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An Online Tool for Preliminary Design and Techno-Economic Analysis of District Geothermal Heating and Cooling Systems

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Abstract

District geothermal heating and cooling systems (DGHCS) have significant benefits for reducing energy consumption as well as building- and grid-level peak electric demand. Currently, no publicly available tools are available to effectively design and conduct techno-economic analysis of DGHCS. GeoWISE was originally developed for preliminary design and techno-economic analysis of geothermal heating and cooling systems in an individual commercial or residential building. This paper introduces recent upgrades of GeoWISE that allow users to design and conduct techno-economic analysis of DGHCS. Several new features are implemented in GeoWISE to allow selection and specification of multiple new or existing buildings. A database of information for over 125 million existing U.S. buildings was used in GeoWISE that allows users easily locate existing buildings of interest based on street addresses, and optionally edit information of the buildings (e.g., footprint, vintage, principal functions, number of floors, window-to-wall ratio). Unique energy simulation models of the selected buildings are then automatically created using the Automatic Building Energy Modeling (AutoBEM) and EnergyPlus simulations are performed to predict thermal loads of the buildings. A simplified DGHCS is then designed and simulated to predict its energy use. A central borehole heat exchanger (BHE) of the DGHCS is sized using the RowWise algorithm of GHEDesigner to meet the thermal loads within user-specified land areas for installing BHE. The upgraded GeoWISE reports the needed capacity of heating and cooling equipment in each building, design of the central BHE, energy consumption reduction, and energy cost saving resulting from using DGHCS compared with conventional HVAC systems. A case study is showcased using the upgraded GeoWISE to design and conduct techno-economic analysis of a simplified DGHCS.

Keywords: District geothermal heating and cooling system, Building energy simulation, Design and techno-economic analysis

1. Introduction

Air-source heat pumps (ASHPs) are the most widely used type of electric-driven heat pump. Their heating and cooling capacity, along with overall efficiency, are significantly affected by ambient air conditions. To ensure reliable operation in cold weather, ASHPs typically incorporate electric resistance heaters to provide supplemental heating when outdoor temperatures are low, and heating demand is high. However, this supplemental operation can substantially increase consumption and peak demand of electricity. Recent studies [1-3] indicate that large-scale adoption of ASHPs could lead to higher annual electricity consumption and a shift in peak electricity demand from summer to winter. Such seasonal shifts may significantly affect power grid operations and require major investments in electric infrastructure.

One possible solution to address this matter is adoption of ground source heat pump (GSHP) technology. Previous studies (e.g., [4, 5]) reported that GSHPs are typically 20-40% more energy efficient than conventional heating and cooling systems. Liu et al. (2015) [6] reported that the cumulative capacity of GSHPs

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installed in the United States had reached 3.9 million refrigeration tons (approximately equivalent to serving 1.4 million households) in 2012. Another study reports a reduction of 20–40% and 30–50%, respectively for heating and cooling, of the energy demand in buildings could be potentially achieved with GSHPs when compared with ASHPs. However, the installation and adoption of GSHP is hindered by its high initial cost, mostly due to the cost of drilling boreholes in the ground for installing borehole heat exchangers (BHE). District geothermal heating and cooling systems (DGHCS) offer substantial advantages for achieving sustainable and efficient heating and cooling in urban environments. These systems enable heat recovery among interconnected buildings that have diverse load profiles through a shared water loop [7]. This configuration has potential to improve system performance by maintaining stable source temperatures, which improves the coefficient of performance (COP) of individual heat pumps and reduces electricity consumption for space conditioning [8], as well as lowering both building- and grid-level peak electric demand [9]. However, until now, there have been no publicly available tools capable of effectively designing and performing techno-economic analyses of DGHCS.

