DEVELOPMENT OF A HIGH-EFFICIENCY, COST-EFFECTIVE GROUND SOURCE HEAT PUMP SYSTEM FOR SINGLE-FAMILY HOUSES

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Xiaoou Hu

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DEVELOPMENT OF A HIGH-EFFICIENCY, COST-EFFECTIVE GROUND SOURCE HEAT PUMP SYSTEM FOR SINGLE-FAMILY HOUSES

By

Xiaoou Hu

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Yao Yu, Ph.D.
Chair

Zhili (Jerry) Gao, Ph.D.

David Crutchfield, AIA/NCARB.

Approved:

07/29/2021
Date

Xuefeng (Michael) Chu, Ph.D.
Department Chair

ABSTRACT

Multi-Source Heat Pump systems are intended to achieve a high system efficiency through the combined or alternate use of two or more sources for a heat pump. This thesis entails the research work to develop a hybrid Ground Source Heat Pump (GSHP) system integrated with a dry cooler with vertical underground loops for single-family houses. TRNSYS is used to verify the feasibility of this integrated system, so as to optimize the control strategy and quantify the energy and energy cost savings. The primary objective is to demonstrate the improved system efficiency of the GSHP through the combined use of a dry cooler in a single-family house under the eight ASHRAE-defined climates. The results indicate that the integrated system would not be an optimal option for houses located in cold climates, but it is feasible to be implemented in hot/warm areas to increase system efficiency at low cost.

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1. INTRODUCTION

1.1. Background

At present, the world is facing two critical concerns: 1) environmental pollution due to the usage of fossil fuels and 2) the effects on climates due to greenhouse gas emissions. Building conditioning is one of the major “contributors” leading toward the change of climates (Forsen, 2005). With the development of modern technologies, environment-friendly building conditioning equipment is designed and utilized around the world to help reduce greenhouse gas emissions. Equipment, such as solar Photovoltaics (PV) panels, wind turbines, and dam generators, are some examples of beneficial technologies that have been widely implemented and studied in the past decades. Their effectiveness in reducing pollution and greenhouse gas emissions has been proven. Figure 1 shows the amount of CO^2 emissions by sectors in million metric tons, where residential and commercial usages are playing a major part.

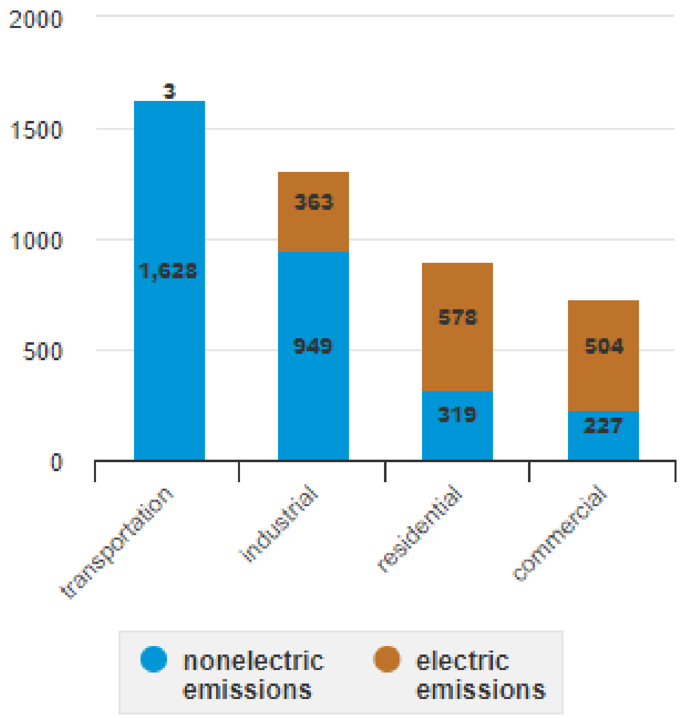


Figure 1. CO^2 emissions by sectors
(Source: Energy Information Administration)

With the growing demand for energy usage and concerns about environmental effects caused by the use of fossil fuels, the development and utilization of renewable energy have become an inevitable trend in the future blueprint. Renewable energy is defined as clean energy from sources that are naturally and constantly replenished. Renewable energy is virtually reproducible by nature but still a limited amount per unit at a time (EIA, 2020). The known renewable energy includes biomass, hydropower, geothermal, wind, and solar, etc. As shown in Figure 2, in the year of 2020, the primary energy consumption in the U.S. was 92.94 quadrillion British Thermal Units (Bus), where renewable energy accounts for 11.59 quadrillions (12%). Renewable energy can play an important role in providing an alternative solution to effectively reduce greenhouse gas emissions. According to the Energy Information Administration (EIA)'s report, the share of renewables in the U.S. will increase to 42% in 2050 (Nalley, 2021). Thus, studies and research that focus on developing higher energy-efficient and cost-effective systems using renewable energy are important and necessary tasks for future development.

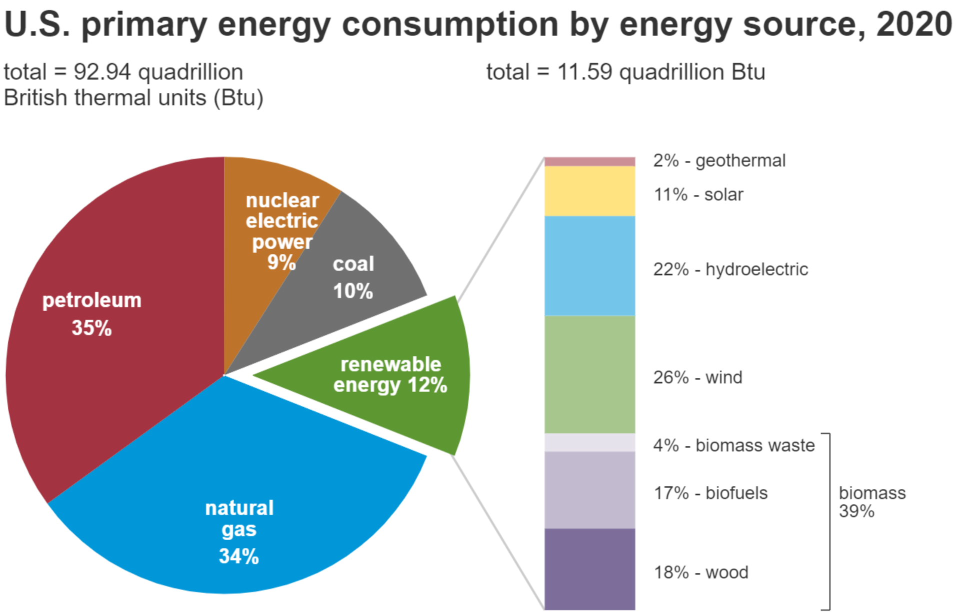


Figure 2. U.S. primary energy consumption by energy source in 2020
(Source: Energy Information Administration).

As Figure 3 shown below, the residential and commercial buildings consume about 39% of the total energy consumption in the U.S. (NREL. 2017). As buildings consume a huge amount of electrical energy, the Heating, Ventilation, and Air Conditioning (HVAC), Domestic Hot Water (DWH), and internal loads account for most of the energy consumption in building systems. To be more specific, the HVAC consumes almost half of the building energy consumption, approximately 10-20% of total energy consumption in developed countries (Cao et al., 2016). This huge amount of energy consumption also indicates a great potential of energy savings if systems that have higher efficiency are available to be widely deployed. Thus, developing more energy-efficient equipment or systems for buildings, e.g., for space heating and/or cooling, is a meaningful and worthy approach to achieve energy-saving purposes. A great example is the heat pump system, a high-efficiency and cost-effective equipment, which has the potential for reducing building energy consumption, if widely utilized as an alternative to conventional heating or cooling devices, such as furnaces, boilers, and conventional air conditioners.

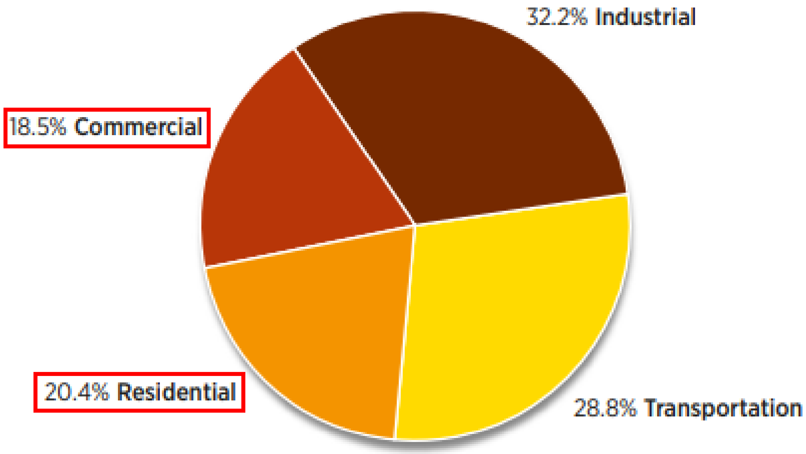


Figure 3. U.S. energy consumption by sector
(Source: National Renewable Energy Laboratory)

1.2. Heat Pump Systems

1.2.1. Heat Pump Technology

To understand what a heat pump is, first, let’s think of a refrigerator that can transfer the heat from inside and release it to the surrounding outside environment. Similar to a refrigerator, a heat pump is a pump that can “pump” the heat energy between the source and load sides. Also, unlike the refrigerator, as Figure 4 shown, a heat pump is capable of extracting the heat from outside to the indoor space to generate heating effect. According to the type of the source, heat pump systems can be generally classified into air source heat pump (ASHP) and ground source heat pump (GSHP) systems (Sarbu, 2014). ASHP can extract thermal energy (heat or cold) from ambient air, which is easy to access and thus contributes to its wide implementations. But the biggest drawback of ASHP systems is their relatively low system efficiencies and reduced heating/cooling capacities, compared to GSHP systems, especially during extreme hot/cold weather conditions (Valizade, 2013). Auxiliary electric heating elements are typically equipped with ASHPs to ensure enough heat can be provided during the coldest days. Unlike ASHPs, GSHPs exchange thermal energy with the ground, whose temperature is virtually constant year-round at depths typically lower than about 30 feet. This allows GSHP systems to meet the entire heating and cooling loads across the outside weather spectrum and do so in the coldest winter temperature without auxiliary electric heat. Because the energy exchange temperatures are always very favorable, GSHP systems operate at much higher efficiencies and lower electricity costs than their air-source counterparts. Comparing with an efficient gas boiler with 90% of efficiency, the GSHP can reach up to 450% for heating (Valizade, 2013). The downside (key market barrier) of GSHP systems, however, is they are more expensive to install and typically need incentives to be competitive, and they usually require multiple exchange boreholes that are difficult to install in many locations. Thus, there is a gap (technology- and market-wide) for a cost-effective, high-efficiency heat pump system that is suitable for building applications.

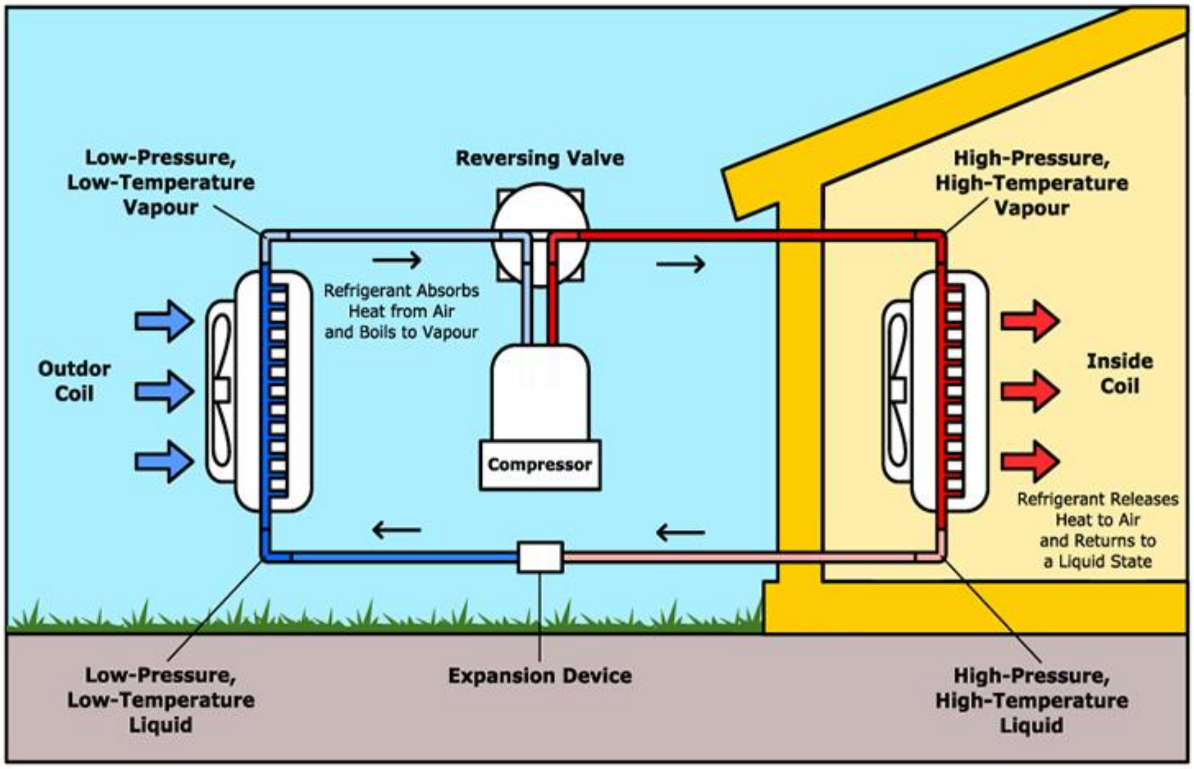


Figure 4. Working cycle of a heat pump during heating mode
(OSB, 2019).

1.2.2. Air Source Heat Pump

A heat pump's refrigeration system consists of a compressor, an expansion device, and two coils typically made of copper tubing (one indoors and one outside), which are surrounded by aluminum fins to aid heat transfer. In heating mode, liquid refrigerant in the outside coils extracts heat from the ambient air and evaporates into a gas. The indoor coils release the heat from the refrigerant as it condenses back into a liquid. A reversing valve near the compressor (Figure 5) can change the direction of the refrigerant flow for cooling, as well as for defrosting the outdoor coils in winter (DOE, 2021).

Figure 5. Air source heat pump
(Source: Department of Energy)

With the development of the economy and the improvement of people's living quality standards, ASHP systems have been widely implemented and used in central and southern areas of the United States (Baxtera et al., 2013). In these regions, the average temperatures are comparatively high in the winter, and thus the ASHP can meet the space heating requirement quite well. Even though the ASHP can be implemented under most of the climate conditions, including exchange heat under extreme temperatures tied to some unpredictable local weather, it cannot entirely meet the heating requirement in cold climates in the Northeast, across the northern tier, and in the intermountain regions in the west without expensive electric auxiliary heat (Bertsch, 2008). Most importantly, that high electric demand will occur simultaneously in buildings and homes across the region and severely strain the existing electric grid. ASHPs also need to periodically defrost their outdoor coils during winter. These cycles can increase seasonal electric consumption by 15-20% (Wang et al., 2015). Thus, although the benefits of ASHP systems cannot be ignored, there are still limitations and downsides to avoid them being implemented in every location, especially the locations that have extreme or unpredictable weather conditions.

1.2.3. Ground Source Heat Pump

As the first claim on a heat pump to extract heat from earth by H. Zoelly as early as 1912, the first documented ground source heat pump application in practice happened in 1945, Indianapolis, USA (Sanner, 2017). The term “Ground Source Heat Pump (GSHP)” has become an inclusive term to describe the types of heat pumps that using earth, underground water, surface water, or other earth-based heat exchange as the heat source/sink. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ASHRAE, 2011) has grouped GSHP systems into 3 categories, i.e., Surface Water Heat Pump systems (SWHPs), Ground-Water Heat Pump systems (GWHPs), and Ground-Coupled Heat Pump systems (GCHPs). The development of GSHP allows the system to have dual functions for both heating and cooling operations. The GSHP system circulates water or a mixture of water and antifreeze around a loop of pipe, known as “ground loop,” that is buried underground horizontally or vertically. While a heat pump is operating during the heating mode, the heat from the ground source will be absorbed by the ground loop fluid, which carries the heat back to the heat pump. The heat collected can be used to heat up spaces or hot water of a building. The fluid after heat exchanging will re-circulate back to the ground to absorb more heat in order to enable continuous operation. With the same theory, during the cooling mode, the heat of a building will be absorbed by the heat pump and then carried by the fluid to be eventually released into the underground region to achieve cooling effect for the building. The GSHP systems have higher energy efficiencies compared with conventional air conditioning systems or ASHP systems, due to the fact that the underground environment provides a higher temperature for heating and lower temperature for cooling with less temperature fluctuation compared with ambient air and thus contributes to a steady performance of the system (Sarbu et al., 2014).

Unlike conventional forced-air furnaces, GSHP offers unconventional heating to buildings as a steady heating source. It can provide constant heat and, more importantly, it is clean energy —there is no residue or dust around the house compared to buildings with forced-air heating systems in big cities (Omer, 2008).

With the same working principle, a GSHP (Figure 6) operates just like a conventional air-source heat pump by transferring heat from one side of the system to another, rather than creating it. But different from the air-source ones, a GSHP transfers heat to and from the underground, instead of ambient air, to provide cooling and heating for buildings at high efficiency. For example, in summer, the soil temperature in North Dakota could be much cooler (around 53 °F below the frost line) than the outside ambient air (could be more than 90°F), and in winter, the underground can still maintain at a steady and higher temperature than the air (could be below -20^{o}F). Thus, a GSHP system is a high-efficient system that can minimize operating energy consumption with lower utility costs, while constantly providing heat or cold to indoor environments (Rybach et al., 2000) (Valizade, 2013) (Omer, 2008) (Sanner, 2017). According to Omer, “They use 20–40% less energy for heating and 30–50% less energy for cooling when compared to conventional systems that use fossil fuels or electricity” (Omer, 2008). The past studies have proven that the GSHP systems are more cost effective than all other heating systems using natural gas, coal, fuel oil, or electric resistance, with the natural gas heating system as the main competitor of the GSHPs (Pulat, et al., 2009) (Esen, at al. 2006). Nevertheless, the high initial cost of GSHP systems, which are normally about 30-50% higher than ASHP systems, is still a barrier that limits the wide application of this technology (Hepbasli et al., 2003) (IRS, 2021).

Most of the previous studies chose vertical boreholes as the core part of a GSHP system for a residential building, considering the limitations of land areas required (Yang et al., 2010). Regardless of its high initial cost, a GSHP system with vertical boreholes has the benefits of smaller land area requirements for installation and higher energy efficiency compared with horizontal-loop systems (Choi et al., 2011) (Yang et al., 2010). In some regions of North America, however, horizontal GSHP systems could be more practical due to a large amount of land area available around residential buildings for the installation of horizontal loops (Hou et al., 2019).

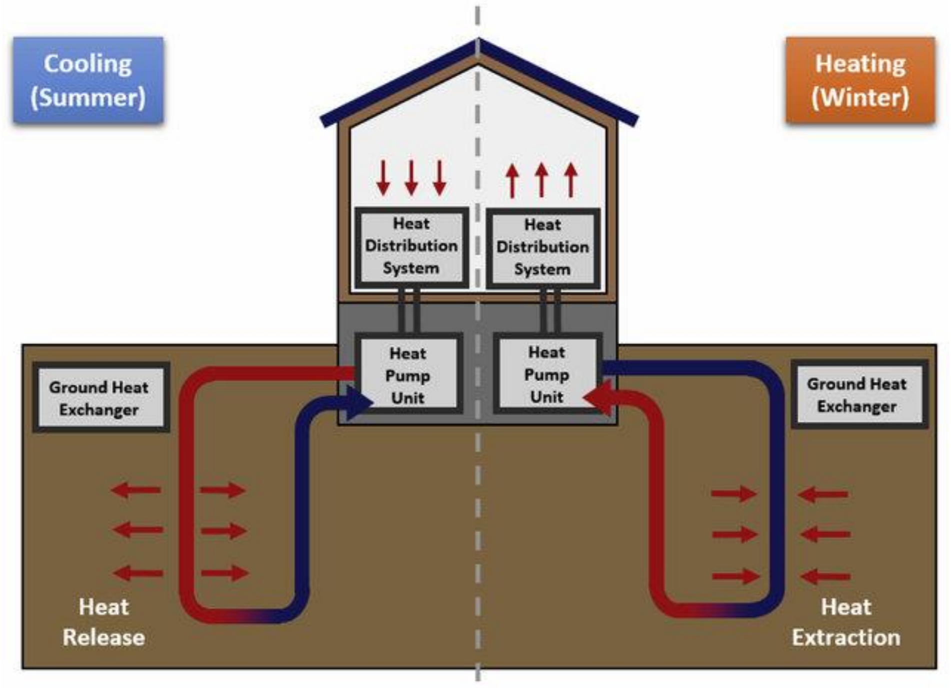


Figure 6. Concept of the ground source heat pump (GSHP) system (Jeon et al., 2018).

In previous studies, most of the research has discussed the advantages of GSHP systems compared with conventional systems for space heating or cooling, and some of them focused on the use of auxiliary equipment, such as solar thermal collectors, to improve the energy efficiency (Rad et al., 2013) (Biglarian et al., 2019) (Nam et al., 2015). However, there are only very few studies talking about the use of dry fluid coolers as an alternative or assisted heat exchanger to enhance system efficiency. As the previous studies indicated (Biglarian et al., 2019) (Nam et al., 2015) (Rad, 2013), a GSHP system can cooperate with other heating or cooling sources other than the ground, which provides a wide range of possibilities in finding alternative sources for use in GSHP systems.

1.2.3.1. Closed Loop systems

As the most important component in a GSHP system, the ground loop allows fluid to carry heat and then transfer it between the system and the ground. Generally, there are two types of loop systems, closed and open loops. The closed loop systems are the most commonly and popularly used systems, where the fluid circulates inside of the circulation loop without direct contact with the ground or other water bodies. Normally, a loop for a horizontal closed-loop system is buried below the ground surface from 4-6 feet (Piechowski, 1999) (DOE, 2021), and vertical loops are typically inserted in boreholes drilled with a depth between 100-400 feet below the ground surface (DOE, 2021). The loop can not only be placed in the earth, but also in water bodies, such as ponds, lakes, or rivers near a building depending on the local conditions. Figure 7, 8, 9 shows the different types of loop systems.

1.2.3.1.1. Horizontal Loop Systems

The horizontal type of heat exchanger consists of straight or coiled tubes which are buried in a trench at a depth of approximately 4 – 6 feet (Piechowski, 1999) (Jones et al., 1996). Due to its short depth of implementation, it will require a wide area of ground for the system to be installed. Comparatively, it has much less difficulty for excavation and installation compared to vertical loops with boreholes since it normally requires less amount of initial installation fees. There were many studies conducted previously to evaluate the performance and cost-effective benefits of GSHP systems using horizontal loops (Mei, 1989) (Healy, 1997) (Petit, 1998). The past research indicates that horizontal GSHP systems reach a more favorable coefficient of performance (COP) compared to the air source systems, and the horizontal systems offer the best cost effectiveness compared to other closed-loop systems (Yang et al., 2010).

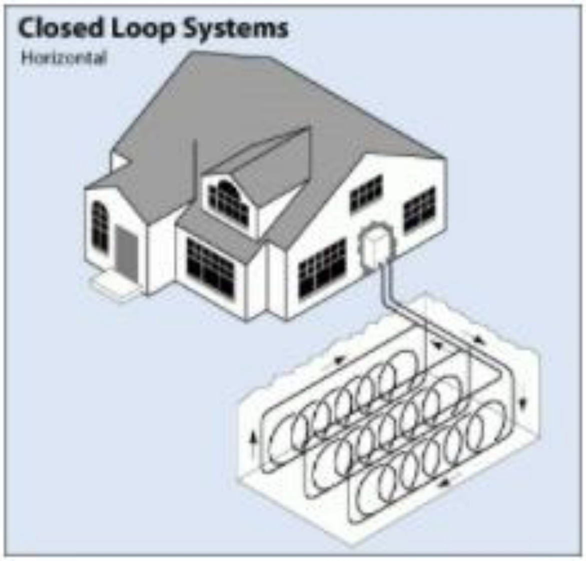


Figure 7. Horizontal loop systems
(Source: Department of Energy)

1.2.3.1.2. Vertical Loop Systems

Among the other types of loop systems, vertical loop systems are getting more attention due to their advantages, such as improved energy efficiency and relatively small space required for installation (Kim et al., 2018). With these advantages, vertical loop GSHP systems have a higher distribution rate than horizontal loop systems, and since their loops are buried in the deep earth with a depth of 100 – 400 feet (DOE, 2021), vertical loop systems are usually less disturbed by the outside air than horizontal loop systems. It thus allows the system to maintain at a more stable entering and leaving temperature, and they have been widely used in buildings that have large cooling and heating loads (Lim, 2010).

The downside of vertical loop systems, however, is the high installation cost, especially for borehole drilling that is more expensive than just trenching and excavating for horizontal loops (Omer, 2008) (Self et al., 2013). For residential applications, vertical GSHP systems are particularly suitable, since residential houses normally have limited space in the backyards for the deployment of long horizontal loops (Yang et al., 2009).

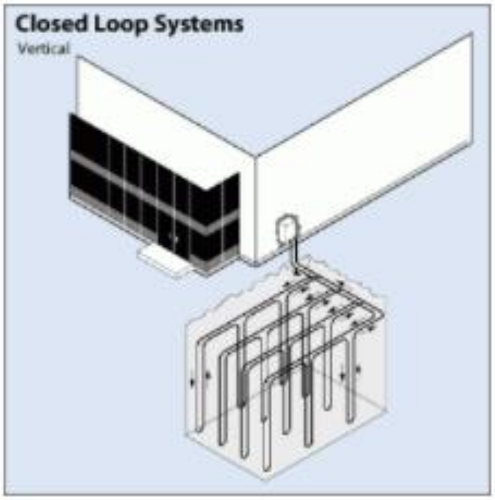


Figure 8. Vertical loop systems
(Source: Department of Energy)

1.2.3.2. Open Loop Systems

As Figure 9 shown, there is another type of loop system which directly uses water from the ambient environment as the heat source or sink. In comparison to close loop systems, the open loop system is more suitable and economical for buildings with a large scale of heating and cooling demands (Athresh et al., 2016), because it does not have a delay for the heat transferring compared with close loop systems, and it uses a large amount of water, e.g., underground water (Figure 9), which can continuously maintain at a relatively constant temperature. However, the system with open loops will be exposed directly to minerals in the mine water that can potentially damage the equipment, especially when the systems are installed in ochre rich environments (Banks et al., 2009).

With the more energy-efficient technology, higher capital costs are normally offset by in-use energy saving using reasonable assumptions or during operation. The most critical thing they are worried about is if the initial cost/investment will be recovered through the estimated payback period.

Although all the benefits of GSHP system sound very attractive and favorable, the average payback term for GSHP is relatively longer in comparison with other conventional systems. In Nagano's study, the average payback term for the investment of GSHP system is 10 years compared with oil boilers and air conditioning (AC) systems, 9 years compared with gas boilers and AC systems, and 14 years compared with ASHP systems (Nagano et al., 2006). Regions that have higher energy prices and/or large demands of heating and cooling will be most beneficial to apply GSHP systems. Respectively, the application of GSHP systems is not economical when comparing them with conventional natural gas heating devices in some regions due to the low price of natural gas or other fuel types for heating in those regions compared to electricity (Esen et al., 2006).

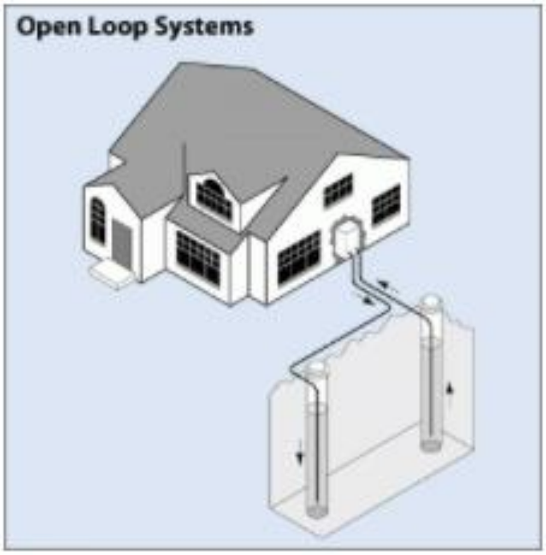


Figure 9. Open loop systems
(Source: Department of Energy)

From all those above, even though the ASHP is environment-friendly and relatively energy-efficient, it is not applicable for all climate conditions and locations. This fact brings more interest into applying GSHP systems due to their wide applications and relatively stable ground temperatures that can be achieved as the source for space heating and cooling. With the flexible options of choosing heating and cooling sources to partially replace underground loops, there are potentials of designing a new innovative GSHP system with lower initial cost and shorter payback term.

1.3. Dry Fluid Cooler

A dry fluid cooler or dry cooler is an outdoor device with a heat exchanging function. It can achieve heat transfer between ambient air and fluid circulating through the dry cooler. It consists of a fan, liquid circulation loops, and coils. As Figure 10 shown, the hot process fluid enters the inlet header (shown in red), and after releasing heat to the amibient air, the cool process fluid exits the unit through the connection (shown in blue). Due to its straightforward and robust design, a dry cooler normally has relatively low initial and maintenance costs. Because it works by exchanging heat between air and fluid, the dry cooler mainly relies on ambient air temperatures. Also, due to this feature, it can be deployed in most locations including both hot and cold climate regions. Because the air temperature is an very important element for a dry cooler, it would have better performance if applied in areas that don’t have extreme weather conditions. However, there are limitations to dry coolers. With no additional heating or cooling unit built inside, at its peak performance, a dry cooler can only raise or lower the fluid temperature up or down towards air temperatures.

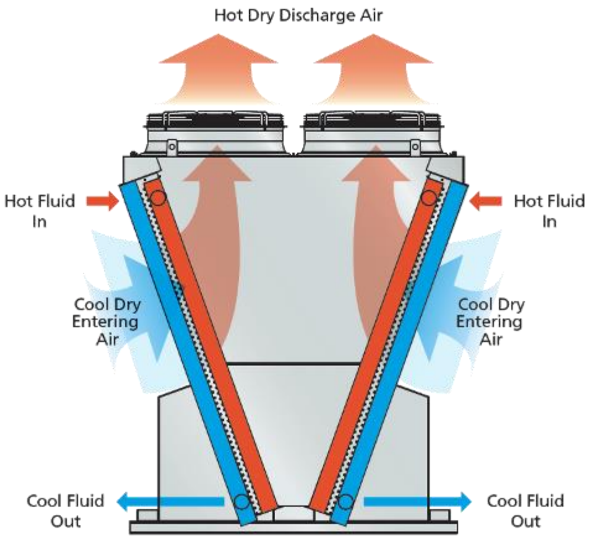


Figure 10. Dry cooler working principle
(Source: https://www.evapco.com/products/closed-circuit-coolers-air-cooled/eco-air-series-adiabatic-cooler).

With the advantages of dry coolers, such as low cost and feasibility of being deployed in most areas/climates, it is beneficial if considered dry coolers as an additional source for GSHP systems to replace part of the underground loops.

1.4. Simulation Software for Modeling Dry Cooler and GSHP System

The TRNSYS is a transient system simulation software tool with a modular structure that has been specially designed to develop simple or complex systems related to the energy usage of single or multi-zone buildings (Mergi, 2014). The TRNSYS simulation software consists of verities of components, including weather data, building, solar radiation, control systems, etc. After 35 years of its commercial availability, the TRNSYS has become a flexible, component-based software that can meet researchers' and practitioners' needs in the energy simulation community. During this research, TRNSYS was used for building and system modeling and simulations, whose results were processed and analyzed and will be shown in the following chapters.

2. RESEARCH OBJECTIVES AND APPROACHES

2.1. Research Problem and Objectives

Based on all the information introduced above, even though the air source heat pump systems have high energy efficiency and environmentally friendly, they still have the limitations to be implemented in all climates or locations. The facts that bring more attention to the development of the GSHP systems are their stable performance and higher energy efficiency. As the major barrier of implementing GSHP systems, the high initial cost has always been a problem during the research discussion, where the drilling cost of underground borehole normally takes a big part (Cho et al., 2014) (Lu et al., 2017) (Noorollahi et al., 2017) (Allaerts et al., 2015) (Croteau et al., 2015). With the maturely developed technology of a dry cooler, its applicability and reliability have been proven. Considering its low cost and wide feasibility, there is a great potential of using a dry cooler to cooperate with a GSHP system as alternative heat source/sink when outdoor weather is favorable. With the inexpensive dry cooler that can be used to take care of some of heating and cooling loads, the initial cost of an entire GSHP system can be reduced due to the possible reduction of the boreholes size.

In the past decades, several studies (Ahamed et al., 2018) (Du et al., 2012) (Ma et al., 2010) (Guo et al., 1994) have been conducted in developing numerical models to simulate the microclimates and energy loads of buildings, e.g., to build coorporation with solar panels or other components. However, there are not many discussions regarding the use of a dry cooler as an alternative source for a GSHP system (Hou et al., 2019). Although there are few studies discussing about the feasibilities of designing a low-cost GSHP system integrated with a dry cooler, the cost effectiveness of this system has still not been quantified. Currently, there are no residential multi-source heat pump offerings manufactured or sold in the U.S., and therefore this would be the development of an entirely new market stream.

This research is focused on designing a hybrid GSHP system integrated with a dry cooler to achieve adequate system performance and efficiency while reducing the initial cost by shortening the underground loop length. The purpose of this study is to develop an energy-efficiency, cost-effective GSHP system design for the use of single-family houses, which is expected to draw more attention and interest from the owners and encourage engineers and designers to use the proposed system in the HVAC design.

The objectives to be accomplished during this study are to:

- Discuss the feasibility of the GSHP system when integrated with a dry cooler for the purpose of optimizing system efficiency.
- Analyze the impacts of the integrated GSHP system on its efficiency and cost in eight climate zones defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (DOE, 2015).
- Conduct cost analysis of the system using an inexpensive dry cooler to handle some of the heating and cooling load of buildings, which allows the reduction of the expensive ground loops in achieving equal or higher system efficiency with lower initial costs.

The proposed system will have the potential to reduce fossil fuel consumption and CO_2 emissions. It is expected to give a better and cheaper solution for single-family houses when choosing an HVAC system, especially for low-income households.

2.2. System Design

There is a large middle ground that uses the best aspects of these two competing technologies (ASHP and GSHP) that can reduce costs while improving performance and has yet to be commercially exploited for the residential market: the multi-source heat pump system (Figure 11). By adding an air exchange device (dry cooler) into a standard ground source system design, the heat pump unit is equipped with two loops (air source loop and underground loop). The underground region has dual functions, i.e., as an element for heat exchange or storage. Water from a loop with a more desirable temperature is supplied to the source side of the heat pump. Additionally, the use of the underground region as a heat storage element may allow some degree of thermal storage when the heat pump unit is off (no load).

As shown in Figure 11, a Ground Source Heat Pump (GSHP), an Air Source Loop (ASL), and an Underground Loop (UL) are connected with a three-port valve and two pumps, allowing four possible operation modes/configurations as shown, which are described below.

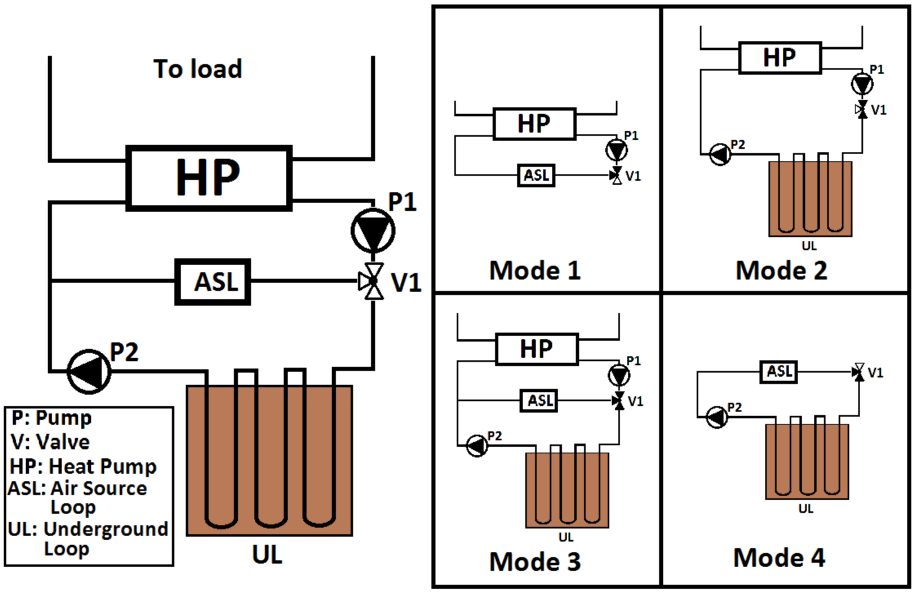


Figure 11. Multi-mode hybrid heat pump system design with dry cooler

- Mode 1: Air Source Loop only
- Mode 2: Underground Loop only
- Mode 3: Air source and underground loops are connected in parallel, which allows the load allocation between them for system performance optimization.

- Mode 4: Underground thermal storage that allows the use of the ASL to convey cold/heat to the underground region for energy storage for later use (also known as Thermal Storage Mode)

The ground loop in Figure 11 could be any type of liquid pipe arrays buried in the ground, such as boreholes or trenches, but vertical boreholes were studied during this study. The main reasons are: 1) vertical boreholes take the least area for installation considering that the average free land areas of single-family houses are very limited (Al-Dabbas et al., 2013) (Fujii et al., 2004); and 2) vertical boreholes normally are installed at a depth of 100 - 400 feet underground, and thus they have more stable thermal storage capacity compared to horizontal loops, which are typically buried underground at a depth of 4 – 6 feet (Lee et al., 2009) (Tabrizi and Shariyate, 2018) (Battocletti et al., 2013). For the air source loop in the GSHP based solution, a dry fluid cooler is used to exchange heat from/to ambient air. The potential energy savings of this system can be achieved by the combined/alternate use of these modes at their desired conditions. The alternate use of Mode 1 and Mode 2 allows the system to select the more desirable elements between the underground region and the outdoor ambient air, as the heat source for heating or heat sink for cooling.

Mode 3 represents the combined use of both the air and ground source loops by splitting the flow from the heat pump into two paths for both loops. This mode is useful to deal with higher cooling/heating loads by splitting the loads at the source side of the heat pump, e.g., if dehumidification is needed in a building even though it is not a typical concern in residential buildings or homes.

When the heat pump is off (no load), Mode 4 will be selected if the outdoor air temperature is desired (warm or cold enough) to allow the preconditioning of the underground region for either heating or cooling purposes. In this mode, the air source and ground source loops are connected in series, allowing the use of the air source loop to transfer useful thermal energy collected from the ambient air (either cold or heat) to the underground region to have at least some degree of underground thermal storage. The underground region with higher or lower temperatures contributes to higher COPs (Coefficient of Performance) or EERs (Energy Efficiency Ratio) in heating and cooling modes, respectively. The collecting and conveying of heat or cold down to the earth depends on climates and/or if it is a heating-/cooling-dominated building. For example, for a heating-dominated building located in a cold-climate region, a warmer underground region is more practical when considering its potential for improving the annual average COP.

The key technical challenge/risk in bringing the innovation to market involves the use of an inexpensive air source loop, i.e., if the use of it allows the significant reduction of the expensive ground loops in achieving equal or higher system efficiency with lower initial costs compared to those when a conventional GSHP is used. On the one hand, an insignificant reduction in underground loops will not achieve enough cost savings, and on the other hand, too much size reduction in search of further cost savings could add risk to satisfactory performance during extended hot or cold weather. Therefore, a balance point exists between the system cost and efficiency. To overcome this challenge, computer simulations using TRNSYS were conducted to optimize the system sizing (especially the sizes of the air and ground source loops).

Specifically, the goal of this research is to develop a design for this type of multi-source heat pump system used in a single-family house located in different climate zones in the U.S. It is important to validate its feasibility based on different climate zones, including extreme cold or hot areas. This will open up applicability to nationwide and beyond. Both technical and financial aspects were included during this study, which provides a guide/reference for design parameters and cost/benefit analysis in using this type of system. This study is intended to identify the most appropriate design for given climate zones based on a trade-off between price and performance. It also provides a useful reference for designers who would like to use this cost-effective multi-source heat pump system in their design.

3. NUMERICAL STUDIES

3.1. Building and Baseline System Information and Modeling

This section describes the building (Section 3.1.1) and the baseline system (Section 3.1.2) selected in the study. The establishment of the building and system models (Section 3.1.3) allows the research team to evaluate the performance of the designed multi-source heat pump system in the following sections by comparing them in terms of system efficiency (COP/EER), heating and cooling capacities, and cost effectiveness. The effect of time step size on the simulation results was also quantified, and an appropriate time step size was suggested after time-step independence analysis (Section 3.1.3.1). Model calibration was also conducted to ensure the validity of the baseline models for further evaluations.

3.1.1. Building Information

The building I selected is a single-family detached house that was used by the Pacific Northwest National Laboratory (PNNL) to simulate energy savings associated with changes in energy codes and standards, whose results were used by the U.S. Department of Energy’s Building Energy Codes Program to evaluate published versions of the building energy code (DOE, 2021). The basic building information is summarized in Table 1. The floor plan of the building is shown in Figure 12. The building was assumed to be located in various climate zones across the U.S., whose weather conditions are dependent on the specified location and thus will be shown shortly afterward. Additionally, the building construction types, such as walls, roof, windows, etc., are various depending on the local building codes used at the specified location and thus will be discussed later.

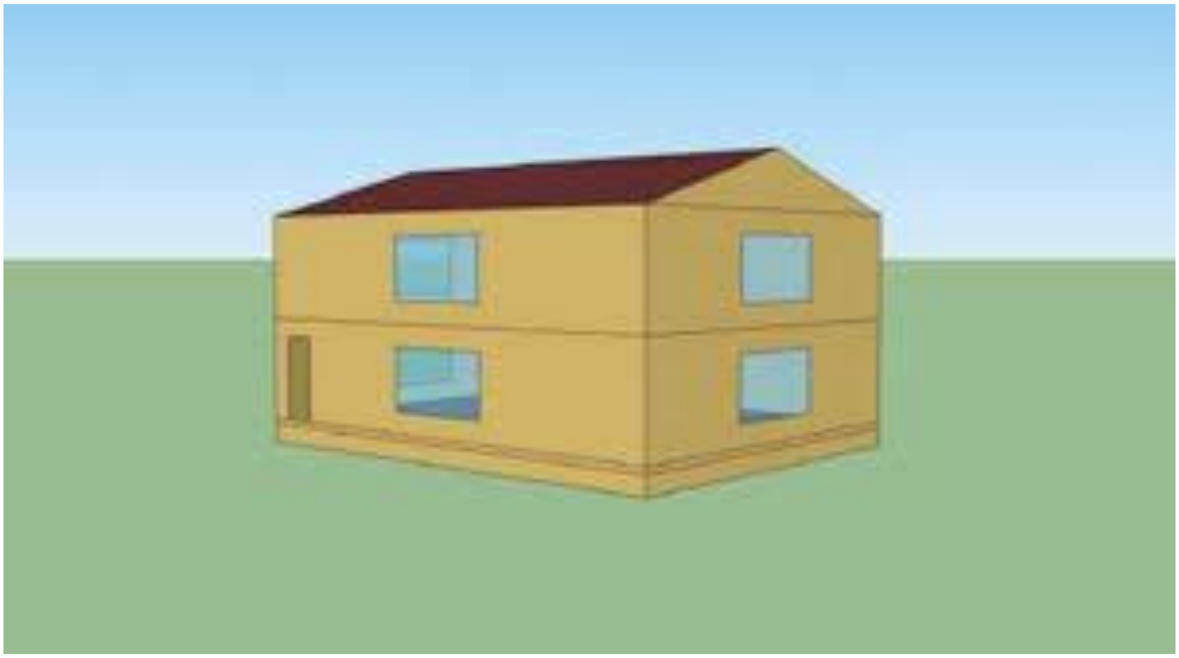


Figure 12. Target building
(Source: TRNSYS)

Table 1. Basic building information

Building Type	Single-Family House			
Number of Floors	2			
Building Total Area [ft^2]	3,601			
Total Conditioned Area [ft^2]	2,401			
Window-Wall Ratio	14.1%			
Window Area [ft^2]	**North**	**East**	**South**	**West**
	89.3	89.3	89.3	89.3
Gross Wall Area [ft^2]	**North**	**East**	**South**	**West**
	679.5	586.1	679.5	586.1
Gross Roof Area [ft^2]	1,265.4			
Zone Volume [ft^3]	**Living (Conditioned)**		**Attic (Unconditioned)**	
	17,102		3,004	

3.1.2. Baseline System Information

The baseline Heating, Refrigerating, and Air-Conditioning (HVAC) system used in the target building is a conventional vertical closed-loop single U-tube GSHP system. The size and capacity of the system to be used in the target building (Figure 12) located in different climate zones will be various depending on the heating and cooling loads based on the local climates and building codes applied. Therefore, the detailed system information will be discussed in Section 3.2.

3.1.3. Building Energy Modeling

The original building energy model was established by the PNNL in EnergyPlus. I re-established the energy model in the TRNSYS environment, where more complicated control strategies and system integration can be simulated and implemented in TRNSYS to meet the need of the project. The established model was optimized through time-step independence analysis (Section 3.1.3.1) and then calibrated against the EnergyPlus results (Section 3.1.3.2) to ensure the model parameter settings in TRNSYS are consistent with those used by the PNNL in EnergyPlus. A GSHP system equipped in the target house located in Bismarck, North Dakota, was selected and used in the model validation and calibration, whose information is detailed in Table 2.

Table 2. Information of the system used in the model validation and calibration

Parameters	**Bismarck**
GSHP system type	Vertical Closed Loop
Number of Boreholes	4
Borehole Depth [ft]	200
Borehole Separation Distance [ft]	20
Borehole Length [ft]	800
Underground Pipe Length [ft]	1,600
Ground Thermal Conductivity [Btu/hr.ft.F]	1.5
Ground Heat Capacity [Btu/ft^3/F]	39.93
Outer Radius of U-Tube Pipe [inch]	0.525
Inner Radius of U-Tube Pipe [inch]	0.375
Pipe Thermal Conductivity [Btu/hr.ft.F]	0.24
Grout Thermal Conductivity [Btu/hr.ft.F]	0.81
Borehole Radius [inch]	2.5
Initial Ground Temperature [F]	53
Borehole Length per ton [ft/ton]	198.5
Underground Pipe Length per ton [ft/ton]	396.6
Number of Heat Pump Units	Water-to-Air HP: 1
HP rated air flow rate [CFM]	1640
HP rated water flow rate [GPM]	12
HP water flow rate per ton [gpm/ton]	2.98
HP Rated Heating Capacity [Btu/hr]	39,300
HP Rated Heating COP	3.40
HP Rated Cooling Capacity [Btu/hr]	48,400
HP Rated Cooling EER	16.35

3.1.3.1. Time-Step Independence Analysis

Time steps are series of discrete bins of time used to solve transient modeling problems (Tabares-Velasco, 2016). Previous studies indicate that building energy simulation results are dependent on time steps used in the simulation, and “the shorter the time step, the more accurate the solution is.” (Tabares-Velasco, 2016). The commonly used time step of one hour (default setting in most commercial building energy modeling tools) may result in errors as high as 60%

in some cases when comparing the results with 1-hour resolution to those with 1-minute resolution in time step (Tabares-Velasco, 2016).

