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Recent Development and Application of Geothermal Heat Pump Systems in Cold-Climate Regions of the US: A Further Investigation

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Abstract

A Geothermal Heat Pump (GHP) system is known to have enormous potential for building energy savings and the reduction of associated greenhouse gas emissions, due to its high Coefficient Of Performance (COP). The use of a GHP system in cold-climate regions is more attractive owing to its higher COP for heating compared to conventional heating devices, such as furnaces or boilers. Many factors, however, determine the operational performance of an existing GHP system, such as control strategy, part/full-load efficiency, the age of the system, defective parts, and whether or not regular maintenance services are provided. The omitting of any of these factors in design and operation stages could have significant impacts on the normal operation of GHP systems. Therefore, the objectives of this paper are to further investigate and study the existing GHP systems currently used in buildings located in cold-climate regions of the US, in terms of system operational performance, potential energy and energy cost savings, system cost information, the reasons for installing geothermal systems, current operating difficulties, and owner satisfaction to date. After the comprehensive investigation and in-depth analysis of 24 buildings, the results indicate that for these buildings, about 75% of the building owners are very satisfied with their GHP systems in terms of noise, cost, and indoor comfort. About 71% of the investigated GHP systems have not had serious operating difficulties, and about 85% of the respondents (building owners) would suggest this type of system to other people. Compared to the national median of energy use and energy cost of typical buildings of the same type nationwide, the overall performance of the actual GHP systems used in the cold-climate regions is slightly better, *i.e.* about 7.2%

energy savings and 6.1% energy cost savings on average.

Keywords

Existing Geothermal Heat Pump, Heating COP, Onsite Survey, Energy and Energy Cost Savings, Cold Climate

1. Introduction

According to the Buildings Energy Data Book [1], the US consumes approximately 19% of the total energy of the world, in which buildings (commercial and residential) account for 41% of the US energy consumption. However, only 9% of the US building energy is renewable. Additionally, 45% of US carbon dioxide (CO_2) emissions are caused by buildings, compared to 21% for industry and 34% for transportation [1]. Due to a large amount of fossil fuel consumption nationwide for buildings, incentives/tax credits are given by local governments or utility companies to encourage the use of renewable energy. A Geothermal Heat Pump (GHP) system is one of the systems that make use of renewable energy, *i.e.* underground heat/cold, for space heating/cooling in buildings.

It has been well known that a GHP system has enormous potential for building energy savings and the reduction of associated greenhouse gas emissions, due to its high operational efficiency. This type of system takes advantage of the nearly stable underground temperatures to reject/extract heat to/from underground regions. The use of a GHP system in cold-climate regions is more attractive owing to its higher Coefficient Of Performance (COP) for heating compared to conventional heating devices, such as furnaces or boilers, which typically consume natural gas and have a heating efficiency of up to 90% - 95%. Therefore, plenty of studies have existed in this research area for many years [2]-[12]. For example, most recently, David *et al.* [2] and Arat and Arslan [3] in 2017 demonstrated the use of large-scale GHP systems for district heating. Liu *et al.* [4] in 2015 investigated the feasibility and performance of GHP systems used in three cold-climate regions of China, and they found that Beijing, as one of the three investigated regions, is the most suitable city for GHP systems, compared to the other two cities, *i.e.* Shenyang and Qiqihaer. In 2013, Self *et al.* [5] compared GHP heating with other heating options, and found out that the use of GHP systems is economically advantageous if the local electricity price is low, which also has the lowest effect on the environment considering the low CO_2 emissions. An energy and exergy flow analysis was performed by Lohani and Schmidt [6] in 2010 considering different heating options, including fossil fuels, ground and air source heat pump systems. The result of this comparison revealed that the GHP heating system is better than air source heat pumps and other conventional heat options. The investigation performed by Urchueguía *et al.* [7] in 2008 on GHP systems revealed that the heating energy savings of the investigated GHP systems can be as high as 60% compared to conventional air-source heat pump systems. Studies on the use of GHP system for greenhouse heating have existed for a number of years [13]-[21]. Moreover, GHP systems can be used for snow melting on pavements and bridge decks [22] [23] [24] [25] [26].

This high performance and the potential for energy and/or energy cost savings give building owners, who are living in cold-climate areas of the US, another option when making the decision on what type of heating system to install in buildings/houses. Additionally, designers/engineers have another alternative to meet local codes/standards and in the meanwhile to bring the green concept into their designs. From the perspectives of governments, designers, and/or engineers, the motivations for the design and use of a GHP system in a real project could be due to its low energy consumption and its reduced effect on the environment. From the building owners' perspectives, however, the capital and operational costs could be the top priorities, especially for private sector projects. Convincing people is not easy, especially convincing them to spend more money now and wait for the payback year after year. In this way, designers/engineers have the responsibilities to educate people (building owners) and show them the potential benefits of using a costly system, e.g. a short payback period. For this reason, the potential benefits of using a GHP system are quantified in a form of energy and energy cost savings in comparison to so-called conventional systems, even though most of the building owners have no idea what the conventional systems referred by designers/engineers actually are. The gap in the understanding of building mechanical system design between designers and building owners may leave hidden troubles for the future use and operation of GHP systems. For example, William [27] conducted a comparison of carbon emission between residential heating and cooling options and found that for a residential building located in Daytona Beach, Florida, and equipped with a high-efficiency GHP system, no significant energy savings were observed compared to a conventional air-conditioning system. This was apparently against the original expectation of the building owner and the designer team.