Oak Ridge National Laboratory (ORNL) has developed a web-based, user-friendly techno-economic analysis tool, GeoWISE, for rapidly assessing the feasibility of applying GSHP to any given building [10]. GeoWISE is built on EnergyPlus and OpenStudio, key components of the U.S. Department of Energy's Building Energy Simulation program and incorporates the latest advancements in BHE modelling. GeoWISE uses a database of information for over 125 million existing U.S. buildings that allows users to select a building by street address and optionally edit building information (e.g., footprint, vintage, principal functions, number of floors, window-to-wall ratio) [11]. GeoWISE was upgraded in 2025 to allow users to preliminarily design and perform techno-economic analyses for DGHCS. The new features that enable simulation of DGHCS and a case study of a simplified DGHCS using the upgraded GeoWISE are presented in the following sections.

2. Overview of Upgraded GeoWISE for simulating simplified DGHCS

GeoWISE seamlessly integrates three software tools to automatically perform equipment sizing and energy simulations, including (1) Automatic Building Energy Modelling (AutoBEM) to process multiple types of data, extract building-specific descriptors, generate building energy models [12]; (2) GHEDesigner to auto-size BHEs [13]; and (3) OpenStudio (OS) and EnergyPlus to calculate building energy use. The previous version of GeoWISE was for simulating GSHP systems implemented in individual buildings. GeoWISE was upgraded in 2025 to allow users to define multiple buildings that are conditioned with the DGHCS and size a central BHE to meet thermal loads of the selected buildings. Figure 1 illustrates the schematic diagram of a 2–pipe DGHCS, which is comprised of a central BHE with multiple boreholes, a 2-pipe (one for supply and the other for return) water loop connecting multiple buildings with the central BHE, and multiple water-to-air heat pumps (WAHP) installed in buildings. Figure 2 shows the simulation workflow implemented in GeoWISE for simulating the DGHCS. The heat loss and thermal mass of the common water loop connecting the buildings and the central BHE were not accounted for in the current version of GeoWISE.

GeoWISE requires minimal user input to create an energy simulation model of a building. The users in the United States can simply enter street address to locate existing buildings of interest. Once the buildings are selected, GeoWISE automatically populates modifiable building characteristics based on the Model America (MA) database [11]. If a building is not available in the MA database (e.g., a new construction), users can provide needed inputs and draw building footprint to define the building.

The required inputs for borehole field properties include depth and spacing of boreholes, as well as ground thermal conductivity. As an option, users can draw boundaries on the map to specify the available land area for installing boreholes. If a user specifies the available land area for boreholes, GeoWISE will employ the RowWise algorithm of GHEDesigner to determine the number and depth of boreholes needed for meeting the thermal loads, as well as the layout of boreholes in the available land area. Otherwise, GeoWISE will use the Near-Square method of GHEDesigner to size BHE, assuming sufficient land area is available.

The required building properties include climate zone, building type, vintage, footprint, number of floors, floor to floor height, and window-to-wall ratio. GeoWISE allows users to select from 15 U.S. climate zones, 20 different building types, and 8 different vintages. Based on inputs of building properties, GeoWISE will create energy simulation models using the AutoBEM. The detailed information of buildings (e.g., HVAC system, occupancy and operation schedules, and properties of building envelopes) are adopted from DOE's prototype building models [14] for the same climate zone, building type, and vintage as the selected buildings.

The current version of GeoWISE supports analyses in five countries, including the United States, Sweden, Denmark, Norway, and Belgium, with plans to expand to additional regions in future releases. For non-U.S. locations, users can manually navigate the world map and draw building footprint using the "New Building" option, as demonstrated in Figure 3a. Figure 3b shows the graphical tools available on a built-in world map for drawing or modifying building footprint and defining available land area for boreholes.