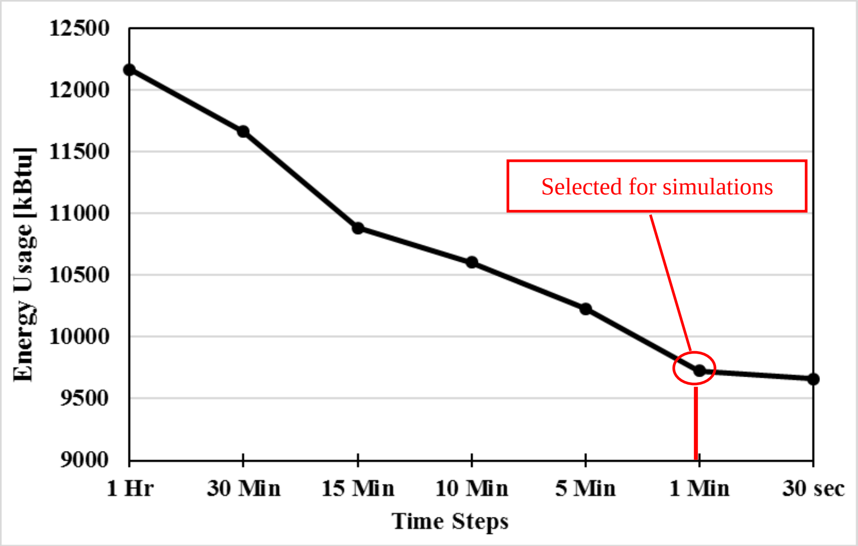


Figure 13. Time-step dependency analysis result

The time-step dependency issue was also observed in this study. Figure 13 shows the energy consumption results of the GSHP system (heat pump + ground-loop water pump) used in the target building between January and April (4 months) with various time steps between 1 hour to 30 seconds. As shown, the difference of the results between 1-hr and 30-second resolutions is as high as 20% (12,164 kBtu vs. 9,662 kBtu). The coarse resolution in simulation time, e.g., 1 hr, ignores the detailed control behavior to the room air temperature within the one-hour interval, especially when an on-off control strategy is involved, which is a common way to control room air temperatures in most of the single-family houses. This can be seen in Figures 14, 15, and 16.

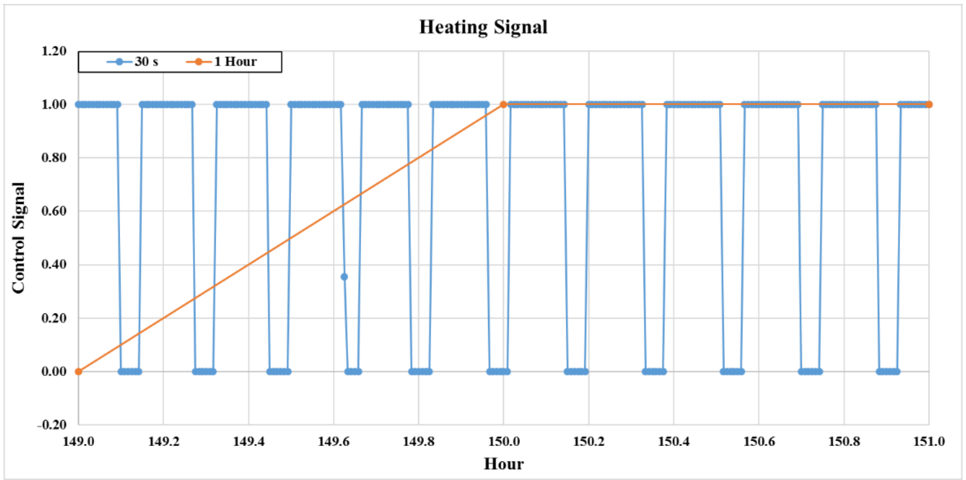


Figure 14. Heat pump control signal (1 = on, 0 = off)

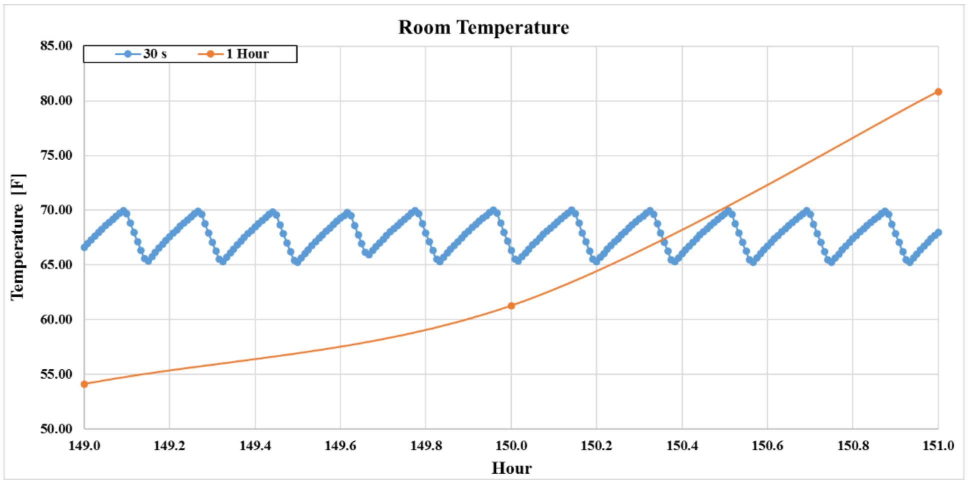


Figure 15. Room air temperature

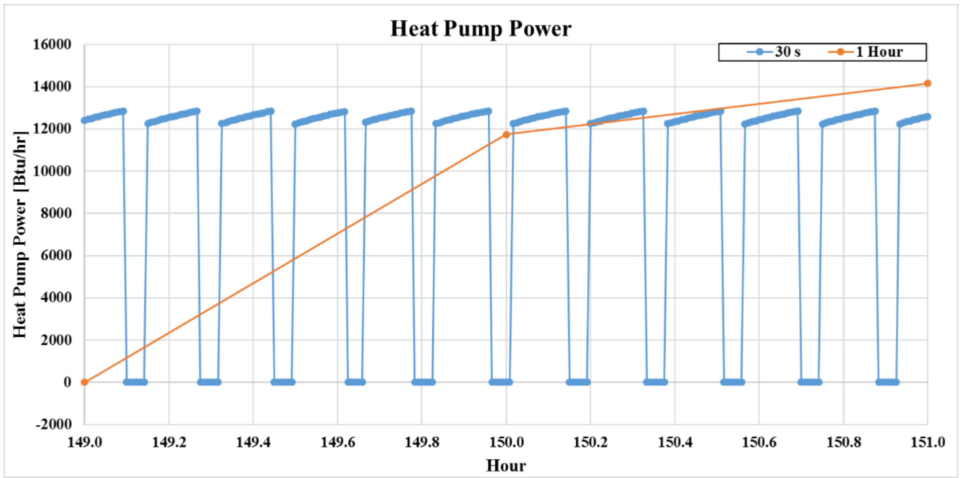


Figure 16. Heat pump power consumption

Figure 14 shows the control signal (1 = on, 0 = off) to turn on the heat pump to provide heating effect to the room/building located in Bismarck, ND; Figure 15 shows the controlled room air temperature; and Figure 16 shows the corresponding heat pump energy consumption.

When a coarse time resolution is used, e.g., 1 hr (orange lines), at the time of Hour 149 (in a day in January and Hour 0 starts at 12 am of January 1st), the room air temperature (Figure 15) is below the set point, i.e., 68 ± 2^{o}F, so then the heat pump unit is on at Hour 150 to increase the room air temperature. At Hour 151 (one hour later), the room air temperature is higher than the set point, so then the heat pump is off.

When a fine time resolution is used, e.g., 30 seconds (blue lines), the heat pump is turned on and off frequently and each time it keeps on for about 5-6 minutes (Figure 14), which explains why more errors are brought when a coarser time resolution, e.g., 5 minutes or larger, is used in the simulation (Figure 13). By using a fine resolution, the room air temperature is also controlled properly with small fluctuations around the set point (Figure 15). This simulation result is closer to reality and thus has higher accuracy than the coarse resolution results.

By looking at the heat pump energy consumption (Figure 16), during the three hours (Hour 149-151), the total heat pump energy consumption calculated using the 1-hr time step is 25,890 Btu, which is higher than the result (18,435 Btu) with the time step of 30 s. This example explains why the default time step, i.e., 1 hr, is not acceptable for use in this study, and a time step less than 5 minutes, e.g., 1 minute, is more desirable and was thus selected in the following TRNSYS simulations to ensure the reliability and accuracy of the simulation results, after reviewing the time-step dependency analysis result shown in Figure 13. This time-step dependency analysis result is consistent with those from the previous studies, such as (Tabares-Velasco, 2016) (Dos Santos et al., 2004) (Garde et al., 2001).

3.1.3.2. Model Validation and/or Calibration

The key components of the simulation work, i.e., the models for Heat Pump, Dry Fluid Cooler, and the target building, were validated and/or calibrated before using them in the study to ensure the reliability of the simulation results.

3.1.3.2.1. Heat Pump Model

The water-to-air heat pump model used in TRNSYS is Type 919. To validate the model before using it in the study, lab experiments were conducted, where a small water-to-air heat pump unit was purchased and installed (Figure 17), whose performance data are shown in Table 3. Type-K thermocouples with data loggers, a water flow meter, and an anemometer were used to measure the air and water temperatures, water flow rate, and air velocity, as shown in Figure 18. The experiment design is shown in Figure 19, where water from a water tank was fed to the source side of the heat pump, and meanwhile, at the load side, conditioned air was supplied to the room to provide heating/cooling effects. Inlet and outlet water/air temperatures were measured and recorded.

Figure 17. Heat pump unit for model validation

The two measured parameters, including return air and water temperatures to the heat pump unit (Figure 20), were used as the inputs to the heat pump model (Type 919). The results, in terms of outlet air (at the load side) and water (at the source side) temperatures, between measurements and simulations were compared and shown in Figure 21, and good agreements were observed, indicating that the model Type 919 is suitable and can be used in this study.

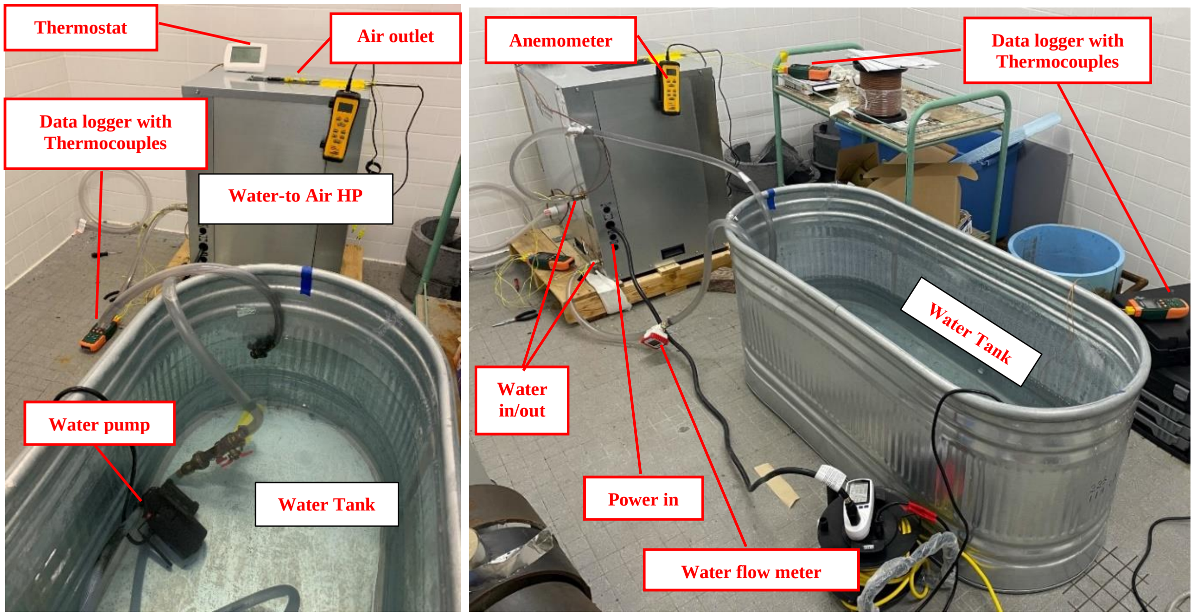


Figure 18. Heat pump performance testing experiment

Table 3. Heat pump data for model validation

Manufacturer	GeoComfort by Enertech
Model	GVS009
HP Rated Cooling Capacity [Btu/hr]	10,900
HP Rated Cooling EER	17.4
HP Rated Heating Capacity [Btu/hr]	8,500
HP Rated Heating COP	3.6
HP air flow rate [CFM]	300/350/400
HP water flow rate [GPM]	1.1/1.7/2.3

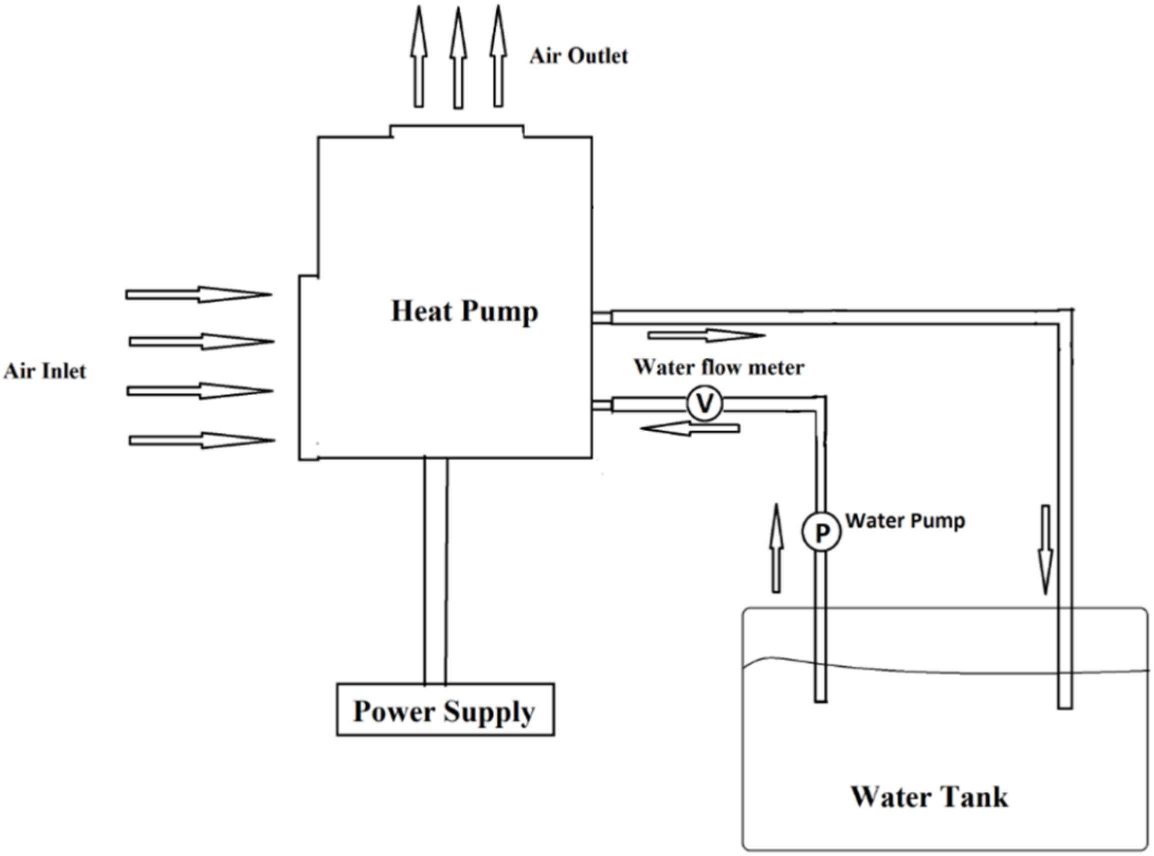


Figure 19. Experiment design

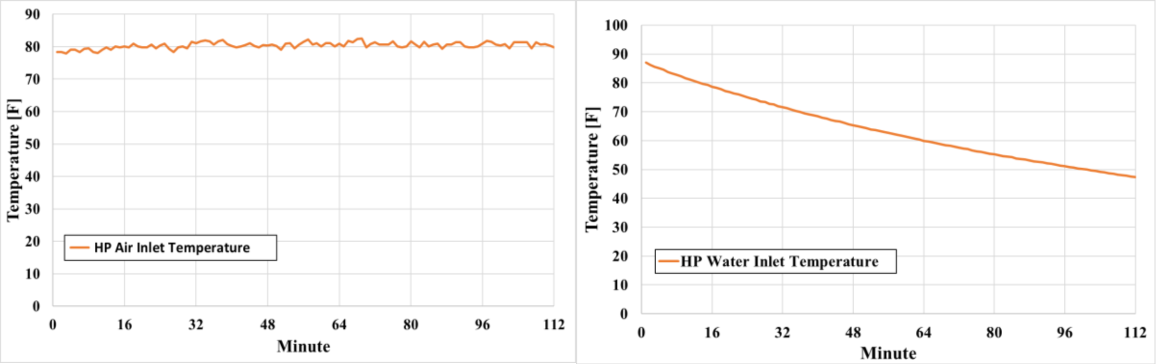


Figure 20. Measured data as inputs for TRNSYS simulations

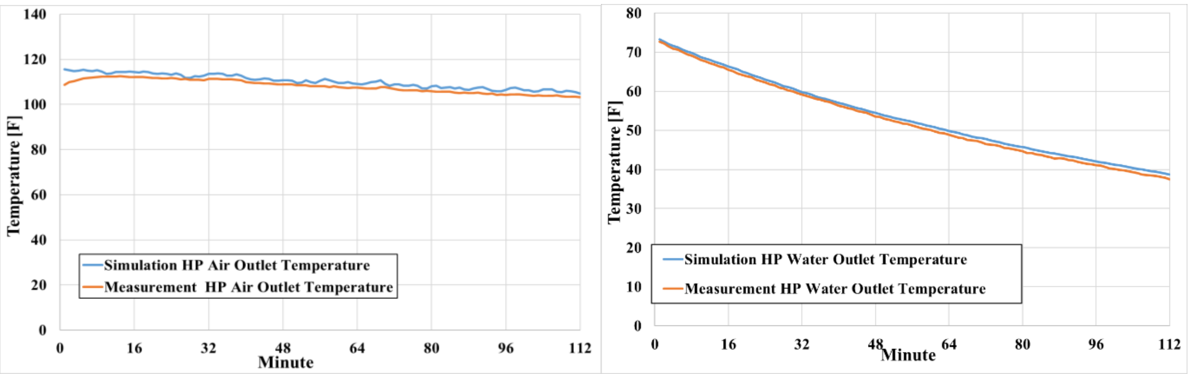


Figure 21. Result comparison between measurements and simulations

3.1.3.2.2. Dry Fluid Cooler Model

The dry fluid cooler model used in TRNSYS is Type 511. The simulation result by using this type was compared with the data from the manufacturer's product catalog (Table 4). As shown in the table, with the given inputs, the output from the simulation, i.e., outlet water temperature, is consistent with the data provided in the catalog.

Table 4. Dry fluid cooler data for model validation

Catalog Data		**Simulation Data**	
DC Heat Rejection Capacity [BTUH]	51,600	Simulation Air Flow Rate [CFM]	3,500
DC Water Flow Rate [GPM]	15	Simulation Inlet Fluid Temperature [F]	85
DC Air Flow Rate [CFM]	3,500	Simulation Water Flow Rate [GPM]	15
Design Inlet Air Temperature [F]	70	Simulation Inlet Air Temperature[F]	70
Design Inlet Fluid Temperature [F]	85	Simulation Ambient Temperature[F]	70
Design Ambient Temperature [F]	70		
Design Outlet Water Temperature [F]	78	Simulation Outlet Water Temperature [F]	78.02

3.1.3.2.3. Overall System Models (Heat Pump + Vertical Boreholes + Building)

The EnergyPlus results, i.e., monthly heating and cooling energy consumption of the heat pump, are available (DOE, 2021), which allows me to calibrate the developed models for the entire GSHP system, including Type 919 for the heat pump, Type 56 for the target building, and Type 557a for vertical ground loop boreholes, in TRNSYS to further improve its accuracy after the time-step independence analysis. In the model calibration process, the established model in

TRNSYS was calibrated against the monthly energy consumption result obtained from the EnergyPlus model, which has already been validated and proved by the PNNL. The calibrated parameters mainly include infiltration rates, and occupancy, lighting, and equipment schedules. Figure 22 compares the EnergyPlus and TRNSYS results, in terms of monthly heating (a), cooling (b), and total (c) energy consumption of the heat pump system. According to the ASHRAE Guideline 14 (2014) (ASHRAE, 2014), the TRNSYS model can be considered as a calibrated model if the errors between the monitored (EnergyPlus results) and simulated data (TRNSYS results) are within the allowable limits of the Normalized Mean Bias Error (NMBE) (Equation 1) and Coefficient of Variation of Root Mean Square Error (CVRMSE) (Equation 2).

$$NMBE = \frac{\sum_{i=1}^{N1}(S_i - M_i)}{\sum_{i=1}^{N1} M_i} \times 100\% \tag{1}$$

$$CVRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N1}(S_i - M_i)^2}{N1}}}{\frac{\sum_{i=1}^{N1} M_i}{N1}} \times 100\% \tag{2}$$

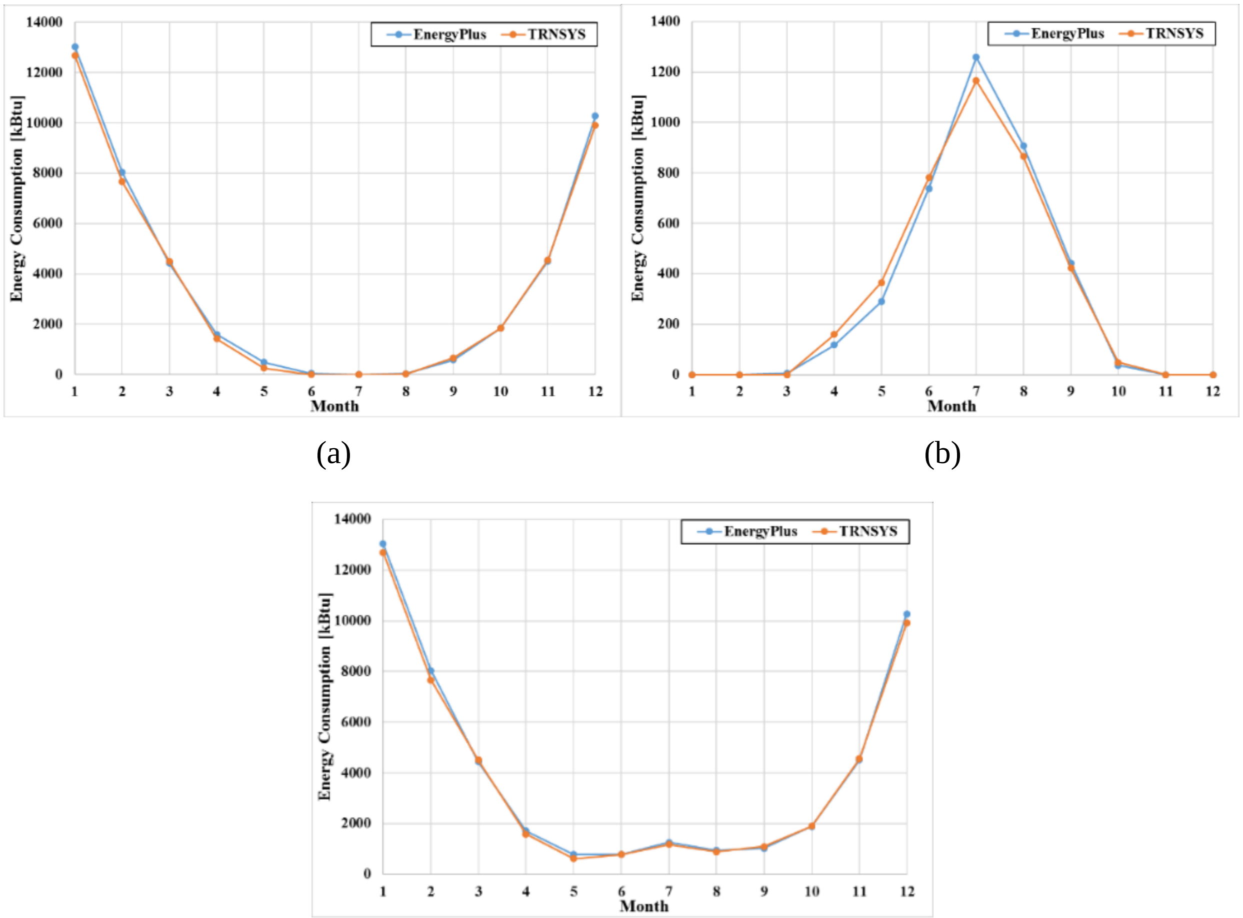
where *Si* represents the simulated (TRNSYS) result per month; *Mi* represents the monitored (EnergyPlus) data per month; and *i* represents the time interval, i.e., month.

As shown in Figure 22, a “goodness-of-fit” is achieved, and the corresponding NMBEs and CVRMSEs of heating, cooling, and total energy usage calibration results are shown in Table 5, and obviously these NMBE and CVRMSE values are all within the acceptable limits, i.e., (±5% for NMBE and 15% for CVRMSE) according to the ASHRAE Guideline 14 (2014) (ASHRAE, 2014).

Table 5. Calibration results

	Heating	**Cooling**	**Total**
NMBE (%)	-2.96 %	0.29 %	-2.71 %
CVRMSE (%)	5.41 %	12.99 %	4.81 %

The purposes of calibrating the model are to 1) increase the reliability of the simulation results of this study and 2) determine the occupancy, lighting, and equipment schedules that are distinct and difficult to know but will have significant impacts on the energy consumption of GSHP systems. These calibrated schedules for lighting, occupancy, and equipment are shown in Figure 23.

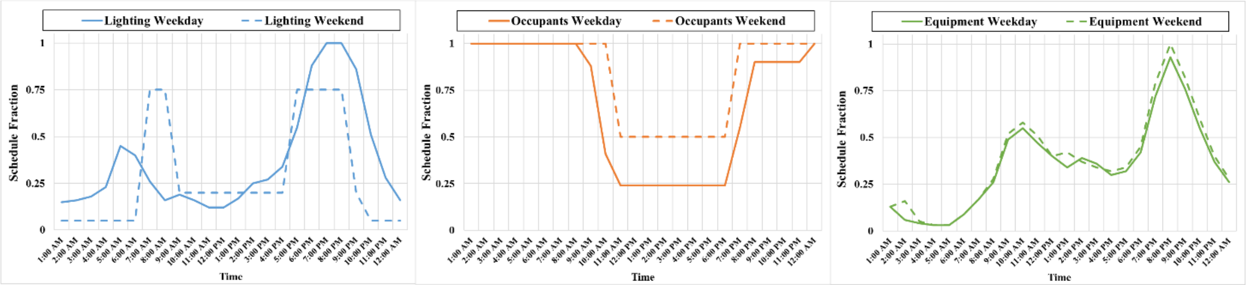


(a)

(b)

(c)

Figure 22. Calibration results
(a: heat pump heating energy consumption; b: heat pump cooling energy consumption; c: heat pump total energy consumption)



(a) (b) (c)

Figure 23. Lighting (a), occupancy (b), and equipment (c) schedules

3.2. Multi-Source Heat Pump System Development and Simulation

3.2.1. General System Information

After the time-step independence analysis and model calibration/validation, the developed model in TRNSYS is intended to predict the performance of the GSHP system when integrated with a dry fluid cooler (Figure 11) and used in eight different Climate Zones (CZ) across the U.S., designated by the International Energy Conservation Code (IECC) and ASHRAE (Baechler et al., 2010). Eight cities were considered in this study as the representatives of the eight CZs. These cities are listed in Table 6 and shown in Figure 24. The weather conditions of these cities used in the simulations were extracted from the TMY3 Weather Data (NREL, 2021).

Table 6. Eight CZ cities

Climate Zone	City
CZ 1	Miami, Florida
CZ 2	New Orleans, Louisiana
CZ 3	Atlanta, Georgia
CZ 4	Kansas City, Kansas
CZ 5	Omaha, Nebraska
CZ 6	Minneapolis, Minnesota
CZ 7	Bismarck, North Dakota
CZ 8	Anchorage, Alaska

This section describes the various design schemes and control strategies of the multi-source heat pump systems (Figure 11) when used in different CZs and subject to different local building energy code requirements. Table 7 summarizes the local code requirements for the target building if located in these eight cities/CZs, according to 2018 ASHRAE 90.2 (ASHRAE standard, 2018)

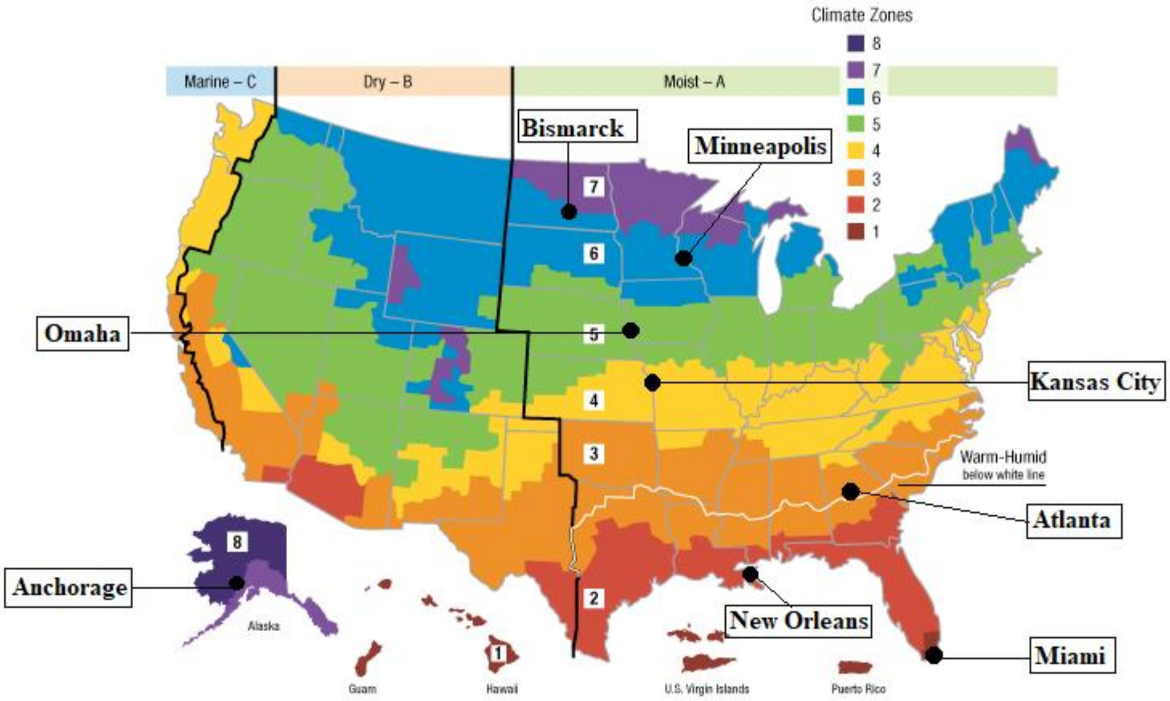


Figure 24. Representative cities of the eight CZs in the study
(Source: https://www.insulfoam.com/climate-zones/)

Table 7. Code requirements in different cities/CZs (ASHRAE standard, 2018)

City/CZ		SHGC	U-factors (Btu/hr.ft^2.F)			
		Glazed Fenestration	Fenestration	Roof	Wall	Floor
CZ-1	**Miami, Florida**	0.25	0.50	0.035	0.084	0.064
CZ-2	**New Orleans, Louisiana**	0.25	0.40	0.030	0.084	0.064
CZ-3	**Atlanta, Georgia**	0.25	0.35	0.030	0.060	0.047
CZ-4	**Kansas City, Kansas**	0.40	0.35	0.026	0.060	0.047
CZ-5	**Omaha, Nebraska**	NR (0.40) *	0.32	0.026	0.060	0.033
CZ-6	**Minneapolis, Minnesota**	NR (0.40) *	0.32	0.026	0.045	0.033
CZ-7	**Bismarck, North Dakota**	NR (0.40) *	0.32	0.026	0.045	0.028
CZ-8	**Anchorage, Alaska**	NR (0.40) *	0.32	0.026	0.045	0.028

*NR – No Requirement (SHGC-0.40 was used)

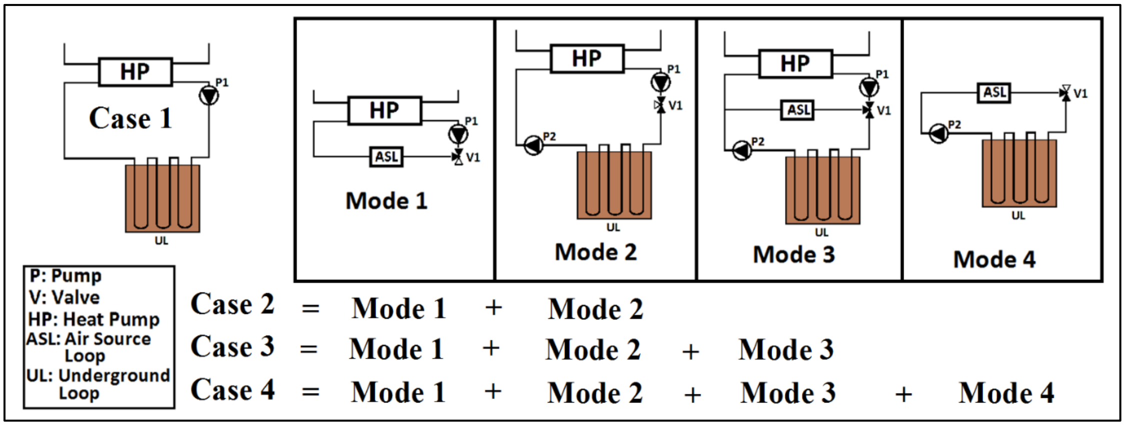


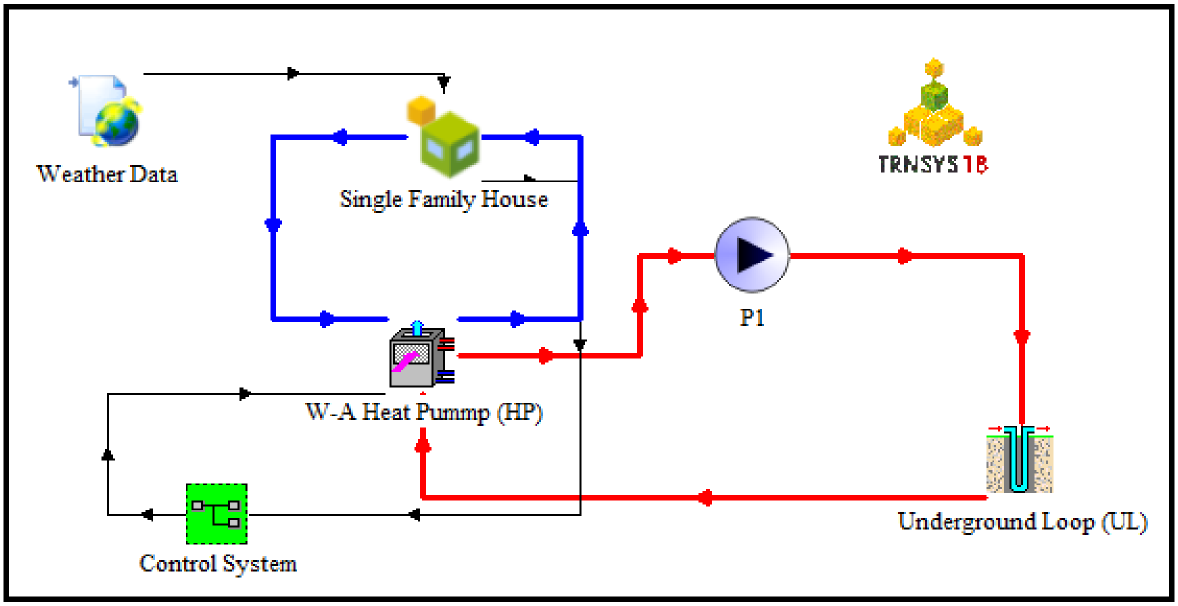
Figure 25. Different case scenarios

The following sub-sections describe the detailed design development in each CZ or target city, along with corresponding simulation and cost-effective analysis results and relevant discussions.

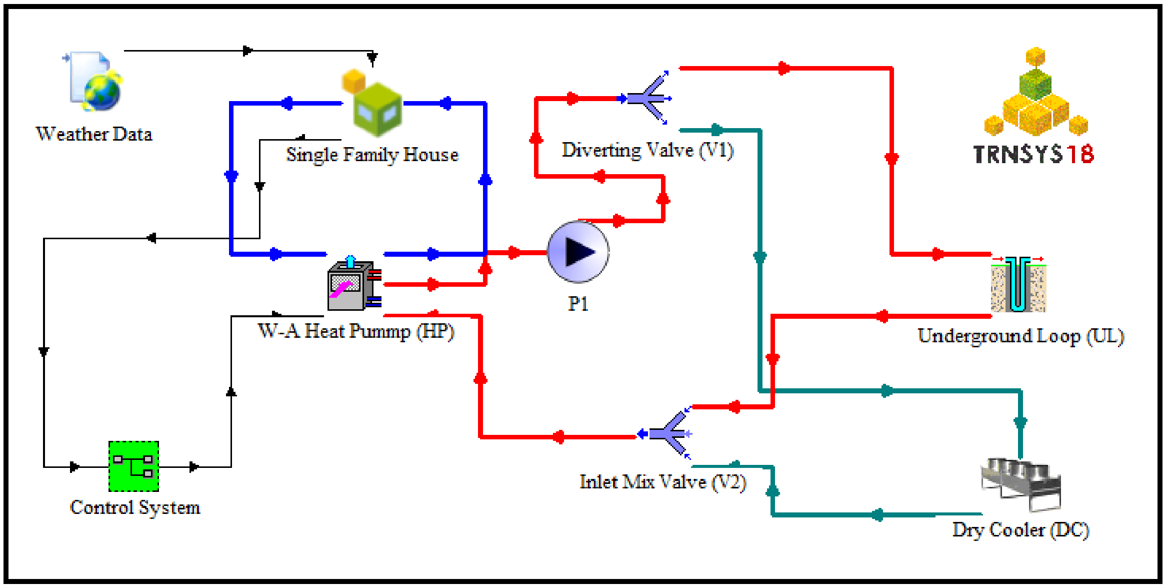
In the study of each CZ/city, four cases were considered, which are listed below.

- Case 1: Conventional Ground Source Heat Pump System – To use the underground loop only (Baseline System), as shown in Figure 25.
- Case 2: Ground Source Heat Pump integrated with a dry fluid cooler – To accomplish the Control Mode of 1 and 2, as shown in Figure 25.
- Case 3: Ground Source Heat Pump integrated with a dry fluid cooler – To accomplish the Control Mode of 1, 2, and 3, as shown in Figure 25.
- Case 4: Ground Source Heat Pump integrated with a dry fluid cooler – To accomplish the Control Mode of 1, 2, 3, and 4, as shown in Figure 25.

The purpose of establishing the four case scenarios is to evaluate the effectiveness of the four different control modes and to compare them with each other in order to find out the most appropriate control strategies for the developed system used under various weather conditions. The different TRNSYS models corresponding to the four cases were developed, which are shown in Figure 26. As shown, the major TRNSYS components used in the study are Type 15: Weather data processor; Type 56: Multi-zone building model; Type 919: Water-to-air heat pump model; Type 557a: Vertical underground loop model; Type 511: Dry fluid cooler model; Type 114: Circulation water pump model; Type 647: Fluid diverting valve model; and Type 649: Mixing valve model.

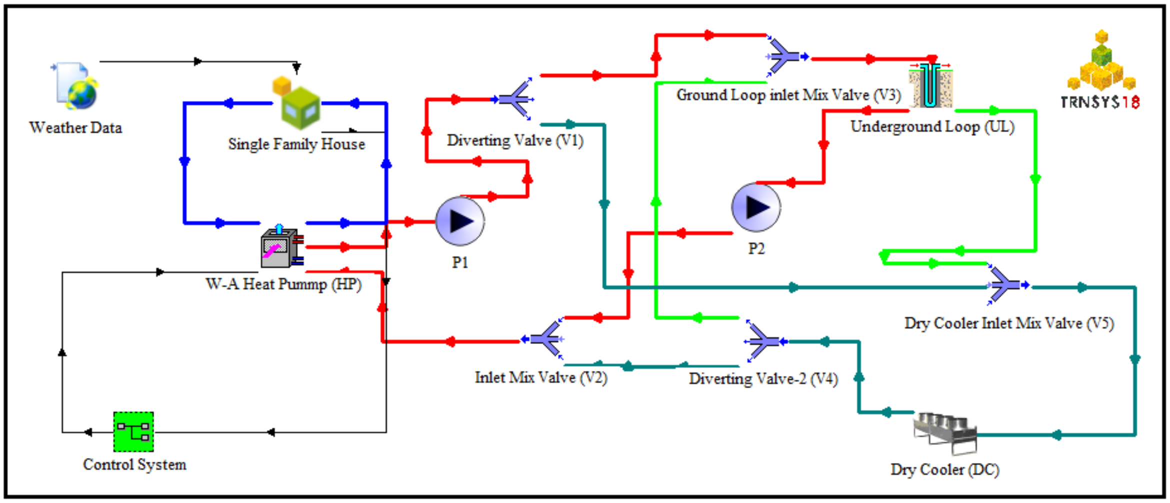


Case 1 model



Case 2 & 3 model

Figure 26. TRNSYS models for the four cases



Case 4 model

Figure 26. TRNSYS models for the four cases (continued)

The general control strategies for the four cases are illustrated in Figures 27 and 28. Figure 27 shows the thermostat control sequence that tells when the heat pump system is on or off and operates at either heating or cooling mode under various outdoor and room conditions in summer and winter. Room air temperatures are kept around 68 ^{o}F in winter, considering the common practice among users of building simulation programs (Fabi et al., 2013) (Agarwal et al., 2011), and in summer, the heat pump will not provide heating effect unless the room air temperature is too low, e.g., 64 ^{o}F, in a cool summer night. A set point of 75 ^{o}F is used for cooling as a typical value used by designers and engineers (Shirey et al.) (Agarwal et al., 2011) (Hong et al., 2014). This control strategy is to ensure that the system does not alternate between heating and cooling modes frequently in a short period of time to avoid unnecessary heating or cooling operation.

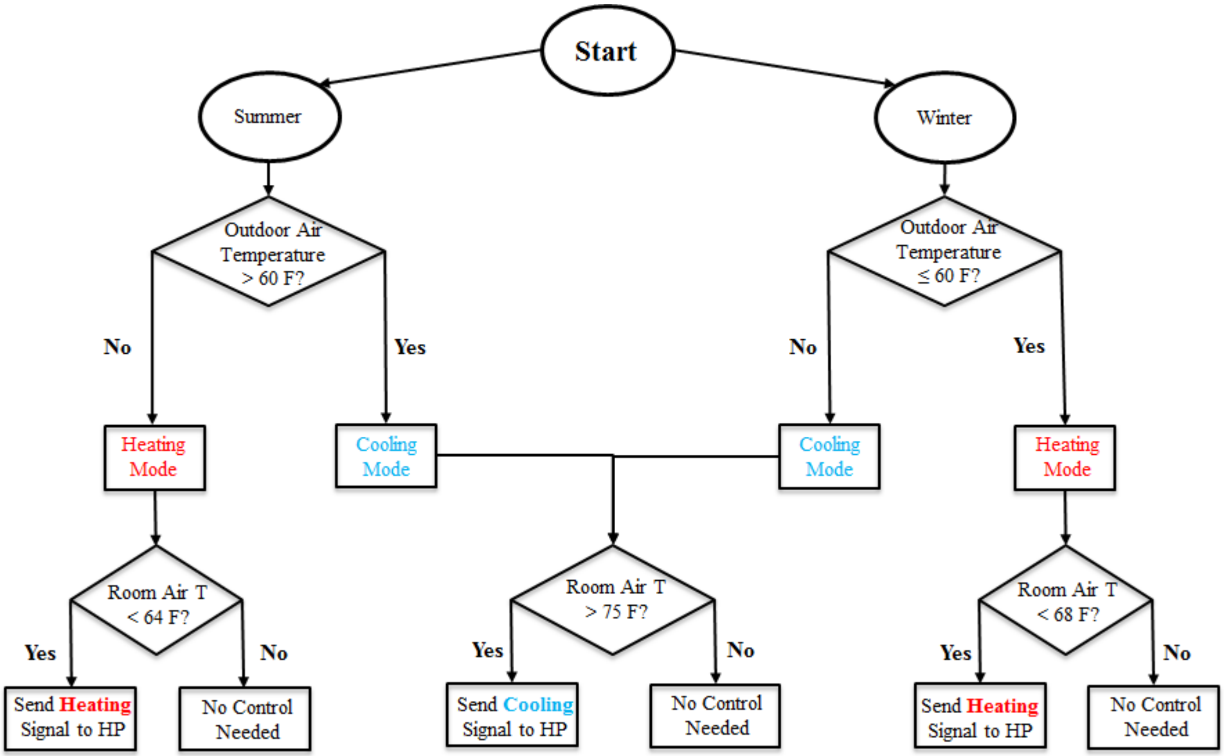


Figure 27. Thermostat control sequence

Figure 28 shows the conditions that allow the heat pump system to switch between different control modes for Cases 1-4 (Figure 25) when the system is on and calling for heat or cold depending on the thermostat control sequence (Figure 27). To determine which heat source/sink to be used by the heat pump for heating/cooling between the Underground Loop (UL) and Dry Cooler (DC), the outlet water temperatures from both the UL and DC are compared to each other, and if the heat pump is calling for heat, the one that can provide warmer return water is used as the heat source, while if the heat pump is calling for cold, then the one that can provide cooler return water is used as the heat sink. The dead band of 1 ^{o}F is used, and when the outlet temperatures from the UL and DC are within the dead band, the water flow from the heat pump is split into 50%/50% to circulate into the UL and DC, respectively (Case 3 in Figure 25). When the heat pump is off, i.e., it is not calling for heat nor cold, and if the ambient air temperature is desirable (warm or cool enough for heat or cold collection and storage), the

DC would be used to collect heat (for cold climate regions, such as CZ-6, 7, and 8) or cold (for hot climate regions such as CZ-1, 2, and 3), which is then conveyed to the underground region for thermal energy storage. To do so, the system needs to ensure that the ambient air temperature is higher (for heat collection) or lower (for cold collection) than the ground temperature, i.e., the difference between the outlet water temperatures from both the UL and DC is at least 7 ^{o}F. The 1 ^{o}F and 7 ^{o}F dead bands are the results of control strategy optimization through a number of simulations.