Actually, there is an essential difference for a GHP system between simulation/expectation mode and real operation mode. A real existing system, not including a system built up in a lab for research purposes, may operate very differently from a simulated system through computer modeling, which is assumed to be controlled ideally and that no regular maintenance is needed. The operation of an existing GHP system could be influenced by many factors that usually cannot be fully included in computer simulations, such as

- the actual control strategies implemented by building owners or operators and if they are appropriately designed for the building usage,
- defective parts in the system,
- the age of the system which may be too old to maintain the high efficiency,
- implementation of regular maintenance services to maintain normal operation of the system.

The omitting of any of these factors in design and operation stages could have significant impacts on the normal operation of GHP systems as well as the achievement of expected energy and energy cost savings. Therefore, the study described in this paper aims to further investigate existing GHP systems installed in buildings located in cold climates of the US, e.g. in the state of North Dakota, representing the Climate Zone 6 and 7 as described in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard [28]. The significance of this study focuses on the following aspects,

- finding out whether these systems are operating as anticipated and designed
- comparing these systems with national median buildings (the Environmental Protection Agency (EPA)'s Energy Star Target Finder [29] result for a national median property), in terms of building energy use and energy cost
- identifying common operating difficulties of these existing GHP systems
- identifying the possible barriers to the wide application of GHP systems in the northern regions of the US
- demonstrating owner's satisfaction with their GHP systems
- investigating the motivations of building owners in installing GHP system in the first place
- investigating the capital cost information of installing GHP systems in cold-climate regions of the US (in terms of $\$/m^2$)
- providing a reference to building designers/contractors for GHP applications and establishing the acceptance of potential end users in cold-climate regions

The methodologies used in this study mainly include on-site surveys and investigations through questionnaires, data and information request and collection, as well as data classification and analysis.

Although similar studies [30]-[39] were done, where some commercial buildings equipped with GHP systems were investigated at different times, in terms of system performance, operating difficulties, owner satisfaction, etc., our study can be considered as an extension or a further investigation based on the existing studies and will focus on the recent development and application of GHP systems in cold-climate regions of the US. This is also regarded as the purpose/goal of this study.

2. On-Site Surveys and Investigations

As the first step of this study, on-site surveys and investigations took place, which included three tasks, *i.e.* selecting the target buildings, obtaining the permissions for on-site investigations, and preparing the survey documents.

2.1. Selecting the Target Buildings

The target buildings in this study are the buildings located in cold-climate regions of the US (North Dakota) and equipped with GHP systems (closed-loop, open-loop, and/or direct-exchange if available).

Manz [40] conducted an investigation in 2011 about the locations of geothermal installations in the cold-climate regions (**Figure 1**). In this figure, different colors and sizes of spots represent the different numbers of geothermal

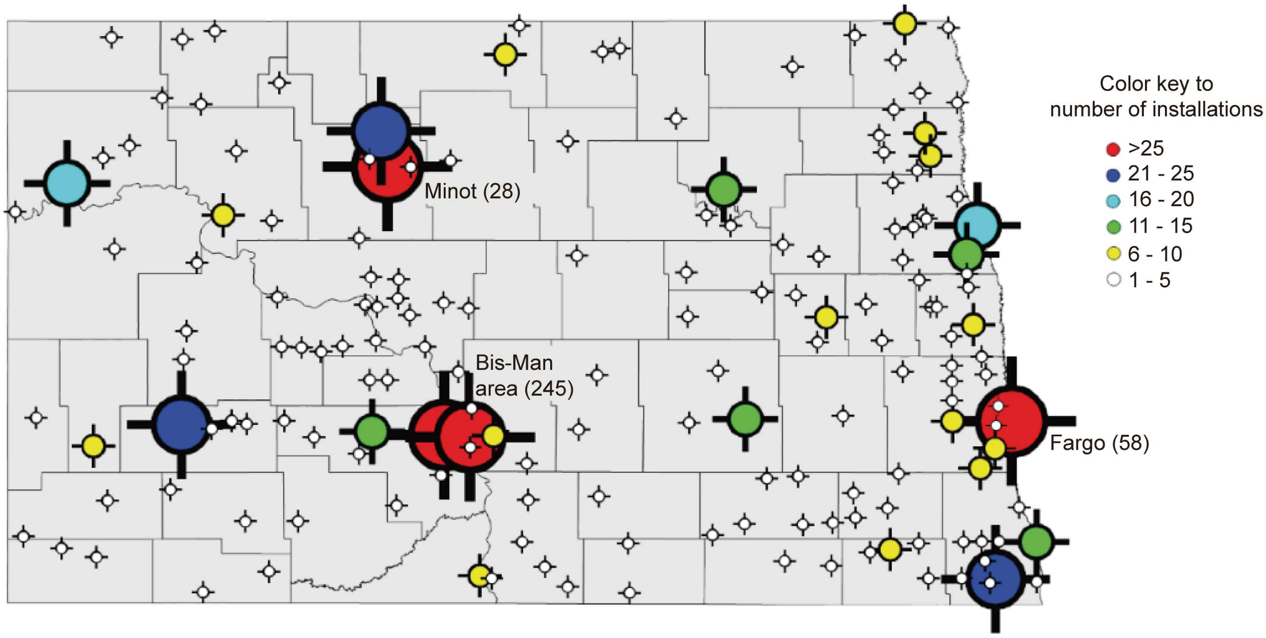

Figure 1. Locations of geothermal installations in North Dakota [40].

installations. This figure was regarded as a reference in this study when selecting target buildings.