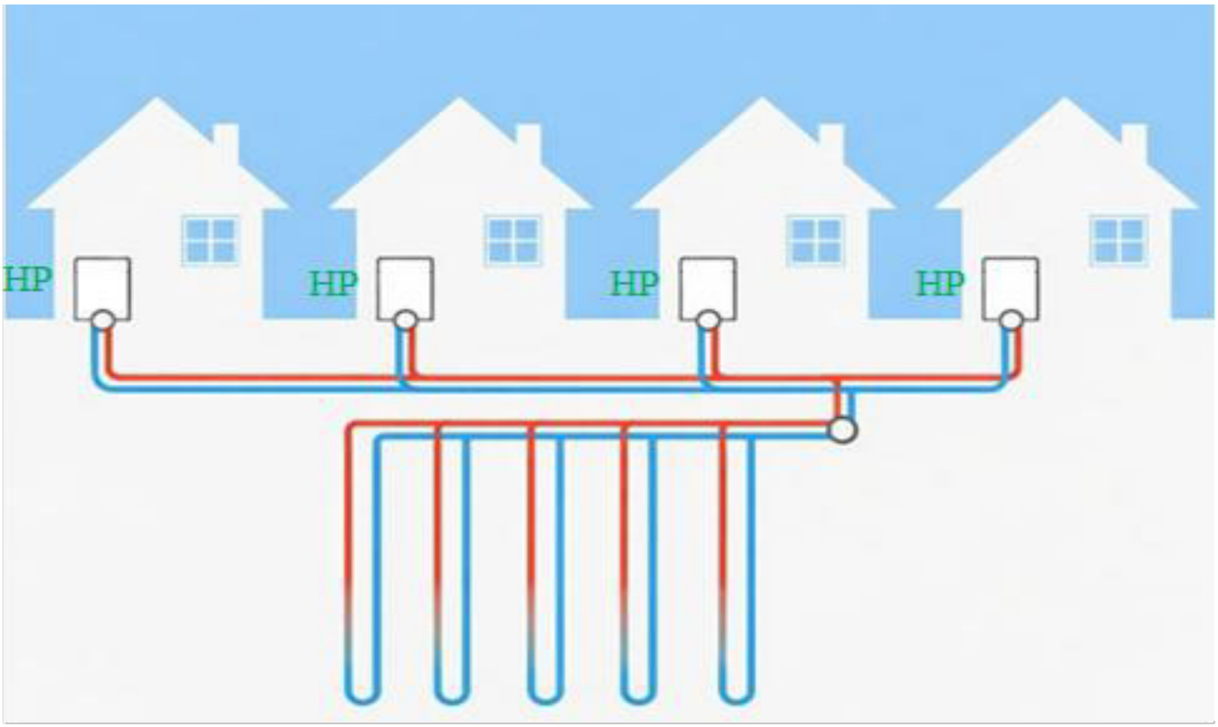

Figure 1. Schematic diagram of a simplified 2–pipe district DGHCS

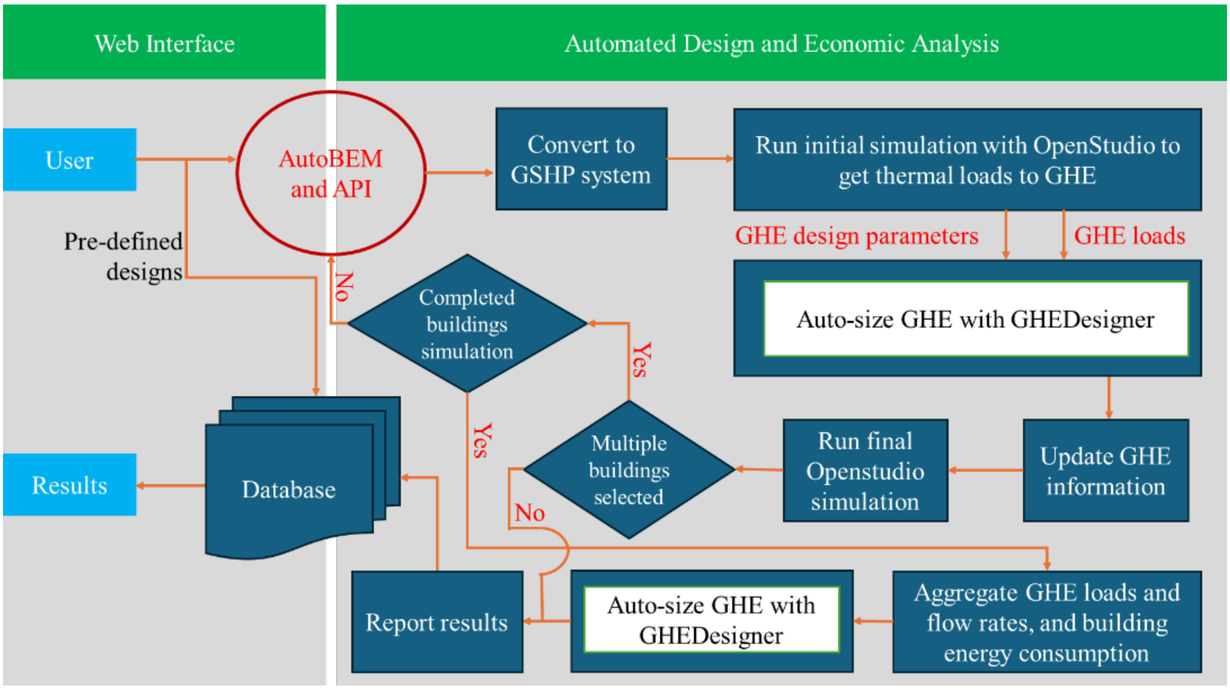

Figure 2. Simulation workflow implemented in GeoWISE for simulating the simplified DGHCS.