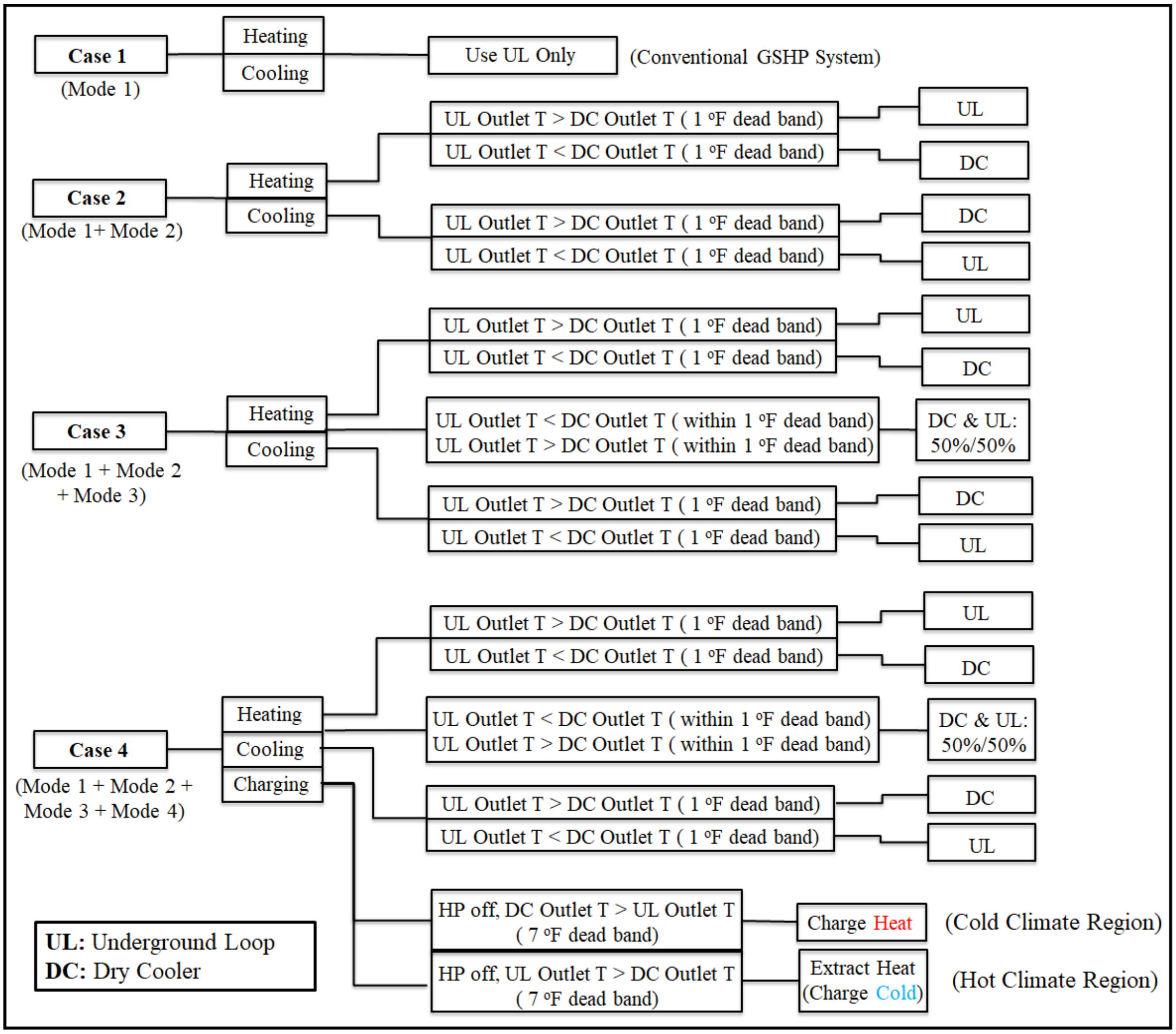


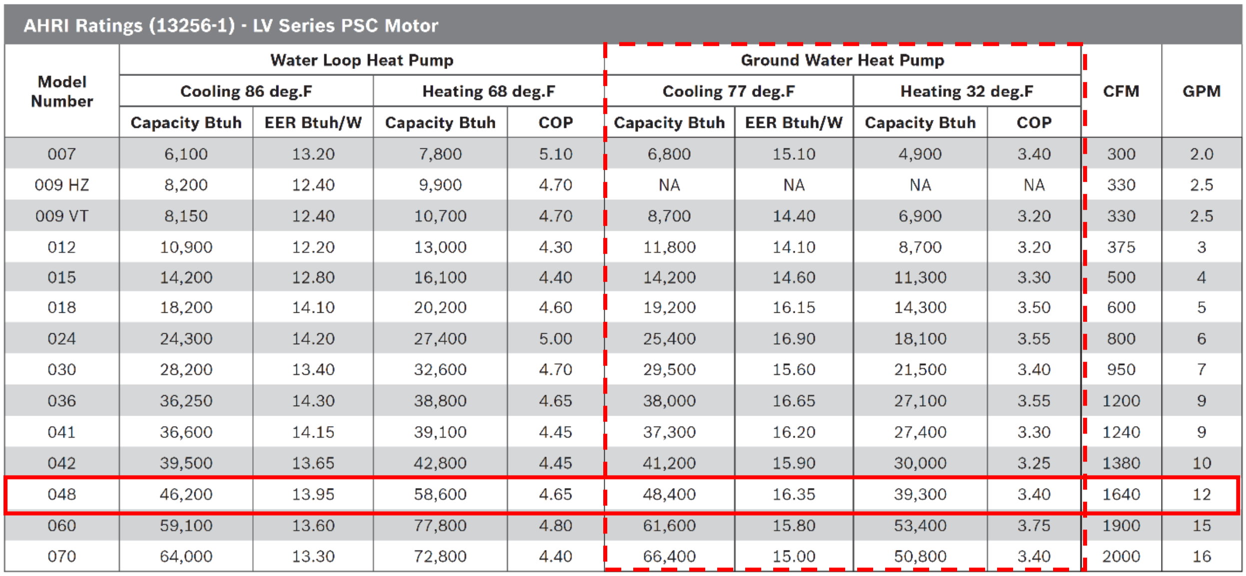
Figure 28. Controls for the four cases

3.2.2. Sizing of Case 1 System

The size of the baseline system (Case 1) (Figure 25) was determined by using TRNSYS. Take the CZ 7 - Bismarck, North Dakota, as an example. The peak heating and cooling loads are 37,400 Btu/hr and 31,410 Btu/hr, which occur in January and July, respectively. Hence, the heat pump unit (BOSCH LV048) was selected based on its rated heating capacity (39,300 Btu/hr) for this heating-dominated building located in CZ 7. The rated performance data of the heat pump unit is shown in Figure 29.

GLHEpro was then used to determine the underground borehole size with the building heating and cooling loads estimated by using the TRNSYS. GLHEpro is a popular tool for engineers and designers to design and support GSHP installations (GLHEpro, 2021). The monthly maximum and minimum return water temperatures of the selected heat pump unit (with 4 vertical boreholes at a depth of 200 ft for each) for CZ-7 over the course of 240 months (20 years) can be found in Appendix A. As shown, the return water temperatures vary between around 65 ^{o}F and 30 ^{o}F, which indicate that 4 boreholes with the borehole depth of 200 ft (the total borehole length of 800 ft) are appropriate for the heat pump unit selected to meet the heating and cooling loads of the house located in Bismarck ND, since, typically, a return water temperature between approximately 30 ^{o}F and 95 ^{o}F is acceptable for a conventional GSHP (Shonder et al., 2001) in determining borehole size. Additionally, according to the type of heat pump selected, the acceptable minimum and maximum return water temperatures is 30 ^{o}F for heat pump heating and 110 ^{o}F for heat pump cooling, as shown in Figure 30. Hence, using a range between 30 ^{o}F and 95^{o}F is more conservative in system design and sizing considering the variation of heat pump capacity and performance when heat pumps from different manufactures are considered. Similar approach was used to size the baseline systems (Case 1 system) for other

CZs/Cities, whose results are summarized in Table 8, and the corresponding GLHEpro results are included in Appendix A.



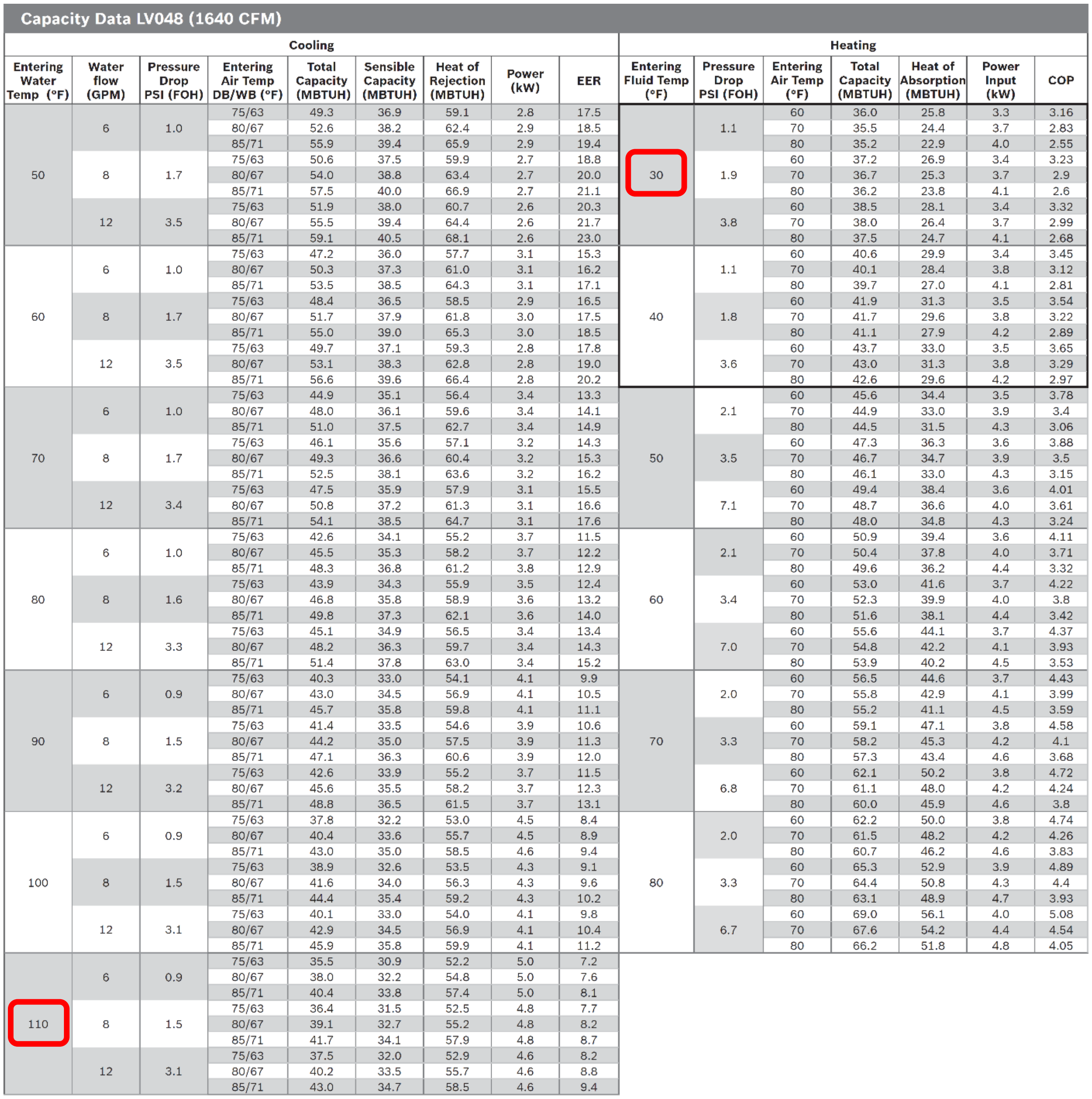
AHRI Ratings (13256-1) · LV Series PSC Motor

Model Number	Water Loop Heat Pump				Ground Water Heat Pump				CFM	GPM
	Cooling 86 deg.F		Heating 68 deg.F		Cooling 77 deg.F		Heating 32 deg.F			
	Capacity Btuh	EER Btuh/W	Capacity Btuh	COP	Capacity Btuh	EER Btuh/W	Capacity Btuh	COP		
007	6,100	13.20	7,800	5.10	6,800	15.10	4,900	3.40	300	2.0
009 HZ	8,200	12.40	9,900	4.70	NA	NA	NA	NA	330	2.5
009 VT	8,150	12.40	10,700	4.70	8,700	14.40	6,900	3.20	330	2.5
012	10,900	12.20	13,000	4.30	11,800	14.10	8,700	3.20	375	3
015	14,200	12.80	16,100	4.40	14,200	14.60	11,300	3.30	500	4
018	18,200	14.10	20,200	4.60	19,200	16.15	14,300	3.50	600	5
024	24,300	14.20	27,400	5.00	25,400	16.90	18,100	3.55	800	6
030	28,200	13.40	32,600	4.70	29,500	15.60	21,500	3.40	950	7
036	36,250	14.30	38,800	4.65	38,000	16.65	27,100	3.55	1200	9
041	36,600	14.15	39,100	4.45	37,300	16.20	27,400	3.30	1240	9
042	39,500	13.65	42,800	4.45	41,200	15.90	30,000	3.25	1380	10
048	46,200	13.95	58,600	4.65	48,400	16.35	39,300	3.40	1640	12
060	59,100	13.60	77,800	4.80	61,600	15.80	53,400	3.75	1900	15
070	64,000	13.30	72,800	4.40	66,400	15.00	50,800	3.40	2000	16

Figure 29. AHRI ratings of BOSCH heat pumps

3.2.3. Sizing of Case 2, 3, and 4 Systems

It is expected that the advanced control strategies (Cases 2, 3, and 4 shown in Figure 25) plus the use of additional heat-source/sink element, i.e., a dry fluid cooler, contribute to the reduction of the borehole size and thus the initial cost of a GSHP system. To properly size the systems for Cases 2, 3, and 4 and to quantify the impact of various control strategies on the system sizing, detailed energy modeling and simulations are required, which have been accomplished in TRNSYS. Results, including simulation results and sizing information, are shown and discussed in the following sections depending on the location of the house in different climate zones. Table 8 summarizes the various system design parameters, such as heat pump capacities, number of boreholes, etc., corresponding to the different local code requirements, as well as the unique weather condition in each selected location. In Table 8, three different borehole lengths (or numbers of boreholes) for each CZ were considered to evaluate the possible reduction of borehole length without losing the heating and cooling capacities of the system when a dry cooler is added and used. The first borehole length, e.g., 1,000 ft under CZ-3, represents the appropriate borehole size for a conventional GSHP system (Case 1). The borehole length was then reduced by about 25% (750 ft under CZ-3) and eventually 50% (Bottarelli et al., 2016) (500 ft under CZ-3) to investigate the feasibility of reducing borehole length/size to achieve initial cost reduction without compromising system performance and capacity.



Capacity Data LV048 (1640 CFM)

Cooling									Heating						
Entering Water Temp (°F)	Water flow (GPM)	Pressure Drop PSI (FOH)	Entering Air Temp DB/WB (°F)	Total Capacity (MBTUH)	Sensible Capacity (MBTUH)	Heat of Rejection (MBTUH)	Power (kW)	EER	Entering Fluid Temp (°F)	Pressure Drop PSI (FOH)	Entering Air Temp (°F)	Total Capacity (MBTUH)	Heat of Absorption (MBTUH)	Power Input (kW)	COP
50	6	1.0	75/63	49.3	36.9	59.1	2.8	17.5	30	1.1	60	36.0	25.8	3.3	3.16
			80/67	52.6	38.2	62.4	2.9	18.5			70	35.5	24.4	3.7	2.83
			85/71	55.9	39.4	65.9	2.9	19.4			80	35.2	22.9	4.0	2.55
	8	1.7	75/63	50.6	37.5	59.9	2.7	18.8		1.9	60	37.2	26.9	3.4	3.23
			80/67	54.0	38.8	63.4	2.7	20.0			70	36.7	25.3	3.7	2.9
			85/71	57.5	40.0	66.9	2.7	21.1			80	36.2	23.8	4.1	2.6
	12	3.5	75/63	51.9	38.0	60.7	2.6	20.3		3.8	60	38.5	28.1	3.4	3.32
			80/67	55.5	39.4	64.4	2.6	21.7			70	38.0	26.4	3.7	2.99
			85/71	59.1	40.5	68.1	2.6	23.0			80	37.5	24.7	4.1	2.68
60	6	1.0	75/63	47.2	36.0	57.7	3.1	15.3	40	1.1	60	40.6	29.9	3.4	3.45
			80/67	50.3	37.3	61.0	3.1	16.2			70	40.1	28.4	3.8	3.12
			85/71	53.5	38.5	64.3	3.1	17.1			80	39.7	27.0	4.1	2.81
	8	1.7	75/63	48.4	36.5	58.5	2.9	16.5		1.8	60	41.9	31.3	3.5	3.54
			80/67	51.7	37.9	61.8	3.0	17.5			70	41.7	29.6	3.8	3.22
			85/71	55.0	39.0	65.3	3.0	18.5			80	41.1	27.9	4.2	2.89
	12	3.5	75/63	49.7	37.1	59.3	2.8	17.8		3.6	60	43.7	33.0	3.5	3.65
			80/67	53.1	38.3	62.8	2.8	19.0			70	43.0	31.3	3.8	3.29
			85/71	56.6	39.6	66.4	2.8	20.2			80	42.6	29.6	4.2	2.97
70	6	1.0	75/63	44.9	35.1	56.4	3.4	13.3	50	2.1	60	45.6	34.4	3.5	3.78
			80/67	48.0	36.1	59.6	3.4	14.1			70	44.9	33.0	3.9	3.4
			85/71	51.0	37.5	62.7	3.4	14.9			80	44.5	31.5	4.3	3.06
	8	1.7	75/63	46.1	35.6	57.1	3.2	14.3		3.5	60	47.3	36.3	3.6	3.88
			80/67	49.3	36.6	60.4	3.2	15.3			70	46.7	34.7	3.9	3.5
			85/71	52.5	38.1	63.6	3.2	16.2			80	46.1	33.0	4.3	3.15
	12	3.4	75/63	47.5	35.9	57.9	3.1	15.5		7.1	60	49.4	38.4	3.6	4.01
			80/67	50.8	37.2	61.3	3.1	16.6			70	48.7	36.6	4.0	3.61
			85/71	54.1	38.5	64.7	3.1	17.6			80	48.0	34.8	4.3	3.24
80	6	1.0	75/63	42.6	34.1	55.2	3.7	11.5	60	2.1	60	50.9	39.4	3.6	4.11
			80/67	45.5	35.3	58.2	3.7	12.2			70	50.4	37.8	4.0	3.71
			85/71	48.3	36.8	61.2	3.8	12.9			80	49.6	36.2	4.4	3.32
	8	1.6	75/63	43.9	34.3	55.9	3.5	12.4		3.4	60	53.0	41.6	3.7	4.22
			80/67	46.8	35.8	58.9	3.6	13.2			70	52.3	39.9	4.0	3.8
			85/71	49.8	37.3	62.1	3.6	14.0			80	51.6	38.1	4.4	3.42
	12	3.3	75/63	45.1	34.9	56.5	3.4	13.4		7.0	60	55.6	44.1	3.7	4.37
			80/67	48.2	36.3	59.7	3.4	14.3			70	54.8	42.2	4.1	3.93
			85/71	51.4	37.8	63.0	3.4	15.2			80	53.9	40.2	4.5	3.53
90	6	0.9	75/63	40.3	33.0	54.1	4.1	9.9	70	2.0	60	56.5	44.6	3.7	4.43
			80/67	43.0	34.5	56.9	4.1	10.5			70	55.8	42.9	4.1	3.99
			85/71	45.7	35.8	59.8	4.1	11.1			80	55.2	41.1	4.5	3.59
	8	1.5	75/63	41.4	33.5	54.6	3.9	10.6		3.3	60	59.1	47.1	3.8	4.58
			80/67	44.2	35.0	57.5	3.9	11.3			70	58.2	45.3	4.2	4.1
			85/71	47.1	36.3	60.6	3.9	12.0			80	57.3	43.4	4.6	3.68
	12	3.2	75/63	42.6	33.9	55.2	3.7	11.5		6.8	60	62.1	50.2	3.8	4.72
			80/67	45.6	35.5	58.2	3.7	12.3			70	61.1	48.0	4.2	4.24
			85/71	48.8	36.5	61.5	3.7	13.1			80	60.0	45.9	4.6	3.8
100	6	0.9	75/63	37.8	32.2	53.0	4.5	8.4	80	2.0	60	62.2	50.0	3.8	4.74
			80/67	40.4	33.6	55.7	4.5	8.9			70	61.5	48.2	4.2	4.26
			85/71	43.0	35.0	58.5	4.6	9.4			80	60.7	46.2	4.6	3.83
	8	1.5	75/63	38.9	32.6	53.5	4.3	9.1		3.3	60	65.3	52.9	3.9	4.89
			80/67	41.6	34.0	56.3	4.3	9.6			70	64.4	50.8	4.3	4.4
			85/71	44.4	35.4	59.2	4.3	10.2			80	63.1	48.9	4.7	3.93
	12	3.1	75/63	40.1	33.0	54.0	4.1	9.8		6.7	60	69.0	56.1	4.0	5.08
			80/67	42.9	34.5	56.9	4.1	10.4			70	67.6	54.2	4.4	4.54
			85/71	45.9	35.8	59.9	4.1	11.2			80	66.2	51.8	4.8	4.05
110	6	0.9	75/63	35.5	30.9	52.2	5.0	7.2							
			80/67	38.0	32.2	54.8	5.0	7.6							
			85/71	40.4	33.8	57.4	5.0	8.1							
	8	1.5	75/63	36.4	31.5	52.5	4.8	7.7							
			80/67	39.1	32.7	55.2	4.8	8.2							
			85/71	41.7	34.1	57.9	4.8	8.7							
	12	3.1	75/63	37.5	32.0	52.9	4.6	8.2							
			80/67	40.2	33.5	55.7	4.6	8.8							
			85/71	43.0	34.7	58.5	4.6	9.4							

Figure 30. Capacity data of the heat pump unit selected

Table 8. System design summary

Parameters	**CZ-1**			**CZ-2**			**CZ-3**			**CZ-4**			**CZ-5**			**CZ-6**			**CZ-7**			**CZ-8**		
	Miami			**New Orleans**			**Atlanta**			**Kansas City**			**Omaha**			**Minneapolis**			**Bismarck**			**Anchorage**		
Heat Pump Manufacturer, Model, and Type	BOSCH LV036~ LV048 (Single Stage)																							
GSHP system type	Vertical Closed Loop																							
Number of Boreholes	9	6	3	6	4	3	5	3	2	4	3	2	4	3	2	4	3	2	4	3	2	6	3	3
Borehole Depth [ft]	200		300	200			200	250		200			200			200			200			200	300	200
Borehole Separation Distance [ft]	20																							
Borehole Length [ft]	1,800	1,200	900	1,200	800	600	1,000	750	500	800	600	400	800	600	400	800	600	400	800	600	400	1,200	900	600
Underground Pipe Length [ft]	3,600	2,400	1,800	2,400	1,600	1,200	2,000	1,500	1,000	1,600	1,200	800	1,600	1,200	800	1,600	1,200	800	1,600	1,200	800	2,400	1,800	1,200
Ground Thermal Conductivity [Btu/hr.ft.F]	1.5																							
Ground Heat Capacity [Btu/ft^3/F]	39.93																							
Outer Radius of U-Tube Pipe [inch]	0.525																							
Inner Radius of U-Tube Pipe [inch]	0.375																							
Pipe Thermal Conductivity [Btu/hr.ft.F]	0.24																							
Grout Thermal Conductivity [Btu/hr.ft.F]	0.81																							
Borehole Radius [inch]	2.5																							
Initial Ground Temperature [F]	77.2			71.1			64			56.3			54			48.4			53			41.6		
Borehole Length per ton [ft/ton]	524	350	262	366	244	183	316	237	158	199	149	99	199	149	99	199	149	99	199	149	99	298	223	149
Underground Pipe Length per ton [ft/ton]	1,409	700	524	732	488	366	632	474	316	398	298	198	398	298	198	398	298	198	398	298	198	596	446	298
Number of Heat Pump Units	Water-to-Air HP: 1																							
HP rated air flow rate [CFM]	1,380			1,240			1,200			1,640														
HP rated water flow rate [GPM]	10			9						12														
HP water flow rate per ton [GPM/ton]	2.91			2.76			2.84			2.98														
HP Rated Heating Capacity [MBH]	30.0			27.4			27.1			39.3														
HP Rated Heating COP	3.25			3.30			3.55			3.40														
HP Rated Cooling Capacity [ton]	3.43			3.26			3.17			4.03														
HP Rated Cooling EER	15.90			16.20			16.65			16.35														
DC Heat Rejection Capacity [BTUH]	51,600																							
DC Water Flow Rate [GPM]	15																							
DC Air Flow Rate [CFM]	3,500																							

3.3. Results and Discussion

This section summarizes a comprehensive analysis and comparison of the simulation results across the eight CZs. Section 3.3.1 discusses the performance related to the heat pump unit, as well as the overall system, including not only the heat pump unit but also the dry cooler and water pumps. Section 3.3.2 details the cost analysis result with the intention of evaluating the cost-effectiveness of the designed system (Figure 11) used in different CZs with various control strategies. In CZ-1, 2, and 3, cold was collected by using the dry cooler in Mode 4 (Figure 25), while heat was collected in CZ-6, 7, and 8. Collecting cold or heat was determined based on if the target building located in a specified CZ/city is heating- or cooling-dominated, which can be identified by looking at Figure 31 that shows the heating and cooling hours of a conventional GSHP system used in the eight CZs over the course of an entire year. As shown in this figure, the GSHP system spends the majority of the time over a year on space heating in CZ-6, 7, and 8, and on space cooling in CZ-1, 2, and 3. Nevertheless, the heating and cooling hours in CZ-4 and 5 are approximately equal (Figure 31), and therefore, additional simulations were involved in identifying if charging cold or heat to the underground region is more appropriate for the systems located in these two climates, respectively.

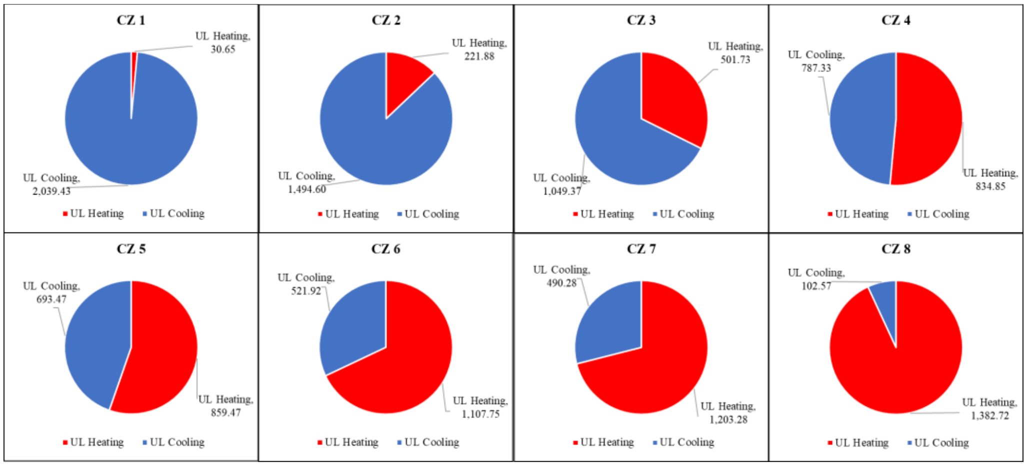


Figure 31. Heating and cooling operation hours over one year for eight CZs

3.3.1. System Performance

3.3.1.1. Heat Pump Performance

The average heating COPs and cooling EERs for the 1st year, 20th year, and 20 years of the heat pump unit used in eight CZs with different borehole lengths and control strategies (Cases 1, 2, 3, and 4) are shown in Figures 32 and 33. The corresponding maximum and minimum heat pump return water temperatures and ground temperatures over the course of 20 years can be found in Figures 34 and 35, respectively.

As shown in Figure 32, higher heating COPs are achieved in hot/warm climates, such as CZ-1, 2, and 3, due to the sufficient heat contained in the ambient air and ground in these climates, compared with cold climates, such as CZ-6, 7, and 8. For example, the average ground temperature in Miami (CZ-1) is around 77.2 ^{o}F, which is reduced to around 41.6 ^{o}F in Anchorage (CZ-8), as shown in Table 8 and Figure 36. Additionally, heating COPs decrease as the borehole size is reduced. The results of Cases 2 and 3 are very close to those of Case 1, especially in cold climates, which indicates that Modes 1, 2 and 3 as described in Figure 36 do not help much in increasing the performance of a system used in cold climates. The primary reason for that is the dry fluid cooler is not used very often for space heating, since the condition to trigger the use of the dry cooler, i.e., the return water temperature is more desirable (warmer for heating) from the dry cooler than that from the underground region, is difficult to meet, especially in the cold climate zones. This can be seen from the results of the heating and cooling hours (pie charts) in Appendix B, which illustrate the hours of the key components of the system operating for one year, i.e., the dry fluid cooler and the heat pump, under the four control modes for both space heating and cooling with different borehole lengths. As shown in these pie charts, the dry cooler is rarely used for space heating during the one-year period (DC Heating) compared to the use of underground loops (UL Heating) in Cases 2 and 3, and as the decrease of the borehole size, the operating hours of the dry cooler are increased. This indicates that the ambient air becomes more and more favorable as a source for heating and cooling if the borehole size is reduced. For example, for Case 4 in CZ-7, the dry cooler is operating for about 400 hours to charge the ground with heat when the borehole length is 800 ft, and the number of charging hours of the dry cooler is reduced to about 300 hours with the borehole length of 600 ft and then 200 hours with 400 ft. This is because of the more frequent use of the dry cooler for space heating/cooling instead of charging the ground, as the reduction of the borehole size, thus resulting in the shorter charging time for the dry cooler in consideration of the condition to trigger Mode 4, i.e., the heat pump is off, and neither the dry cooler nor the underground loop is being used for space heating or cooling.

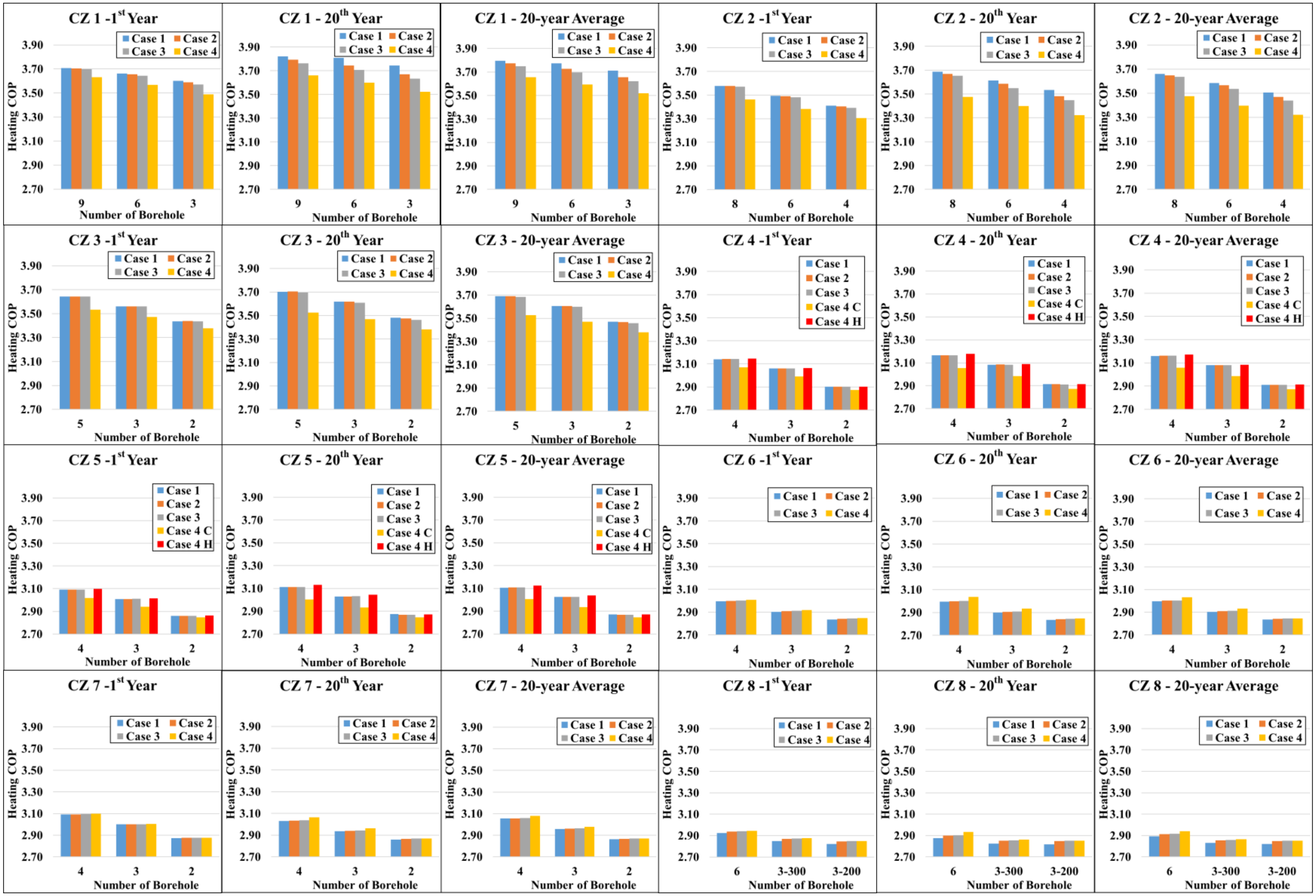


Figure 32. Average heating COPs for the 1st year, 20th year, and 20 years

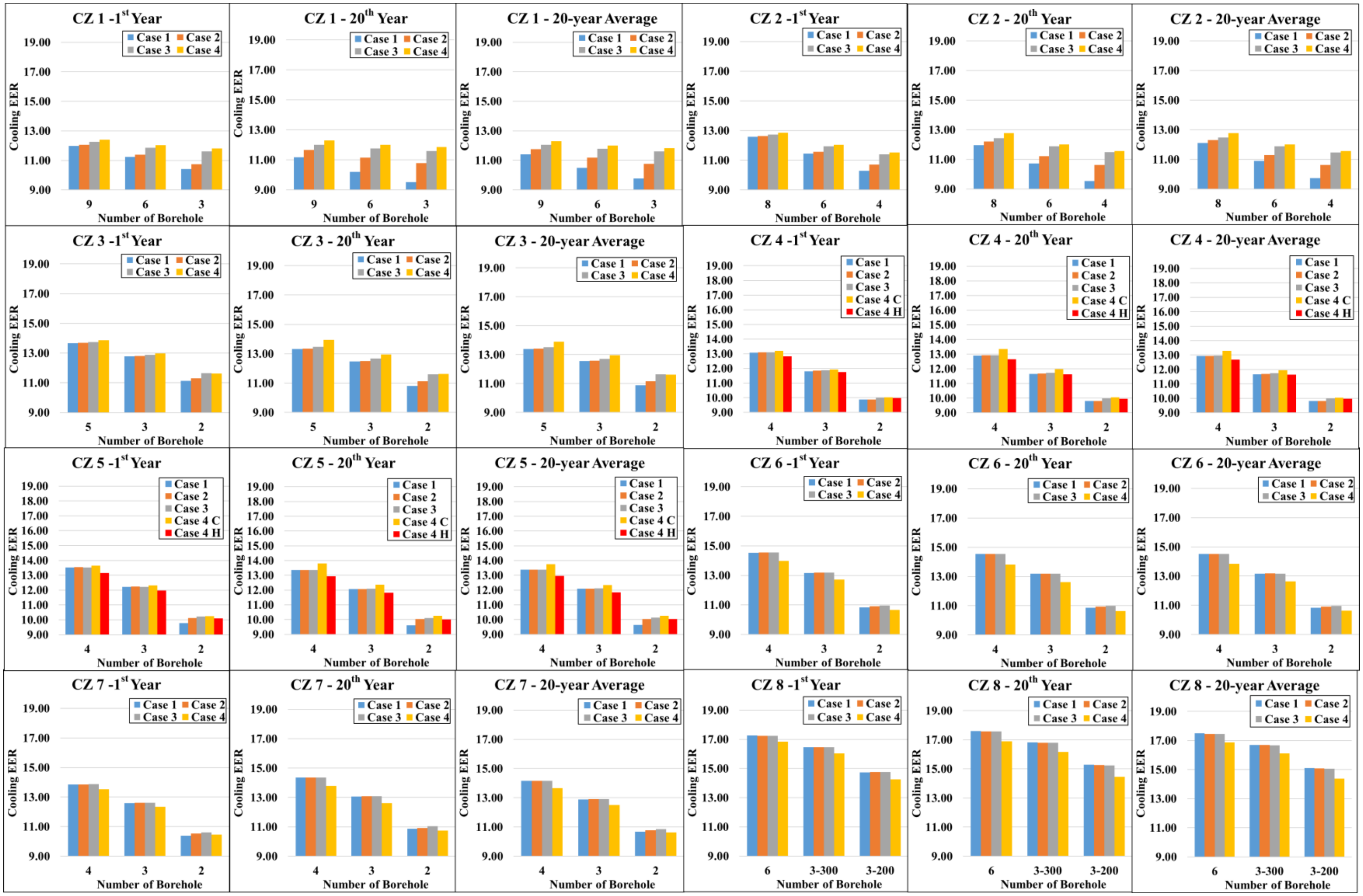


Figure 33. Average cooling EERs for the 1st year, 20th year, and 20 years

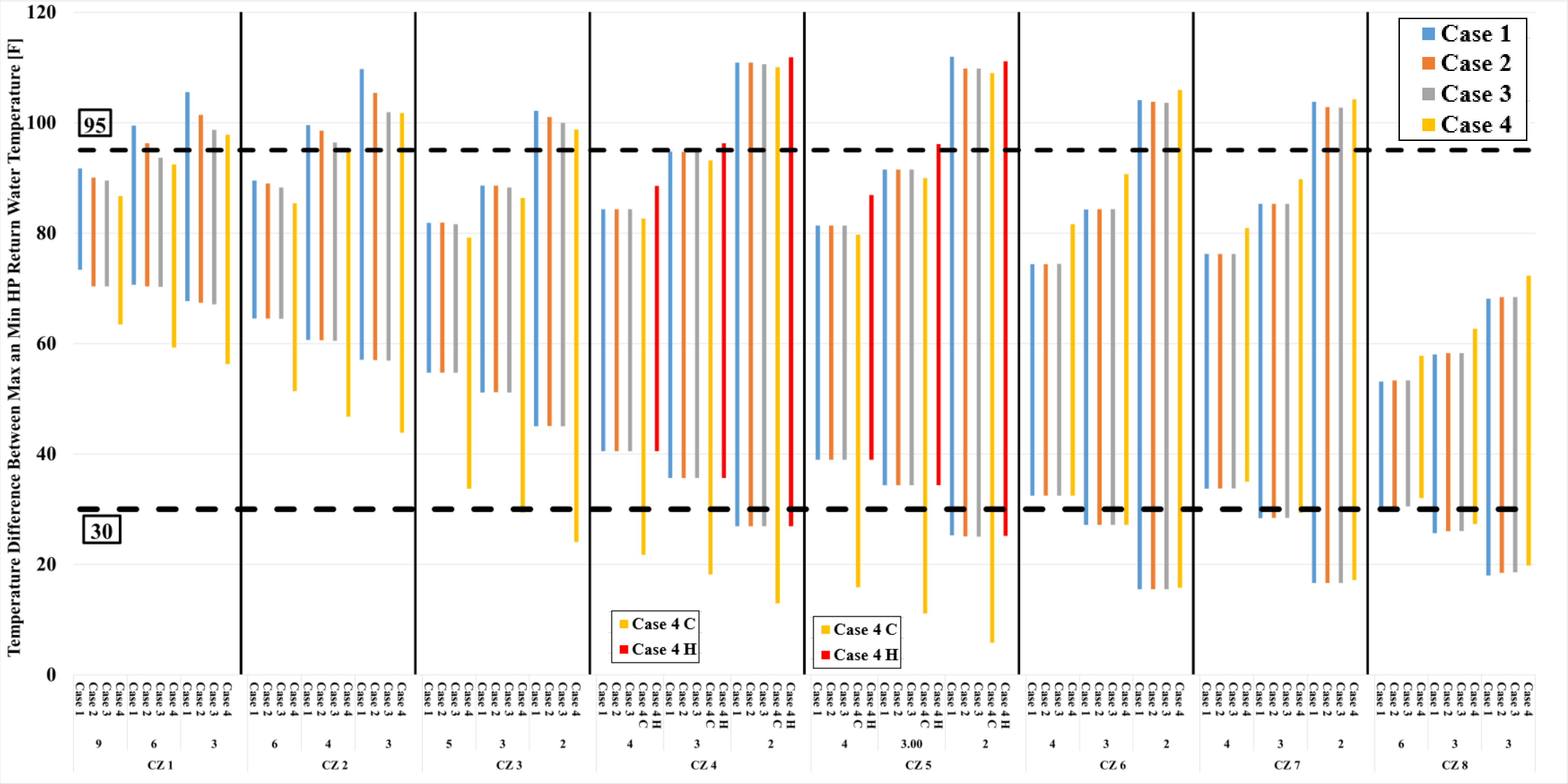


Figure 34. Max. and min. heat pump return water temperatures over 20 years

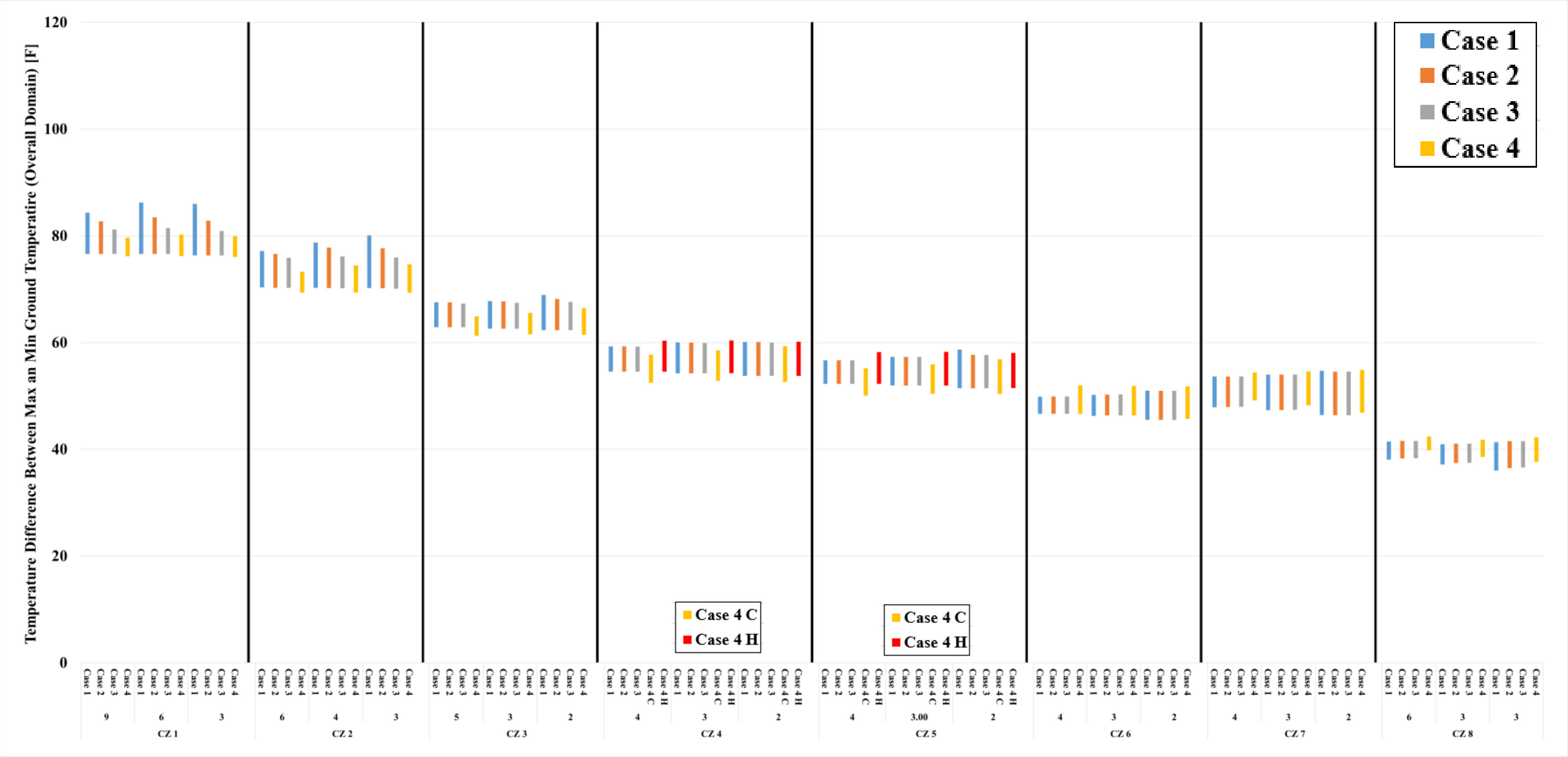


Figure 35. Max. and min. ground temperatures (overall underground domain) over 20 years

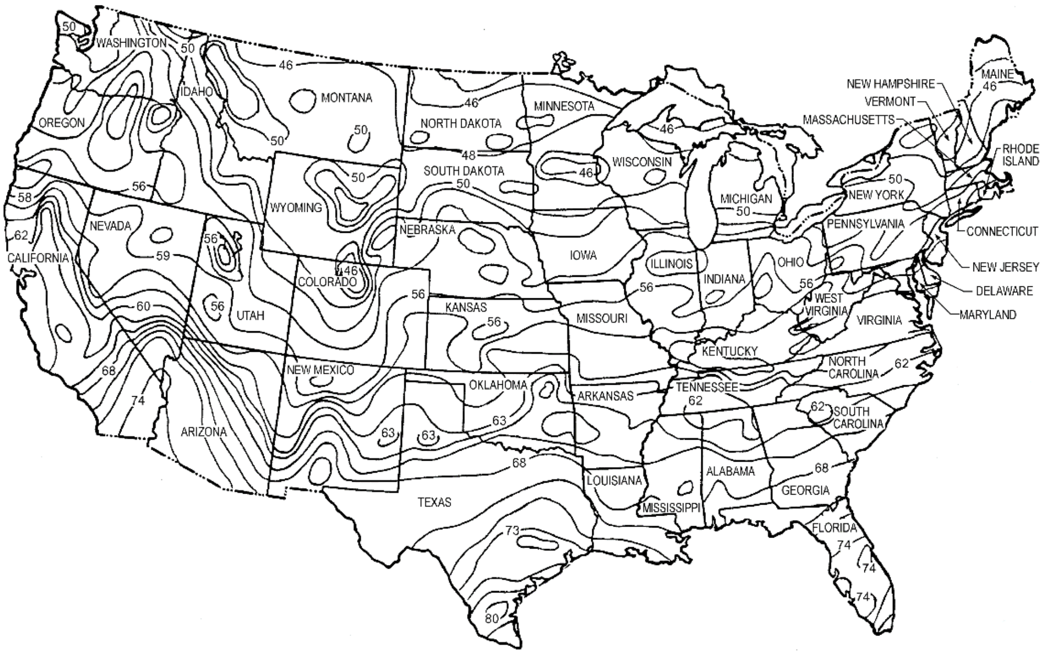


Figure 36. Approximate groundwater temperature (^{o}F) in the United States (ASHRAE Handbook, 2015)

Another observation from Figure 32 is that for hot climates (CZ-1 and 2), the heating COPs for Cases 2 and 3 are lower than those of Case 1. The reason for that is some of the building heat is released to the ambient air through the dry cooler instead of the ground, which makes the ground temperature slightly lower than that of Case 1, and thus negatively affects the heat pump heating COPs. Also, due to the lower ground temperature in Cases 2 and 3, the corresponding cooling EERs are higher than those of Case 1, as shown in Figure 33, for CZ-1 and 2. This may indicate that Mode 1, 2 and 3 are suitable for space cooling in hot climates but would do more harm than good for space heating in hot climates.

By comparing with other cases, lower heating COPs were observed in Figure 32 for Case 4 when cold is collected by the dry cooler and charged to the ground (CZ-1, 2, and 3), thus resulting in the lower ground and heat pump return water temperatures, as shown in Figures 34 and 35. When heat is collected and charged to the ground in cold climates, such as CZ-6, 7, and

8, higher heating COPs are achieved due to the warmer ground and heat pump return water temperatures (Figures 34 and 35). By comparing the results between the 1st and 20th year, it concludes that heating COPs increase after the 20-year operation for hot climate zones where the heat pump rejects more building heat to the ground during cooling seasons than that taken from the ground during heating seasons, so that the ground temperature becomes warmer and warmer. Nevertheless, the heating COPs decrease as the weather becomes colder, e.g., in CZ-6, 7, and 8, where the heat pump takes more heat during heating seasons from the ground than that rejected to the ground during cooling seasons and thus lower ground temperatures would be reached after 20-year operation. This can be seen in Appendix B from the monthly max. and min. ground temperatures (near boreholes or overall domain). These phenomena are especially prominent for Case 1. The charging mode (Mode 4 in Case 4) contributes to the balance of the ground temperature between heating and cooling by charging cold in hot climates and heat in cold climates, especially in extreme hot/cold climate zones, and thus the changes in heating COPs for this case are not significant. By looking at CZ-4 and 5, higher heating COPs are achieved when charging heat to the ground (red bars in Figure 32).

From Figure 32, it can also be concluded that for cold climate zones, when the borehole size is cut to 50%, the heating COPs among the four cases are very close to each other, which indicates that the effect of Mode 4 (Case 4) on the system heating performance is minimized as the decrease of the borehole length, because shorter boreholes mean a smaller underground volume that has less storage capacity for thermal energy.