2.2. Obtaining the Permissions

Requests were sent to the building owners through email, fax, or phone call, in order to ask whether they are willing to participate in the survey and to obtain permission for on-site investigations. Responses were received from 37 building owners with the total 84 requests that were sent out. These owners showed the willingness to help our research and provide necessary building information/documents. Eventually, the final list of the target buildings was generated (with 24 of these 37 buildings), considering several factors, such as the building locations and types, the ages of GHP systems, and the richness and availability of the received information and documents of each building. These 24 buildings include 9 college buildings, 6 school buildings, 2 churches, 3 commercial buildings, 2 public buildings, and 2 residential buildings, three of which are LEED (Leadership in Energy and Environmental Design) certified buildings.

Figure 2 indicates the target buildings by different building types. The location of each target building in the final list was selected carefully in order to cover most of the typical areas in the cold-climate regions, as shown in Figure 3.

Another critical factor that needs to be considered in the study is the years the structures and the GHP systems were built and installed. After certain years, some of the heat pump units could be too old to be used due to high maintenance cost and/or low operation efficiency. These target buildings were categorized into two groups depending on the years for which their heat pump systems have been used (Table 1).

As shown in Table 1, no GHPs have the system age of more than 25 years,

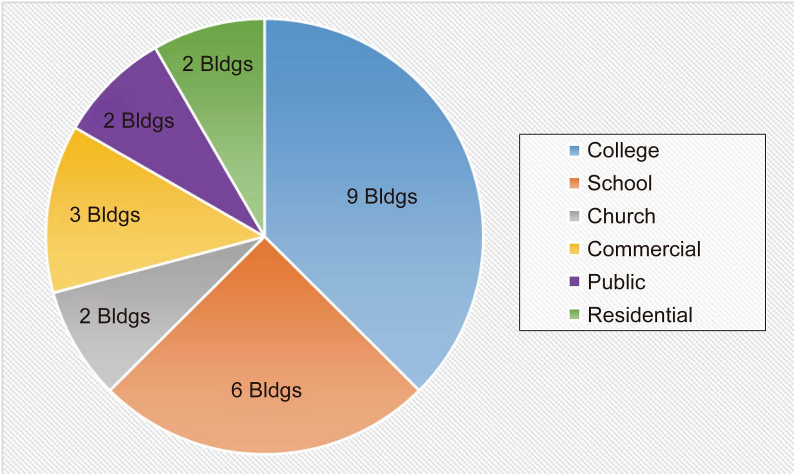

Figure 2. Target building allocation by building type.

Figure 3. Target buildings on a Google map.

Table 1. Two groups for building selection based on the age of heat pump system.

Groups	Heat Pump System Age [years]	Number of Buildings
Group One	<10	13
Group Two	≥10 and ≤25	11

considering the fact that the effective life of an indoor heat pump unit is typically 20 - 25 years, and thus older heat pump units had already been replaced with new ones in buildings.

2.3. Preparing the Survey Documents

The survey documents were prepared for the on-site investigations, including the following:

- The on-site survey questionnaires for building owners, end users and/or maintenance staffs. Questions in the questionnaires include the reasons for installing a GHP system, the capital costs of the building and Heating, Ventilation and Air Conditioning (HVAC) systems, if there are operating difficulties, and the satisfaction of the owners and/or end users, as well as the basic building and system information including building type, building floor area, the ages of building and HVAC system, the numbers of heat pump units and boreholes/wells, and service providers.
- A list indicating the detailed building information that needs to be requested from the owners and/or the design companies, including design plans/drawings (architectural, mechanical, electrical, etc.) and/or specifications, the annual utility bills, the maintenance activity log and cost, and the design documents, such as the Owner's Project Requirements (OPR), the Basis Of Design (BOD), and the installation and operations manuals.

The on-site visits took place right after the obtaining of permissions and the completion of preparing survey documents. During the building visit, the survey questionnaire was completed, and the detailed information and documents were requested and collected. The result of the on-site visit and investigation is organized and demonstrated below.

3. Results and Discussions

Specifically, this paper includes the case studies of 24 target buildings that are located in the cold-climate regions of the US (Climate Zone 6 and 7) and equipped with GHP systems. The results of these 24 case studies are summarized below, including Building Background, Building Mechanical System Parameters, Building Energy Consumption, Building Cost Demonstration, and Owner Satisfaction.

3.1. Building Background

The background information of these 24 target buildings is summarized in Table 2 (with the numbering of buildings from 1 to 24), including building area, building construction year, building type, and whether or not the building is LEED certified. As shown in this table, the target buildings have the building areas between 697 and 25920 m^2, with the building construction years from 1917 to 2013.

Within these 24 buildings, three of them are LEED certified buildings, including one LEED Platinum building, one LEED Gold building, and one LEED Silver building. LEED is one of the most popular green building certification programs used worldwide. LEED typically has four levels of certification, *i.e.* Certified, Silver, Gold, and Platinum. A higher certification level represents a higher achievement in green buildings in terms of sustainability.

Table 2. Building background summary.