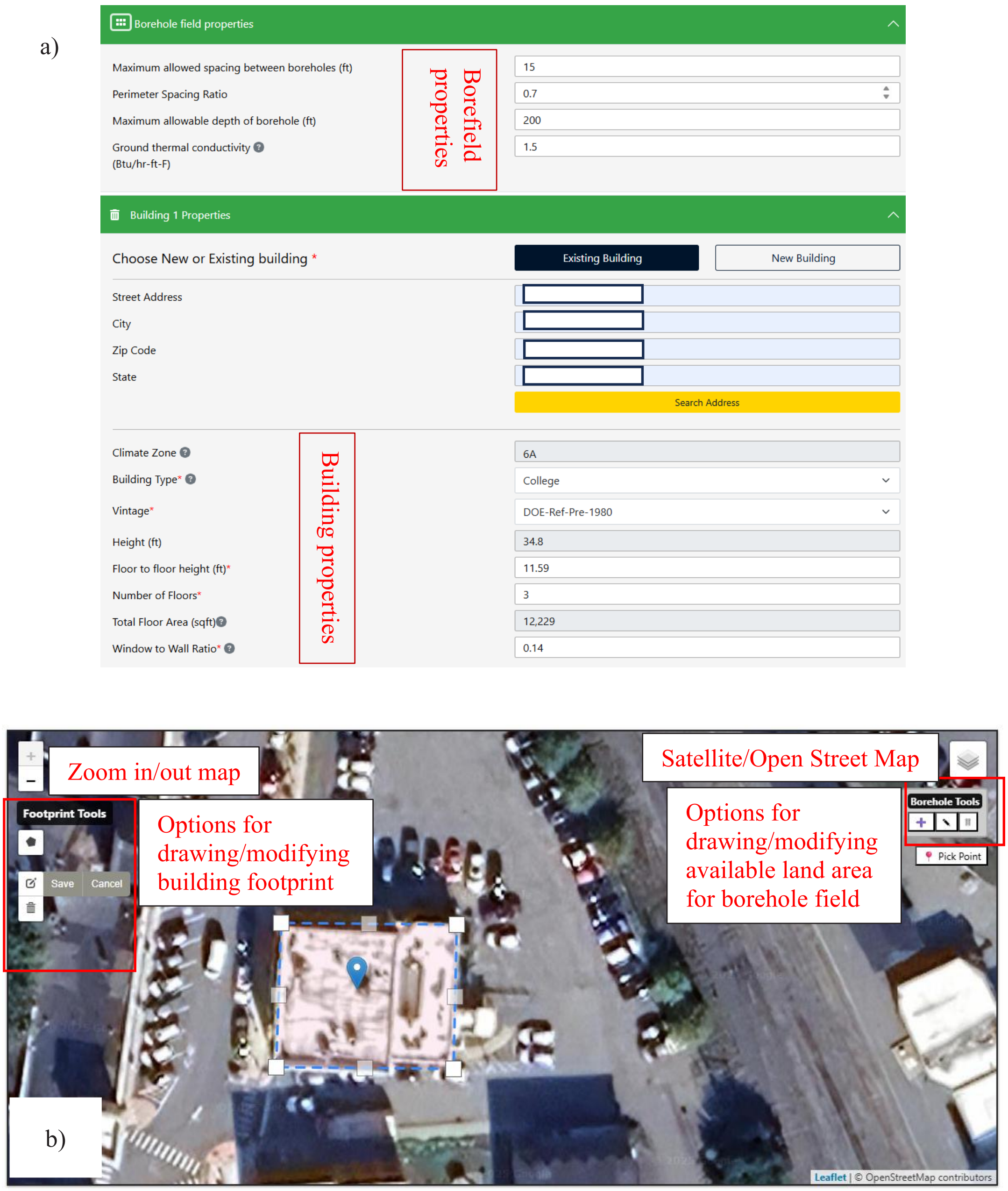

Figure 3. a) Required input fields with modifiable values in GeoWISE. And b) Graphical tools in the build-in world map for drawing/modifying building footprint and available area for boreholes.

Table 1 lists the design parameters of BHE used in GeoWISE, which cannot be modified by users. The allowable BHE supply temperatures provided in Table 1 are the maximum and minimum expected from BHE over the lifespan of the DGHCS. It does not mean that the supply temperature of BHE will vary between the minimum and maximum during a year. The maximum and minimum temperatures presented in the table represent typical criterion for sizing BHE used in conventional GSHP systems. To the best knowledge of the authors, there has not been any well-established criterion for sizing BHE used in DGHCS.

The nominal coefficient of performance (COP) of WAHPs installed in buildings is 4.0 for heating and 6.5 for cooling at the rating conditions for the ground loop application described in ANSI/AHRI/ASHRAE/ISO Standard 13256-1 Water-to-Air and Brine-to-Air Heat Pumps – Testing and Rating for Performance. Default performance curves of EnergyPlus for WAHPs are used in simulations to adjust the heating and cooling COPs in response to variations in supply temperatures of BHEs and return air conditions in buildings.

Table 1. Design parameters for the vertical borehole heat exchanger used in GeoWISE

Parameter	Default value	Parameter	Default value
Borehole radius	0.0762 (m)	Grout heat capacity	3901 (kJ/m^3-K)
U-tube pipe thickness	0.002 (m)	Undisturbed ground temperature	Site-specific. Calculated with the method developed by Xing and Spitler [15]
U-tube pipe outer diameter	0.027 (m)		
U-tube leg spacing	0.025 (m)		
Pipe conductivity	0.39 (W/m-K)		
Pipe heat capacity	1542 (kJ/m^3-K)	Allowable BHE supply temperature	Maximum 35℃
Grout conductivity	1.29 (W/m-K)		Minimum 1℃

3. Description of a case study