Compared to heating COPs, nearly opposite conclusions were drawn for cooling EERs across the eight CZs. As shown in Figure 33, higher cooling EERs are achieved in cold climates, such as CZ-6, 7, and 8, due to the sufficient cold contained in the ambient air and ground in these climates, compared with hot climates. Additionally, cooling EERs decrease as the borehole size is reduced. The results of Cases 2 and 3 are very close to those of Case 1 for cold climates, indicating that Modes 1, 2 and 3 (Figure 25) do not help much in increasing system performance in these zones for space cooling. They, however, contribute to the increase of cooling performance of a system used in hot climates, such as CZ- 1 and 2, especially when shorter borehole lengths are used. Lower cooling EERs were observed for Case 4 when heat is collected by the dry cooler and charged to the ground, such as in CZ-6, 7, and 8, compared with other cases, which leads to higher ground and heat pump return water temperatures, as shown in Figures 34 and 35. When cold is collected and charged to the ground in hot/warm climates, such as CZ-1, 2, and 3, higher cooling EERs are achieved for Case 4 due to the cooler ground and heat pump return water (Figures 34 and 35). By comparing the results between the 1st and 20th year, it concludes that cooling EERs increase after 20-year operation in cold climate zones where the heat pump takes more heat during heating seasons from the ground than that rejected to the ground during cooling seasons and thus the ground temperature becomes colder and colder. Nevertheless, the cooling EERs decrease as the weather becomes warmer, e.g., in CZ-1, 2, and 3, where the heat pump rejects more building heat to the ground during cooling seasons than that taken from the ground during heating seasons, so that higher ground temperatures would be reached. This can be seen in Appendix B from the monthly max. and min. ground temperatures (near boreholes or overall domain). These phenomena are especially prominent for Case 1. The charging mode (Mode 4 in Case 4) contributes to the balance of the ground temperature between heating and cooling, especially in extreme hot/cold climates, and thus the changes in cooling EERs for this case are not significant. By looking at CZ-4 and 5, higher cooling EERs are achieved when charging cold to the ground (yellow bars in Figure 33).

Figure 34 shows the ranges between the max. and min. heat pump return water temperatures over the course of 20 years for different cases in various CZs, and the corresponding ground temperature result (overall underground domain) is shown in Figure 35. It is clear that the heat pump return water or ground temperatures decrease as the weather becomes colder from CZ-1 to 8. As the reduction of the borehole size, the differences between the max. and min. return water temperatures are enlarged, which indicates that the capacity for thermal energy storage is reduced when shorter boreholes are used due to the smaller underground volume/domain.

In hot climates (e.g., CZ-1 and 2), where the building is cooling-dominated, the max. return water or ground temperatures decrease as the advanced control strategies are used in Cases 2, 3, and 4, and lower min. return or ground temperatures were observed for Case 4, where cold is collected by using the dry fluid cooler and then transferred to the underground region. The effects of Modes 1, 2, and 3 in Cases 2 and 3 on the system performance are minimized as the weather becomes colder. For Mode 4 in Case 4, the effectiveness of charging cold in hot climates is more significant than that of charging heat in cold climates. The primary reason for that is there is no too much heat that can be extracted from the ambient air by using a dry fluid cooler in cold climates, whereas the cool/cold summer nights of hot/warm climates are an ideal source for the dry fluid cooler to collect and convey cold to the warm ground for space cooling. Higher and lower heat pump return water or ground temperatures were observed in Figures 34 or 35 depending on the use of the dry fluid cooler to collect either heat or cold, respectively, in CZ-4 and 5.

3.3.1.2. Overall System Performance

The annual system energy consumption (left axis) with its associated energy cost (right axis) for multiple years (20 years) is shown in Appendix B, where the total energy usage includes the energy consumption of the heat pump unit, the water pump(s), and the dry fluid cooler if used, and the energy cost was determined based on the average electricity retail price (EIA, 2020) in each specified location, as shown in Table 11. Table 9 details the energy and energy cost results for the 1st and 20th year, as well as the total for 20 years.

To clearly explain the energy consumption results, Figure 37 was generated to demonstrate and compare the energy-saving potentials between the 1st and 20th year of the GSHP system used in the eight CZs under different control modes/cases. These energy-saving percentages were determined based on the system energy consumption result of Case 1 in their corresponding year.

As shown in Figure 37, in cold climates, such as CZ-6, 7, and 8, reducing the borehole size, especially with about 50% reduction, would cause energy penalties in cooling and heating. The percentage for the cooling energy penalty is greater than the heating's, but since the majority of energy is consumed by the GSHP system for space heating, the percentage related to the total energy penalty is not as high as that for space cooling. Charging heat to the ground (Case 4) will further increase the cooling penalty, especially when shorter borehole lengths are involved. The heating penalty, however, is slightly decreased compared to other cases, due to the charge of heat to the underground region, which makes the total penalty percentage nearly unchanged when the borehole length is kept the same among Cases 1 ~ 4. By comparing the results between the 1st and 20th year, most of the total energy penalties for CZ-6, 7, and 8 are slightly decreased (or nearly unchanged in CZ-6) after the 20-year operation, especially when advanced control strategies (Cases 2, 3 and 4) are used, indicating that these control strategies contribute to increasing or maintaining GSHP system's efficiency in the long run. Nevertheless, the effects of these control strategies along with the use of a dry fluid cooler in the cold climates on the system energy-saving potential are not significant, as shown in Figure 37. This implies that 1) not too much heat is contained in the ambient air, especially during winter in these climates, which cannot be effectively collected by using a dry fluid cooler, and/or 2) a single dry cooler is probably not enough to collect sufficient heat from the ambient air to achieve decent energy savings. The potential solutions are to use multiple dry coolers connected together in either series or parallel and/or to use a solar thermal collector(s) instead of a dry cooler in these cold climate regions, which are expected to collect more heat not from the ambient air but the sun, especially during cold winter days.

So, let's look at the results for hot/warm climates in Figure 37, such as CZ-1, 2, and 3. The effectiveness of using the dry cooler is evident , especially for CZ-1, whose savings are around 2.5 % for space cooling and 2.3% for total energy (Case 1 vs. Case 4) during the 1st year if the borehole size remains the same, and after the 20-year operation, the savings are increased and are as high as around 8% for space cooling and 7.4% for total energy. Positive energy savings are still achieved when shorter boreholes are used, especially for Cases 3 and 4, which demonstrates the effectiveness of using the dry cooler with the advanced control strategies (Mode 3 and/or 4) in hot climates. It is also clear to see that a conventional GSHP system (Case 1) would consume more energy after the 20-year operation. The use of a dry cooler with the associated controls (Cases 2, 3, and 4), however, increases the energy-saving potential, especially for Case 4 and in CZ-1, indicating that these control strategies with the use of a dry cooler contribute to increasing GSHP system's efficiency in the long-run in hot climates.

Table 9. Energy consumption and cost

Parameters		CZ-1												CZ-2											
		Miami												New Orleans											
Number of Boreholes		9				6				3 (300 ft)				6				4				3			
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Total Energy Consumption [MMBtu]	1st year	25.9	26.3	26.0	26.2	27.4	27.6	26.8	26.9	29.1	29.1	27.5	27.4	21.3	21.6	20.7	21.5	22.8	23.0	21.8	22.5	24.6	24.5	22.7	23.5
	20th year	27.5	27.3	26.6	26.6	29.7	28.6	27.2	27.2	31.5	29.6	27.6	27.6	22.0	22.2	21.2	21.7	23.8	23.6	22.0	22.7	25.8	24.9	22.7	23.6
	20-year total	541	542	529	530	580	567	542	543	616	590	552	550	437	441	422	434	470	470	439	453	510	496	454	472
Heat Pump Cooling Energy Consumption [MMBtu]	1st year	23.7	23.6	23.3	23.1	25.1	24.9	24.0	23.7	26.8	26.2	24.5	24.2	16.3	16.2	15.7	15.6	17.7	17.6	16.7	16.6	19.4	18.9	17.5	17.4
	20th year	25.2	24.3	23.7	23.3	27.4	25.4	24.2	23.8	29.1	26.3	24.5	24.1	17.0	16.8	16.1	15.7	18.7	18.1	16.8	16.7	20.7	19.1	17.4	17.3
	20-year total	495	483	472	465	534	506	483	476	570	526	490	482	337	333	321	314	369	360	335	333	408	381	348	346
Heat Pump Heating Energy Consumption [MMBtu]	1st year	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.9	4.0	3.8	3.8	4.0	4.0	3.8	3.9	4.0	4.0	3.9	4.0
	20th year	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.9	3.9	3.8	3.8	3.9	3.9	3.8	3.9	3.9	4.0	3.9	4.0
	20-year total	19.4	19.6	19.6	19.9	19.5	19.5	19.6	20.1	19.5	19.7	19.9	20.2	78.1	78.5	75.7	76.9	78.4	78.6	76.4	77.6	79.2	79.8	77.2	78.9
Water Pump Energy Consumption [MMBtu]	1st year	1.3	1.6	1.3	1.3	1.3	1.6	1.3	1.3	1.3	1.6	1.3	1.3	1.1	1.4	1.1	1.1	1.1	1.4	1.1	1.1	1.1	1.4	1.1	1.1
	20th year	1.3	1.6	1.3	1.3	1.3	1.6	1.3	1.3	1.3	1.6	1.3	1.3	1.1	1.4	1.1	1.1	1.1	1.4	1.1	1.1	1.2	1.4	1.1	1.1
	20-year total	25.8	32.0	25.4	25.3	26.3	32.4	25.6	25.5	26.8	32.8	25.7	25.6	22.0	27.5	21.4	21.4	22.5	28.0	21.6	21.7	23.1	28.6	21.9	22.1
Dry Cooler Energy Consumption [MMBtu]	1st year	0.0	0.1	0.4	0.8	0.0	0.2	0.5	0.9	0.0	0.2	0.6	1.0	0.0	0.1	0.1	1.0	0.0	0.1	0.2	0.9	0.0	0.2	0.3	1.1
	20th year	0.0	0.4	0.6	1.1	0.0	0.6	0.8	1.1	0.0	0.7	0.9	1.2	0.0	0.1	0.2	1.1	0.0	0.2	0.3	1.1	0.0	0.4	0.4	1.2
	20-year total	0.0	7.1	11.8	20.7	0.0	10.0	13.9	21.5	0.0	11.9	16.2	22.4	0.0	2.3	3.6	21.3	0.0	3.4	5.9	20.9	0.0	6.5	6.9	24.3
Electricity Consumption [MWh]	1st year	7.6	7.7	7.6	7.7	8.0	8.1	7.8	7.9	8.5	8.5	8.0	8.0	6.2	6.3	6.1	6.3	6.7	6.8	6.4	6.6	7.2	7.2	6.7	6.9
	20th year	8.1	8.0	7.8	7.8	8.7	8.4	8.0	8.0	9.2	8.7	8.1	8.1	6.5	6.5	6.2	6.4	7.0	6.9	6.4	6.7	7.6	7.3	6.7	6.9
	20-year total	158	159	155	155	170	166	159	159	181	173	162	161	128	129	124	127	138	138	129	133	149	145	133	138
Electricity Cost [$*1,000]	1st year	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.5
	20th year	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.8	1.0	0.9	0.8	0.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.5
	20-year total	16.5	16.6	16.2	16.2	17.8	17.4	16.6	16.6	18.8	18.1	16.9	16.8	9.9	10.0	9.5	9.8	10.6	10.6	9.9	10.2	11.5	11.2	10.3	10.7

Parameters		CZ-3												CZ-4														
		Atlanta												Kansas City														
Number of Boreholes		5				3 (250 ft)				2 (250 ft)				4					3					2				
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4C	4H
Total Energy Consumption [MMBtu]	1st year	18.1	18.3	18.0	19.1	18.8	19.1	18.8	19.6	20.4	20.6	20.0	20.8	26.2	26.2	26.3	27.1	26.8	27.5	27.5	27.5	28.3	27.8	29.9	30.1	29.9	30.8	30.1
	20th year	18.3	18.5	18.2	18.9	19.0	19.3	18.9	19.6	20.6	20.7	20.0	20.9	26.3	26.3	26.3	27.0	26.7	27.5	27.5	27.5	28.2	27.8	30.0	30.1	30.0	30.8	30.1
	20-year total	365	370	364	380	380	385	378	392	411	413	400	418	526	526	526	540	535	551	551	551	565	556	600	602	600	617	602
Heat Pump Cooling Energy Consumption [MMBtu]	1st year	10.3	10.3	10.3	10.2	11.0	11.0	10.9	10.8	12.4	12.2	11.9	11.8	10.3	10.3	10.3	10.2	10.5	11.3	11.3	11.3	11.2	11.4	13.2	13.2	13.1	13.1	13.2
	20th year	10.6	10.5	10.5	10.1	11.2	11.2	11.1	10.8	12.6	12.4	11.9	11.8	10.4	10.4	10.4	10.1	10.6	11.4	11.4	11.4	11.1	11.5	13.3	13.3	13.2	13.1	13.2
	20-year total	210	210	209	204	223	223	221	217	251	247	239	237	208	208	208	203	212	228	228	227	223	229	266	266	264	262	265
Heat Pump Heating Energy Consumption [MMBtu]	1st year	6.8	6.8	6.8	6.9	6.9	6.9	6.9	6.9	7.0	7.0	6.9	6.9	14.7	14.7	14.7	14.9	14.7	14.9	14.9	14.9	15.1	14.9	15.3	15.3	15.3	15.4	15.3
	20th year	6.7	6.7	6.7	6.9	6.8	6.8	6.8	6.9	6.9	6.9	6.9	7.0	14.6	14.6	14.6	14.9	14.6	14.8	14.8	14.8	15.1	14.8	15.3	15.3	15.3	15.4	15.3
	20-year total	135	135	135	137	136	136	137	138	138	139	138	139	293	293	293	298	293	297	297	297	302	297	306	306	306	308	306
Water Pump Energy Consumption [MMBtu]	1st year	1.0	1.2	1.0	1.0	1.0	1.3	1.0	1.0	1.1	1.3	1.0	1.1	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4
	20th year	1.0	1.2	1.0	1.0	1.0	1.3	1.0	1.0	1.0	1.3	1.0	1.1	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4
	20-year total	20.0	25.0	20.0	20.1	20.3	25.4	20.3	20.5	21.0	26.2	20.9	21.0	25.5	25.5	25.5	26.0	25.6	26.4	26.4	26.4	26.8	26.4	27.8	27.8	27.8	28.0	27.8
Dry Cooler Energy Consumption [MMBtu]	1st year	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.8	0.0	0.1	0.1	1.0	0.0	0.0	0.0	0.7	0.3	0.0	0.0	0.0	0.6	0.2	0.0	0.1	0.1	1.0	0.2
	20th year	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.8	0.0	0.1	0.1	1.1	0.0	0.0	0.0	0.7	0.2	0.0	0.0	0.0	0.6	0.1	0.0	0.1	0.1	0.9	0.2
	20-year total	0.0	0.0	0.4	18.5	0.0	0.1	0.7	16.6	0.0	1.6	2.2	21.0	0.0	0.0	0.1	13.6	5.2	0.0	0.1	0.2	12.3	3.1	0.0	2.5	2.3	19.0	3.9
Electricity Consumption [MWh]	1st year	5.3	5.4	5.3	5.6	5.5	5.6	5.5	5.7	6.0	6.0	5.9	6.1	7.7	7.7	7.7	7.9	7.9	8.1	8.1	8.1	8.3	8.1	8.8	8.8	8.8	9.0	8.8
	20th year	5.4	5.4	5.3	5.5	5.6	5.6	5.5	5.7	6.0	6.1	5.9	6.1	7.7	7.7	7.7	7.9	7.8	8.1	8.1	8.1	8.3	8.1	8.8	8.8	8.8	9.0	8.8
	20-year total	107	108	107	111	111	113	111	115	120	121	117	123	154	154	154	158	157	162	162	161	165	163	176	177	176	181	177
Electricity Cost [$*1,000]	1st year	0.5	0.5	0.5	0.6	0.5	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.9	0.9	0.9	0.9	0.9
	20th year	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9
	20-year total	10.5	10.7	10.5	11.0	11.0	11.1	10.9	11.3	11.9	11.9	11.6	12.1	15.8	15.8	15.8	16.2	16.1	16.6	16.6	16.6	17.0	16.7	18.0	18.1	18.0	18.5	18.1

Table 9. Energy consumption and cost (continued)

Parameters		CZ-5															CZ-6											
		Omaha															Minneapolis											
Number of Boreholes		4					3					2					4				3				2			
Case		1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4	1	2	3	4	1	2	3	4
Total Energy Consumption [MMBtu]	1st year	24.7	24.7	24.7	25.5	25.2	25.7	25.8	25.7	26.6	26.1	28.5	28.2	28.1	28.8	28.2	25.5	25.5	25.5	26.3	26.5	26.6	26.6	27.2	28.1	28.1	28.1	28.6
	20th year	24.8	24.8	24.8	25.5	25.1	25.9	25.9	25.9	26.6	26.1	28.6	28.2	28.2	28.8	28.2	25.4	25.5	25.5	26.1	26.4	26.5	26.5	27.1	28.1	28.1	28.0	28.6
	20-year total	495	495	495	511	502	517	517	517	532	521	572	565	563	576	564	509	510	510	523	530	530	531	542	562	562	561	572
Heat Pump Cooling Energy Consumption [MMBtu]	1st year	8.9	8.9	8.9	8.8	9.1	9.7	9.7	9.7	9.6	9.9	11.9	11.5	11.5	11.4	11.6	6.6	6.6	6.6	6.8	7.2	7.2	7.2	7.4	8.5	8.4	8.4	8.6
	20th year	9.0	9.0	9.0	8.7	9.2	9.9	9.9	9.9	9.7	10.1	12.1	11.6	11.5	11.4	11.7	6.6	6.6	6.6	6.9	7.1	7.1	7.1	7.4	8.4	8.4	8.4	8.6
	20-year total	179	179	179	175	184	197	197	197	193	200	241	232	230	228	233	131	131	132	137	143	143	143	148	169	169	168	173
Heat Pump Heating Energy Consumption [MMBtu]	1st year	14.6	14.6	14.6	14.8	14.6	14.8	14.8	14.8	15.0	14.8	15.3	15.3	15.2	15.3	15.3	17.7	17.7	17.7	17.6	18.1	18.1	18.1	18.0	18.3	18.3	18.3	18.2
	20th year	14.6	14.6	14.6	14.9	14.5	14.8	14.8	14.8	15.1	14.7	15.2	15.2	15.2	15.3	15.2	17.6	17.6	17.6	17.5	18.0	18.0	18.0	17.9	18.3	18.3	18.3	18.3
	20-year total	292	292	292	297	291	296	296	296	301	295	304	305	305	305	304	353	353	353	351	361	361	361	359	366	366	366	365
Water Pump Energy Consumption [MMBtu]	1st year	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	20th year	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	20-year total	24.1	24.1	24.1	24.6	24.1	24.9	24.9	24.9	25.3	24.9	26.4	26.3	26.2	26.3	26.3	25.0	25.0	25.0	24.9	25.8	25.8	25.8	25.8	26.7	26.7	26.7	26.7
Dry Cooler Energy Consumption [MMBtu]	1st year	0.0	0.0	0.0	0.7	0.4	0.0	0.0	0.0	0.6	0.3	0.0	0.1	0.1	0.8	0.3	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.4
	20th year	0.0	0.0	0.0	0.7	0.3	0.0	0.0	0.0	0.6	0.2	0.0	0.1	0.1	0.8	0.2	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.3
	20-year total	0.0	0.1	0.1	14.0	7.3	0.0	0.1	0.1	12.4	5.2	0.0	1.5	1.5	16.0	4.8	0.0	0.5	0.6	10.5	0.0	0.5	0.5	8.9	0.0	0.5	0.7	6.8
Electricity Consumption [MWh]	1st year	7.2	7.2	7.2	7.5	7.4	7.5	7.6	7.5	7.8	7.6	8.4	8.3	8.2	8.4	8.3	7.5	7.5	7.5	7.7	7.8	7.8	7.8	8.0	8.2	8.2	8.2	8.4
	20th year	7.3	7.3	7.3	7.5	7.4	7.6	7.6	7.6	7.8	7.6	8.4	8.3	8.3	8.4	8.3	7.5	7.5	7.5	7.7	7.8	7.8	7.8	7.9	8.2	8.2	8.2	8.4
	20-year total	145	145	145	150	147	152	152	152	156	153	168	166	165	169	165	149	150	150	153	155	155	156	159	165	165	164	168
Electricity Cost [$*1,000]	1st year	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.9
	20th year	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.9
	20-year total	13.2	13.2	13.2	13.6	13.4	13.8	13.8	13.8	14.2	13.9	15.2	15.0	15.0	15.3	15.0	15.4	15.4	15.4	15.8	16.0	16.1	16.1	16.4	17.0	17.0	17.0	17.3

Parameters		CZ-7												CZ-8											
		Bismarck												Anchorage											
Number of Boreholes		4				3				2				6				3 (300 ft)				3 (200 ft)			
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Total Energy Consumption [MMBtu]	1st year	27.2	27.3	27.3	27.7	28.1	28.1	28.1	28.5	29.8	29.8	29.8	30.0	24.3	24.3	24.4	24.8	24.7	24.7	24.7	25.2	24.9	25.0	25.0	25.4
	20th year	27.3	27.4	27.3	27.8	28.2	28.2	28.2	28.7	29.5	29.6	29.6	30.0	24.5	24.6	24.5	24.9	24.8	24.9	24.9	25.3	24.9	25.0	25.0	25.5
	20-year total	545	546	546	555	563	563	563	572	593	594	593	600	488	489	489	496	495	497	496	505	499	499	499	508
Heat Pump Cooling Energy Consumption [MMBtu]	1st year	6.3	6.4	6.3	6.5	6.8	6.8	6.8	7.0	8.0	7.9	7.9	8.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.7
	20th year	6.1	6.1	6.1	6.4	6.6	6.6	6.6	6.9	7.7	7.7	7.7	7.8	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.7
	20-year total	124	124	124	128	134	134	134	138	156	156	155	158	29	29	29	30	30	30	30	31	32	33	33	34
Heat Pump Heating Energy Consumption [MMBtu]	1st year	19.6	19.6	19.6	19.6	19.9	19.9	19.9	19.9	20.4	20.4	20.4	20.4	21.7	21.6	21.6	21.6	22.0	22.0	21.9	21.9	22.1	22.1	22.1	22.0
	20th year	19.9	19.9	19.8	19.7	20.2	20.2	20.2	20.1	20.4	20.5	20.5	20.5	21.9	21.8	21.8	21.6	22.1	22.1	22.0	22.0	22.2	22.0	22.0	22.0
	20-year total	395	395	395	393	402	402	402	401	409	409	409	409	436	435	435	432	442	441	440	439	443	441	440	440
Water Pump Energy Consumption [MMBtu]	1st year	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	20th year	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	20-year total	26.4	26.4	26.4	26.3	27.2	27.2	27.2	27.2	28.2	28.2	28.1	28.2	22.8	22.7	22.7	22.5	23.3	23.2	23.2	23.1	23.4	23.2	23.2	23.2
Dry Cooler Energy Consumption [MMBtu]	1st year	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.0	0.1	0.1	0.6	0.0	0.1	0.1	0.5	0.0	0.1	0.1	0.5
	20th year	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.1	0.1	0.6	0.0	0.1	0.1	0.6	0.0	0.2	0.2	0.6
	20-year total	0.0	0.4	0.4	7.4	0.0	0.2	0.3	6.1	0.0	0.4	0.5	5.0	0.0	2.1	2.3	11.6	0.0	2.4	2.6	12.0	0.0	2.7	2.9	11.4
Electricity Consumption [MWh]	1st year	8.0	8.0	8.0	8.1	8.2	8.2	8.2	8.4	8.7	8.7	8.7	8.8	7.1	7.1	7.1	7.3	7.2	7.3	7.2	7.4	7.3	7.3	7.3	7.4
	20th year	8.0	8.0	8.0	8.1	8.3	8.3	8.3	8.4	8.7	8.7	8.7	8.8	7.2	7.2	7.2	7.3	7.3	7.3	7.3	7.4	7.3	7.3	7.3	7.5
	20-year total	160	160	160	163	165	165	165	168	174	174	174	176	143	143	143	145	145	146	145	148	146	146	146	149
Electricity Cost [$*1,000]	1st year	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	20th year	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	20-year total	14.1	14.2	14.2	14.4	14.6	14.6	14.6	14.8	15.4	15.4	15.4	15.6	28.9	29.0	29.0	29.4	29.4	29.4	29.4	29.9	29.5	29.6	29.6	30.1

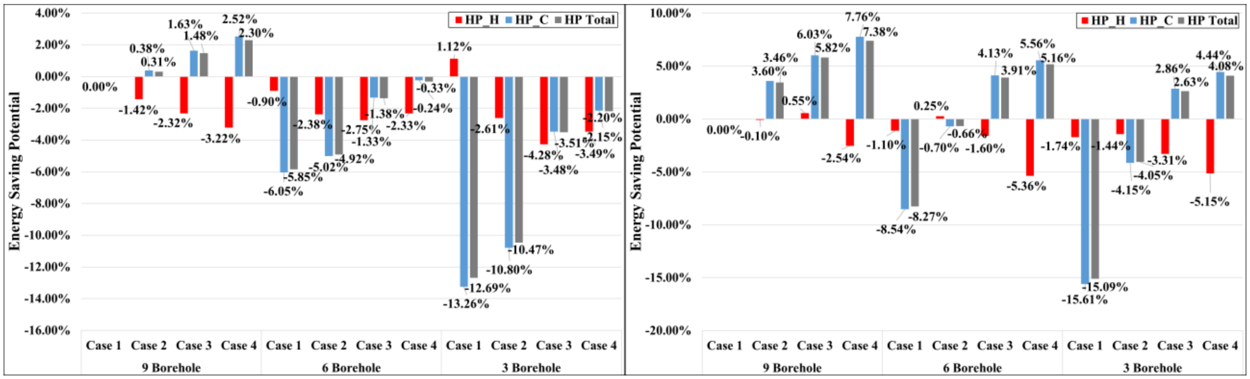
Table 10. Simulation result summary

Parameters		**CZ-1**												**CZ-2**											
		Miami												**New Orleans**											
Number of Boreholes		9				6				3 (300 ft)				6				4				3			
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Max Return Water Temperature [F]		91.7	90.0	89.5	86.7	99.4	96.3	93.6	92.4	106	101	99	97.8	89.5	89.0	88.3	85.4	99.6	98.5	96.4	94.8	110	105	102	102
Min Return Water Temperature [F]		73.3	70.4	70.3	63.5	70.6	70.4	70.2	59.3	67.7	67.4	67.1	56.3	64.5	64.5	64.4	51.4	60.6	60.6	60.5	46.7	57.0	57.0	56.9	43.8
Max. Ground Temperature (Overall Domain) [F]		84.3	82.7	81.2	79.6	86.2	83.5	81.5	80.2	86.0	82.8	80.9	79.9	77.1	76.6	75.9	73.3	78.7	77.8	76.1	74.5	80.1	77.7	75.9	74.6
Min. Ground Temperature (Overall Domain) [F]		76.6	76.6	76.6	76.2	76.6	76.6	76.6	76.2	76.3	76.3	76.3	76.0	70.3	70.3	70.2	69.3	70.3	70.2	70.2	69.4	70.2	70.1	70.1	69.4
Heating COP	1st year	3.7	3.7	3.7	3.6	3.7	3.7	3.6	3.6	3.6	3.6	3.6	3.5	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.3
	20th year	3.8	3.8	3.7	3.7	3.8	3.7	3.7	3.6	3.7	3.7	3.6	3.5	3.7	3.6	3.6	3.5	3.6	3.6	3.5	3.4	3.5	3.5	3.4	3.3
	20-year total	3.8	3.8	3.8	3.7	3.8	3.7	3.7	3.6	3.7	3.7	3.6	3.5	3.7	3.7	3.7	3.5	3.6	3.6	3.6	3.4	3.5	3.5	3.4	3.3
Cooling EER	1st year	12.0	12.1	12.3	12.4	11.2	11.4	11.9	12.0	10.4	10.7	11.6	11.8	12.6	12.6	12.7	12.9	11.4	11.6	11.9	12.0	10.3	10.7	11.4	11.5
	20th year	11.4	11.8	12.1	12.3	10.5	11.2	11.8	12.0	9.8	10.8	11.6	11.8	12.1	12.3	12.5	12.8	10.9	11.3	11.9	12.0	9.7	10.6	11.5	11.6
	20-year total	11.2	11.7	12.0	12.3	10.2	11.2	11.8	12.0	9.5	10.8	11.6	11.8	12.0	12.2	12.4	12.8	10.7	11.2	11.9	12.0	9.5	10.6	11.5	11.6

Parameters		**CZ-3**												**CZ-4**														
		Atlanta												**Kansas City**														
Number of Boreholes		5				3 (250 ft)				2 (250 ft)				4					3					2				
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4C	4H
Max Return Water Temperature [F]		81.8	81.9	81.6	79.2	88.6	88.6	88.3	86.3	102	101	99.9	98.7	84.3	84.3	84.3	82.6	88.5	94.7	94.7	94.6	93.1	96.2	111	111	111	110.0	112
Min Return Water Temperature [F]		54.7	54.7	54.7	33.7	51.1	51.2	51.1	29.4	45.0	45.1	45.0	24.1	40.5	40.5	40.5	21.7	40.5	35.6	35.6	35.6	18.2	35.6	26.9	26.9	26.9	12.9	26.9
Max. Ground Temperature (Overall Domain) [F]		67.5	67.5	67.3	64.9	67.7	67.7	67.4	65.6	68.9	68.2	67.6	66.5	59.3	59.3	59.3	57.7	60.3	60.0	60.0	59.9	58.5	60.4	60.1	60.1	60.0	59.3	60.2
Min. Ground Temperature (Overall Domain) [F]		62.9	62.9	62.9	61.3	62.6	62.6	62.6	61.5	62.3	62.3	62.3	61.4	54.5	54.5	54.5	52.4	54.5	54.2	54.2	54.2	52.8	54.3	53.8	53.8	53.8	52.6	53.8
Heating COP	1st year	3.6	3.6	3.6	3.5	3.6	3.6	3.6	3.5	3.4	3.4	3.4	3.4	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.1	2.9	2.9	2.9	2.9	2.9
	20th year	3.7	3.7	3.7	3.5	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.4	3.2	3.2	3.2	3.1	3.2	3.1	3.1	3.1	3.0	3.1	2.9	2.9	2.9	2.9	2.9
	20-year total	3.7	3.7	3.7	3.5	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.4	3.2	3.2	3.2	3.1	3.2	3.1	3.1	3.1	3.0	3.1	2.9	2.9	2.9	2.9	2.9
Cooling EER	1st year	13.7	13.7	13.7	13.9	12.8	12.8	12.9	13.0	11.1	11.3	11.7	11.6	13.1	13.1	13.1	13.2	12.8	11.8	11.8	11.9	11.9	11.7	9.9	9.9	10.0	10.0	10.0
	20th year	13.4	13.4	13.5	13.9	12.5	12.6	12.7	12.9	10.9	11.2	11.6	11.6	12.9	12.9	13.0	13.3	12.7	11.7	11.7	11.8	12.0	11.6	9.8	9.8	10.0	10.1	10.0
	20-year total	13.3	13.3	13.5	13.9	12.5	12.5	12.7	12.9	10.8	11.1	11.6	11.6	12.9	12.9	12.9	13.3	12.7	11.6	11.7	11.7	12.0	11.6	9.8	9.8	10.0	10.1	10.0

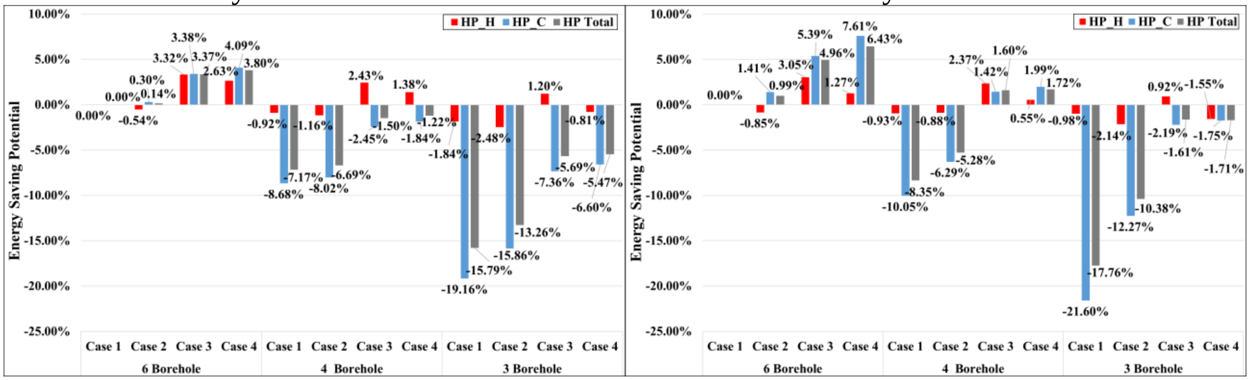
Parameters		**CZ-5**															**CZ-6**											
		Omaha															**Minneapolis**											
Number of Boreholes		4					3					2					4				3				2			
Case		1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4	1	2	3	4	1	2	3	4
Max Return Water Temperature [F]		81	81	81	80	87	91	91	91	90	96	74	74	74	82	84	84	84	91	104	104	104	106	74	74	74	82	84
Min Return Water Temperature [F]		38.9	38.9	38.9	15.8	38.9	34.3	34.3	34.3	11.1	34.3	32.4	32.4	32.4	32.4	27.1	27.1	27.1	27.1	15.5	15.5	15.5	15.7	32.4	32.4	32.4	32.4	27.1
Max. Ground Temperature (Overall Domain) [F]		56.7	56.7	56.7	55.2	58.2	57.3	57.3	57.3	55.9	58.2	49.8	49.9	49.9	52.0	50.2	50.3	50.3	51.8	51.0	51.0	50.9	51.8	49.8	49.9	49.9	52.0	50.2
Min. Ground Temperature (Overall Domain) [F]		52.3	52.3	52.3	50.1	52.3	51.9	51.9	51.9	50.4	52.0	46.6	46.7	46.7	46.7	46.3	46.3	46.3	46.3	45.5	45.5	45.5	45.7	46.6	46.7	46.7	46.7	46.3
Heating COP	1st year	3.1	3.1	3.1	3.0	3.1	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.8	2.8	2.8	2.8	3.0	3.0	3.0	3.0	2.9
	20th year	3.1	3.1	3.1	3.0	3.1	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.8	2.8	2.8	2.8	3.0	3.0	3.0	3.0	2.9
	20-year total	3.1	3.1	3.1	3.0	3.1	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.8	2.8	2.8	2.8	3.0	3.0	3.0	3.0	2.9
Cooling EER	1st year	13.5	13.5	13.5	13.6	13.1	12.2	12.2	12.2	12.3	12.0	14.5	14.5	14.5	14.0	13.2	13.2	13.2	12.7	10.8	10.9	11.0	10.7	14.5	14.5	14.5	14.0	13.2
	20th year	13.4	13.4	13.4	13.7	13.0	12.1	12.1	12.1	12.3	11.8	14.5	14.5	14.5	13.8	13.2	13.2	13.2	12.6	10.8	10.9	11.0	10.6	14.5	14.5	14.5	13.8	13.2
	20-year total	13.3	13.4	13.4	13.8	12.9	12.1	12.1	12.1	12.4	11.8	14.5	14.5	14.5	13.8	13.2	13.2	13.2	12.6	10.9	10.9	11.0	10.6	14.5	14.5	14.5	13.8	13.2

Parameters		**CZ-7**												**CZ-8**											
		Bismarck												**Anchorage**											
Number of Boreholes		4				3				2				6				3 (300 ft)				3 (200 ft)			
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Max Return Water Temperature [F]		76	76	76	81	85	85	85	90	104	103	103	104	53	53	53	58	58	58	58	63	68	68	68	72
Min Return Water Temperature [F]		33.7	33.7	33.7	34.9	28.3	28.4	28.4	29.3	16.6	16.6	16.6	17.1	30.2	30.5	30.5	32.0	25.7	26.0	26.0	27.3	18.0	18.5	18.5	19.8
Max. Ground Temperature (Overall Domain) [F]		53.6	53.6	53.6	54.4	54.0	54.0	54.0	54.6	54.7	54.5	54.5	54.8	41.4	41.6	41.6	42.4	40.9	41.0	41.1	41.8	41.3	41.5	41.5	42.2
Min. Ground Temperature (Overall Domain) [F]		47.9	47.9	47.9	49.2	47.3	47.4	47.4	48.2	46.4	46.4	46.4	46.8	38.0	38.3	38.3	39.8	37.1	37.4	37.5	38.6	36.0	36.5	36.6	37.6
Heating COP	1st year	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.8	2.9	2.9	2.9	2.8	2.8	2.8	2.8
	20th year	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.8	2.9	2.9	2.9	2.8	2.8	2.9	2.9
	20-year total	3.0	3.0	3.0	3.1	2.9	2.9	2.9	3.0	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.8	2.9	2.9	2.9	2.8	2.8	2.9	2.9
Cooling EER	1st year	13.9	13.8	13.9	13.5	12.6	12.6	12.6	12.3	10.4	10.5	10.6	10.5	17.3	17.2	17.2	16.8	16.5	16.5	16.5	16.0	14.7	14.8	14.7	14.2
	20th year	14.2	14.2	14.2	13.7	12.9	12.9	12.9	12.5	10.7	10.8	10.9	10.6	17.5	17.4	17.4	16.9	16.7	16.7	16.7	16.1	15.1	15.1	15.1	14.4
	20-year total	14.4	14.4	14.4	13.8	13.1	13.1	13.1	12.6	10.9	10.9	11.0	10.7	17.6	17.6	17.6	16.9	16.8	16.8	16.8	16.2	15.3	15.3	15.2	14.5



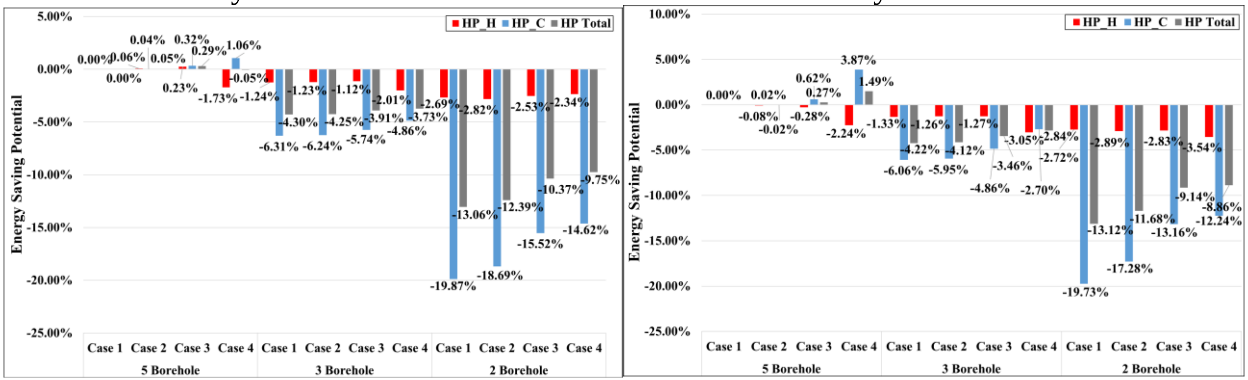
1st year of CZ-1

20th year of CZ-1



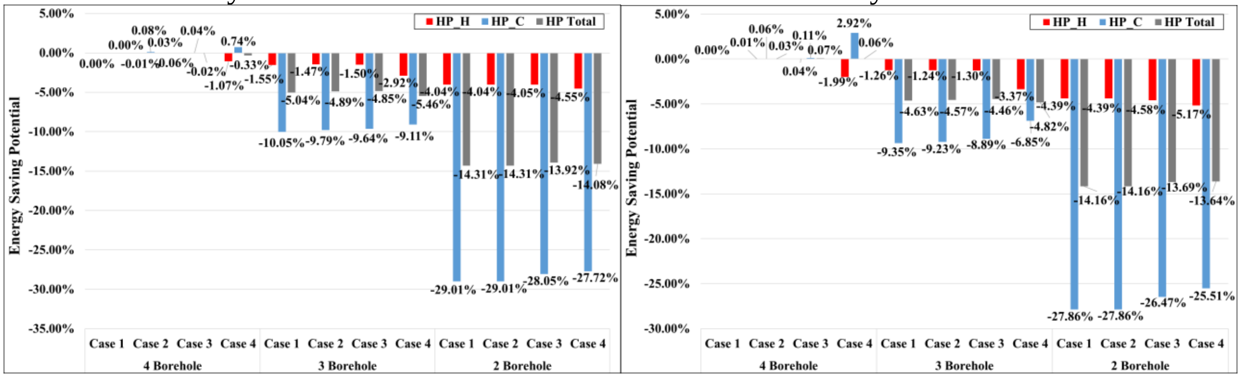
1st year of CZ-2

20th year of CZ-2



1st year of CZ-3

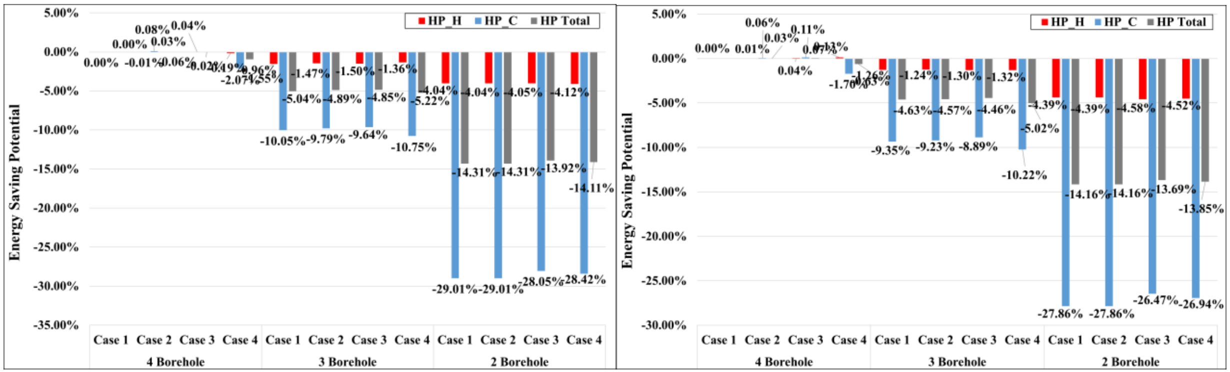
20th year of CZ-3



1st year of CZ-4 (Charge Cold)

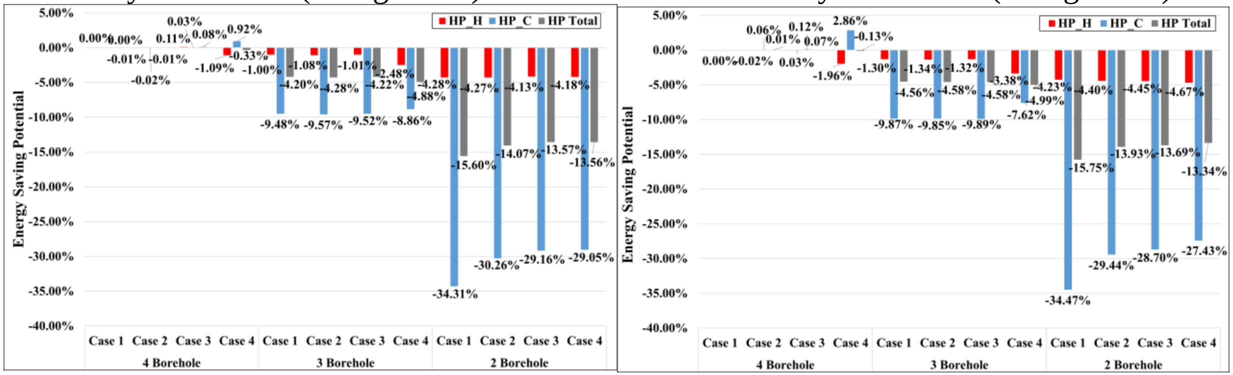
20th year of CZ-4 (Charge Cold)

Figure 37. Energy-saving potentials



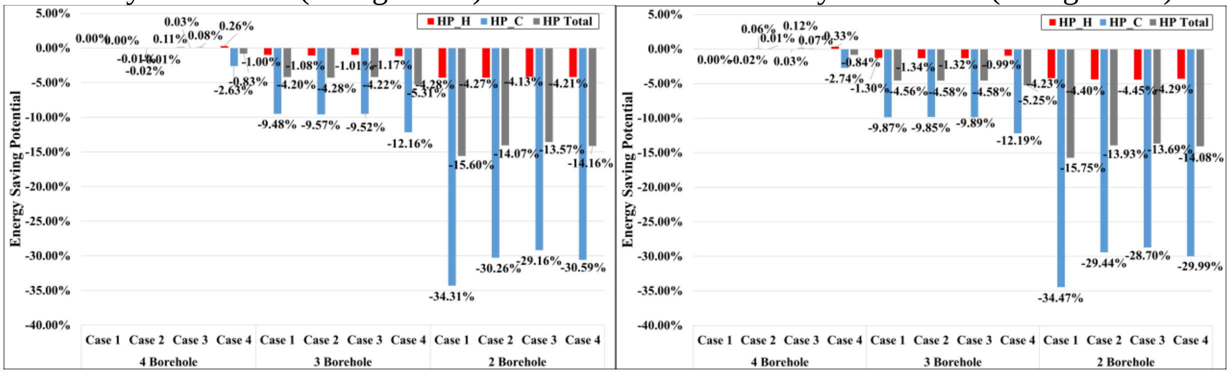
1st year of CZ-4 (Charge Heat)

20th year of CZ-4 (Charge Heat)



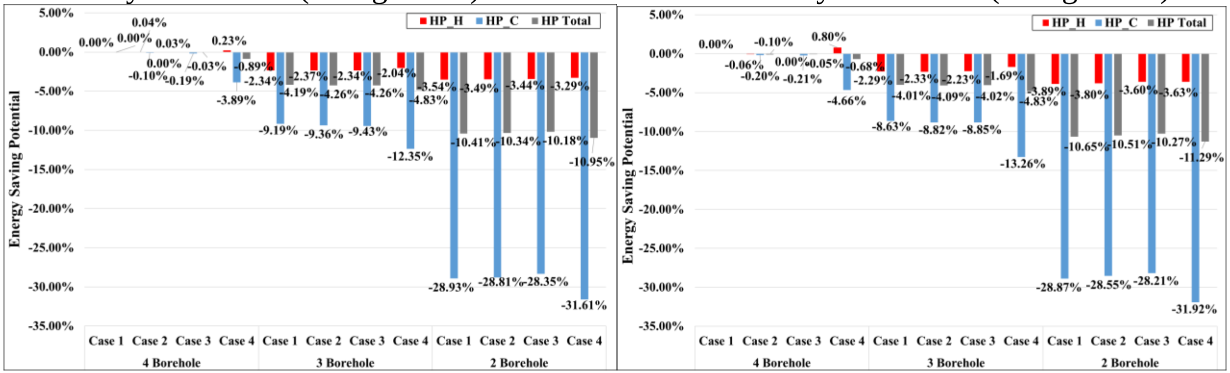
1st year of CZ-5 (Charge Cold)

20th year of CZ-5 (Charge Cold)



1st year of CZ-5 (Charge Heat)

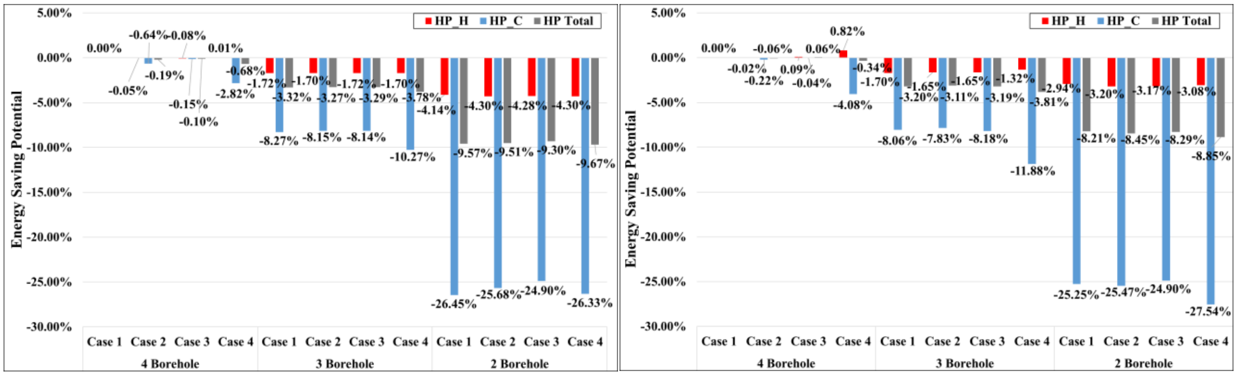
20th year of CZ-5 (Charge Heat)



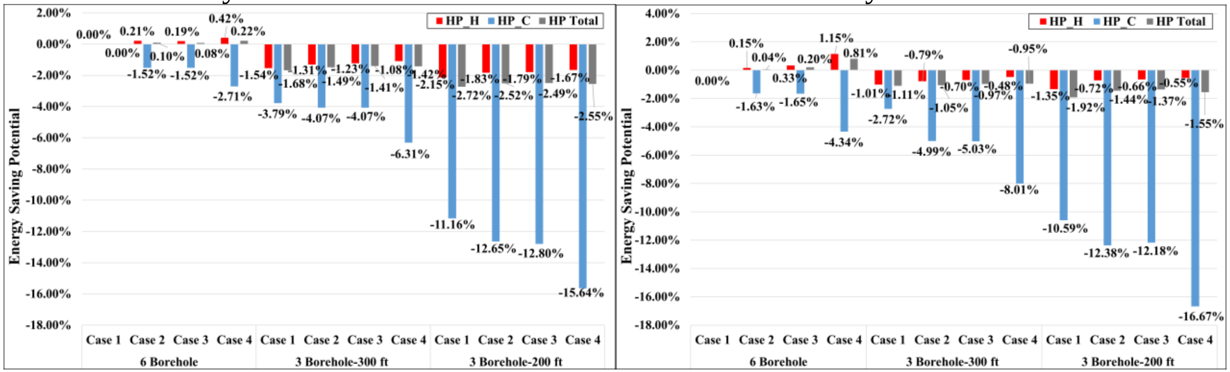
1st year of CZ-6

20th year of CZ-6

Figure 37. Energy-saving potentials (continued)



1st year of CZ-7 20th year of CZ-7



1st year of CZ-8 20th year of CZ-8

Figure 37. Energy-saving potentials (continued)

From the energy-saving point of view, it does not matter to charge either heat or cold to the ground in CZ-4 or 5, since their heating and cooling loads, as well as the associated heating and cooling operation hours, are nearly equal and can be well balanced to each other. Hence, no significant differences were observed in Figure 37 for these two climate zones.