Building Number	Building Total Area [m^2]	Building Construction Year	Building Type	LEED Building
1	12542	2009	College	No
2	9866	2008 2013 for the 4th floor	College	No
3	2973	2010-2012	College	No
4	1782	2006	College	No
5	2604	2003	College/Dormitory	No
6	970	2006	College/Office	No
7	697	2004	College/Office	No
8	3530	2012	College	LEED - Platinum
9	5652	2011	College/Dormitory	No
10	19045	1994	Middle School	No
11	8330	2007 2012 for New Addition	Elementary School	No
12	25920	2011	High School	No
13	8386	1999 2009 for New Addition	Elementary School	No
14	9569	2008	Public School	No
15	9197	1956	High School	No
16	2230	2006	Church	No
17	4645	1917-1932	Church	No
18	4975	2011	Commercial/Airport Terminal	LEED - Silver
19	1249	2012	Commercial/Office	LEED - Gold
20	5342	2008	Commercial/Office	No
21	1118	2009	Public/Fire Station	No
22	Unknown	1992	Public/Office	No
23	Unknown	2002	Residential	No
24	Unknown	2003	Residential	No

3.2. Building Mechanical System Parameters

The mechanical system parameters of these 24 target buildings are summarized in Table 3, including HVAC/GHP installation year, installation type (new or retrofit), GHP system type, the number of boreholes, borehole depth, borehole separation distance, borehole length, borehole length per kW (total cooling capacity), and GHP water flow rate per kW (total cooling capacity). Since each borehole of all the vertical and horizontal GHP systems investigated is configured with a pair of pipes (single U-tube) that are joined by a U-bend at the bottom of the hole, the underground pipe length and the underground pipe length per kW are a factor of 2 larger than the corresponding borehole length and borehole length per kW, respectively, for each system. Therefore, these two parameters,

Table 3. Building mechanical system summary.

BldgNO.	HVAC/GHP Instl. Yr	Instl. Type	GHP type*	NO. of Boreholes	Borehole Depth [m]	Borehole Separation Dist. [m]	Borehole Length [m]	Borehole Length per kW [m/kW]	GHP water flow rate per kW [L/min/kW]
1	2009	New for the addition	V	120	62	4.6	7425	23.4	4.8
2	2008	New	V	504	61	4.6 or less	30724	Unknown	Unknown
3	2010-2012	New	V	130	61	4.6	11887	31.3	5.8
4	2006	New	V	36	61	4.6	2195	13.3	3.0
5	2003	New	V	70	61	4.6	4267	14.8	3.2
6	2006	New	V	30	61	4.6	1829	17.3	3.8
7	2010 for Upgrade	Retrofit/ Upgrade	V	26	61	3 - 4.6	1585	19.4	3.9
8	2012	New	V	142	64	4.6	9089	18.7	3.9
9	2011	New	V	120	91	6.1	10973	20.4	3.3
10	Ground loop and HPs: 1994 73 replacement HPs: 2013	New	V	688	46	3.0	31455	Unknown	Unknown
11	2007 with 50 HPs 2012 for New Addition with 9 new HPs	New	V	288	46 - 61	2.4 - 3.7	13167	17.2	4.3
12	2011	New	V	928	61	Unknown	56571	20.0	3.1
13	1999 with 54 HPs 2009 for New Addition with 3 new HPs	New	V	320	46	2.4 - 3.7	14630	18.1	4.1
14	2008	New	V	384	61	4.6	23409	20.9	3.9
15	2012	Retrofit	V	72	76	6.1	5486	13.3	2.3
16	2006	New	V	48	61	4.6	2926	16.6	3.3
17	2005	Retrofit	V	100	46	Unknown	4572	Unknown	Unknown
18	2011	New	HB	16	7.6 and 12.2	6.1	152/ea. Total: 2432	7.2	2.5
19	2012	New	V	26	61	4.6	1585	12.2	2.6
20	2008	New	V	80	61	4.6	4877	20.2	4.5
21	2009	New	V	18	61	4.6	1097	19.2	4.0
22	1992	New							
23	2002	New				Unknown			
24	2003	New							

*V represents Vertical closed-loop system; HB represents Horizontally Bored closed-loop system.

i.e. underground pipe length and underground pipe length per kW, can be easily determined and are not shown in Table 3 and Table 4. Also in Table 3, some of the system parameters are marked as "Unknown", due to the limited information obtained from the building owners. Table 4 summarizes the average values of these mechanical parameters along with the heat pump efficiency range.

As shown in Table 3, the average age of these 24 investigated GHP systems is about 11 years old, which is about in the middle of the lifespan of a typical heat pump system. A GHP system with this age is appropriate for this study, since it is neither too old nor young and can effectively reflect the operational performance of a typical GHP system.

Most of the GHP systems were the original systems for the investigated buildings, and the owners decided to install them in the first place. The owners of three buildings, *i.e.* Building 7, 15 and 17, decided to use GHP systems after the failures of their original non-GHP systems. The reason for choosing and installing GHP systems in the first place for each target building is summarized in Table 5. According to this table, the common reasons are listed below,

- Lower cooling and heating bills;
- Energy efficiency;
- Environmental concerns.

It is not surprising that "lower cooling and heating bills" ranks the first, but the good thing is that some of the building owners expressed more concerns about energy and environment. These owners, however, are limited to college or school buildings (non-profit organizations). For commercial buildings, reducing the utility bills is still the top concern, which may help them to reduce overhead cost and thus increase profit.

Unsurprisingly, most of the investigated GHP systems are vertical closed-loop systems, as shown in Table 3, which are obviously the most common systems used in these regions and are the most mature and reliable GHP systems for designers/engineers. A horizontally bored closed-loop system was installed in one of the commercial buildings, *i.e.* Building 18. This facility, however, was originally designed to use a vertical closed-loop GHP system until the constructor found an unusually high water table during construction.

Table 4. Average value comparison of mechanical system parameters.