This case study investigates the potential benefits of integrating different types of buildings within a DGHCS to minimize the required total borehole length for meeting all the thermal loads utilizing GeoWISE. The hourly thermal load profiles of various types of buildings exhibit significant variation due to differences in energy-use patterns, occupancy schedules, and operational characteristics of HVAC systems. Accordingly, a numerical analysis was conducted using two representative buildings to examine their influence on the required size of BHE. The three scenarios of combinations of the two types of buildings considered in this analysis are summarized in Table 2. The number of buildings in each scenario was determined to maintain almost same total building floor area across all scenarios (see Table 2).

Table 2. Combination of buildings in a district geothermal heating and cooling system

Cases	Buildings Information	Floor area per building (m^2)	Total building floor area (m^2)
Residential only	12 identical single-family houses	429.92	5159.04
Commercial only	6 identical medium Office building	827.98	4967.88
Mixed	3 identical medium-sized office buildings and 6 identical single-family houses	-	5063.46

Since the energy demand for space conditioning is typically higher in colder regions than in hotter climates [16, 17], this study selected a location in Detroit, MI, which has cold climate. The satellite image and footprint of a medium-sized office building and a single-family house are shown in Figure 4. For consistency, both buildings are assumed to represent pre-1980s vintage, with a floor-to-floor height of 3 m, two stories, and a window-to-wall ratio of 0.2. The ground thermal conductivity for the site is specified as 2.59 W/m·K. The central BHE is sized based on 20-year simulation using GHEDesigner for this analysis. Additional details regarding the building characteristics are available in a previously published report [12].