3.3.2. Cost-Effectiveness Analysis

By considering the rule of thumb, i.e., a return water temperature between 30°F and 95°F is acceptable for a GSHP, the appropriate borehole sizes under each CZ can be determined, as shown in Figure 34 and Table 10, where the cases, whose return water temperatures are within the acceptable range, were highlighted in green in Table 10.

As shown in Table 10, for CZ-1, the system performance is still acceptable by looking at the max. and min. return water temperatures if the borehole size (the number of boreholes) is reduced from 9 to 6 when control modes of 3 and 4 (Cases 3 and 4) are involved. In particular, lower return water temperatures are achieved in Case 4, where the dry cooler is used for cold collection and storage. Control Mode 4 is still an acceptable control strategy for CZ-2 (Case 4) to reduce the borehole size without significantly compromising system performance. For CZ-3, 4, and 5, charging cold to the ground would make the ground and return water temperatures too cold (<30 ^{o}F) for space heating, and thus collecting and charging cold to the ground is not a good practice in these CZs for the specified building and system studied. Additionally, it is possible for the GSHP systems used in these three climate zones to reduce their original borehole sizes (e.g., from 5 to 3 boreholes in CZ-3 and from 4 to 3 in CZ-4 and 5) without using the dry cooler and advanced control modes (Case 1). This is due to the inconsistent simulation results (Montagud et al., 2011) (Ruiz-Calvo et al., 2017) obtained from TRNSYS and GLHEpro that is a popularly used tool by designers for fast GSHP system sizing and thus was used in the first place in the study to determine the borehole length. However, the more detailed results obtained by using TRNSYS, which can include the effect of various control strategies on the simulation results, indicate that shorter borehole lengths are still acceptable for the GSHP systems used in the warm/mild climate zones (CZ-3, 4, and 5). Nevertheless, TRNSYS simulations usually take more time and effort for model establishment and computation compared to GLHEpro and thus is typically not the first-choice tool for underground loop sizing of a GSHP system by HVAC designers.

For cold climates, such as CZ-6, 7, and 8, reducing the borehole size will make the minimum return water temperature too cold for space heating, even though a dry cooler and advanced control modes are used, and thus is not a suggested practice in these climates. The effectiveness of control modes 1, 2, 3 and 4 (Cases 2, 3, and 4) to raise minimum return water temperatures (Table 10) and maximize energy-saving potential (Figure 37) can be negligible due to the limited heat contained in the ambient environment in cold climates. Another way to collect heat in these climate zones from other sources, e.g., a solar thermal collector, would be plausible rather than a dry fluid cooler, which deserves additional studies in the future.

Table 12 shows the cost analysis result, where the initial costs, initial cost savings, and annual operating costs for each studied case are included, which were determined based on the cost information collected from various references (EIA, 2020) (Battocletti et al., 2013) (Dry Cooler, 2020) as shown in Table 11.

Table 11. Cost information used in the cost effectiveness analysis

CZ/City		**HP System (Battocletti et al., 2013) ($/ton)***	**Ground Loop (Battocletti et al., 2013) ($/ft)***	**Dry Fluid Cooler (Dry Cooler, 2020) ($/ton)**	**Electricity Rate (EIA, 2020) (cent/kWh)**
CZ-1	**Miami, Florida**	$ 6,077	$ 14.94	$ 544	10.44
CZ-2	**New Orleans, Louisiana**	$ 7,250	$ 14.94		7.71
CZ-3	**Atlanta, Georgia**	$ 6,077	$ 14.94		9.86
CZ-4	**Kansas City, Kansas**	$ 12,322	$ 14.94		10.26
CZ-5	**Omaha, Nebraska**	$ 4,809	$ 12.99		9.08
CZ-6	**Minneapolis, Minnesota**	$ 4,773	$ 12.99		10.33
CZ-7	**Bismarck, North Dakota**	$ 4,773	$ 12.99		8.85
CZ-8	**Anchorage, Alaska**	$ 5,699	$ 12.99		20.22

*Including material and labor costs

Table 12. Cost analysis result summary

Parameters		CZ-1												CZ-2											
		Miami												New Orleans											
Number of Boreholes		9				6				3 (300 ft)				6				4				3			
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Heat Pump Cost [$*1,000]		21.32												23.74											
Underground Loop Cost [$*1,000]		26.89				17.93				13.45				17.93				11.95				8.96			
Dry Cooler Cost [$*1,000]		0.00	2.38			0.00	2.38			0.00	2.38			0.00	2.38			0.00	2.38			0.00	2.38		
Total Initial Cost [$*1,000]		48.21	50.6	50.59	50.59	39.25	41.63	41.63	41.63	34.77	37.15	37.15	37.15	41.7	44.05	44.05	44.05	35.70	38.08	38.08	38.08	32.71	35.09	35.09	35.09
Initial Saving [$*1,000]		0.00	-2.38	-2.38	-2.38	8.96	6.58	6.58	6.58	13.45	11.07	11.07	11.07	0.00	-2.38	-2.38	-2.38	5.98	3.60	3.60	3.60	8.96	6.58	6.58	6.58
Initial Saving [%]		-	-	-	-	18.6%	14%	13.7%	13.7%	28%	23.0%	23.0%	23.0%	-	-	-	-	14%	8.6%	8.6%	8.6%	21.5%	16%	15.8%	15.8%
Electricity Cost [$*1,000]	1st year	0.79	0.80	0.79	0.80	0.84	0.85	0.82	0.82	0.89	0.89	0.84	0.84	0.48	0.49	0.47	0.49	0.51	0.52	0.49	0.51	0.55	0.55	0.51	0.53
	20th year	0.84	0.84	0.81	0.81	0.91	0.87	0.83	0.83	0.96	0.91	0.85	0.84	0.50	0.50	0.48	0.49	0.54	0.53	0.50	0.51	0.58	0.56	0.51	0.53
Saving at 20th year		0.00	-2.42	-2.02	-2.07	7.75	5.76	6.55	6.51	11.14	9.55	10.72	10.77	0.00	-2.48	-2.04	-2.31	5.23	2.85	3.54	3.23	7.31	5.24	6.19	5.80
Breakeven Year		-	-	-	-	>20	>20	>20	>20	>20	>20	>20	>20	-	-	-	-	>20	>20	>20	>20	>20	>20	>20	>20

Parameters		CZ-3												CZ-4														
		Atlanta												Kansas City														
Number of Boreholes		5				3 (250 ft)				2 (250 ft)				4					3					2				
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4C	4H
Heat Pump Cost [$*1,000]		19.24												49.70														
Underground Loop Cost [$*1,000]		14.94				11.21				7.47				11.95					8.96					5.98				
Dry Cooler Cost [$*1,000]		0	2.38			0.00	2.38			0.00	2.38			0.00	2.38				0.00	2.38				0.00	2.38			
Total Initial Cost [$*1,000]		34.18	36.6	36.6	36.56	30.45	32.83	32.8	32.8	26.71	29.09	29.09	29.09	61.65	64.03	64.0	64.03	64.03	58.66	61.04	61.04	61.04	61.04	55.67	58.05	58.1	58.05	58.1
Initial Saving [$*1,000]		0.00	-2.38	-2.38	-2.38	3.73	1.35	1.35	1.35	7.47	5.09	5.09	5.09	0.00	-2.38	-2.38	-2.38	-2.38	2.99	0.61	0.61	0.61	0.61	5.98	3.60	3.60	3.60	3.60
Initial Saving [%]		-	-	-	-	11%	4.0%	4.0%	4.0%	22%	14.9%	14%	14.9%	-	-	-	-	-	4.8%	1.0%	1.0%	1.0%	1.0%	9.7%	5.8%	5.%	5.8%	5.%
Electricity Cost [$*1,000]	1st year	0.52	0.53	0.52	0.55	0.54	0.55	0.54	0.57	0.59	0.59	0.58	0.60	0.79	0.79	0.79	0.81	0.81	0.83	0.83	0.83	0.85	0.84	0.90	0.90	0.90	0.93	0.90
	20th year	0.53	0.54	0.53	0.55	0.55	0.56	0.55	0.57	0.59	0.60	0.58	0.60	0.79	0.79	0.79	0.81	0.80	0.83	0.83	0.83	0.85	0.84	0.90	0.91	0.90	0.93	0.91
Saving at 20th year		0.00	-2.52	-2.36	-2.80	3.32	0.79	0.97	0.56	6.15	3.69	4.08	3.56	0.00	-2.38	-2.38	-2.79	-2.64	2.25	-0.13	-0.12	-0.54	-0.27	3.77	1.31	1.39	0.89	1.32
Breakeven Year		-	-	-	-	>20	>20	>20	>20	>20	>20	>20	>20	-	-	-	-	-	>20	17	17	11	14	>20	>20	>20	>20	>20

Parameters		CZ-5															CZ-6											
		Omaha															Minneapolis											
Number of Boreholes		4					3					2					4				3				2			
Case		1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4C	4H	1	2	3	4	1	2	3	4	1	2	3	4
Heat Pump Cost [$*1,000]		19.40															19.25											
Underground Loop Cost [$*1,000]		10.39					7.79					5.20					10.39				7.79				5.20			
Dry Cooler Cost [$*1,000]		0.0	2.38				0.00	2.38				0.00	2.38				0.00	2.38			0.00	2.38			0.00	2.38		
Total Initial Cost [$*1,000]		29.79	32.17	32.17	32.1	32.1	27.19	29.5	29.57	29.57	29.57	24.59	26.97	26.97	26.97	26.97	29.64	32.02	32.02	32.02	27.05	29.43	29.43	29.43	24.45	26.83	26.83	26.8
Initial Saving [$*1,000]		0.00	-2.38	-2.38	-2.38	-2.38	2.60	0.22	0.22	0.22	0.22	5.20	2.82	2.82	2.82	2.82	0.00	-2.38	-2.38	-2.38	2.60	0.22	0.22	0.22	5.20	2.82	2.82	2.82
Initial Saving [%]		-	-	-	-	-	8.7%	0.7%	0.7%	0.7%	0.7%	17.4%	9.5%	9.5%	9.5%	9.5%	-	-	-	-	8.8%	0.7%	0.7%	0.7%	17.5%	9.5%	9.5%	9.%
Electricity Cost [$*1,000]	1st year	0.66	0.66	0.66	0.68	0.67	0.68	0.69	0.69	0.71	0.69	0.76	0.75	0.75	0.77	0.75	0.77	0.77	0.77	0.80	0.80	0.80	0.80	0.82	0.85	0.85	0.85	0.86
	20th year	0.66	0.66	0.66	0.68	0.67	0.69	0.69	0.69	0.71	0.69	0.76	0.75	0.75	0.77	0.75	0.77	0.77	0.77	0.79	0.80	0.80	0.80	0.82	0.85	0.85	0.85	0.87
Saving at 20th year		0.00	-2.38	-2.38	-2.79	-2.57	2.01	-0.37	-0.37	-0.77	-0.47	3.17	0.97	1.02	0.68	0.99	0.00	-2.40	-2.41	-2.79	1.98	-0.42	-0.43	-0.76	3.60	1.22	1.25	0.93
Breakeven Year		-	-	-	-	-	>20	8	8	5	7	>20	>20	>20	>20	>20	-	-	-	-	>20	7	7	5	>20	>20	>20	>20

Parameters		CZ-7												CZ-8											
		Bismarck												Anchorage											
Number of Boreholes		4				3				2				6				3 (300 ft)				3 (200 ft)			
Case		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Heat Pump Cost [$*1,000]		19.25												22.99											
Underground Loop Cost [$*1,000]		10.39				7.79				5.20				15.59				11.69				7.79			
Dry Cooler Cost [$*1,000]		0.00	2.38			0.00	2.38			0.00	2.38			0.00	2.38			0.00	2.38			0.00	2.38		
Total Initial Cost [$*1,000]		29.64	32.02	32.02	32.02	27.05	29.43	29.43	29.43	24.45	26.83	26.83	26.83	38.57	40.95	40.95	40.95	34.68	37.06	37.06	37.06	30.78	33.16	33.16	33.16
Initial Saving [$*1,000]		0.00	-2.38	-2.38	-2.38	2.60	0.22	0.22	0.22	5.20	2.82	2.82	2.82	0.00	-2.38	-2.38	-2.38	3.90	1.52	1.52	1.52	7.79	5.41	5.41	5.41
Initial Saving [%]		-	-	-	-	8.8%	0.7%	0.7%	0.7%	17.5%	9.5%	9.5%	9.5%	-	-	-	-	10.1%	3.9%	3.9%	3.9%	20.2%	14.0%	14.0%	14.%
Electricity Cost [$*1,000]	1st year	0.71	0.71	0.71	0.72	0.73	0.73	0.73	0.74	0.77	0.77	0.77	0.78	1.44	1.44	1.44	1.47	1.46	1.47	1.47	1.49	1.48	1.48	1.48	1.50
	20th year	0.71	0.71	0.71	0.72	0.73	0.73	0.73	0.74	0.77	0.77	0.77	0.78	1.45	1.46	1.45	1.47	1.47	1.47	1.47	1.50	1.48	1.48	1.48	1.51
Saving at 20th year		0.00	-2.40	-2.39	-2.63	2.14	-0.25	-0.25	-0.48	3.95	1.56	1.59	1.40	0.00	-2.46	-2.46	-2.88	3.45	1.00	1.01	0.48	7.15	4.74	4.76	4.19
Breakeven Year		-	-	-	-	>20	10	10	7	>20	>20	>20	>20	-	-	-	-	>20	>20	>20	>20	>20	>20	>20	>20

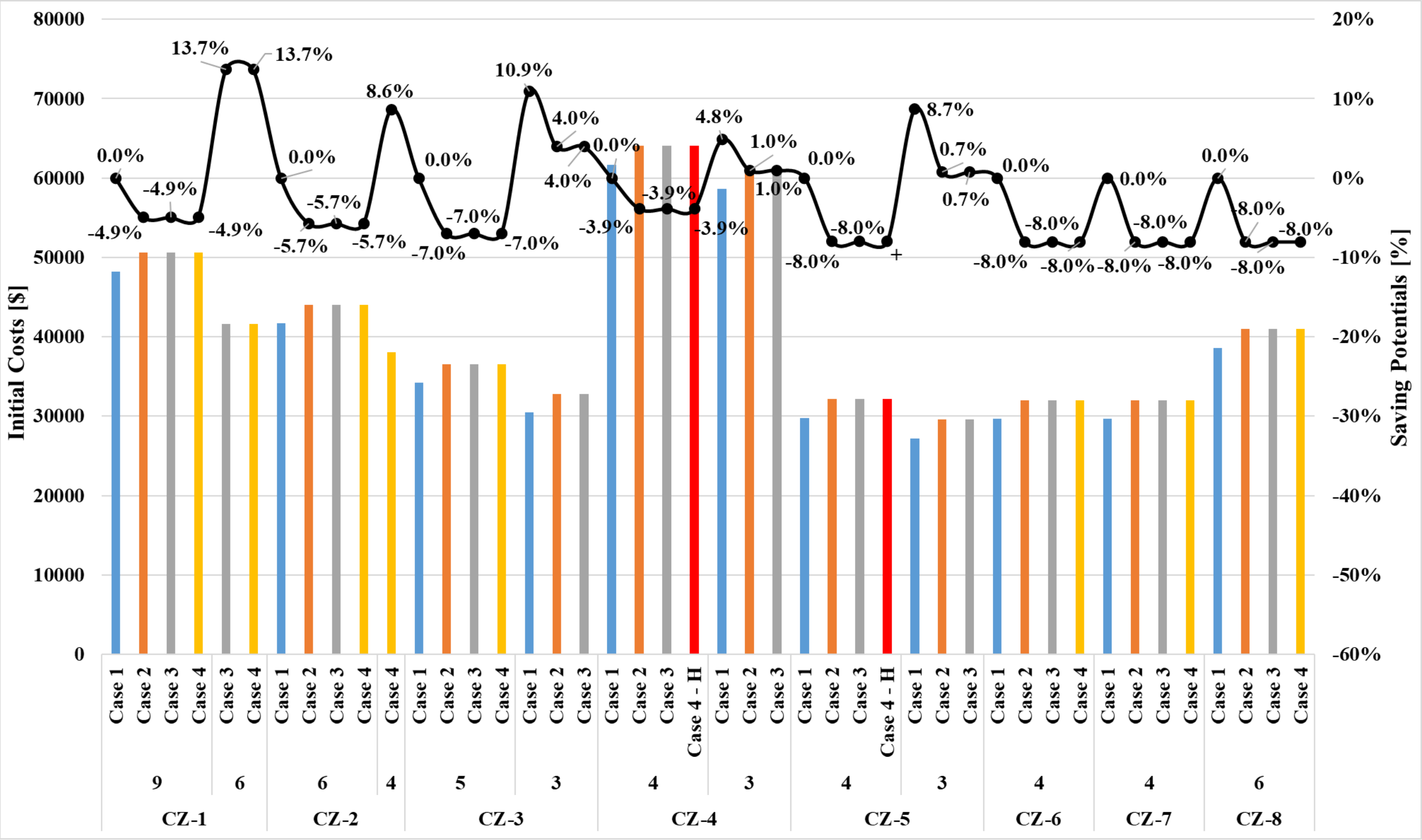


Figure 38. Initial cost and its saving potential

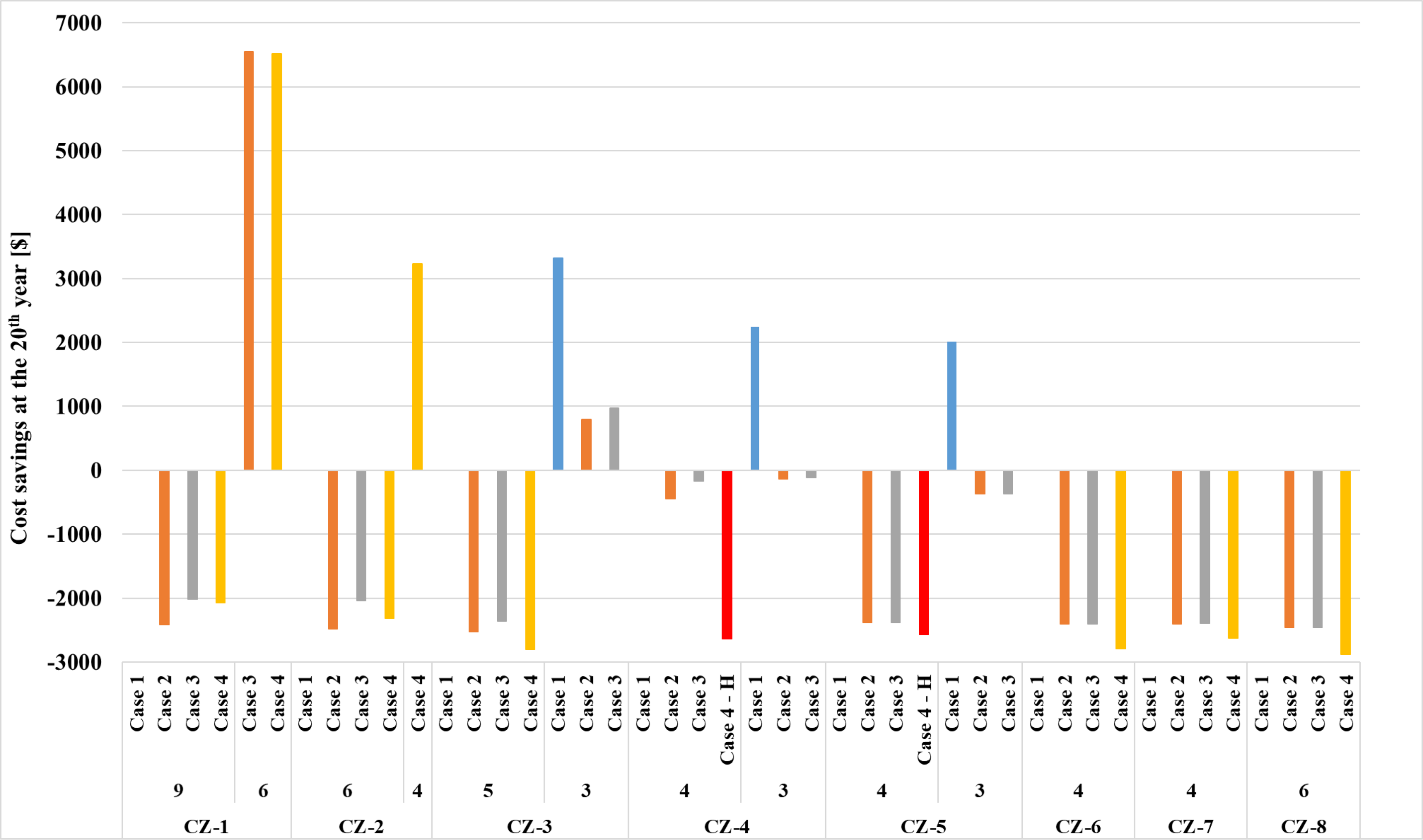


Figure 39. Cost savings at the 20th year

The cost information (Tables 11 and 12) allows the research team to evaluate the cost-effectiveness of each case scenario by identifying its breakeven year, when the potential initial cost savings due to the reduction of borehole size is balanced off by the operating costs year after year. The longer the initial cost savings can last, the better. Figure 38 illustrates the initial costs (left axis) with the associated initial cost-saving potentials (right axis) of the cases, whose return water temperatures are within the acceptable range (highlighted in green in Table 12). Figure 39 shows the cost savings at the 20th year by looking at the total costs, including initial and operating costs, after the 20-year operation. As shown in Table 12 or Figures 38 and 39, for the acceptable cases (highlighted in green), especially for the cases of CZ-1, the breakeven year is > 20 years when the borehole size is reduced from 9 to 6 with the initial cost savings of 13.7% (Cases 3 and 4). Similar results are obtained for the cases of CZ-2, where the breakeven year is > 20 years when the borehole size is reduced from 6 to 4 with the initial cost savings of 8.6% (Case 4). These cost analysis results indicate that the proposed system (Figure 11) is suitable for use in hot climates, which has the potential to reduce the initial cost of a conventional GSHP system by up to around 14% (for the system used in Miami) (Figure 38) with enhanced system efficiency for space cooling (Figure 33) and decent yearly energy savings, e.g., 4~5% at the 20th year for Case 4 of CZ-1 (Figure 37). Additionally, advanced control strategies (Modes 1, 2, 3, and 4), especially Mode 4 (Figure 25), are proven to be effective for the proposed system used in hot climates, particularly in CZ-1 and 2.

4. CONCLUSION AND FUTURE WORK

This study investigated the possibility of using a dry fluid cooler with advanced control strategies in a GSHP system to reduce the borehole size with the intention of increasing the cost effectiveness of the system without compromising system efficiency. TRNSYS simulations were conducted and used in the study, and the conclusions condensed from reams of simulation results are summarized below.

- Advanced control strategies (Mode 1, 2, 3, and 4) with the use of a dry fluid cooler in the designed system (Figure 11) contribute to increasing or maintaining GSHP system's efficiency in the long run by balancing the heating and cooling through charging cold or heat to the ground.
- The impacts of this integrated GSHP system on its efficiency and cost in eight climate zones defined by ASHRAE vary, and the results show that this system design is more suitable in hot/warm climate zones than cold climate zones. The specific conclusions are listed below.
    - The effectiveness of the designed system along with the control modes of 1, 2, 3 and 4 to maximize system efficiency and energy-saving potential can be negligible in cold climates, such as CZ-6, 7, and 8, primarily due to the two possible reasons: 1) not too much heat is contained in the ambient air, especially during winter in these climates, which cannot be effectively collected by using a dry fluid cooler, and/or 2) a single dry cooler is probably not enough to collect sufficient heat from the ambient air to achieve decent energy savings.

- Advanced control strategies (Mode 1, 2, 3, and 4), especially Mode 4 (Figure 36), are proven to be effective for the designed system used in hot climates, such as CZ-1 and 2. The designed system is suitable for use in hot climates, which is able to achieve similar or better performance and capacity of a standard/conventional GSHP system at lower cost. Specifically, it has the potential to reduce the initial cost of a conventional GSHP system by up to around 14% (for the system used in Miami) with enhanced system efficiency for space cooling and decent yearly energy savings, e.g., 4~5% at the 20th year for Case 4 of CZ-1.

Although, as the project goal, advancement for the development and evaluation of a high-efficiency multi-source heat pump system at low cost has been successfully achieved through this study, there remain some unanswered questions and additional research opportunities, as listed below.

- In consideration of different parameters, such as thermostat setpoints and soil properties (soil thermal conductivities, heat capacities, etc.), additional studies could be conducted to quantify their impacts on system efficiency, energy-saving potential, and cost effectiveness in order to further optimize the design of the system.
- Multiple dry coolers connected together in either series or parallel can be used to enhance the effectiveness of the designed system, especially its use in hot/warm climates.
- Using a solar thermal collector(s) instead of a dry cooler is expected to improve the effectiveness of the designed system used in cold climates, which is expected to

collect more heat than a dry fluid cooler(s) not from the ambient air but the sun, especially during cold winter days.

- The use of the designed system in commercial buildings, like offices, is expected to yield greater payoffs, whose heating and cooling load profiles are different from residential buildings' and are not fully driven by the outdoor weather conditions. For example, some of the office buildings located in cold climates are still calling for cold in winter due to a large amount of internal heat released by people, lights, and/or equipment. This makes the use of a dry fluid cooler(s) to collect cold from the ambient environment in cold climates more meaningful and effective.
- A single-stage heat pump unit was involved in the study, and it is expected that additional energy savings can be achieved if a two-stage or variable-stage heat pump is used in the proposed system with the use of a dry fluid cooler(s) or solar thermal collector(s).

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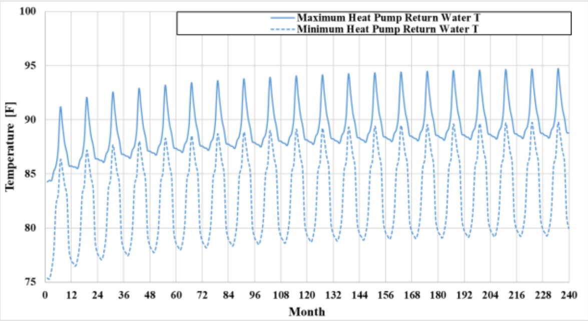
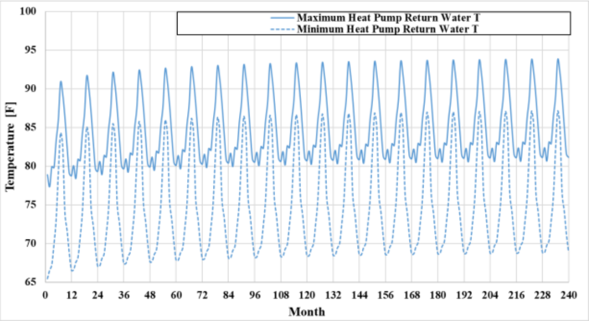
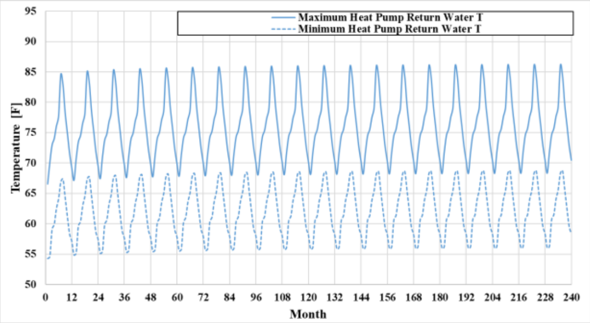
APPENDIX A. GLHEPRO RESULTS - MONTHLY MAX. AND MIN. HEAT PUMP RETURN WATER TEMPERATURES FOR BOREHOLE SIZING



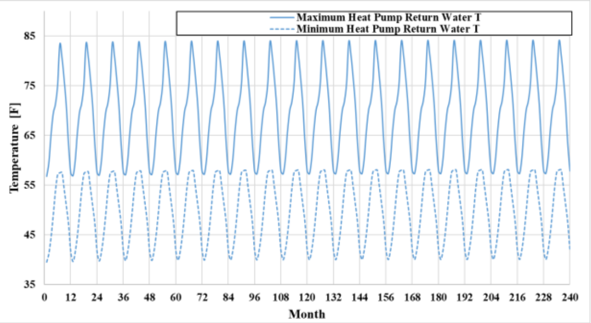
Climate Zone 1 Miami
9 Boreholes (1,800 ft Borehole Length)



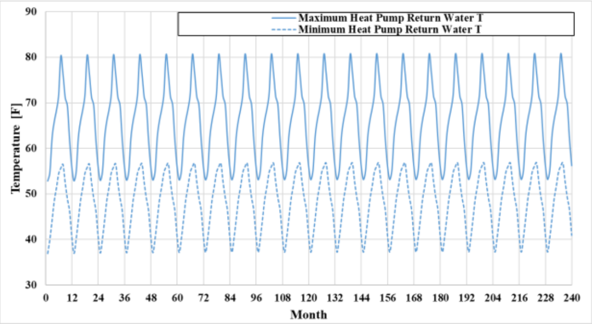
Climate Zone 2 New Orleans
6 Boreholes (1,200 ft Borehole Length)



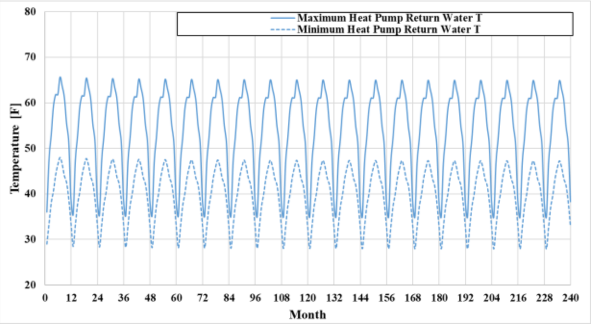
Climate Zone 3 Atlanta
5 Boreholes (1,000 ft Borehole Length)



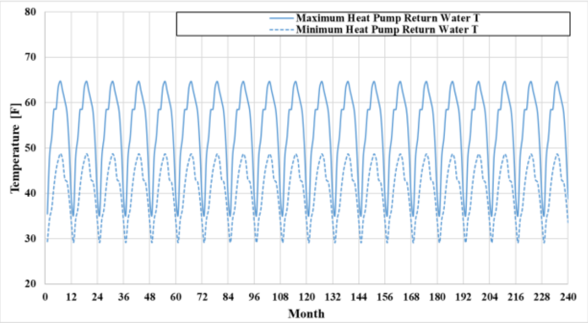
Climate Zone 4 Kansas City
4 Boreholes (800 ft Borehole Length)



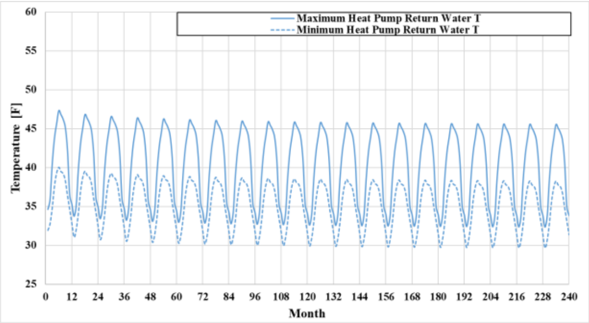
Climate Zone 5 Omaha
4 Boreholes (800 ft Borehole Length)



Climate Zone 6 Minneapolis
4 Boreholes (800 ft Borehole Length)



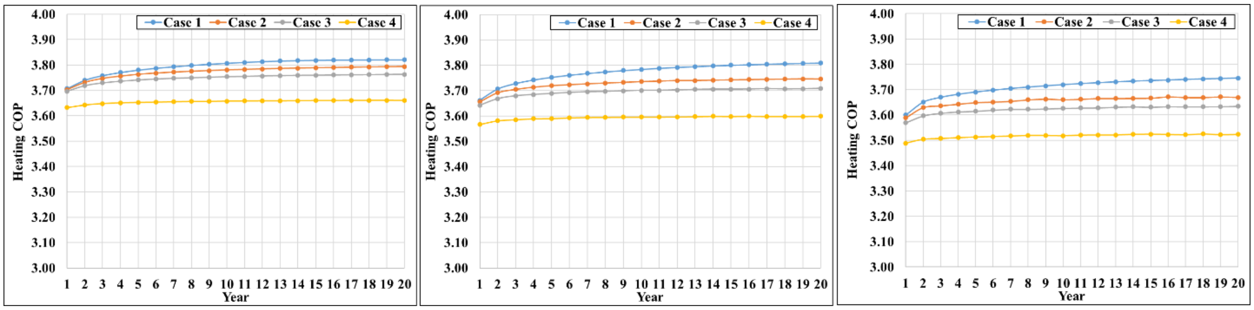
Climate Zone 7 Bismarck
4 Boreholes (800 ft Borehole Length)



Climate Zone 8 Anchorage
6 Boreholes (1200 ft Borehole Length)

APPENDIX B. DETAILED SIMULATION RESULTS

B.1. Climate Zone 1 – Miami

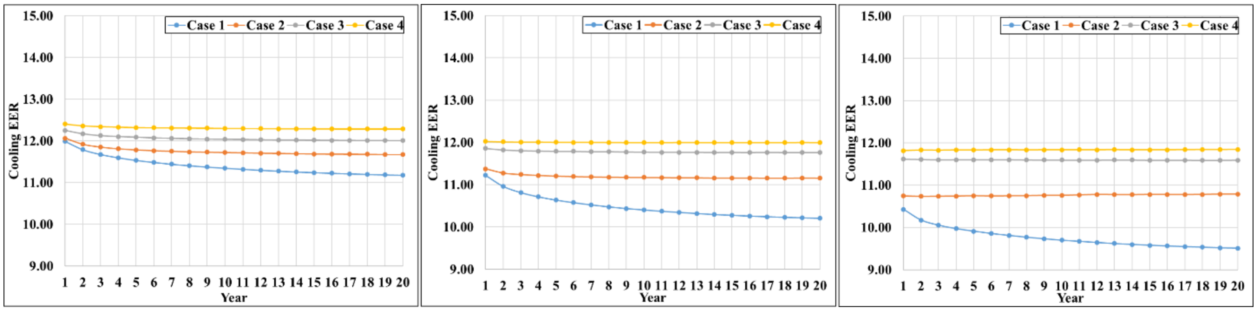


9 Boreholes (1800 ft Borehole Length)

6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

Figure B1. Yearly average heating COPs for 20 years

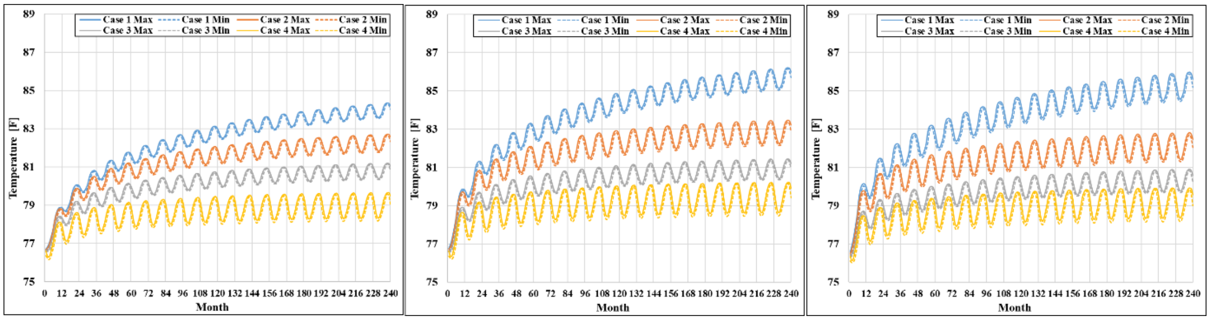


9 Boreholes (1800 ft Borehole Length)

6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

Figure B2. Yearly average cooling EERs for 20 years

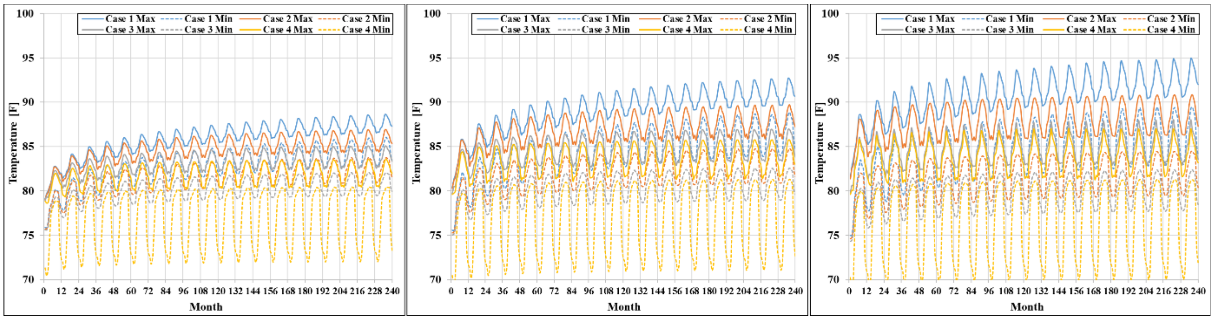


9 Boreholes (1800 ft Borehole Length)

6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

Figure B3. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

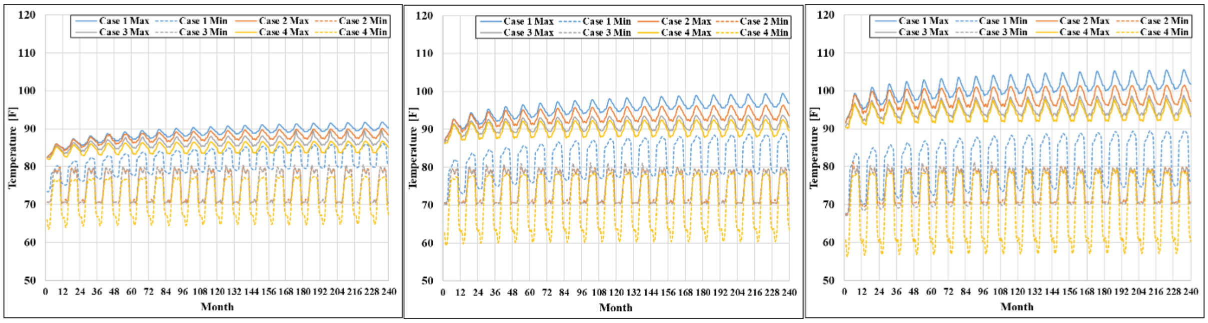


9 Boreholes (1800 ft Borehole Length)

6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

Figure B4. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



9 Boreholes (1800 ft Borehole Length)

6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

Figure B5. Monthly Max. and Min. heat pump return fluid temperature for 20 years

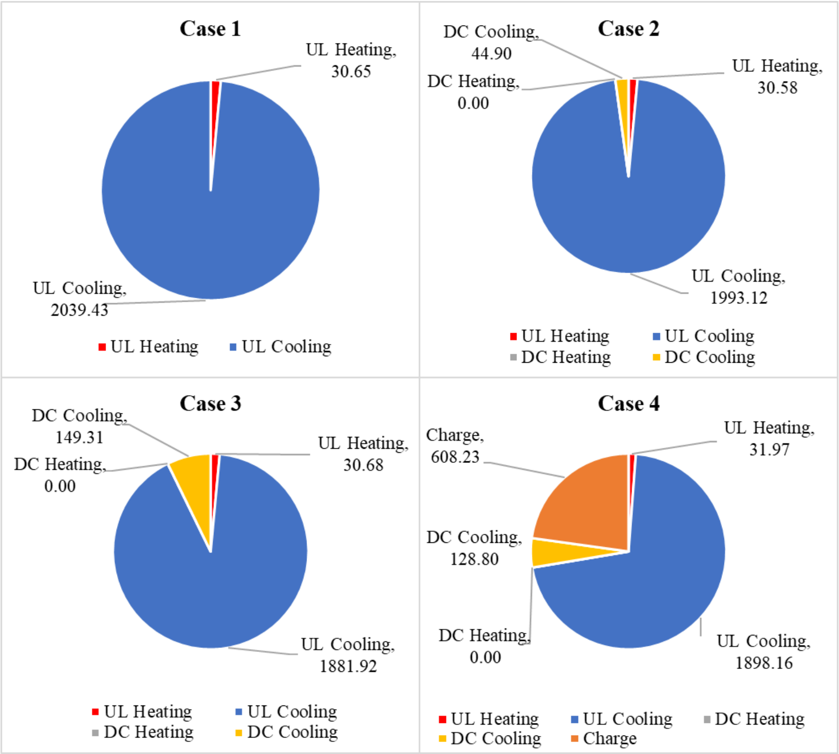


Figure B6. Heating and cooling hours of one year using 9 boreholes (1800 ft)

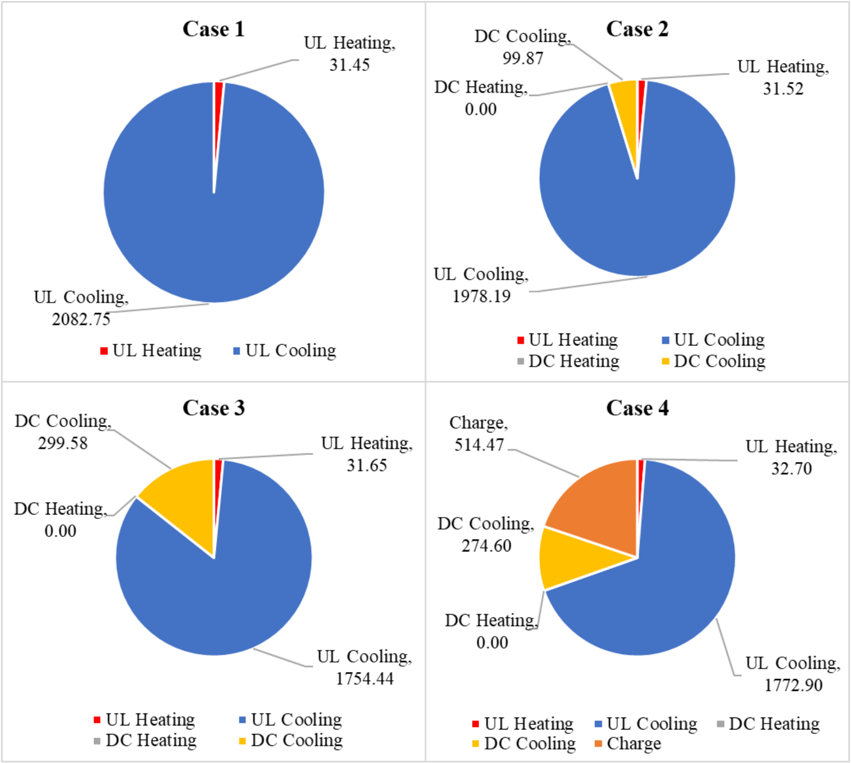


Figure B7. Heating and cooling hours of one year using 6 boreholes (1200 ft)

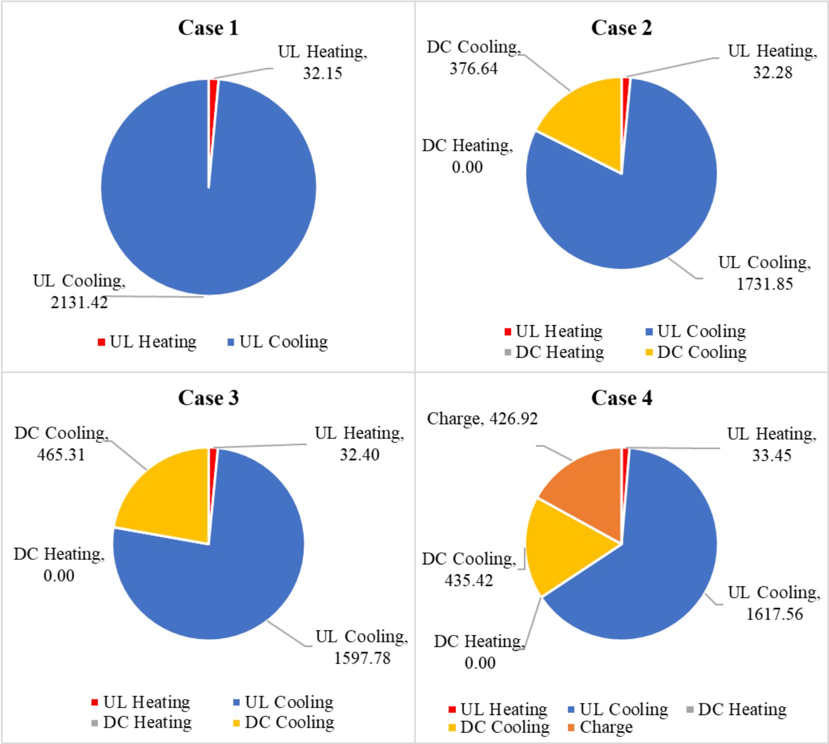
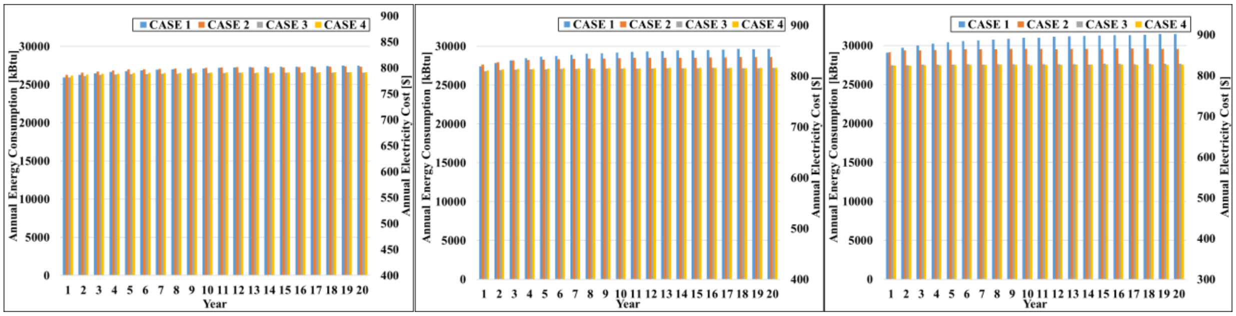


Figure B8. Heating and cooling hours of one year using 3 boreholes (900 ft)