	Average	Range	Typical Value*
Number of Boreholes for Vertical GHP	207**	18 - 928**	Varies
Borehole Depth [m]	Vertical: 63 Horizontally bored: 10	Vertical: 46 - 91 Horizontally bored: 7.6 - 12.2	Vertical: 15 - 137 Horizontally bored: 9.1 - 15.2
Borehole Separation Distance [m]	4.9	2.4 - 6.1	4.6 - 6.1
Borehole Length per kW [m/kW]	18.0	7.2 - 31.3	13.0 - 21.7
GHP water flow rate per kW [L/min/kW]	3.7	2.3 - 5.8	2.7 - 3.2
Heat Pump Efficiency Range	Cooling: 4.16 - 5.07 COP Heating: 3.1 - 3.9 COP	Cooling: 2.46 - 8.79 COP Heating: 2.5 - 6.4 COP	Mini. Cooling: 3.93 COP*** Mini. Heating: 3.1 COP***

*Source: [41] [42]; **for vertical closed-loop GHP systems; *** Source: [28] [43].

Table 5. Reasons for installing GHP systems.

Bldg. NO.	Building Type	Reasons for installing GHP systems
1	College	I wasn't here at the time, but I believe it was to lower heating/cooling bills and for environmental concerns.
2	College	Not Provided (the building was built about 10 years ago, and the persons involved in this building project were gone.
3	College	Energy efficiency
4	College	Energy efficiency
5	College/Dormitory	Energy efficiency
6	College/Office	Not Provided
7	College/Office	Reduce cooling and heating bills More environmentally friendly We were experiencing significant problems with the original system
8	College	Green product environment concerns
9	College/Dormitory	Not Provided (The building and its geothermal system were completed prior to my arrival at the college.)
10	Middle School	Green product environment concerns
11	Elementary School	Green product environment concerns
12	High School	Green product environment concerns
13	Elementary School	Green product environment concerns
14	Public School	Not Provided
15	High School	Outdated HVAC system (original system). Added cooling to create a better learning environment.
16	Church	Design of new building to be more efficient
17	Church	Lower heating and cooling bills
18	Commercial/Airport Terminal	Lower heating and cooling bills
19	Commercial/Office	To aid in obtaining LEED status, and to be seen a good steward of resources in the eyes of our customers, suppliers, and the general public.
20	Commercial/Office	Efficient heating system with low operating cost
21	Public/Fire Station	Not Provided
22	Public/Office	Lower heating and cooling bills (long-term cost savings)
23	Residential	Lower heating and cooling bills (long-term cost savings)
24	Residential	Lower heating and cooling bills (long-term cost savings)

As shown in Table 4, the number of vertical boreholes of these investigated GHP systems varies from 18 to 928. The horizontally bored pipe system has 16 horizontal boreholes that are buried underground with a very long borehole length (152 meters for each) in order to offset the disadvantage of shallower borehole locations underground compared to vertical closed-loop systems. The average borehole depth of the vertical GHP systems is about 63 meters, which is common in these regions, considering the local geologic formation and a relatively high water table. The underground heat exchangers of the horizontally bored system are buried underground with the depth of 7.6 and 12.2 meters (two layers) below the ground surface.

The borehole separation distance shown in Table 3 and Table 4 represents the horizontal distance between two close vertical boreholes. Boreholes that are placed too close to each other may result in the accumulation of building heat or cold in the underground region without effective dissipation. The minimum suggested borehole separation distance is 4.6 meters [41]. As shown in Table 3, the GHP systems of several investigated buildings have the borehole separation distances less than the minimum requirement, including Building 2, 7, 10, 11, and 13. Among these buildings, only Building 2 (a college building) was reported by the owner that the ground temperature has been significantly increased by as much as 21˚C, since the GHP system was originally installed with the ground temperature of around 10˚C. The reason for the increased underground temperature is due to the fact that this facility is south-facing and is covered with a large number of windows, so the cooling degree days are significantly more than the heating degree days (cooling-dominated building). In other words, this building may need cooling instead of heating even during a winter season, due to a large amount of solar gains and/or internal gains because of people (students), lighting, and equipment. Additionally, the separation distance between boreholes is less than the minimum suggested value for a vertical geothermal system (4.6 meters), and the ground heat exchanger length is probably insufficient. As a result, more heat is conveyed and stored into the well field than being removed, which has the effect of increasing the ground temperature over time. This puts extreme stress on the heat pumps and results in inefficient operation, or even may cause the failures or complete shut-down of the GHP system. Figure 4