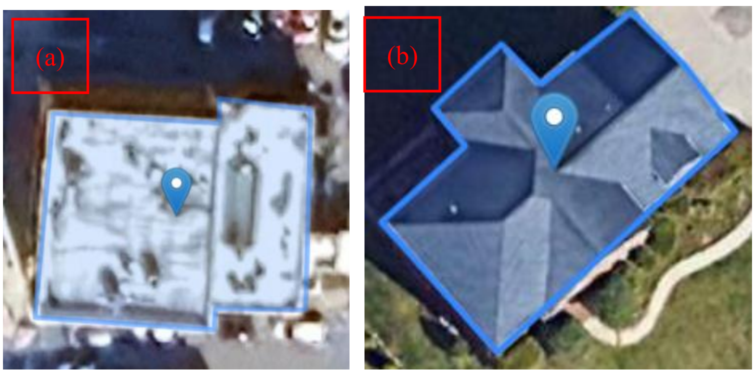

Figure 4. Satellite imagery and corresponding footprints of the (a) commercial and (b) residential buildings modelled in this study.

4. Results and discussion

4.1. Generated building models using GeoWISE

Figure 5 shows the geometry of the building models developed by GeoWISE based on the inputs provided in Section 3. Figure 6 presents the simulation-predicted thermal loads of BHE from each of the two buildings. While BHE thermal loads from the single-family house are smaller than that from the medium-sized office building, the pattern of the two load profiles are similar: extracting heat in winter (negative values) and rejecting heat in summer (positive values). There are sometimes, especially in spring and fall, one building extracts heat from BHE and the other building rejects heat to the BHE, but the simultaneous heating and cooling occurs in less than 5% of the operation time in a year.

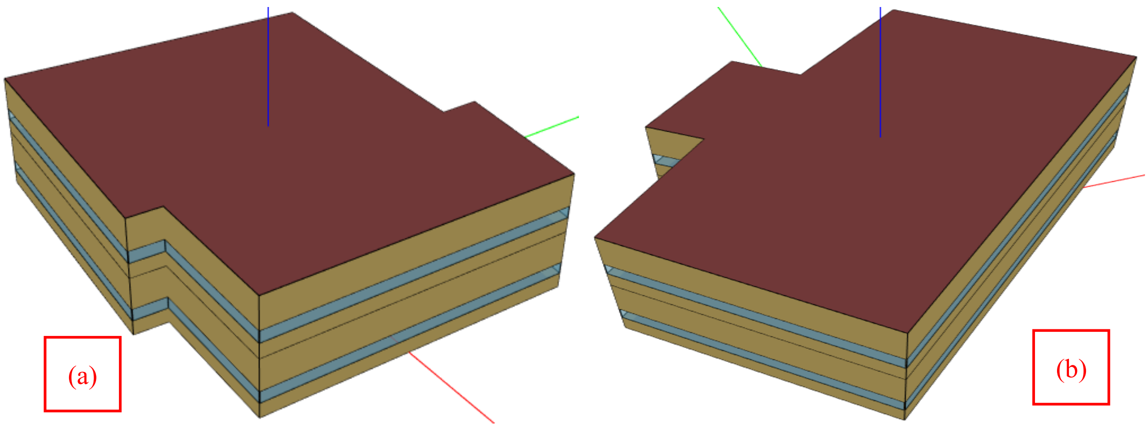

Figure 5. Energy simulation models developed using GeoWISE for (a) a medium-sized office building and (b) a single-family house modelled in this study.