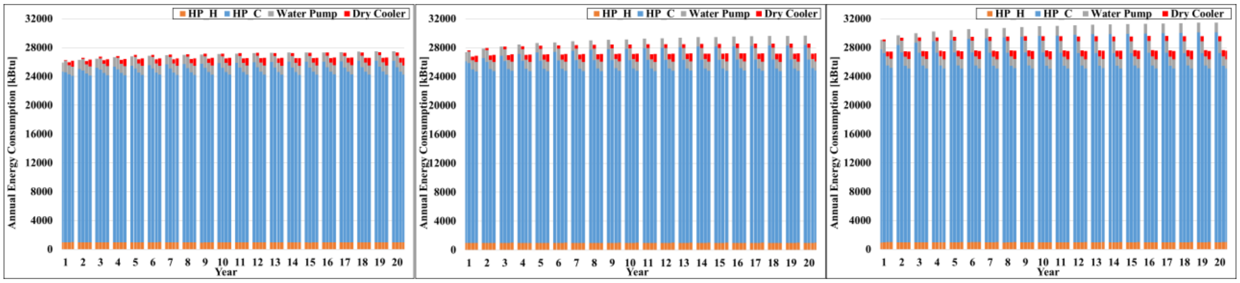


9 Boreholes (1800 ft Borehole Length)

6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

Figure B9. Annual system energy consumption and cost (at ¢10.44/kWh) for 20 years



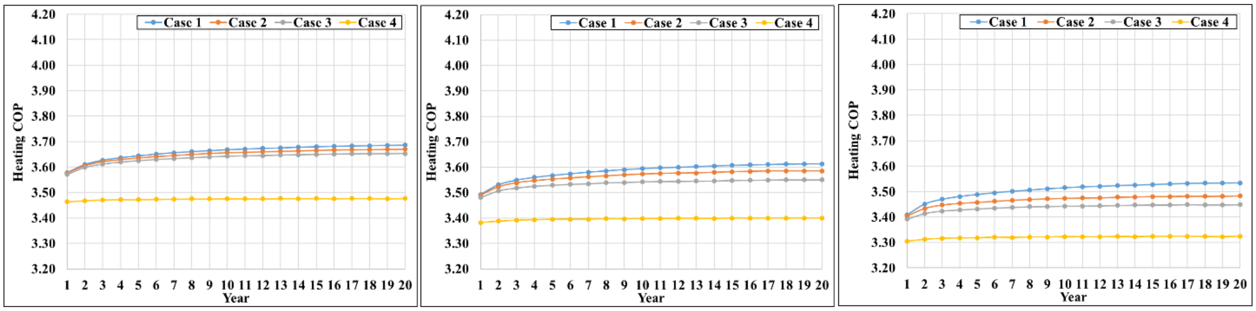
9 Boreholes (1800 ft Borehole Length)

6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

Figure B10. Annual energy consumption by categories for 20 years

B.2. Climate Zone 2 – New Orleans

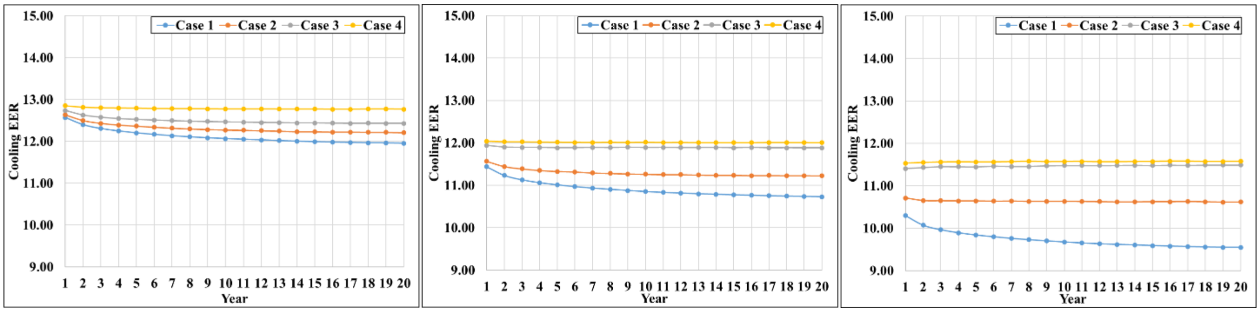


6 Boreholes (1200 ft Borehole Length)

4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B11. Yearly average heating COPs for 20 years

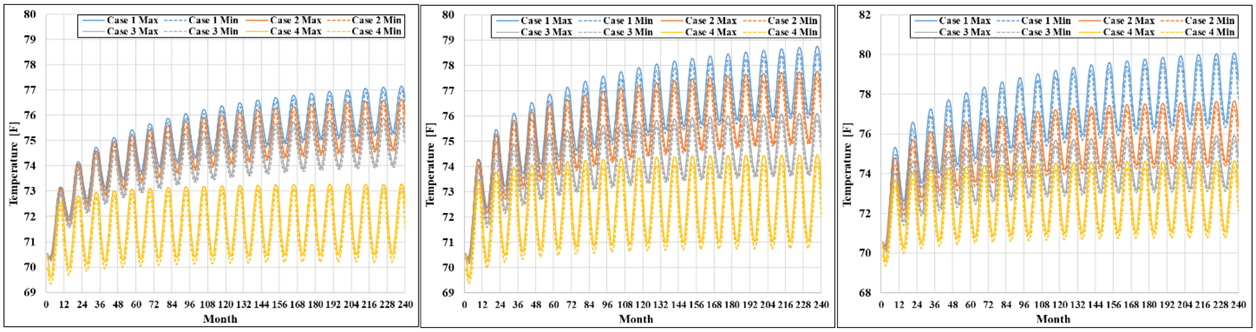


6 Boreholes (1200 ft Borehole Length)

4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B12. Yearly average cooling EERs for 20 years

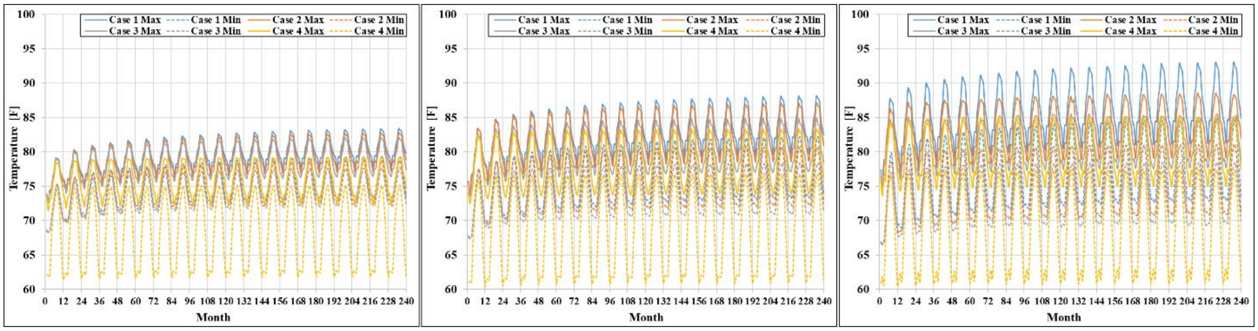


6 Boreholes (1200 ft Borehole Length)

4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B13. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

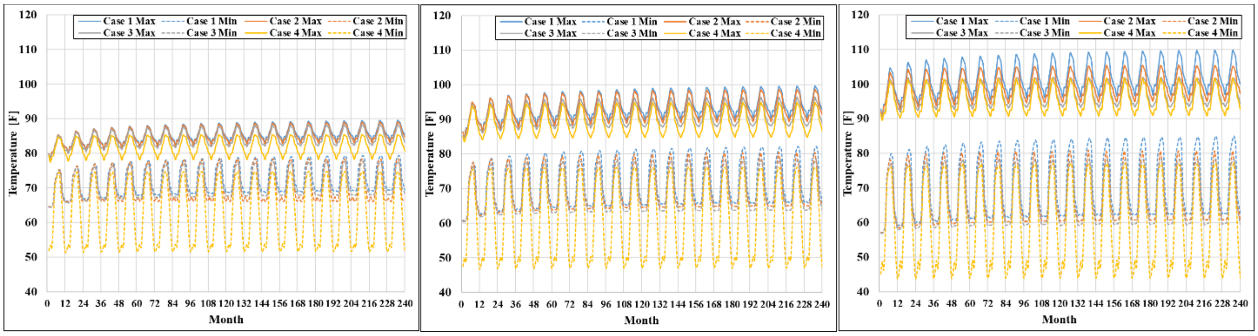


6 Boreholes (1200 ft Borehole Length)

4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B14. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



6 Boreholes (1200 ft Borehole Length)

4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B15. Monthly Max. and Min. heat pump return fluid temperature for 20 years

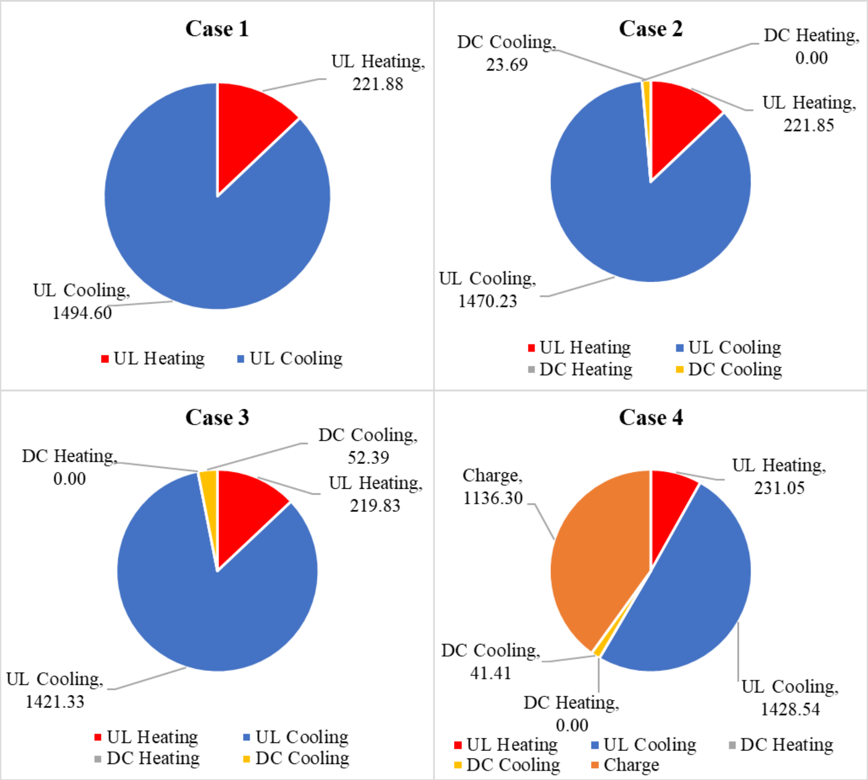


Figure B16. Heating and cooling hours of one year using 6 boreholes (1200 ft)

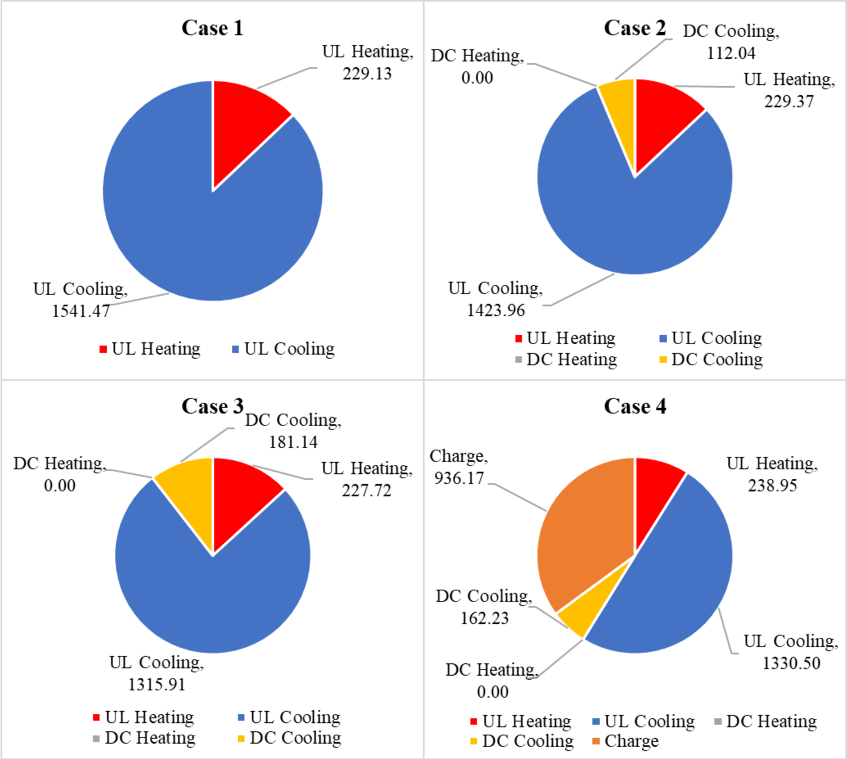


Figure B17. Heating and cooling hours of one year using 4 boreholes (800 ft)

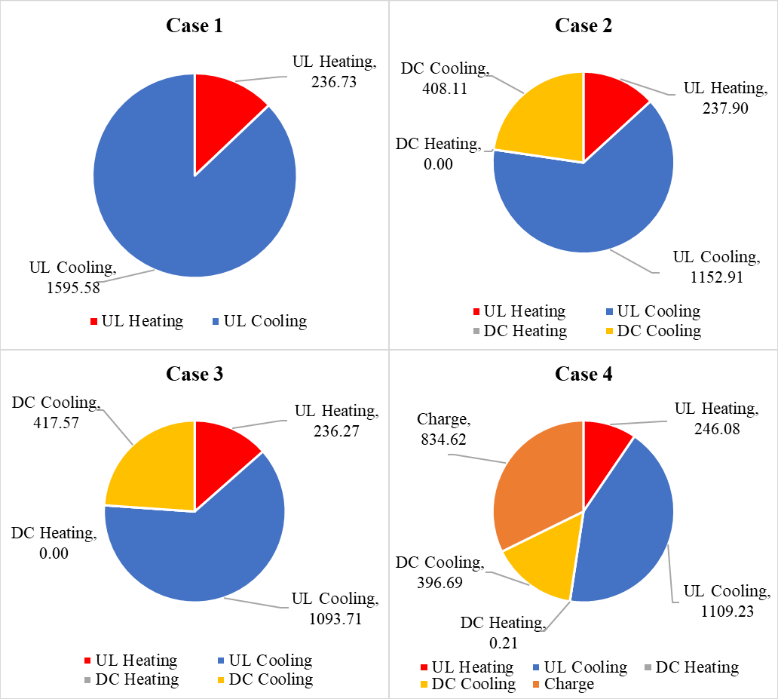
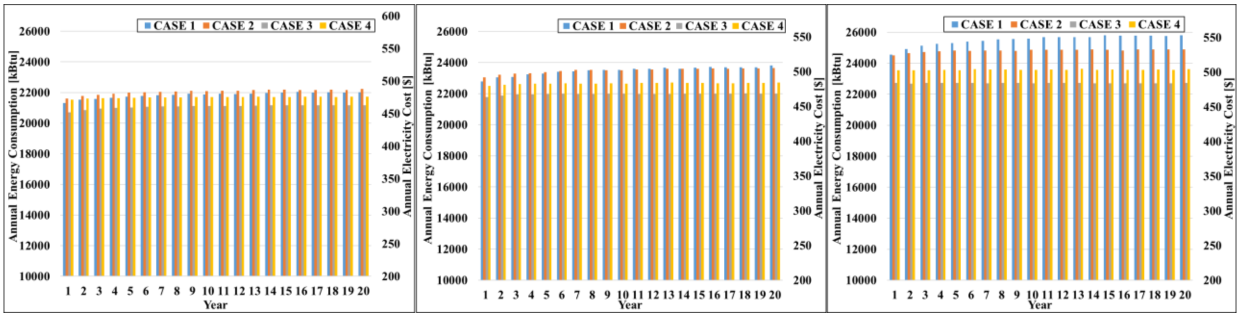


Figure B18. Heating and cooling hours of one year using 3 boreholes (600 ft)

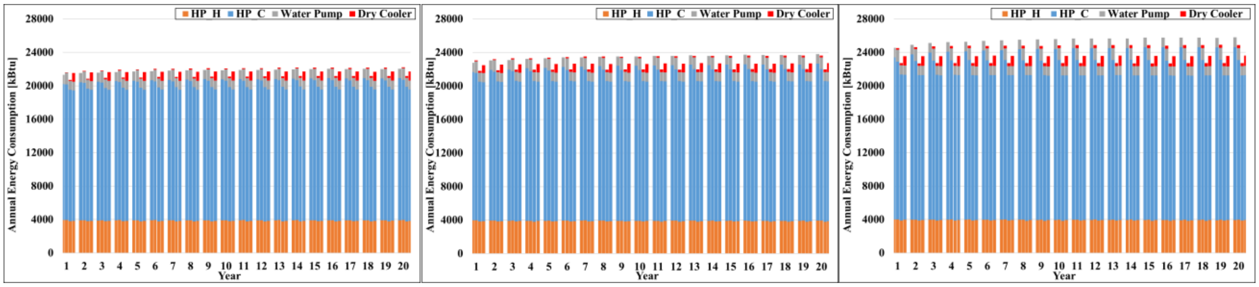


6 Boreholes (1200 ft Borehole Length)

4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B19. Annual system energy consumption and cost (at ¢7.71/kWh) for 20 years



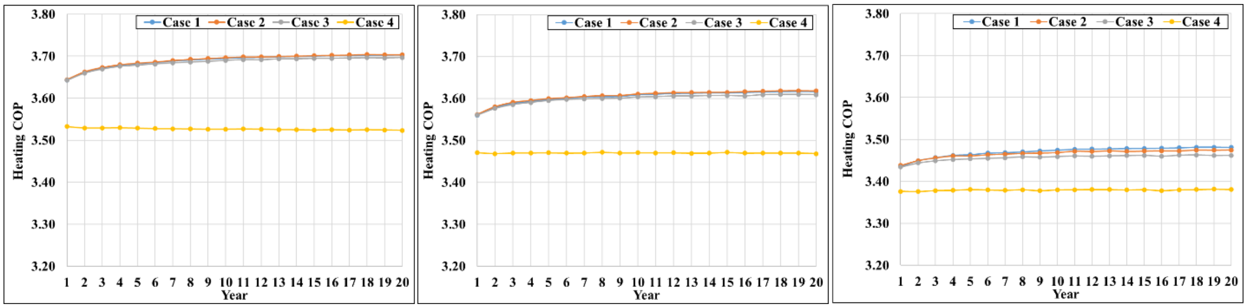
6 Boreholes (1200 ft Borehole Length)

4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B20. Annual energy consumption by categories for 20 years

B.3. Climate Zone 3 – Atlanta

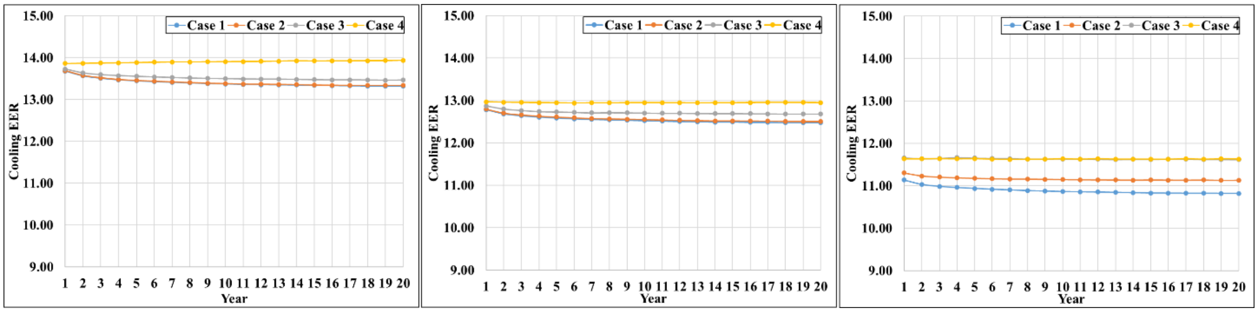


5 Boreholes (1000 ft Borehole Length)

3 Boreholes (750 ft Borehole Length)

2 Boreholes (500 ft Borehole Length)

Figure B21. Yearly average heating COPs for 20 years

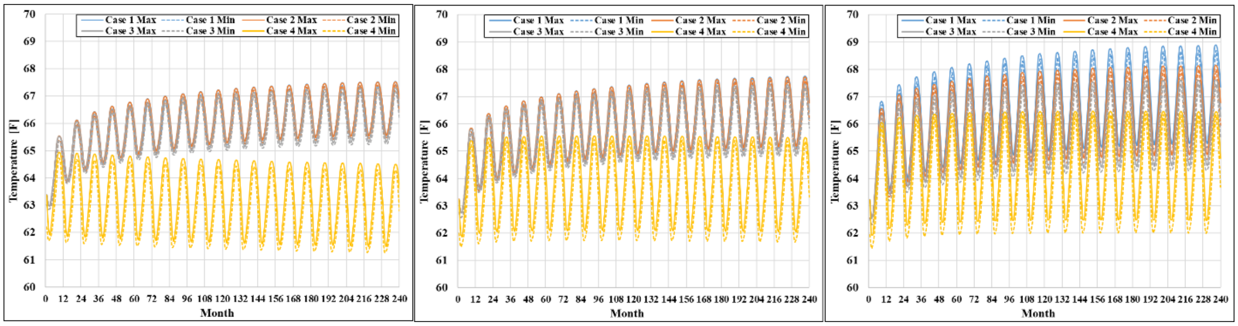


5 Boreholes (1000 ft Borehole Length)

3 Boreholes (750 ft Borehole Length)

2 Boreholes (500 ft Borehole Length)

Figure B22. Yearly average cooling EERs for 20 years

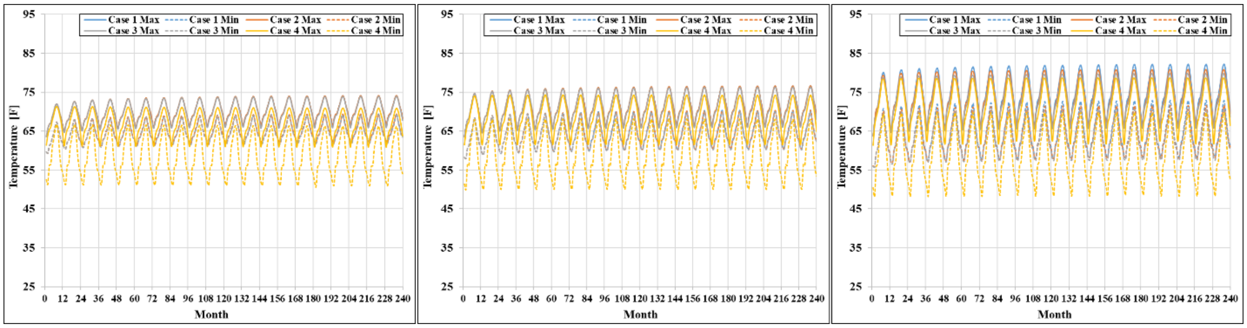


5 Boreholes (1000 ft Borehole Length)

3 Boreholes (750 ft Borehole Length)

2 Boreholes (500 ft Borehole Length)

Figure B23. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

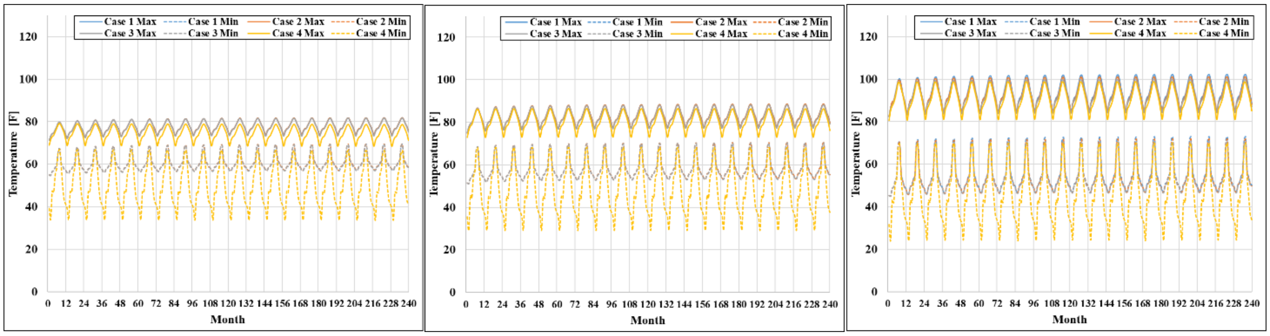


5 Boreholes (1000 ft Borehole Length)

3 Boreholes (750 ft Borehole Length)

2 Boreholes (500 ft Borehole Length)

Figure B24. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



5 Boreholes (1000 ft Borehole Length)

3 Boreholes (750 ft Borehole Length)

2 Boreholes (500 ft Borehole Length)

Figure B25. Monthly Max. and Min. heat pump return fluid temperature for 20 years

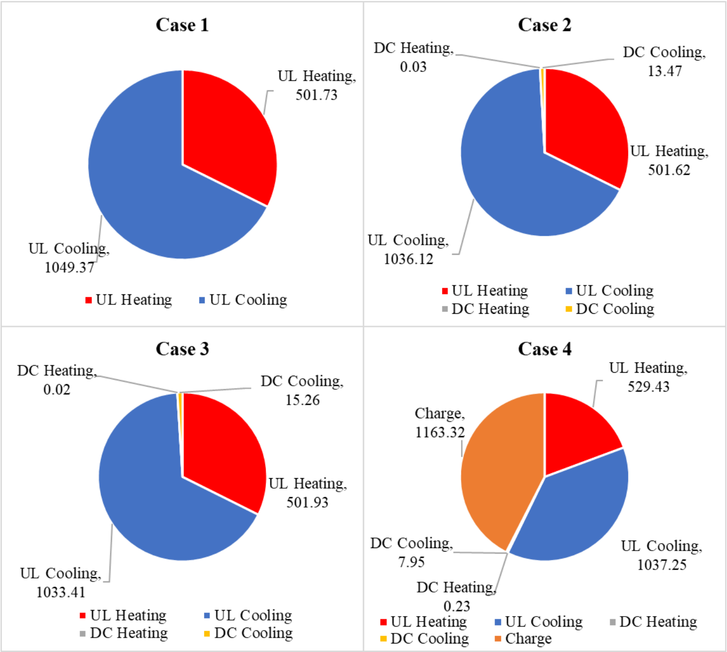


Figure B26. Heating and cooling hours of one year using 5 boreholes (1000 ft)

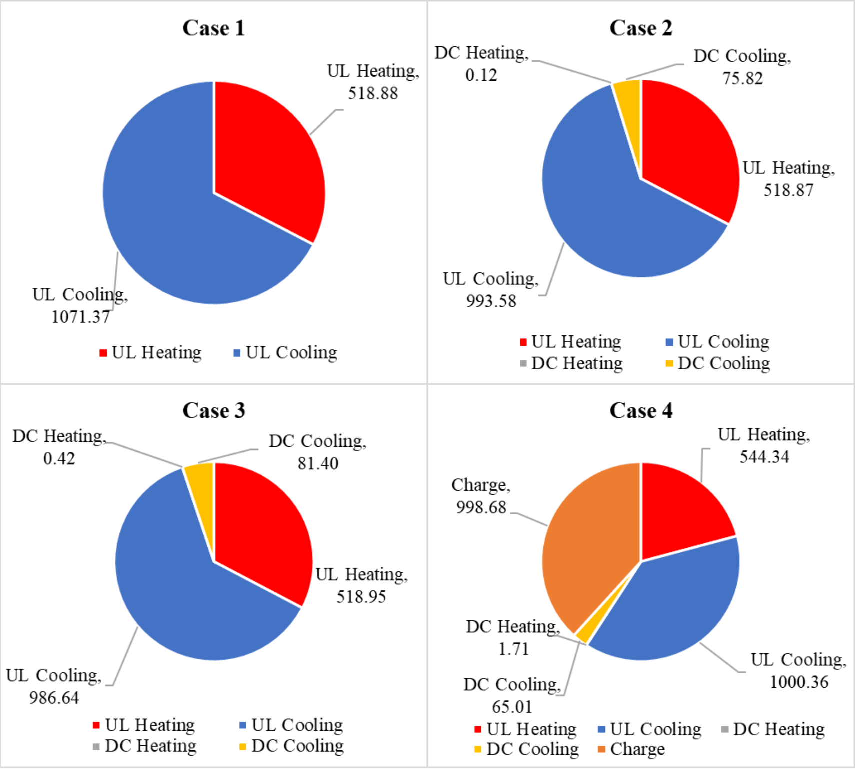


Figure B27. Heating and cooling hours of one year using 3 boreholes (750 ft)

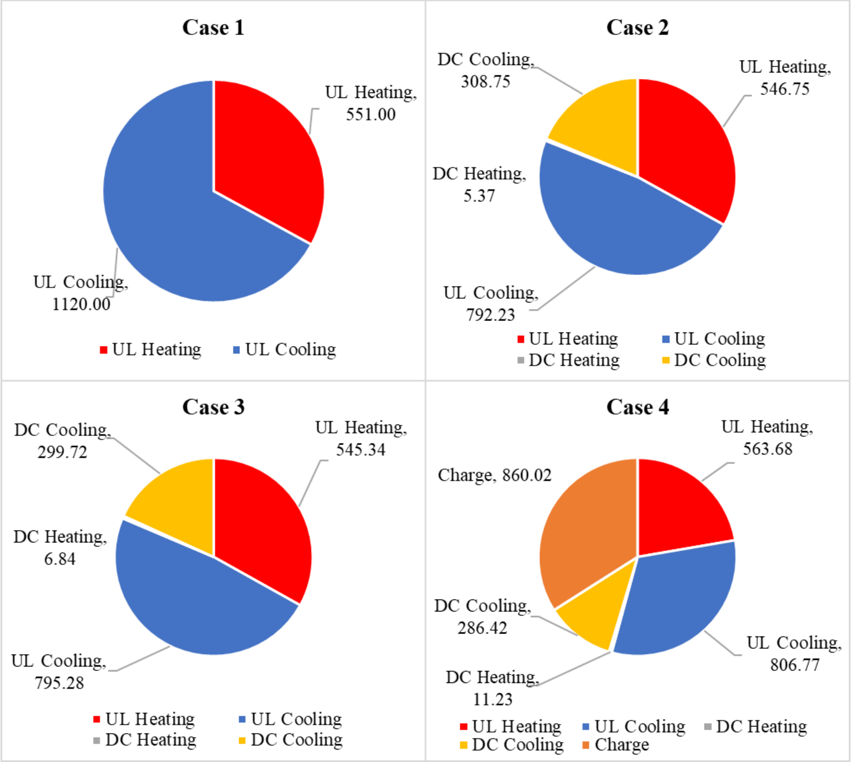
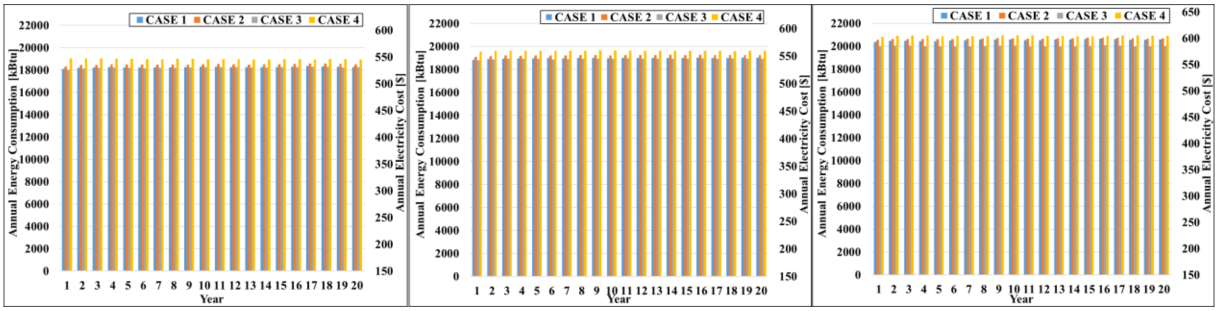


Figure B28. Heating and cooling hours of one year using 2 boreholes (500 ft)

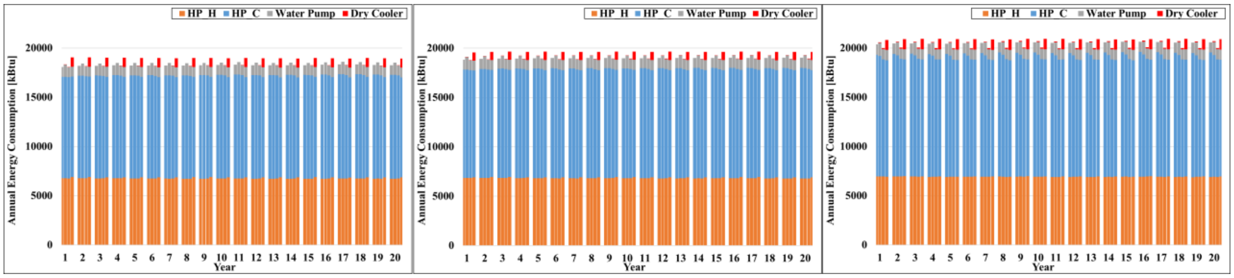


5 Boreholes (1000 ft Borehole Length)

3 Boreholes (750 ft Borehole Length)

2 Boreholes (500 ft Borehole Length)

Figure B29. Annual system energy consumption and cost (at ¢9.86/kWh) for 20 years



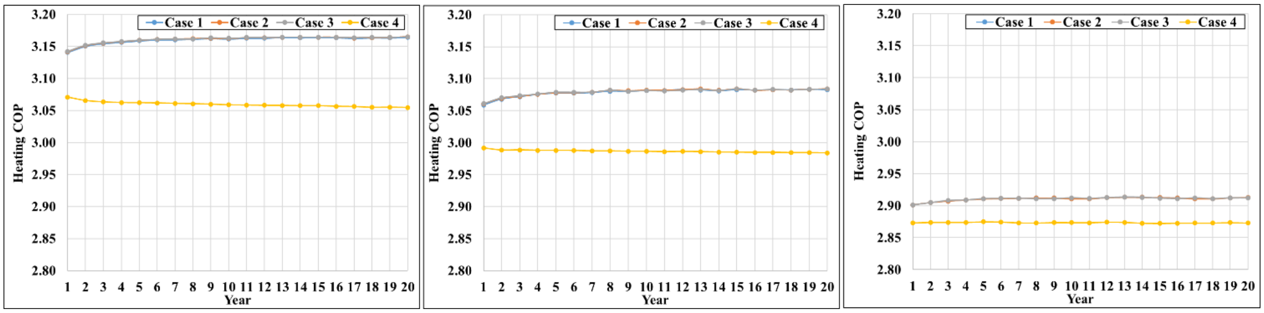
5 Boreholes (1000 ft Borehole Length)

3 Boreholes (750 ft Borehole Length)

2 Boreholes (500 ft Borehole Length)

Figure B30. Annual energy consumption by categories for 20 years

B.4. Climate Zone 4 – Kansas City (Cold Collection and Storage in Mode 4)

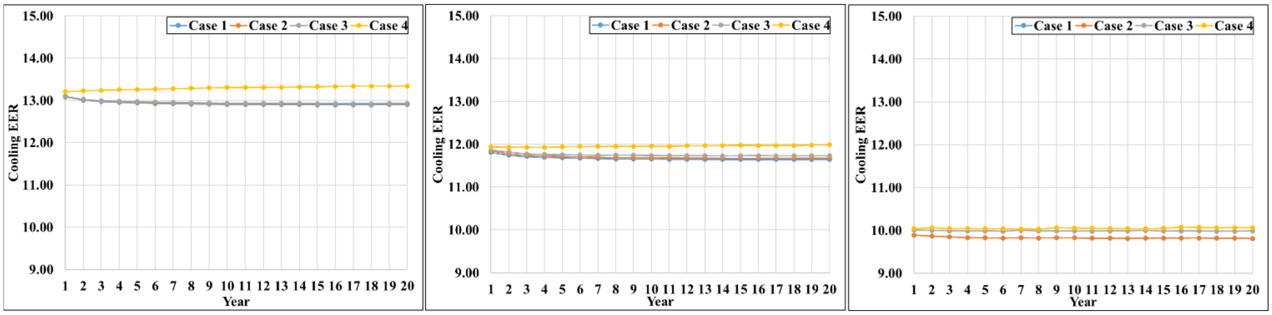


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B31. Yearly average heating COPs for 20 years

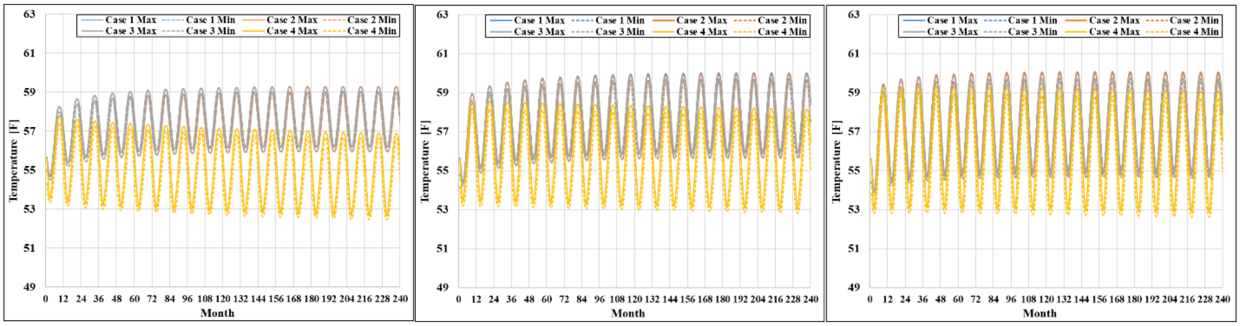


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B32. Yearly average cooling EERs for 20 years

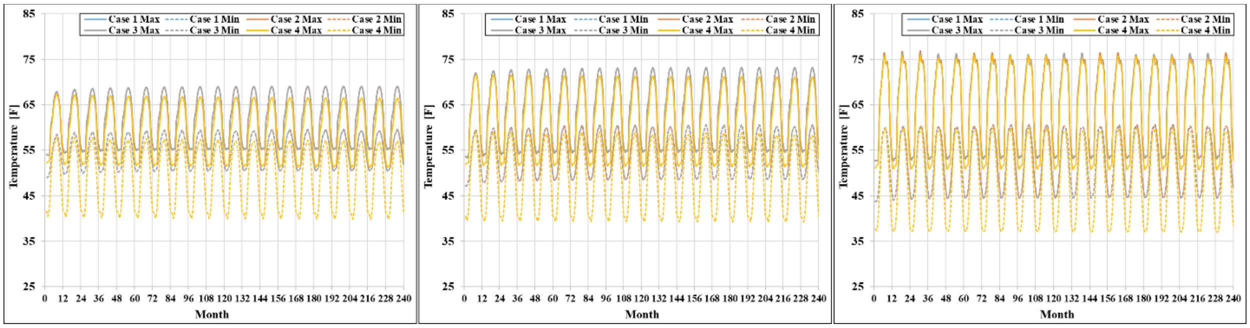


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B33. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

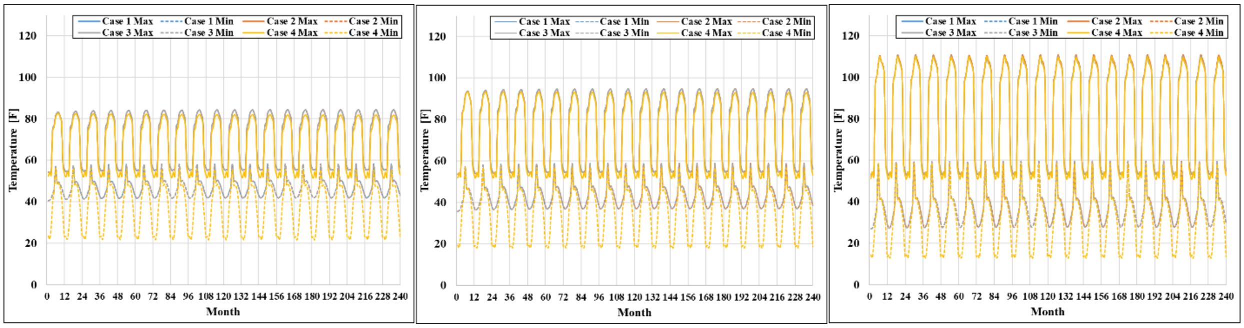


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B34. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B35. Monthly Max. and Min. heat pump return fluid temperature for 20 years

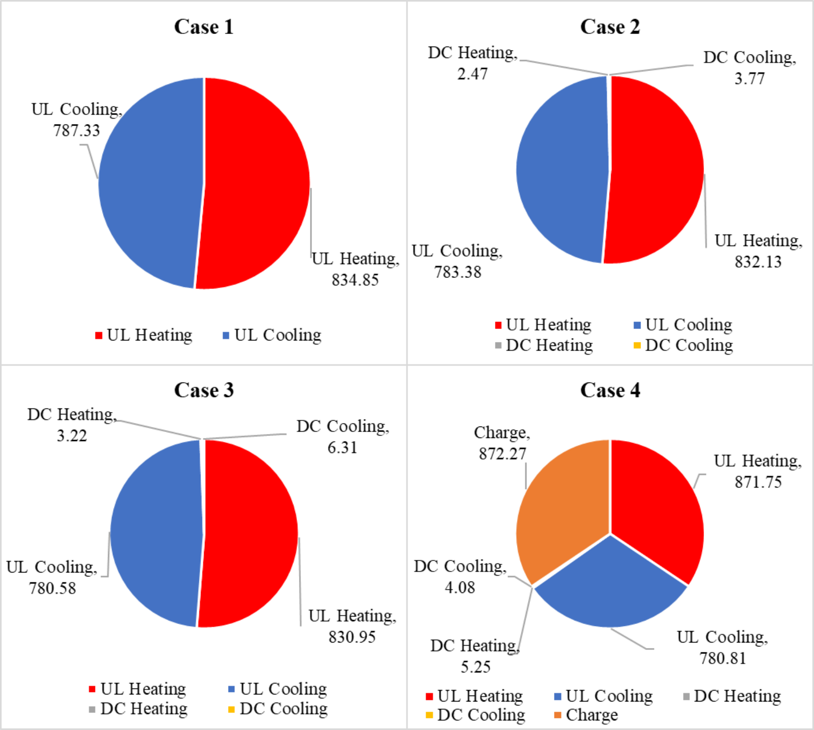


Figure B36. Heating and cooling hours of one year using 4 boreholes (800 ft)

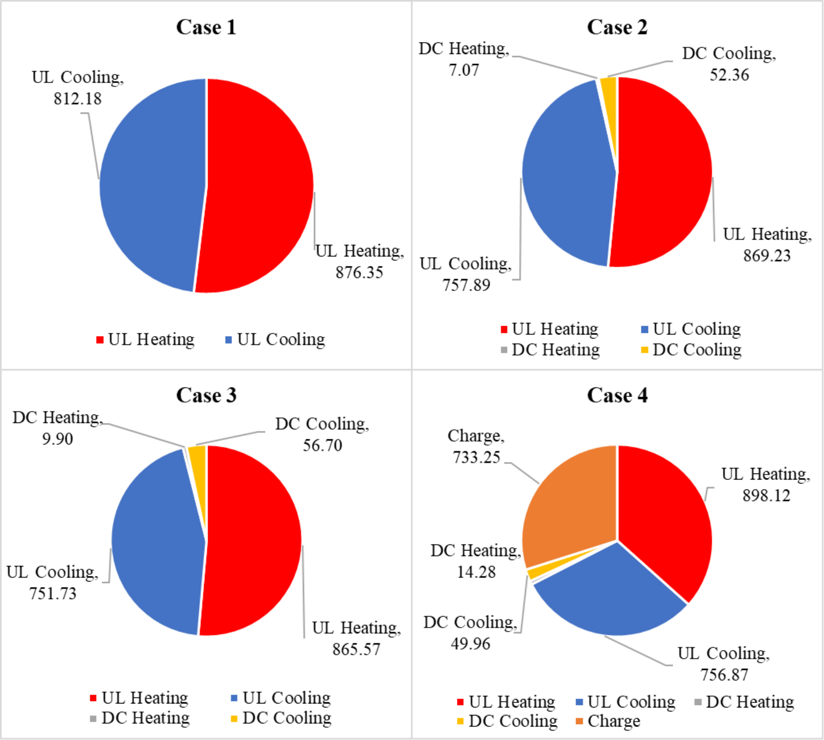


Figure B37. Heating and cooling hours of one year using 3 boreholes (600 ft)

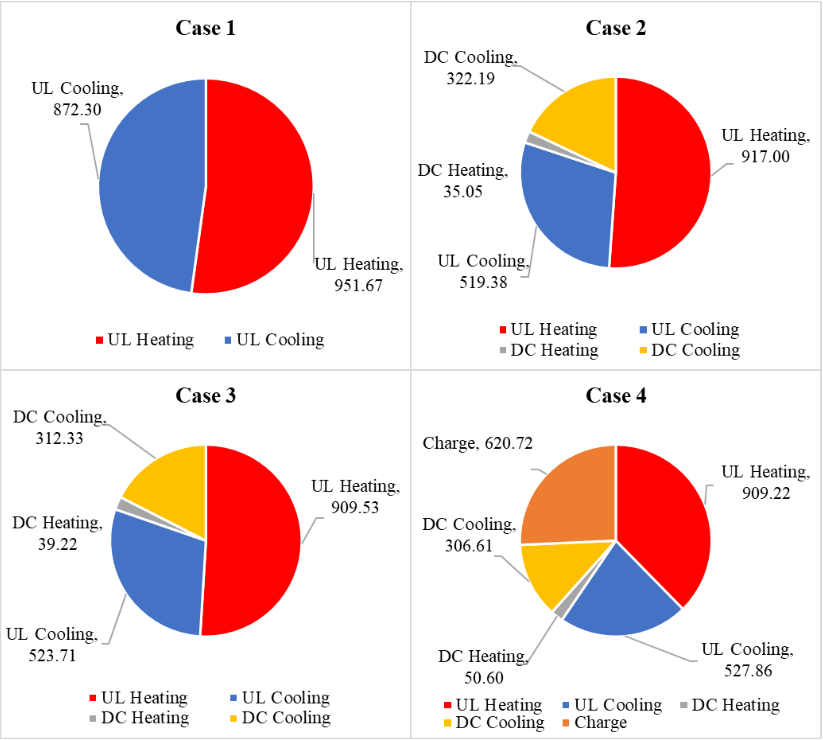
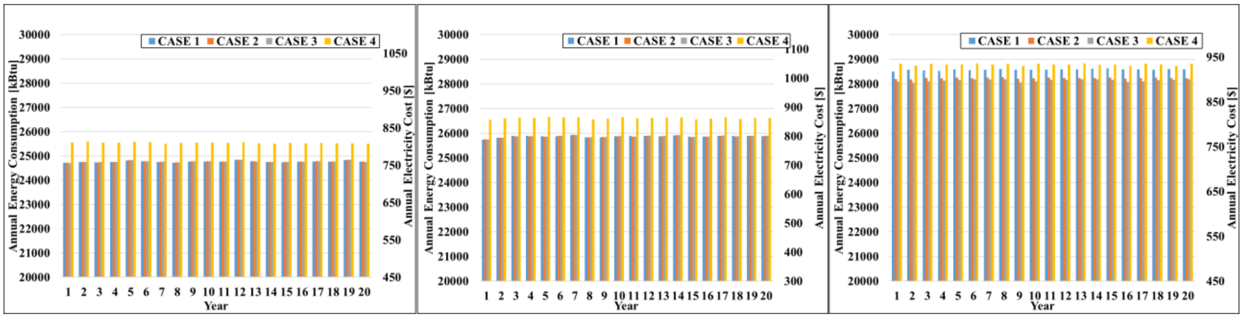


Figure B38. Heating and cooling hours of one year using 2 boreholes (400 ft)

