

3. Improve the capabilities of the automated sizing tool to size both the vertical GHEs and the horizontal GHEs that better fit the available land area. A new feature will be added to the screening tool to allow users to specify the constraints of the land area. The sizing tool will search for a borefield configuration (regular or irregular) and size the BHD within the space constraints to reduce the overall cost of the GHE.

4. Enhance VBGHE modeling to evaluate the benefits of using inclined boreholes and borefields with non-uniform bore depth. Incline boreholes have some advantages over the vertical boreholes when the available land area for drilling boreholes is limited. Nonuniform-depth boreholes (e.g., deeper boreholes on the outside of the borefield and shallower ones in the inner region) could be useful in optimizing the borefield designs.

5. Couple the GHE sizing tool with the new simulation tool for district heating and cooling systems (Hong et al. 2018) to simulate district GHP systems that serve multiple buildings connected with a common water loop and with multiple borefields.

6. Create a large database of the simulation results of the GHP system and conventional HVAC systems by running hundreds of thousands of simulations with the automated GHP screening tool.

7. Create a web-based interface for the GHP screening tool.

8. Release alpha version of the web-based screening too to industry for testing and feedback.

6. CONCLUSIONS

This report introduces and demonstrates a fully integrated and automated screening tool for evaluating the technical and economic feasibility of GHP systems. This tool integrates OS and EnergyPlus with a newly developed auto-sizing tool for VBGHEs. Based on the DOE's prototype building models, this tool can size components of a GHP system based on simulation predicted thermal loads of the building. This tool also predicts energy consumption, carbon emissions, energy costs, and peak demand for energy sources used in both the baseline HVAC system and the GHP system.

The new OS measures and the integration with the GHE auto-sizing tool developed in this project can facilitate a simulation-based holistic design approach, which can optimize the building and GHP system designs to achieve the most cost-effective building energy system. In particular, g-functions can be generated for highly customized configurations and used to size the needed BHD of these configurations for a given thermal load profile of the GHE. In some cases, significant savings in total drilling length may be achieved. However, the calculation of g-functions for highly customized configurations will generally take longer than 5 min. With a newly developed extensive library of g-functions, the automated sizing and simulation process may take less than 5 min on typical personal computers and for commonly used commercial buildings.

The work completed in the first year of this project builds a strong foundation for developing the web-based screening tool and an advanced design tool for optimizing GHP system design. The purpose of the screening tool is to provide a quick assessment regarding the technical and economic viability of the GHP application. Although the result is building specific, it cannot replace detailed energy simulation and a more rigorous design process, which can be facilitated with the advanced design tool to be developed through this project.

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