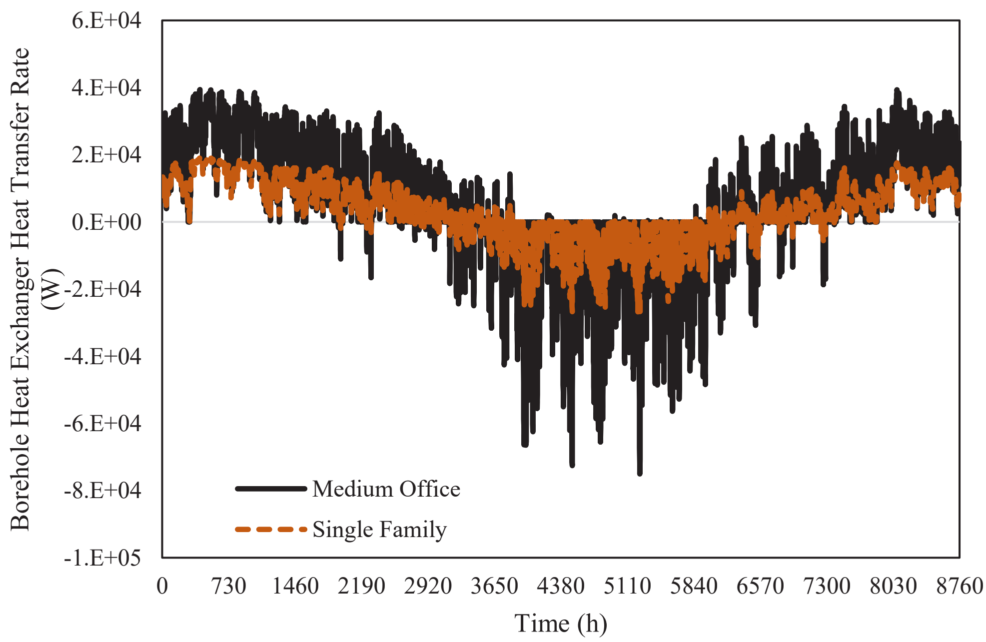

Figure 6. Simulation-predicted BHE thermal loads from each individual building.

4.2. Required total borehole length of the central BHE

Figure 7 shows the required total borehole length (the product of number of boreholes and the depth of each borehole) of the central BHE in each scenario of the simplified DGHCS considered in the study. Since the BHE load profiles and the number of buildings included in each DGHCS differ, the required total borehole lengths also vary. The "Residential only" scenario requires a greater total borehole length as it includes 12 buildings, whereas the "Commercial only" scenario consists of only 6 buildings and the "mixed" scenario includes 9 buildings. Although all scenarios have the similar total building floor area, the required BHE sizes differ due to variations in the aggregated thermal loads of the buildings included in each scenario.

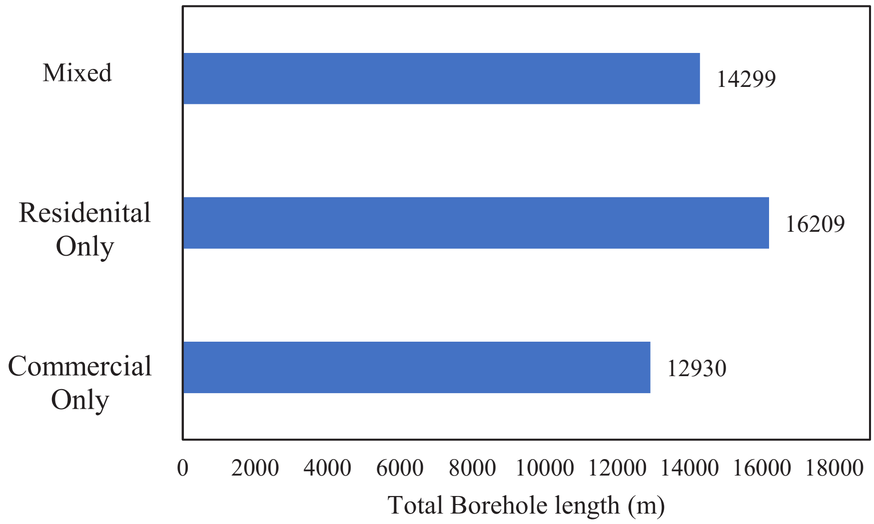

Figure 7. Required total borehole length in each scenario of the simplified DGHCS.