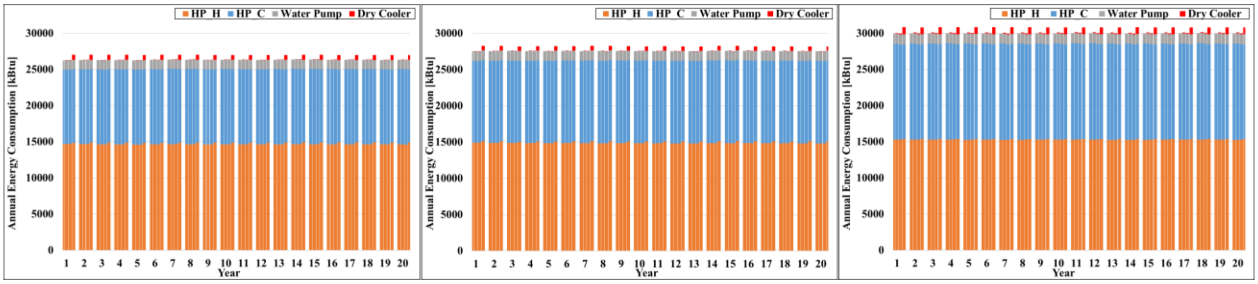


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B39. Annual system energy consumption and cost (at ¢10.93/kWh) for 20 years



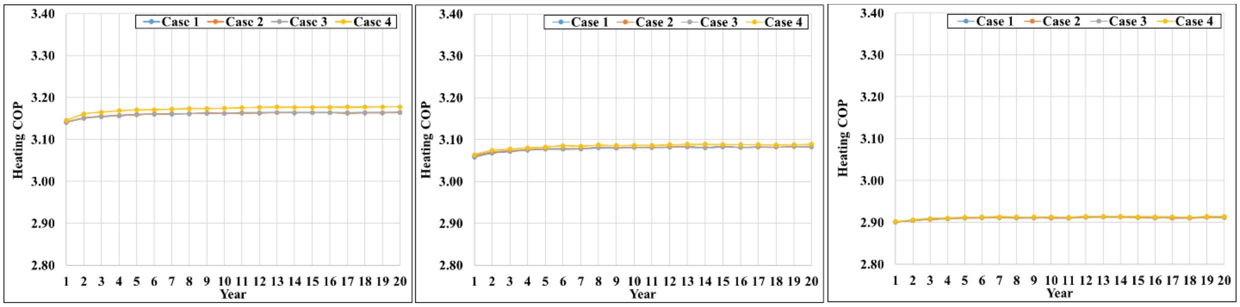
4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B40. Annual energy consumption by categories for 20 years

B.5. Climate Zone 4 – Kansas City (Heat Collection and Storage in Mode 4)

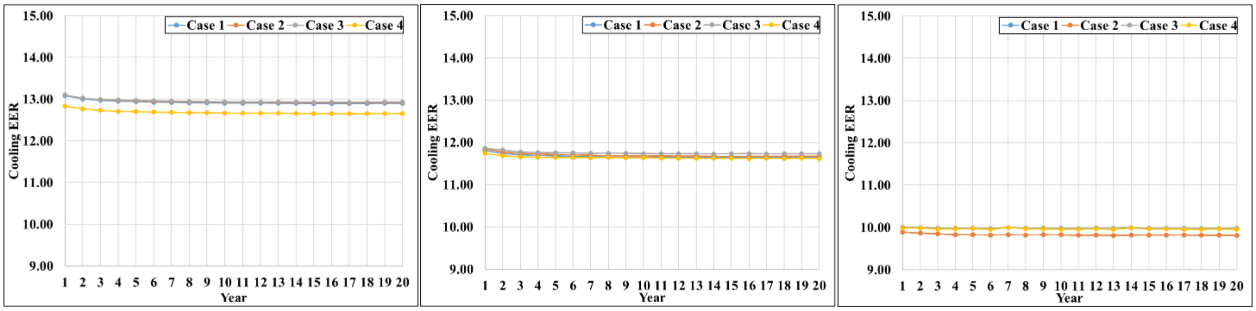


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B41. Yearly average heating COPs for 20 years

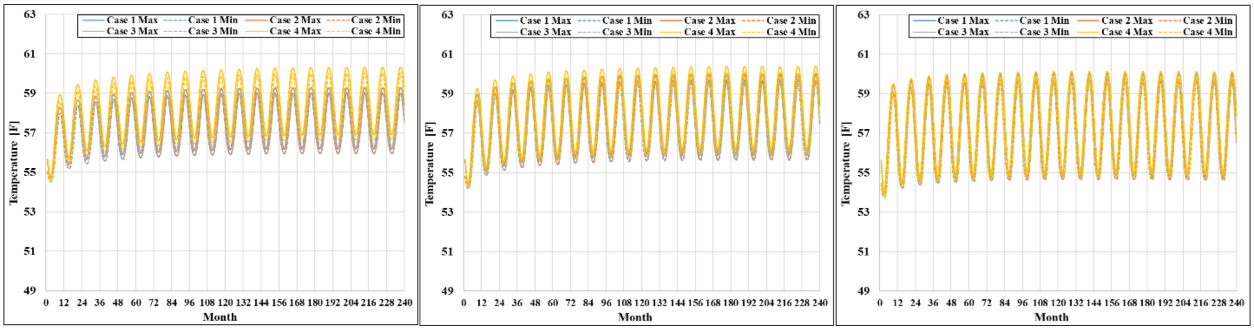


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B42. Yearly average cooling EERs for 20 years

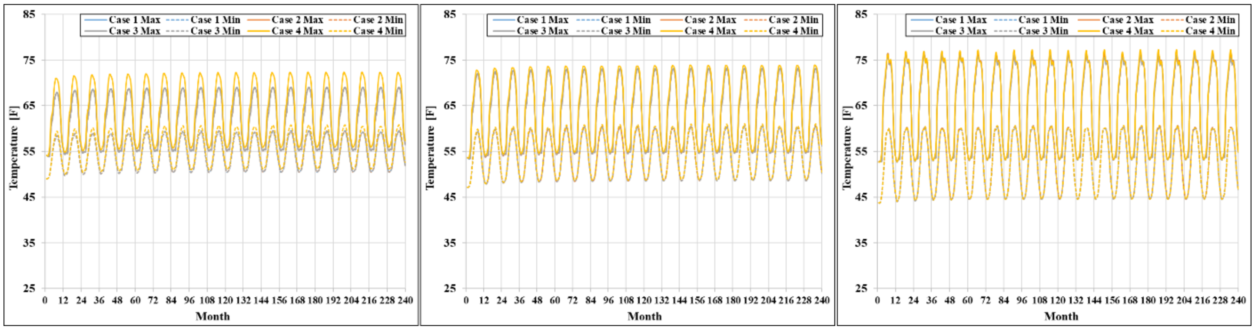


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B43. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

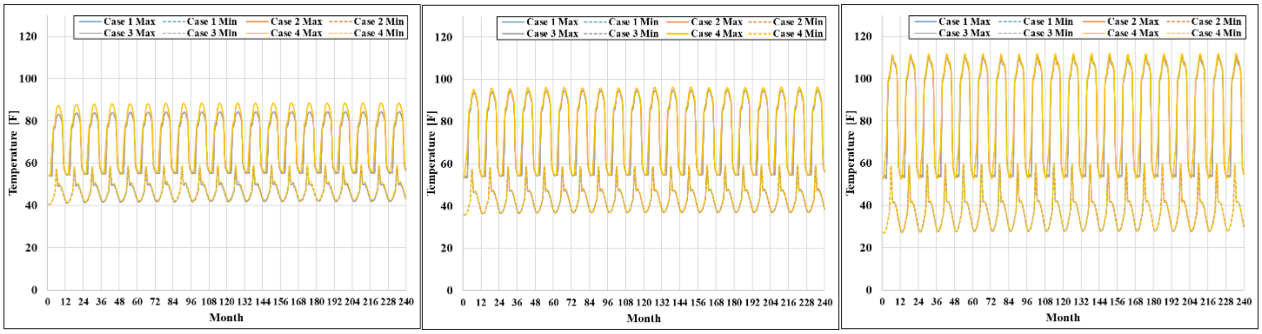


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B44. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B45. Monthly Max. and Min. heat pump return fluid temperature for 20 years

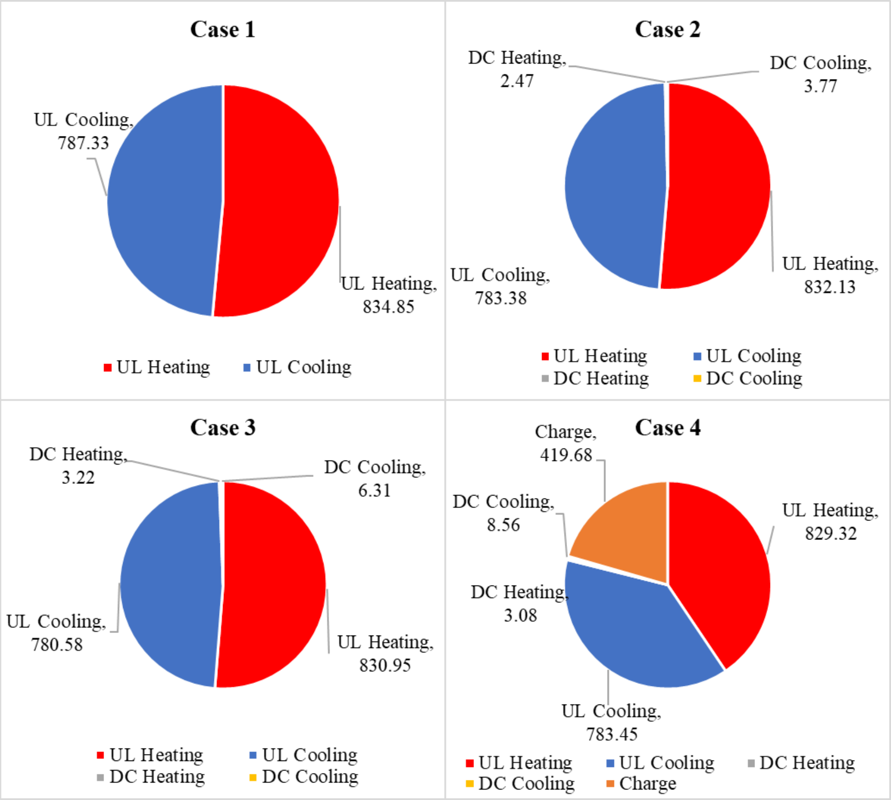


Figure B46. Heating and cooling hours of one year using 4 boreholes (800 ft)

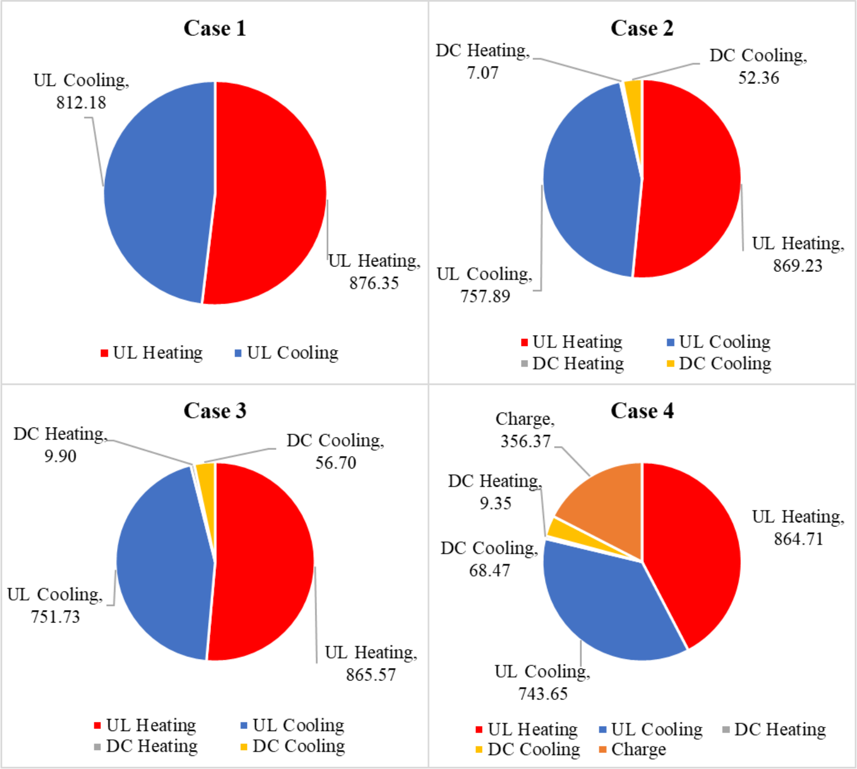


Figure B47. Heating and cooling hours of one year using 3 boreholes (600 ft)

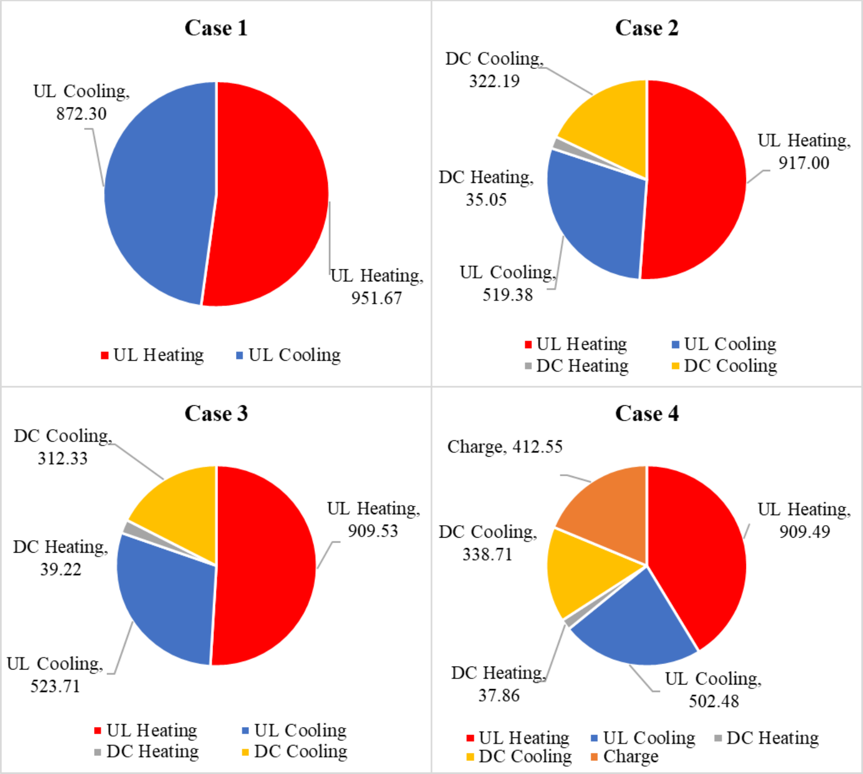
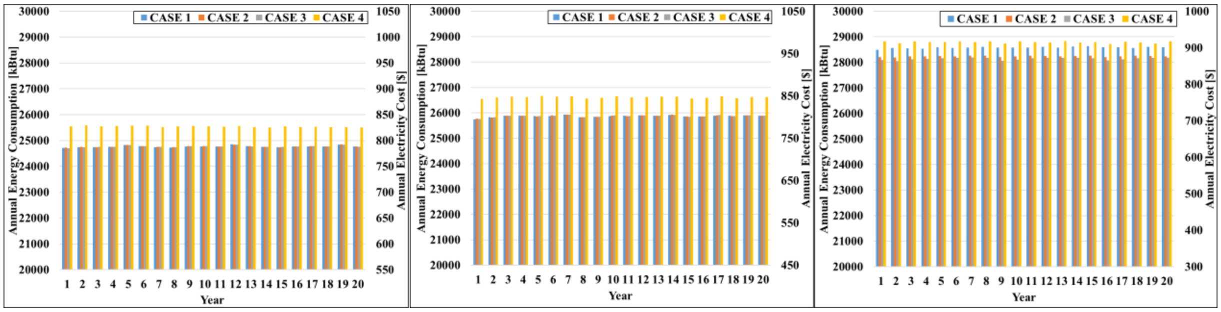


Figure B48. Heating and cooling hours of one year using 2 boreholes (400 ft)

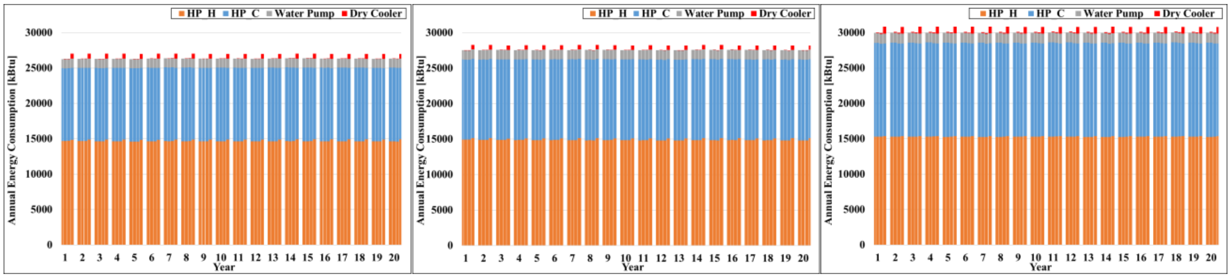


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B49. Annual system energy consumption and cost (at ¢10.93/kWh) for 20 years



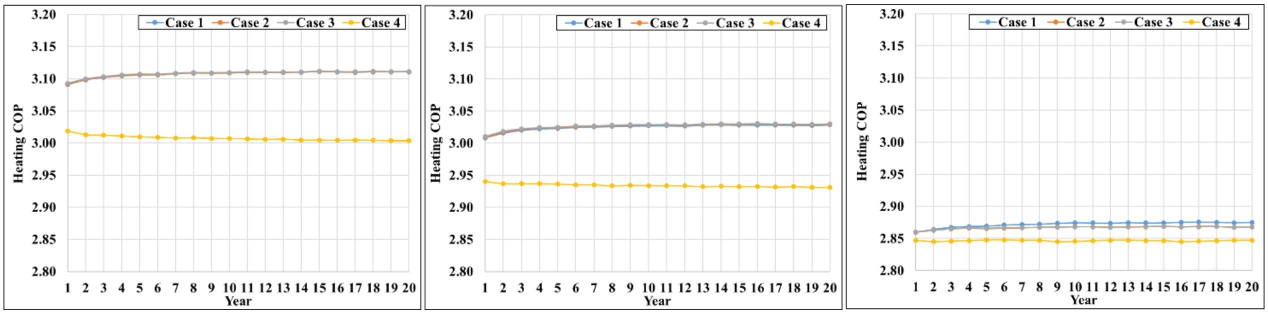
4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B50. Annual energy consumption by categories for 20 years

B.6. Climate Zone 5 – Omaha (Cold Collection and Storage in Mode 4)

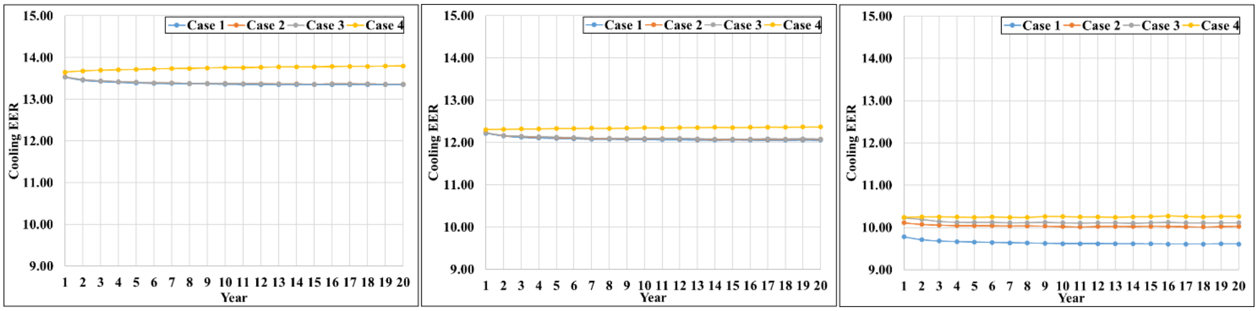


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B51. Yearly average heating COPs for 20 years

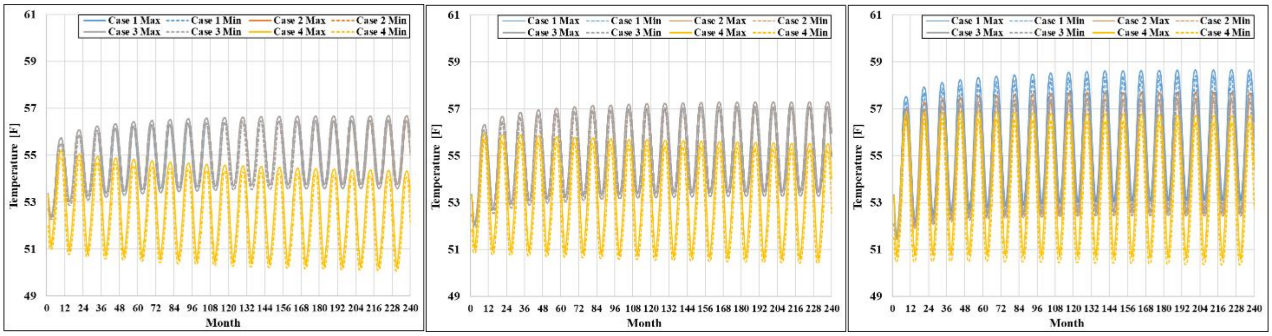


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B52. Yearly average cooling EERs for 20 years

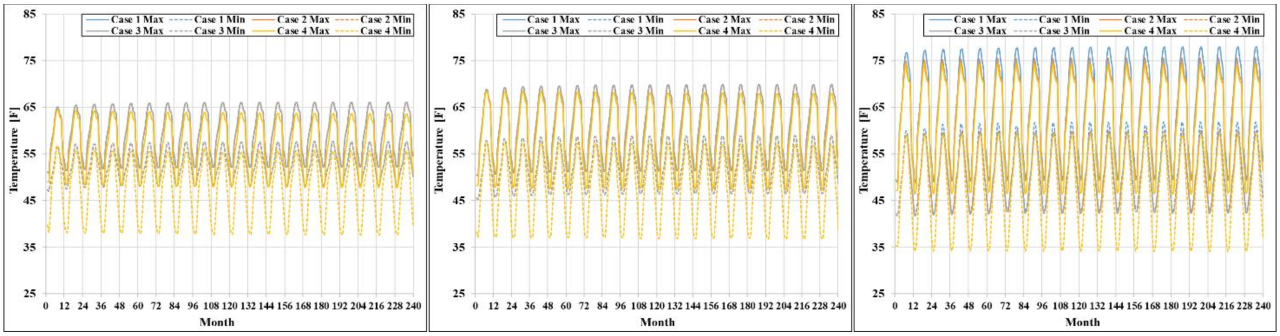


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B53. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

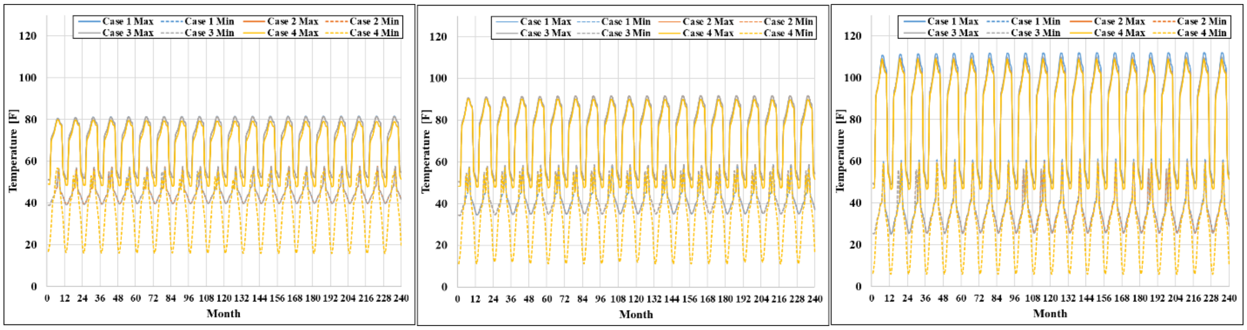


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B54. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B55. Monthly Max. and Min. heat pump return fluid temperature for 20 years

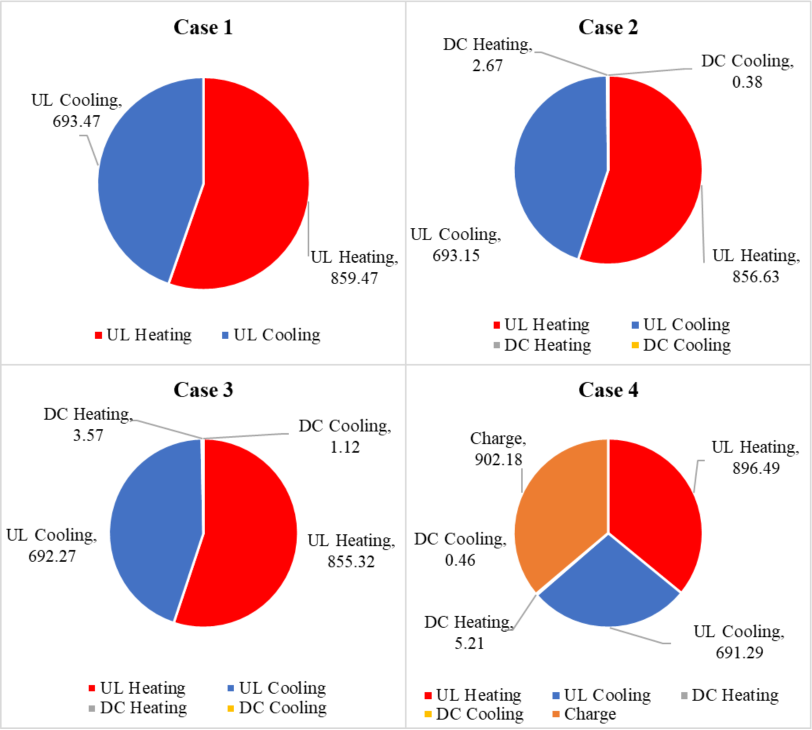


Figure B56. Heating and cooling hours of one year using 4 boreholes (800 ft)

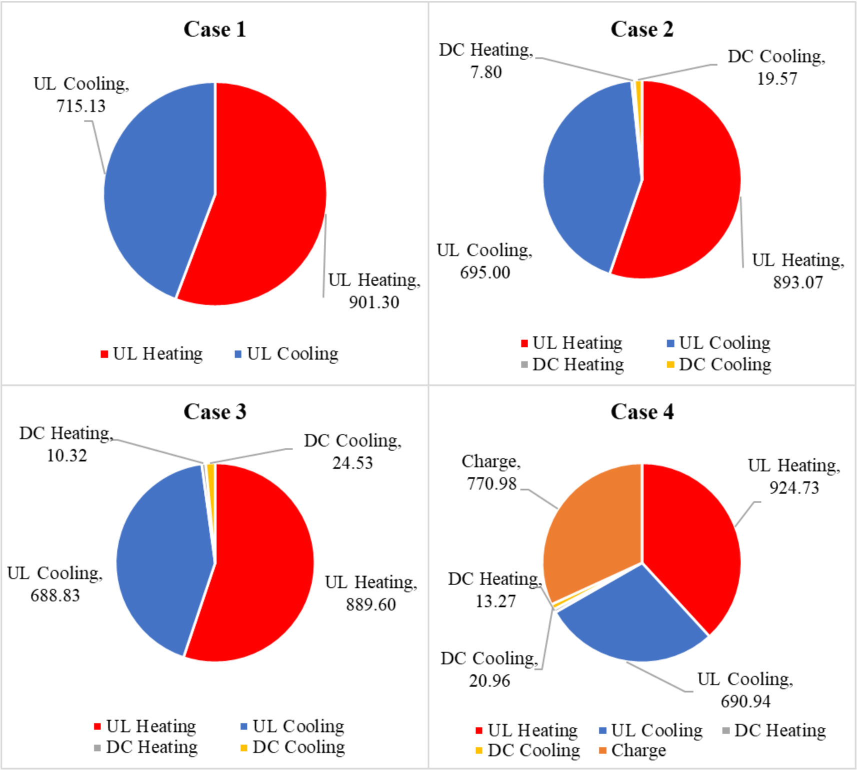


Figure B57. Heating and cooling hours of one year using 3 boreholes (600 ft)

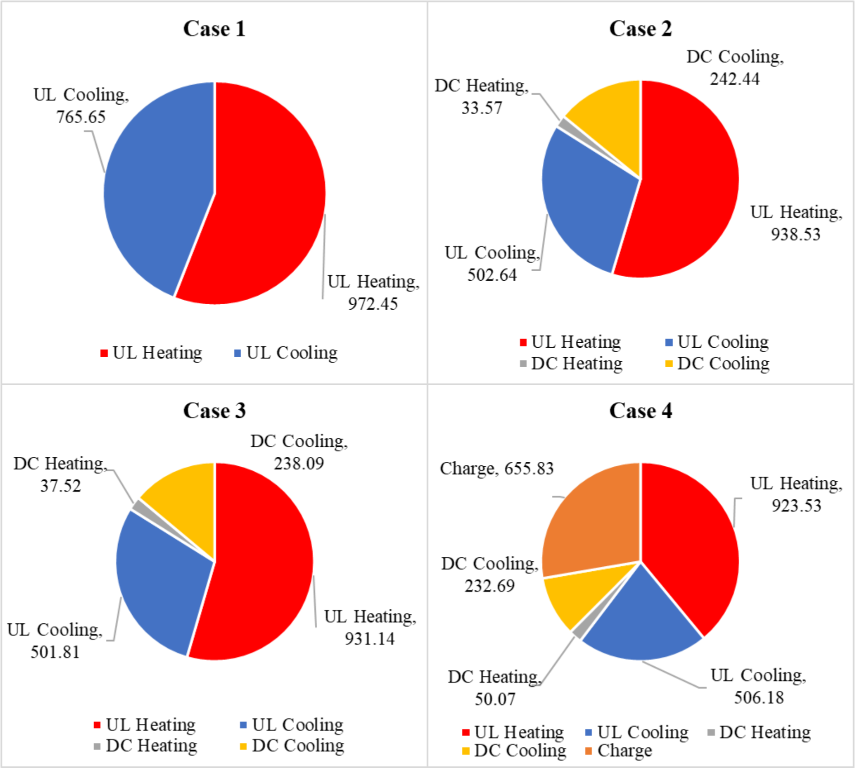
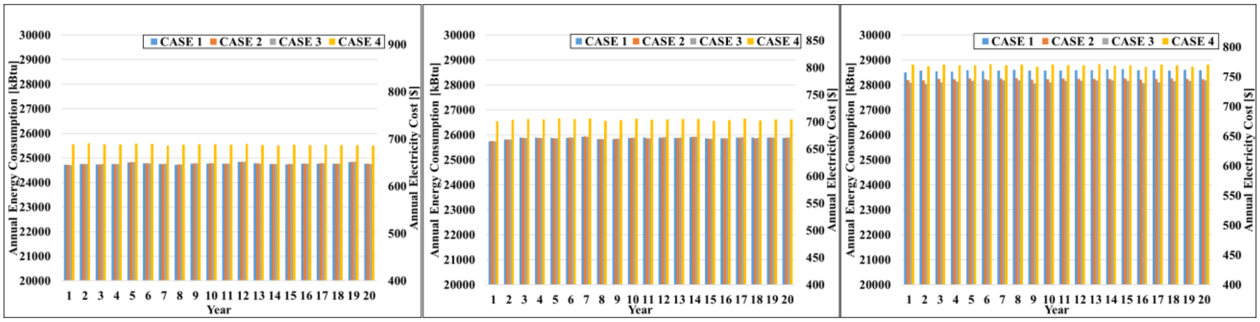


Figure B58. Heating and cooling hours of one year using 2 boreholes (400 ft)

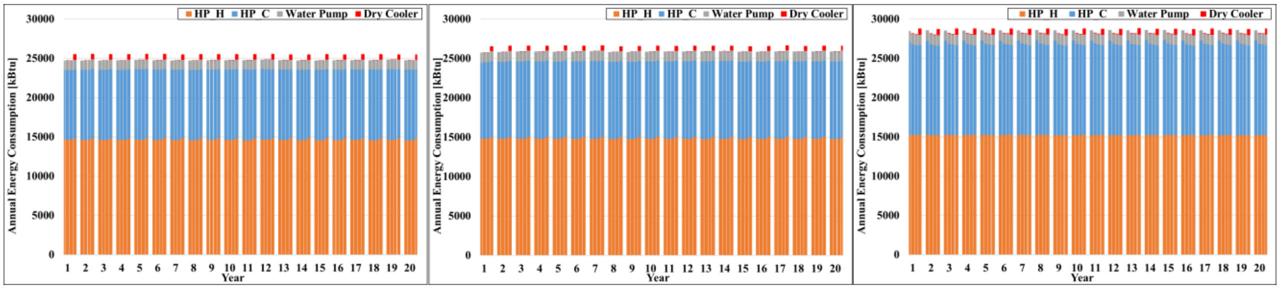


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B59. Annual system energy consumption and cost (at ¢9.08/kWh) for 20 years



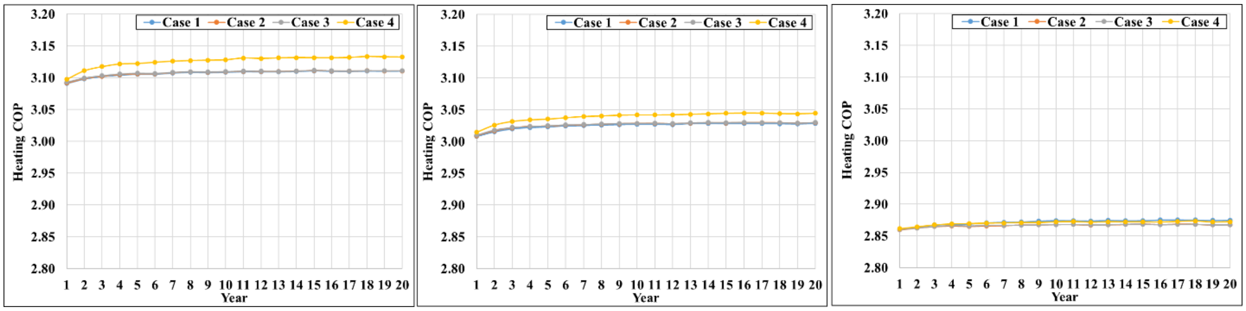
4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B60. Annual energy consumption by categories for 20 years

B.7. Climate Zone 5 – Omaha (Heat Collection and Storage in Mode 4)

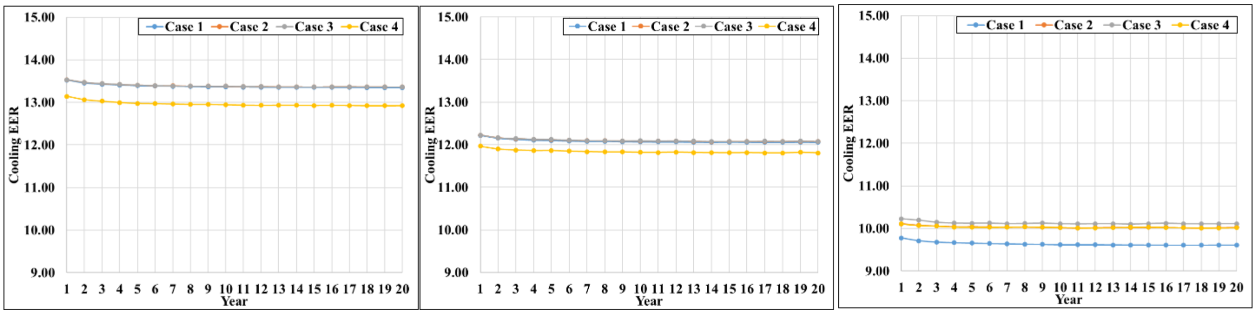


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B61. Yearly average heating COPs for 20 years

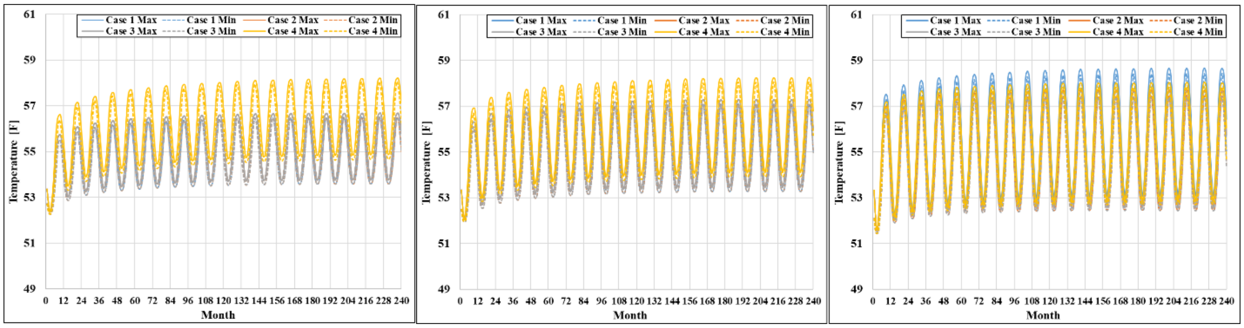


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B62. Yearly average cooling EERs for 20 years

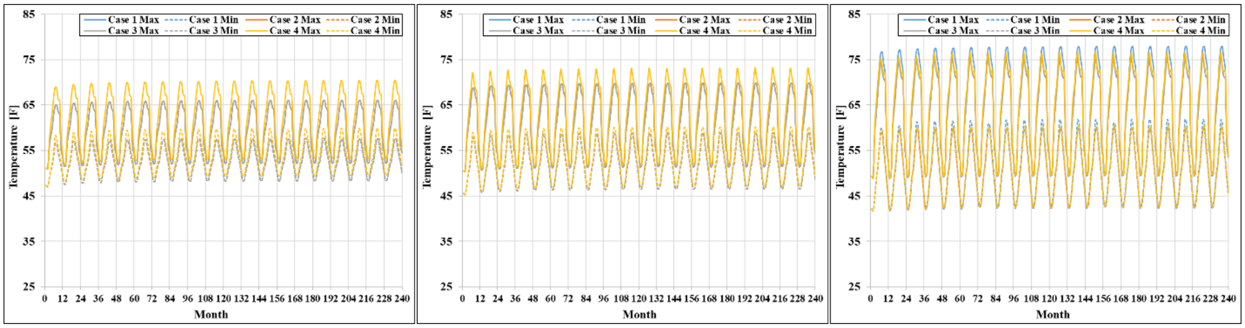


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B63. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

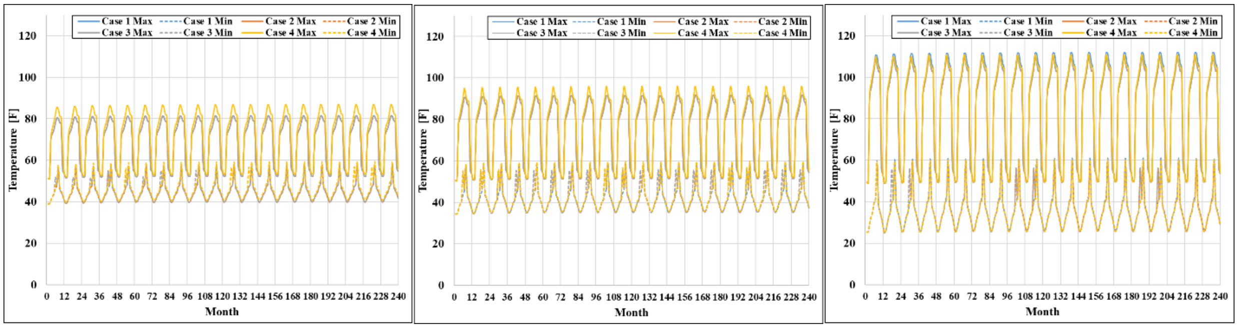


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B64. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B65. Monthly Max. and Min. heat pump return fluid temperature for 20 years

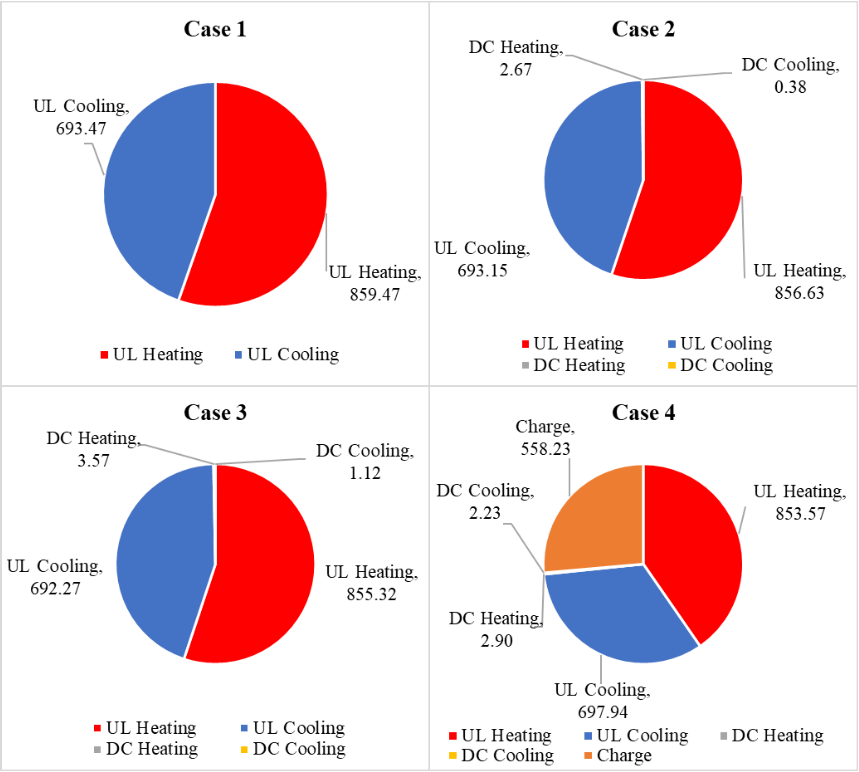


Figure B66. Heating and cooling hours of one year using 4 boreholes (800 ft)

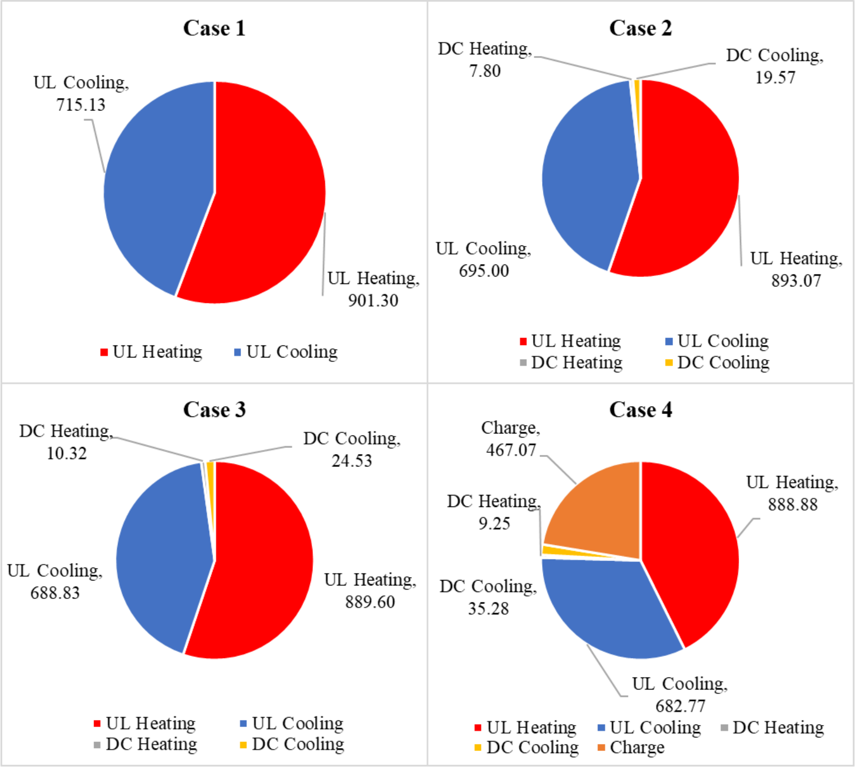


Figure B67. Heating and cooling hours of one year using 3 boreholes (600 ft)

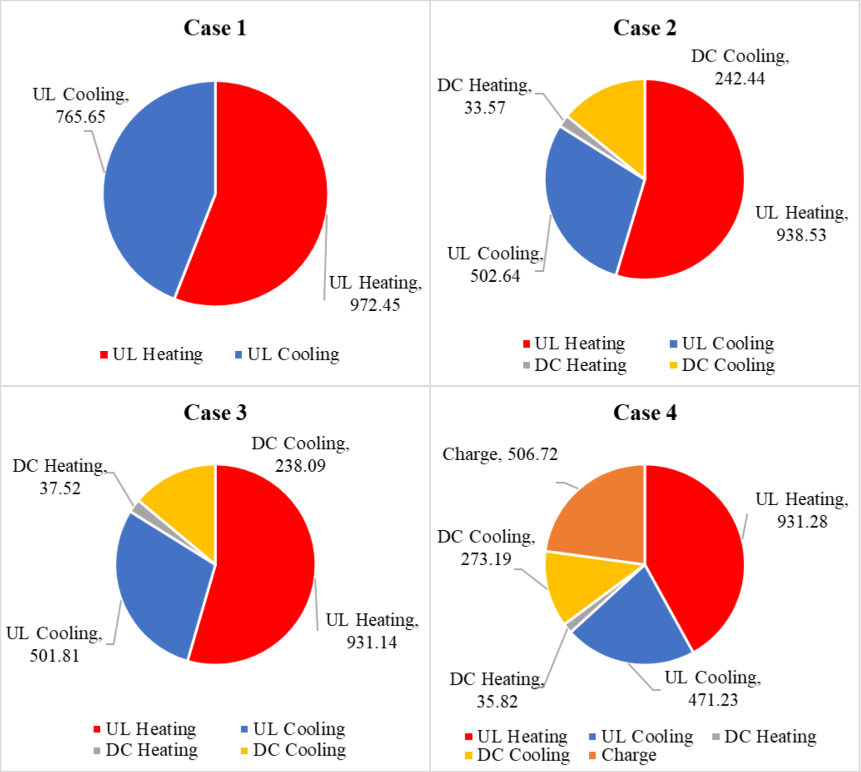
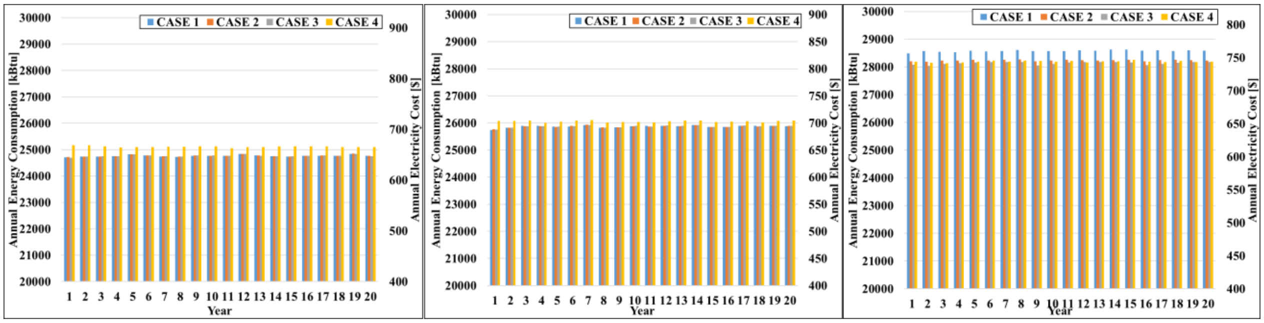


Figure B68. Heating and cooling hours of one year using 2 boreholes (400 ft)

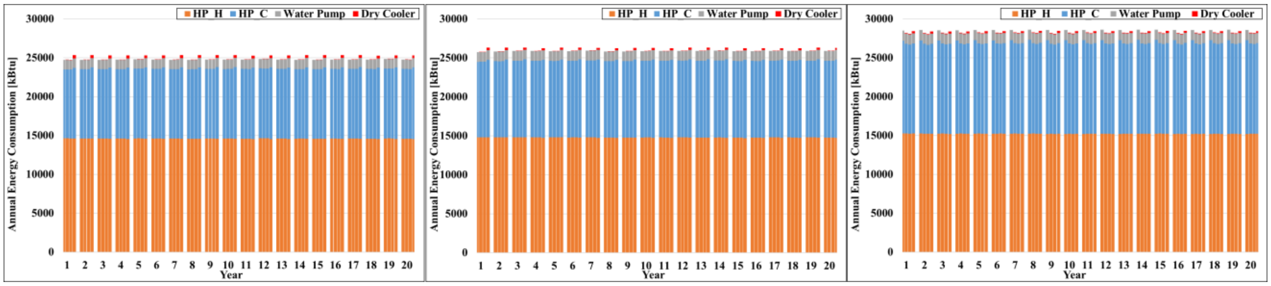


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B69. Annual system energy consumption and cost (at ¢9.08/kWh) for 20 years