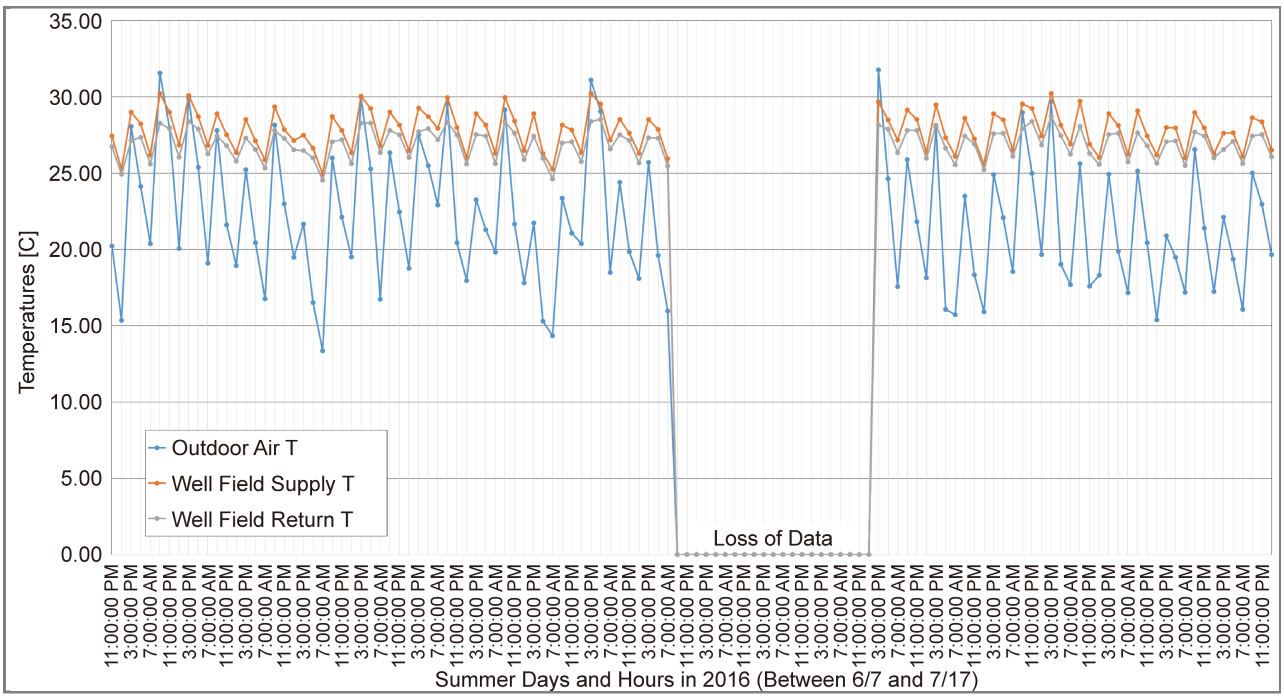

Figure 4. Ground water temperature profiles during the summer of 2016.

shows the supply and return water temperatures of the ground loop against the outdoor dry-bulb air temperatures during the summer of 2016 (6/7 - 7/17) with the full operation of the circulation pump. This indicates a very small loop temperature differential, and it follows a low efficiency and cooling capacity.

A solution to this problem in this building is to use a hybrid GHP system by adding an additional sink element of thermal energy to deal with the unbalanced heat rejection. Therefore, a dry cooler was installed with the GHP system of this building in 2016. This installation allows water being returned to the ground to first be cooled by this dry cooler during the colder months of the year, and thus the cooler water is circulated into the warmer ground to effectively cool it down over time. With this system in place, it is expected by the building owner to take about three years of continual running of the system in the winter months to cool the ground temperature to an appropriate level.

So far, for the other buildings, *i.e.* Building 7, 10, 11, and 13, there have been no complaints reported by the building owners regarding the operations of their GHP systems, such as warm ground, low heat pump efficiency, or high utility cost. The potential threats, however, still exist for these buildings and/or other buildings with a relatively insufficient ground heat exchanger length, such as Building 18 or 19, which should get the attention of the building owners/operators.

As shown in **Table 4**, the average design value of the borehole length per kW (total cooling capacity) for these investigated GHP systems is 18 m/kW, which is in the middle range of the suggested values shown in this table.

The average water flow rate per kW (total cooling capacity) of all the investigated systems shown in **Table 4** is 3.7 L/min/kW (a range between 2.3 and 5.8), which is slightly more than the upper level of the typical values (2.7 - 3.2 L/min/kW). The higher L/min/kW might indicate the oversizing of the water flow rate in the underground loops in several buildings, e.g. the college building of Building 3, which has the design L/min/kW of 5.8. The oversizing may result in higher pump power and increased operational costs.

The heat pump efficiency range for each GHP system investigated is shown in **Table 4**. The average cooling efficiency is between 4.16 and 5.07 COP, and the heating efficiency is between 3.1 and 3.9 COP. Considering the average age (11 years) of these 24 investigated GHP systems, these average efficiency values are compared with the minimum efficiencies of the relatively old standard [28] [43], *i.e.* 3.93 COP for cooling and 3.1 COP for heating. It appears that these average efficiencies of the actual GHP systems all meet the minimum code/standard requirements.

3.3. Building Energy Consumption

In this study, the building energy consumption of these 24 buildings was analyzed and demonstrated in a comparative way, where the online tool of EPA's Target Finder Calculator was used. The Energy Star Target Finder is EPA's online calculator that helps architects, engineers, and property owners and managers assess the energy performance and track energy costs and carbon emissions of commercial building designs and existing buildings [29]. The Energy Star Target Finder result represents the national median of energy performance of buildings similar to the target ones in the US. The use of this online tool allows to approximately identify the energy savings between the current GHP system and a system for a similar building nationwide. Table 6 shows the energy use and energy savings for each target building, where Site EUI (Energy Use Intensity) represents the amount of heat and electricity consumed by a building as reflected in the utility bills. The energy consumption information for several buildings is not shown in this table (marked as "Not Available"), due to the limited information obtained from the building owners.

Table 6. Energy use and savings.