The results for the "Commercial and residential combined" shown in Figure 8 represent the arithmetic sum of the total borehole lengths required for the "commercial only" and "residential only" scenarios. Similarly, the "Mixed twice" result shown in Figure 8 represents twice (x2) the total borehole length of the "mixed" scenario presented in Figure 7. The results indicate that, rather than designing a DGHCS for buildings of the same type, it is more effective to combine different building types for reducing the required total borehole length because this approach can take advantage of heat recovery among buildings with different thermal demands (i.e., the simultaneous heating and cooling). In the present study, it was observed that for six commercial and twelve residential buildings, creating a mixed DGHCS reduced the total borehole length requirement by 541 m compared to having separate DGHCS for each building type. For the simplified cases considered in this study, the overall reduction in borehole length requirement is only about 2%. However, for scenarios that include buildings with significantly different load profiles, such as data centers and residential buildings, the reduction in the needed BHE size could be much larger.

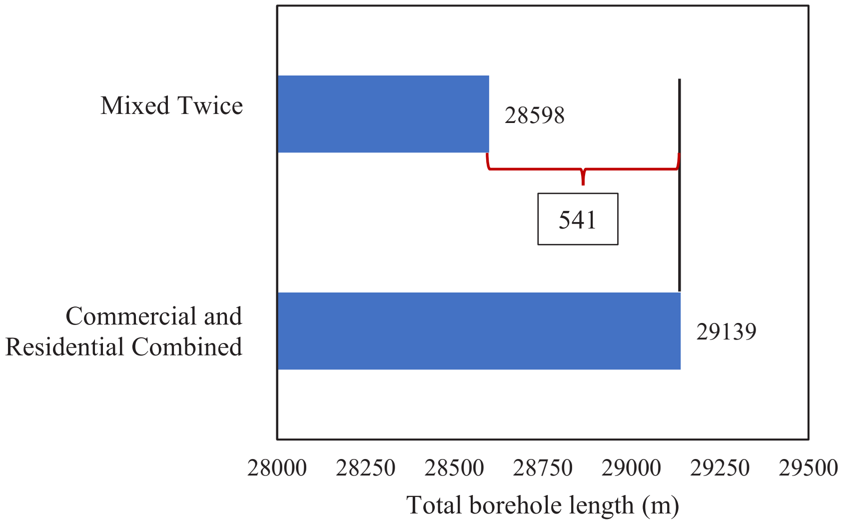

Figure 8. Required total borehole length for conditioning 6 commercial buildings and 12 residential buildings using two different scenarios of the simplified district geothermal heating and cooling system.

5. Limitation and future updates

As noted above, the current version of GeoWISE does not account for heat loss or the thermal inertia of water in the 2-pipe water loop. Additionally, the building energy simulation model created in the current version treats each floor as one thermal zone and thus cannot account for different thermal loads between perimeter and core zones of a building, which is important for more accurately capturing the simultaneous heating and cooling demands in large commercial buildings. Future versions of GeoWISE are expected to address these limitations.

6. Conclusions

GeoWISE has been upgraded in 2025 to enable users to preliminarily design and conduct techno-economic analysis of district geothermal heating and cooling systems that connect multiple buildings and a central borehole heat exchanger through a two-pipe common water loop. Built-upon a large database containing information of over 125 million U.S. buildings and the state-of-the-art tools for building energy simulation, GeoWISE requires minimal input from users to automatically conduct equipment sizing and energy simulations that are needed for evaluating the technical and economic feasibility of GSHP systems for individual buildings (in previous version), and the district geothermal heating and cooling systems for multiple buildings.

A case study has demonstrated the capability of GeoWISE for evaluating various scenarios of district geothermal heating and cooling systems. The results of the case study indicate that combining buildings with diverse load profiles could enable heat recovery through the common water loop, which reduces thermal loads and thus downsize the required borehole heat exchangers.

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