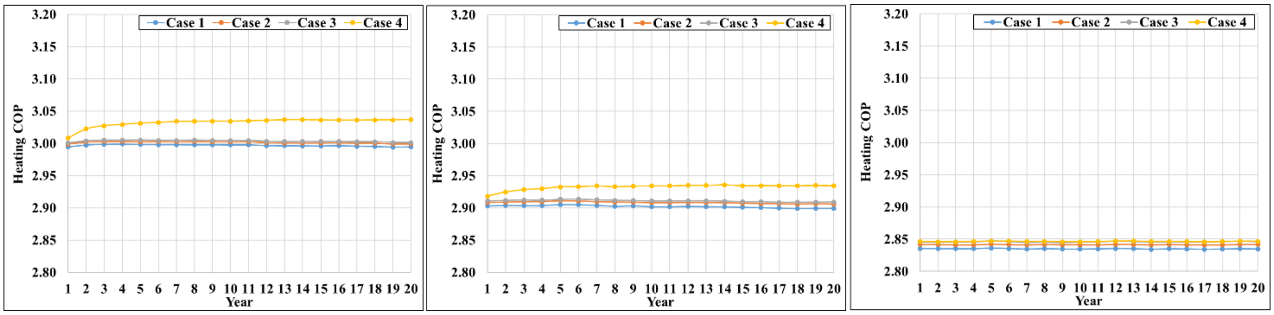
4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B70. Annual energy consumption by categories for 20 years

B.8. Climate Zone 6 – Minneapolis

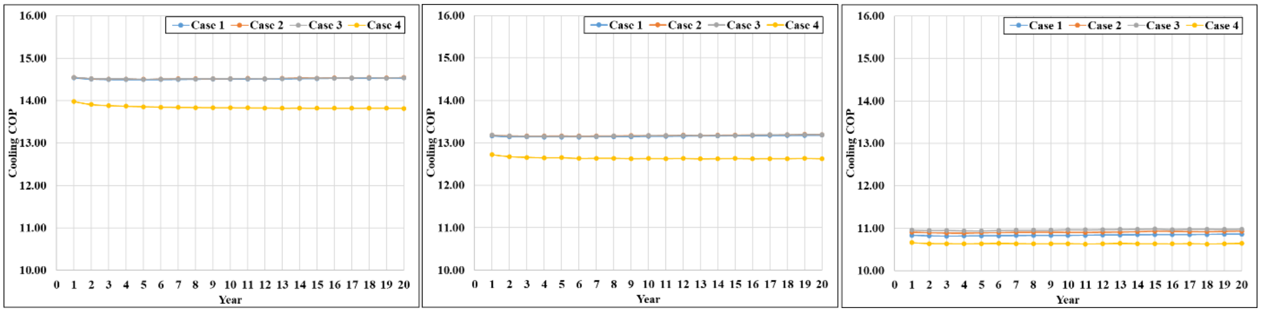


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B71. Yearly average heating COPs for 20 years

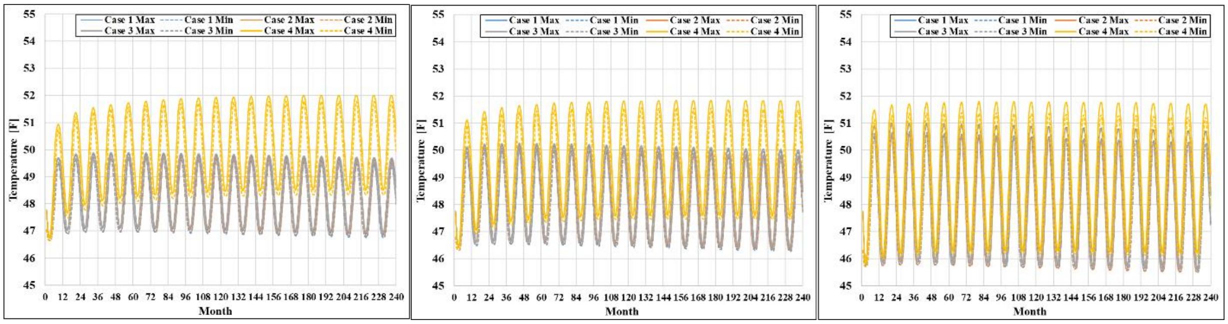


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B72. Yearly average cooling EERs for 20 years

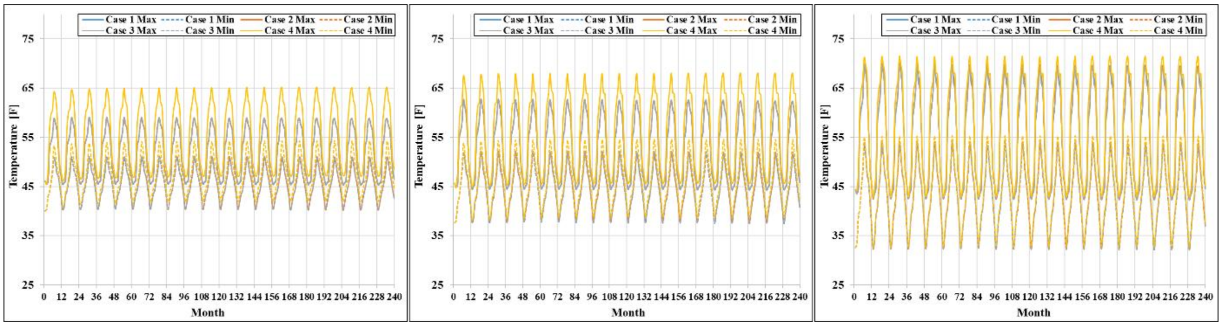


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B73. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

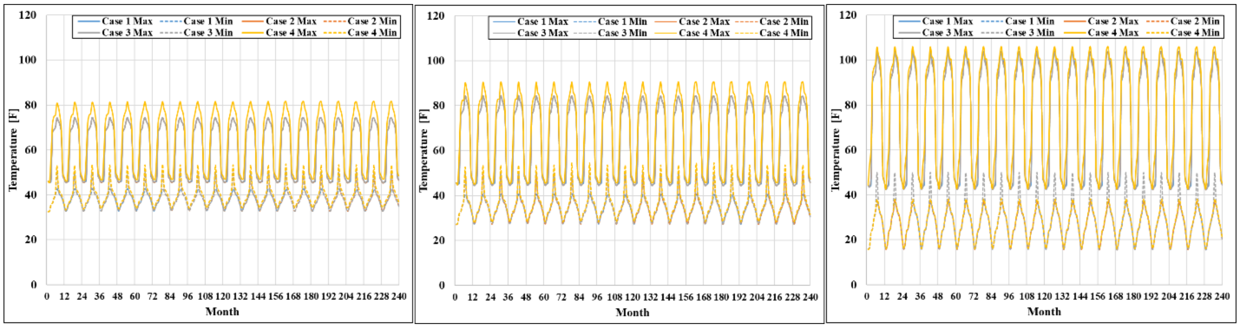


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B74. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B75. Monthly Max. and Min. heat pump return fluid temperature for 20 years

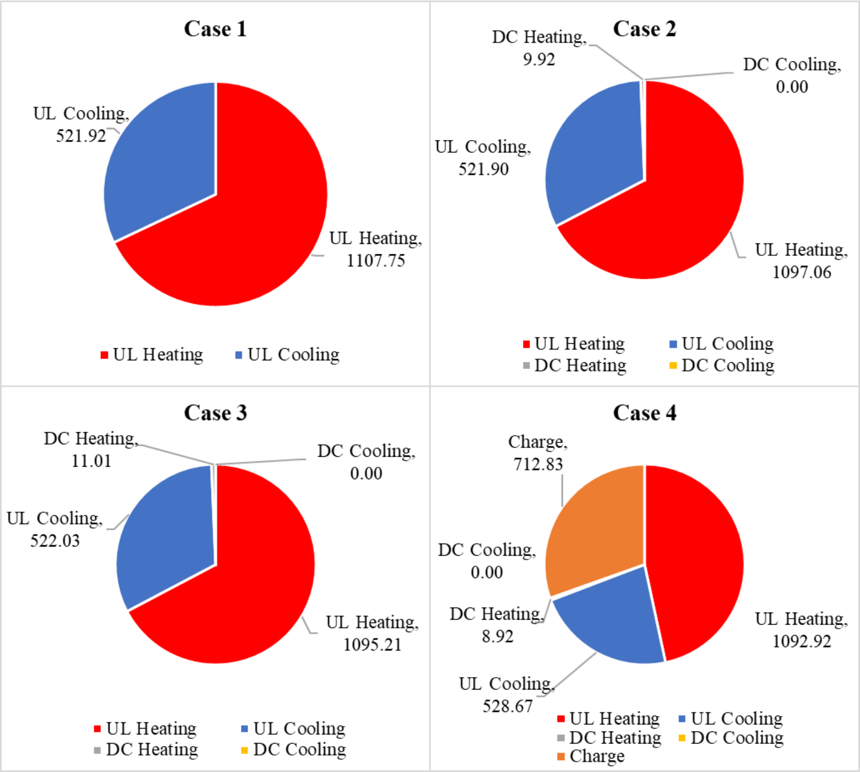


Figure B76. Heating and cooling hours of one year using 4 boreholes (800 ft)

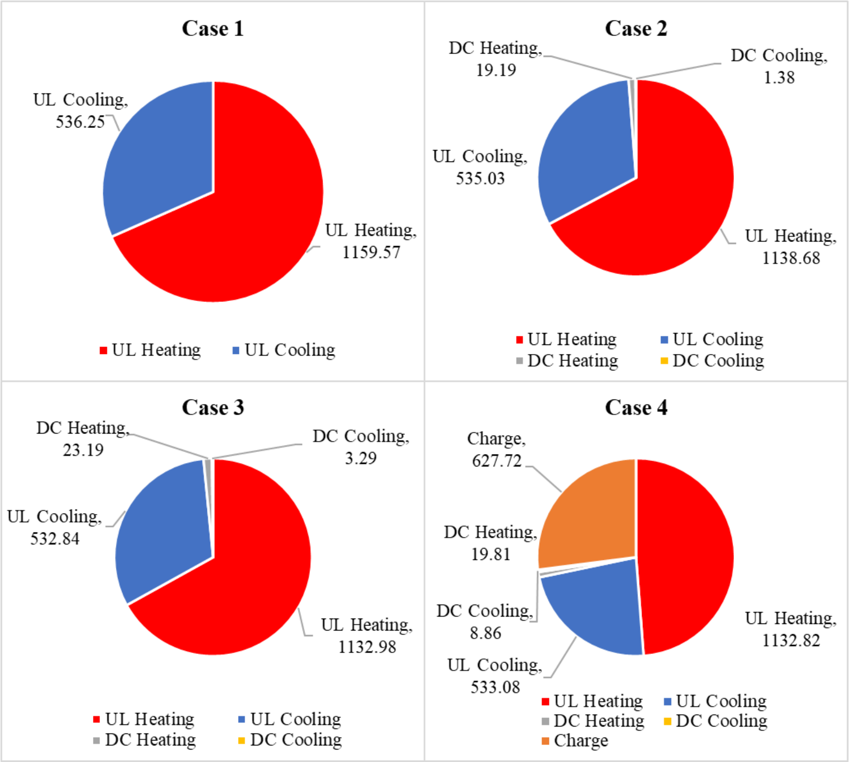


Figure B77. Heating and cooling hours of one year using 3 boreholes (600 ft)

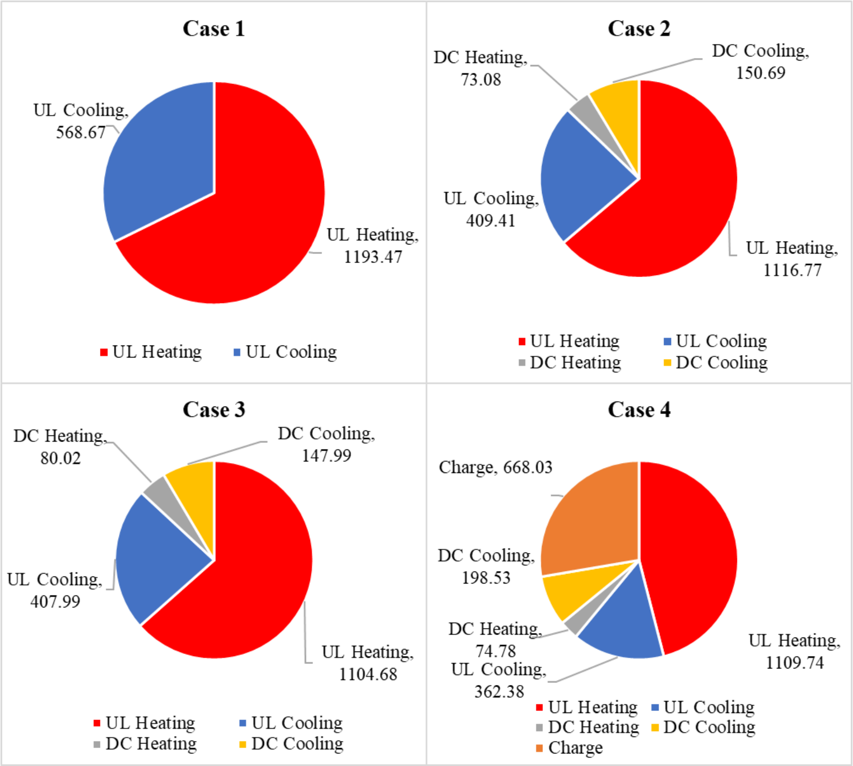
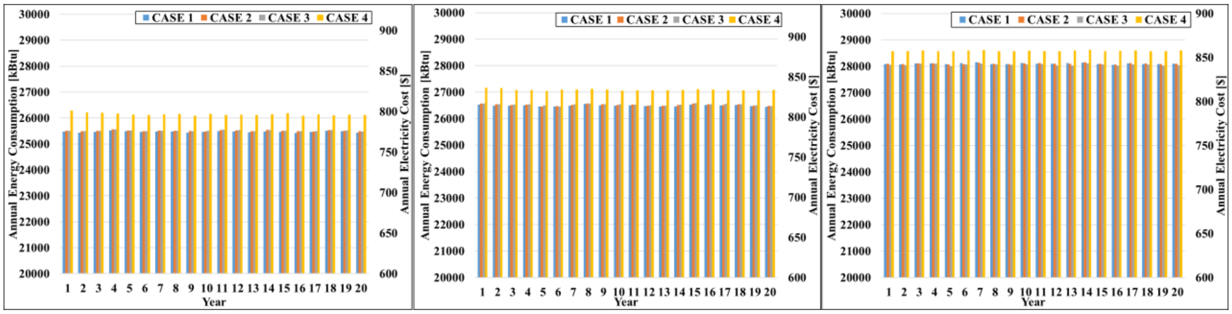


Figure B78. Heating and cooling hours of one year using 2 boreholes (400 ft)

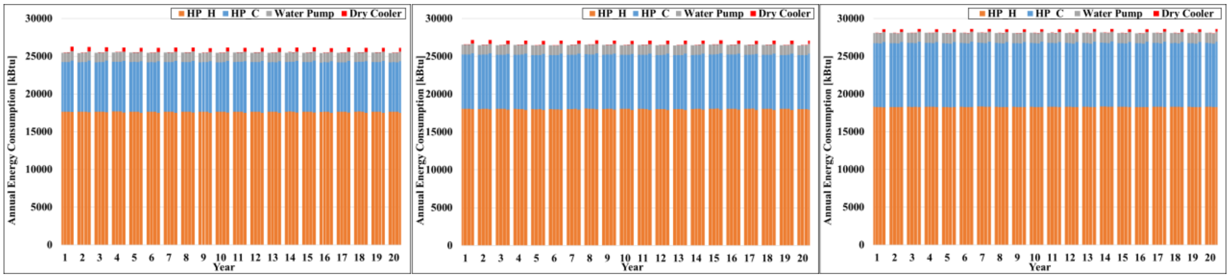


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B79. Annual system energy consumption and cost (at ¢10.33/kWh) for 20 years



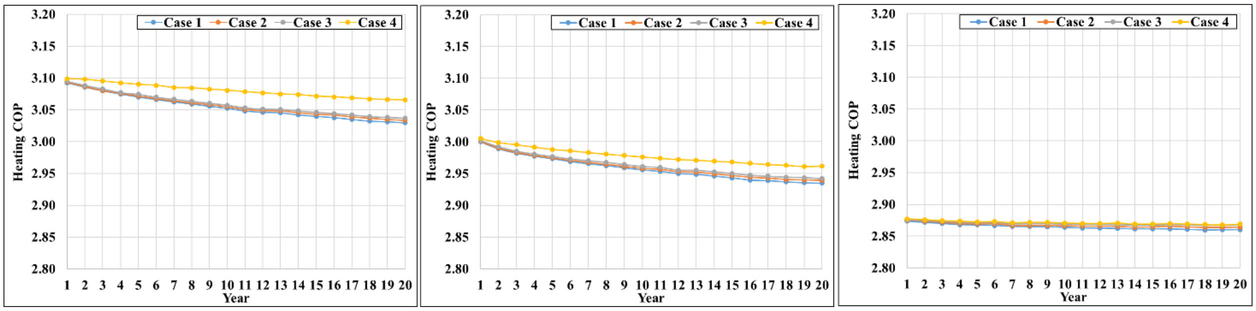
4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B80. Annual energy consumption by categories for 20 years

B.9. Climate Zone 7 – Bismarck

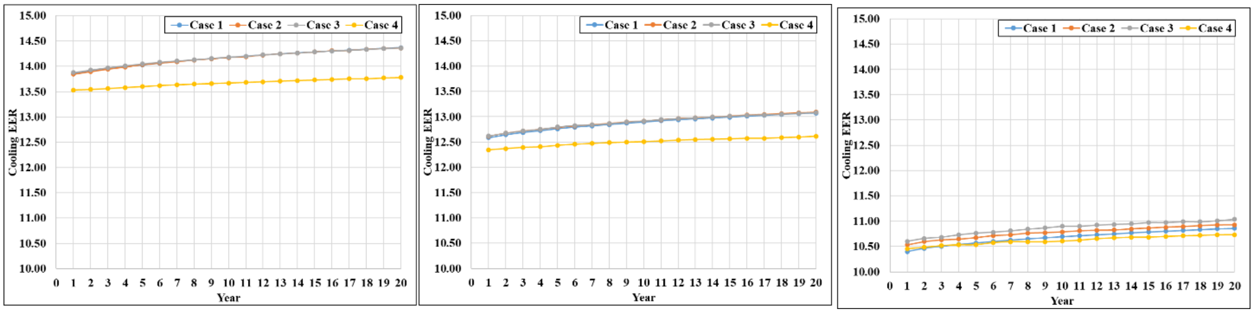


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B81. Yearly average heating COPs for 20 years

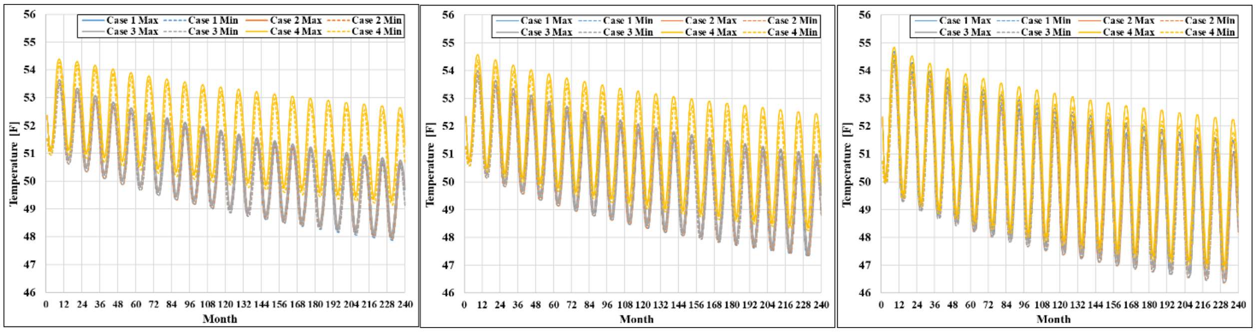


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B82. Yearly average cooling EERs for 20 years

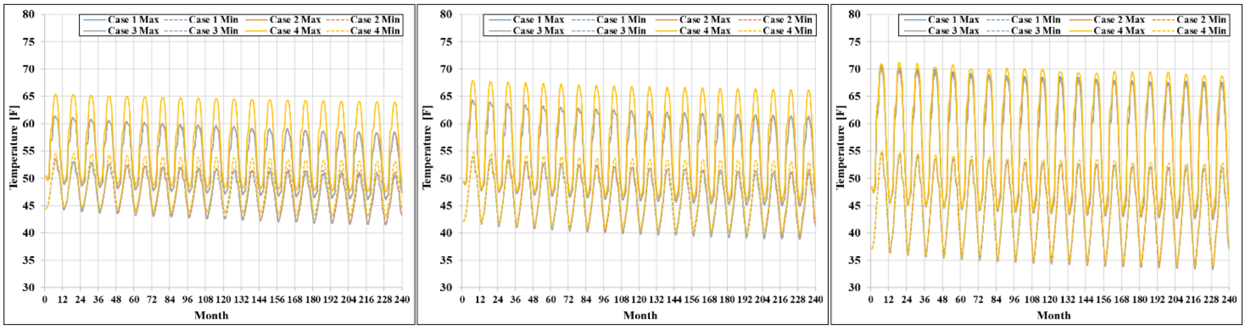


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B83. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

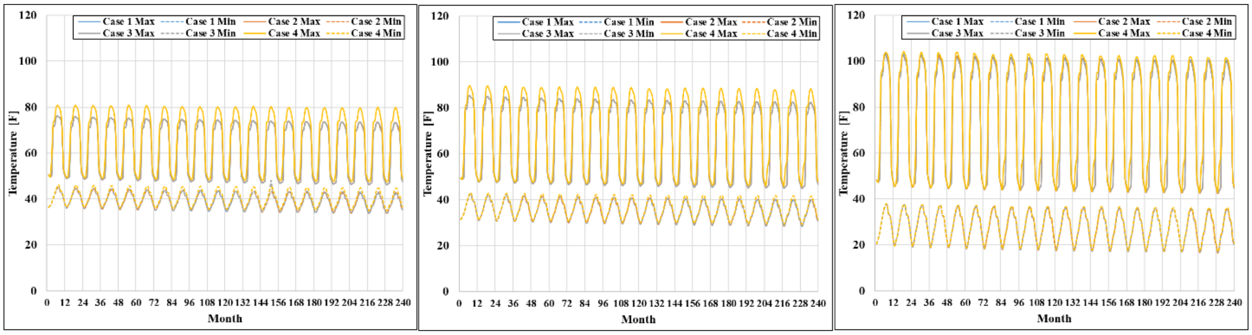


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B84. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B85. Monthly Max. and Min. heat pump return fluid temperature for 20 years

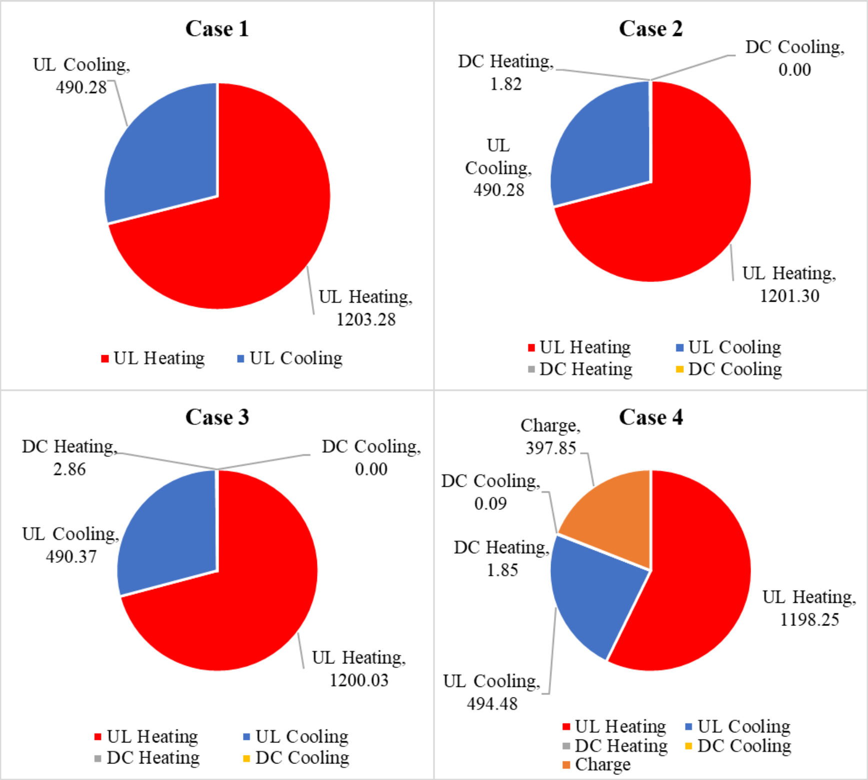


Figure B86. Heating and cooling hours of one year using 4 boreholes (800 ft)

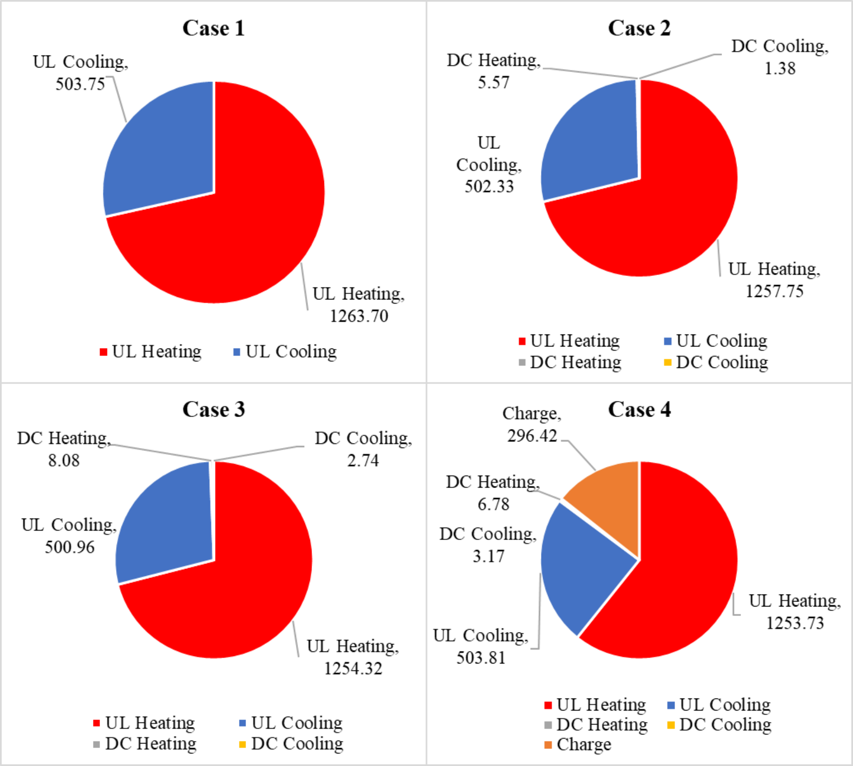


Figure B87. Heating and cooling hours of one year using 3 boreholes (600 ft)

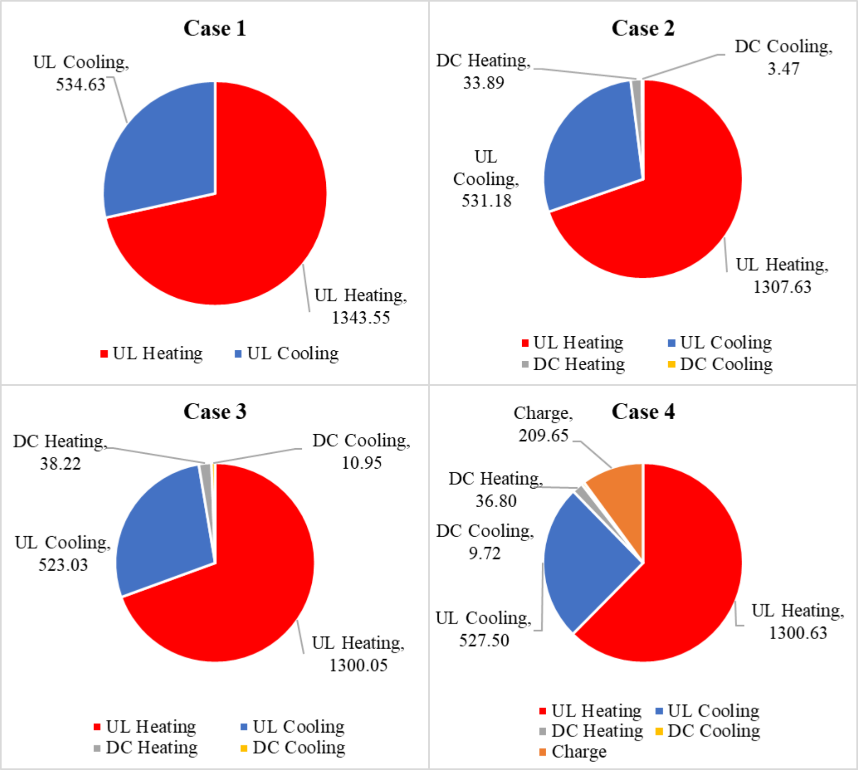
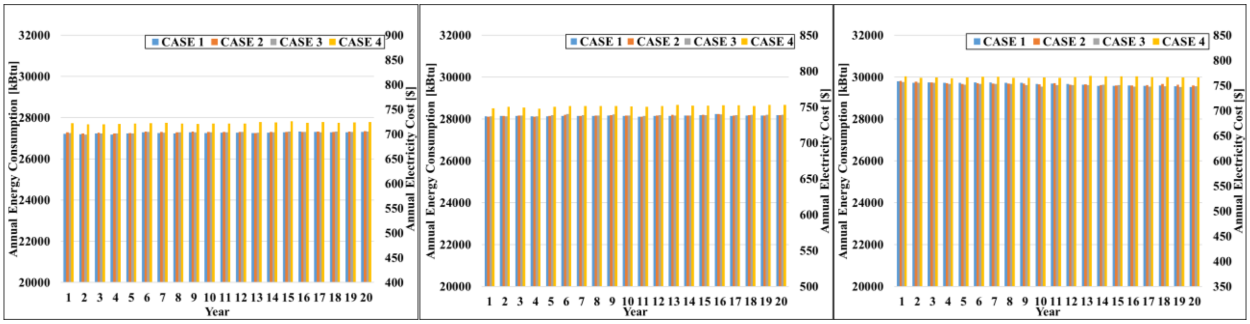


Figure B88. Heating and cooling hours of one year using 2 boreholes (400 ft)

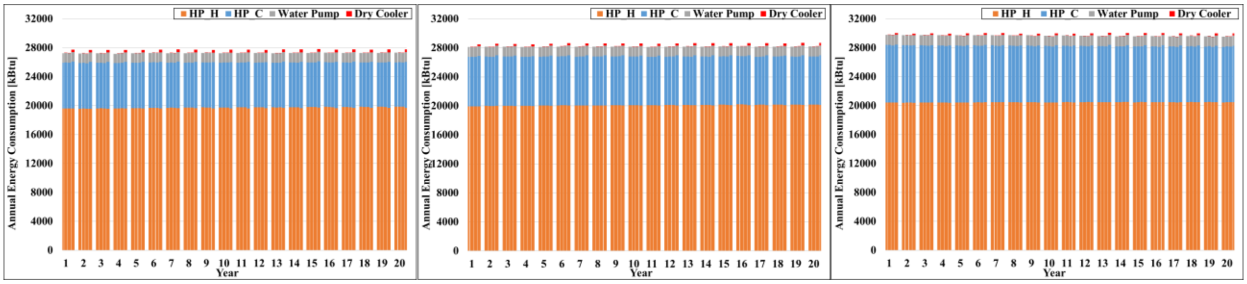


4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B89. Annual system energy consumption and cost (at ¢8.85/kWh) for 20 years



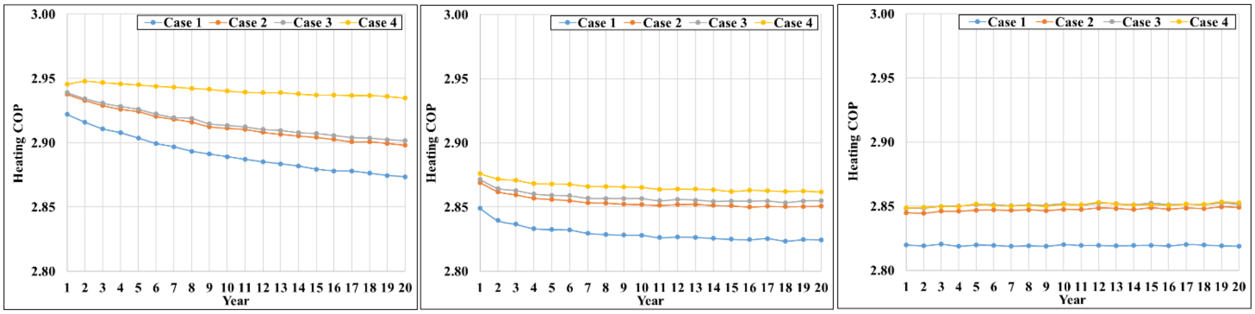
4 Boreholes (800 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

2 Boreholes (400 ft Borehole Length)

Figure B90. Annual energy consumption by categories for 20 years

B.10. Climate Zone 8 – Anchorage

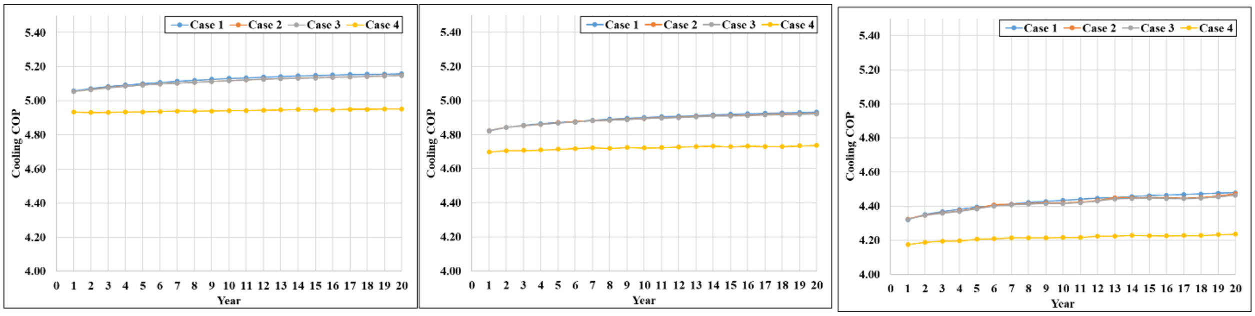


6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B91. Yearly average heating COPs for 20 years

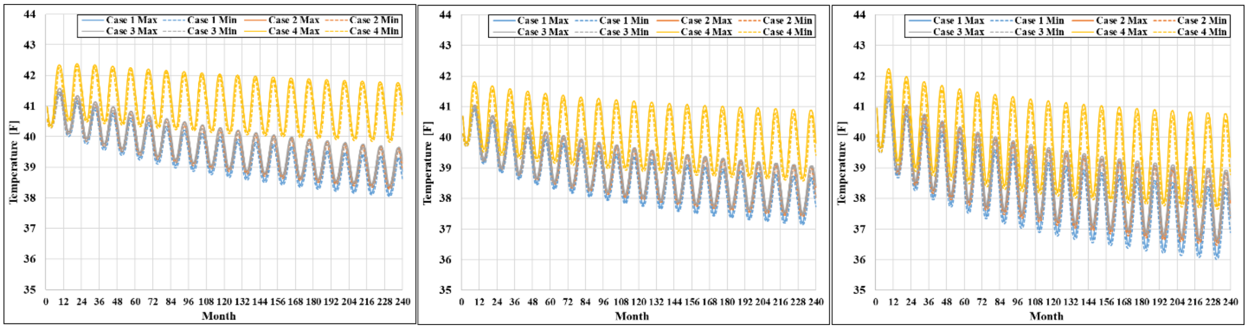


6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B92. Yearly average cooling EERs for 20 years

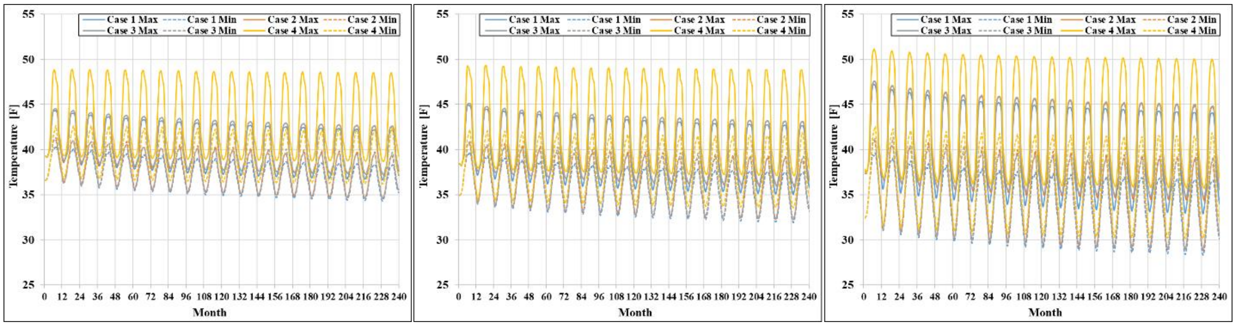


6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B93. Monthly Max. and Min. ground temperature (overall underground domain) for 20 years

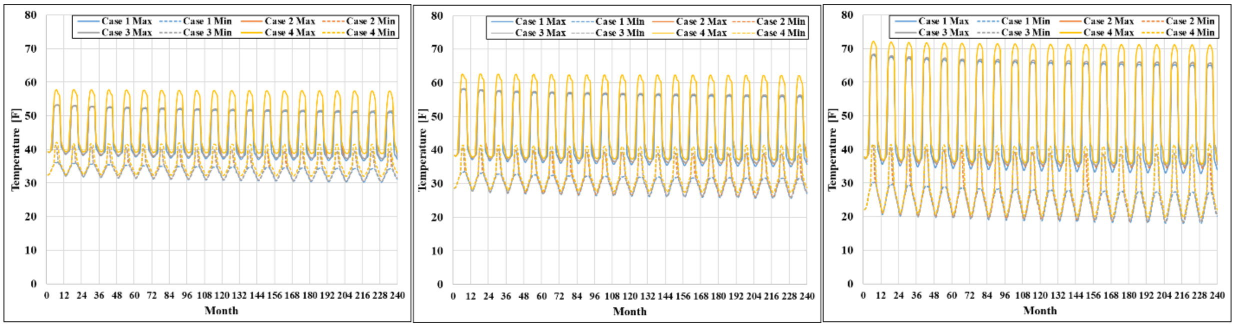


6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B94. Monthly Max. and Min. ground temperature (near boreholes) for 20 years



6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B95. Monthly Max. and Min. heat pump return fluid temperature for 20 years

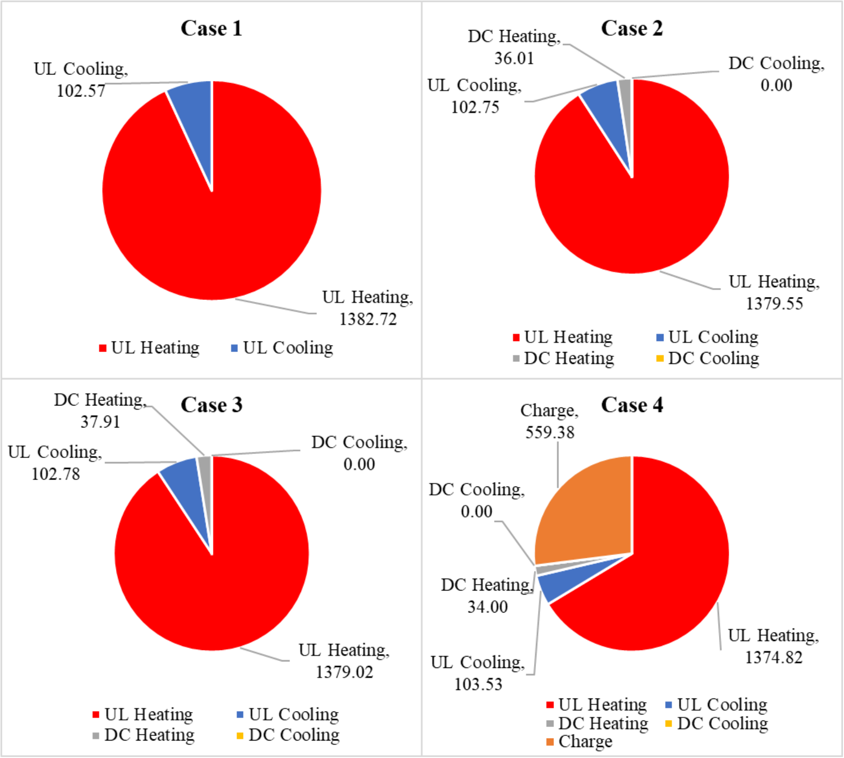


Figure B96. Heating and cooling hours of one year using 6 boreholes (1200 ft)

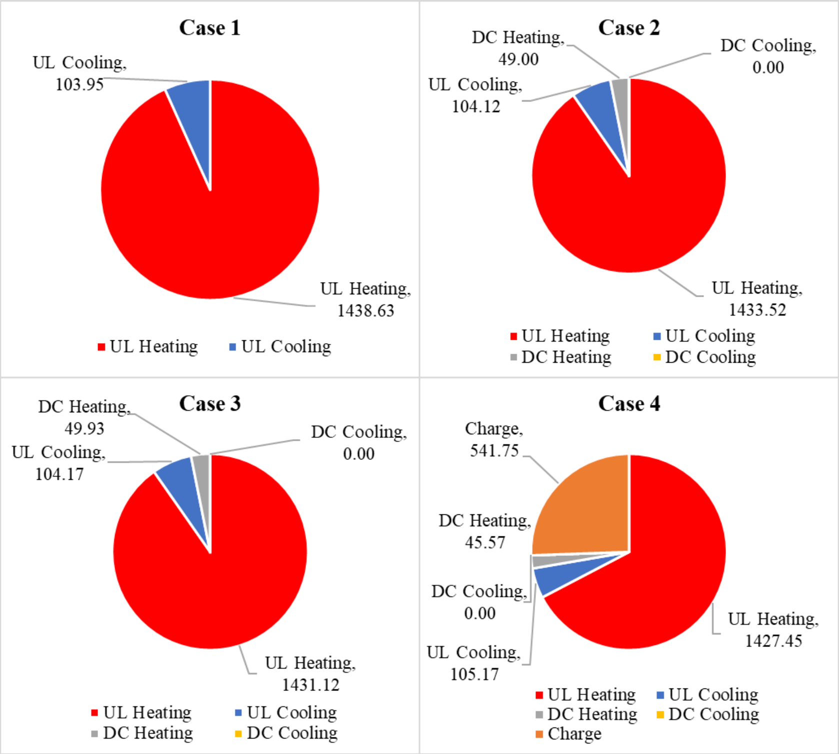


Figure B97. Heating and cooling hours of one year using 3 boreholes (900 ft)

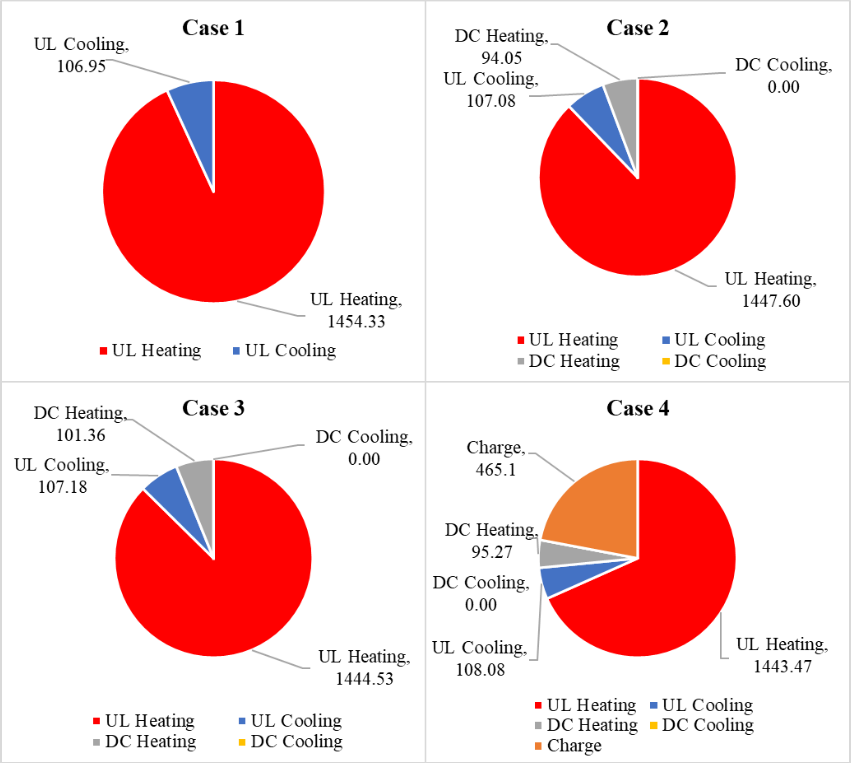
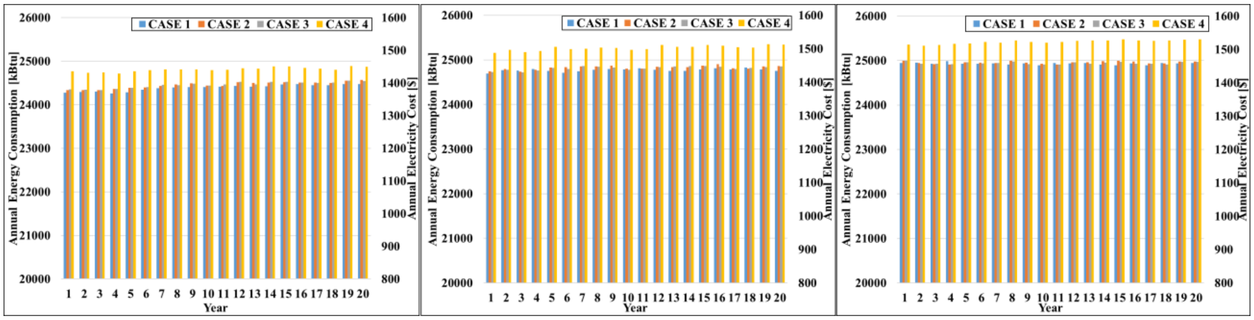


Figure B98. Heating and cooling hours of one year using 3 boreholes (600 ft)

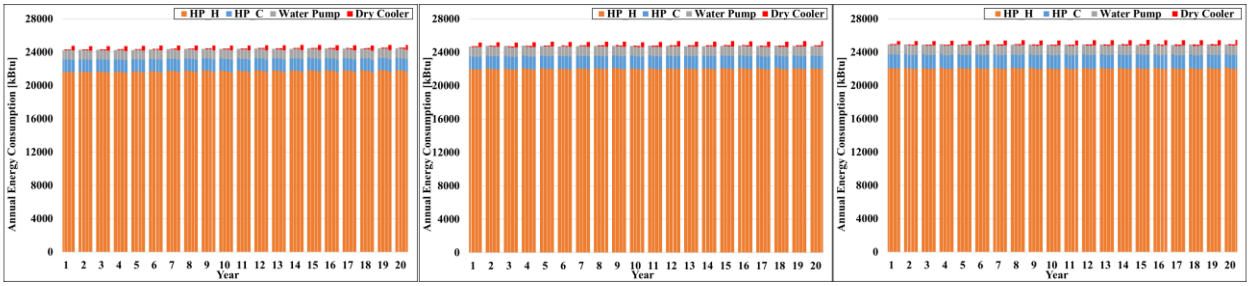


6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B99. Annual system energy consumption and cost (at ¢20.22/kWh) for 20 years



6 Boreholes (1200 ft Borehole Length)

3 Boreholes (900 ft Borehole Length)

3 Boreholes (600 ft Borehole Length)

Figure B100. Annual energy consumption by categories for 20 years