Bldg. NO.	Site EUI [kWh/m²/yr]		
	Actual GHP System	EPA Similar Building	Energy Savings Compared to Similar Buildings (EPA)
1	233.3	371.6	37%
2	255.7	263.9	3%
3	152.5	268.7	43%
4	Not Available		
5			
6	154.7	162.3	5%
7	246.6	181.8	-36%
8	165.1	271.2	39%
9	Not Available		
10	179.9	133.5	-34%
11	129.4	142.1	10%
12	176.8	138.9	-28%
13	157.9	164.2	4%
14	Not Available		
15	135.8	145.2	7%
16	96.9	97.9	1%
17	164.8	162.3	-2%
18	274.7	300.5	9%
19	137.0	200.5	32%
20	145.2	217.2	34%
21	220.0	215.9	-2%
22	Not Available		
23			
24			

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The corresponding energy cost savings are shown in Table 7, and Table 8 summarizes the average values of the site EUIs, energy cost densities, and energy and energy cost savings mentioned before. As shown in Table 8, the average energy cost density of these investigated buildings is about \$13.13/m^2/yr, which is lower than the average energy cost density of the EPA similar buildings (\$14.96/m^2/yr). Compared to the national median (EPA results), the overall performance of the actual GHP systems used in these regions is slightly better, *i.e.* about 7.2% energy savings and 6.1% energy cost savings on average. As shown in Table 7, reduced savings or even no cost savings are found when comparing some of the investigated buildings with EPA similar buildings (the national median), such as Building 7, 10, 12, 17, and 21. For these buildings, the advantage of using GHP systems is not fully apparent, which could be caused by

Table 7. Energy cost savings.

Bldg. NO.	Energy Cost Density [\$/m^2/yr]		Energy Cost Savings Compared to Similar Buildings (EPA)
	Actual GHP System	EPA Similar Building	
1	\$13.24	\$21.10	37%
2	\$20.34	\$20.88	3%
3	\$12.16	\$21.42	43%
4	Not Available		
5			
6	\$12.92	\$13.67	5%
7	\$16.79	\$12.49	−35%
8	\$15.18	\$19.27	21%
9	Not Available		
10	\$11.09	\$8.29	−34%
11	\$9.47	\$10.66	11%
12	\$13.35	\$10.44	−28%
13	\$11.30	\$11.84	4%
14	Not Available		
15	\$8.72	\$9.36	7%
16	\$8.50	\$8.61	1%
17	\$7.00	\$6.89	−2%
18	\$22.17	\$26.05	15%
19	\$14.32	\$20.99	32%
20	\$12.92	\$19.48	34%
21	\$14.21	\$12.81	−11%
22	Not Available		
23			
24			

the inappropriate design or control strategy, defective parts, lack of maintenance, etc. Further in-depth investigations in these buildings are needed to find out the real reasons.

Table 9 shows the average values of the site EUIs, energy cost densities, and energy and energy cost savings by different building types, where the information for residential buildings is not shown, due to the limited energy information obtained from the building owners for that type of building. As shown in this table, college, commercial, and public buildings had higher site EUIs and energy cost densities compared to school or church buildings, mainly due to various operation schedules of different types of buildings. Unlike the other buildings, church buildings are not necessary to operate heavily during weekdays, and school buildings are not typically used very often during a summer break. Additionally, this table shows that positive energy and energy cost savings were achieved for commercial and college buildings, while school, church, and public buildings consumed more energy and had higher utility costs compared to the national median EPA results. The discussions above may indicate that the more often and heavier a GHP system is used, the more energy and energy cost savings would be achieved.

Table 8. Average value comparison of energy and energy cost savings.

	Average	Range
Site EUI - Actual GHP System [kWh/m^2/yr]	178.1	96.9 - 274.7
Site EUI - EPA Similar Building [kWh/m^2/yr]	202.4	97.9 - 371.6
Energy Cost Density - Actual GHP System [$/m^2/yr]	13.13	7.00 - 22.17
Energy Cost Density - EPA Similar Building [$/m^2/yr]	14.96	6.89 - 26.05
Energy Savings Compared to Similar Buildings (EPA)	7.2%	−36% - 43%
Energy Cost Savings Compared to Similar Buildings (EPA)	6.1%	−35% - 43%

Table 9. Average value comparison of energy and energy cost savings by building type.

	College	School	Church	Commercial	Public
Site EUI - Actual GHP System [kWh/m^2/yr]	201.4	156.0	131.0	185.6	220.0
Site EUI - EPA Similar Building [kWh/m^2/yr]	253.2	144.9	130.1	239.3	215.9
Energy Cost Density - Actual GHP System [$/m^2/yr]	15.07	10.76	7.75	16.47	14.21
Energy Cost Density - EPA Similar Building [$/m^2/yr]	18.19	10.12	7.75	22.17	12.81
Energy Savings Compared to Similar Buildings (EPA)	15%	−8%	−1%	25%	−2%
Energy Cost Savings Compared to Similar Buildings (EPA)	12%	−8%	−1%	27%	−11%

3.4. Building Cost Demonstration

Table 10 shows the average costs of the investigated buildings, including capital building cost, total HVAC system cost, and annual repair and maintenance expenses per building floor areas.

Table 11 shows the comparison of the average HVAC/GHP system cost (including the exterior and interior HVAC system costs) among different investigations and studies over time. Figure 5 indicates the trend of the average system cost in terms of $/m^2. As shown in this figure, the average system cost rises gradually among the investigations from 1995 to 2017, and it has been increased by 143% (from 97.63 to 237.45 $/m^2). This increase may indicate the loss of cost effectiveness to install and use a GHP system in a building, due to a longer payback period. This may eventually result in the loss of attraction of building owners/developers to GHP systems, who would rather use conventional HVAC systems that usually have low capital costs but consume more energy and fossil fuels, which will be against the original intention of the state or local governments about energy efficiency and environmental protection. Therefore, the financial support either from governments or utility companies, or both, would give a much needed shot in the arm to the popularity of GHP systems in North America by improving the cost effectiveness of using GHP systems, and thus encouraging the nationwide installation of GHP systems and making use of geothermal energy.

Table 10. Average building and HVAC costs.

	Average	Range
Capital building cost per floor areas [$/m^2]	1804.05	676.84 - 4810.11
Total HVAC cost per floor areas [$/m^2]	237.45	117.54 - 384.71
HVAC system average annual repair and maintenance cost per floor areas [$/m^2]	1.08	0.54 - 1.61

Table 11. Average HVAC cost comparison.

		Total HVAC cost per floor areas ($/m^2)
ASHRAE, 1995 [30]	Average	97.63
	Range	28.74 - 154.36
ASHRAE, 1998 [31]	Average	100.32
	Range	28.74 - 175.99
Zimmerman, 2000 [39]	Average	140.79
	Range	97.95 - 187.40
Kavanaugh *et al.*, 2012 [35]	Average	223.35
	Range	143.59 - 280.94
This Paper (2017)	Average	237.45
	Range	117.54 - 384.71

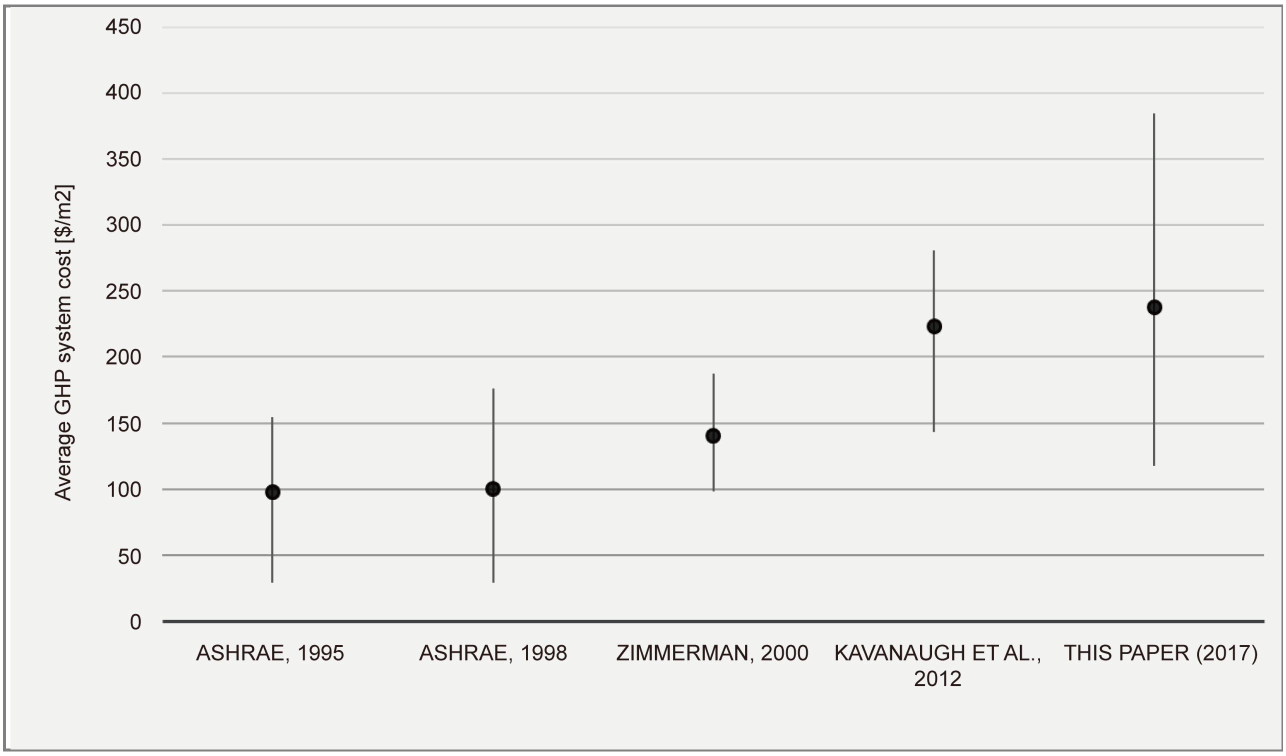

Figure 5. Trend of average HVAC/GHP system costs over time.

3.5. Owner Satisfaction

In the survey questionnaires, the respondents were asked to answer these three questions:

1) Are you satisfied with the current HVAC system in terms of noise, cost, and indoor comfort? Any complaints from building end users?

2) As you know, are there any operating difficulties of the geothermal heat pump system?

3) Would you like to suggest geothermal heat pump systems to others, like your friends?

Figures 6-8 show the survey results for these three questions. As shown in Figure 6, 75% of the respondents who answered the first question are very satisfied with their GHP systems in terms of noise, cost, and indoor comfort. About 71% of the investigated GHP systems (according to the total respondents who answered the second question) have not had serious operating difficulties (Figure 7), and 85% of the respondents who answered the third question would suggest this type of system to other people (Figure 8).

Several key points or takeaways from this survey are summarized and listed below, which were provided by building owners/operators.

- High initial costs of GHP system and whether it is affordable for building owners.
- Warm ground issues for GHP systems due to the unbalanced heating and cooling loads and inappropriate underground loop design.
- Inappropriate thermostat control strategies may cause discomfort.

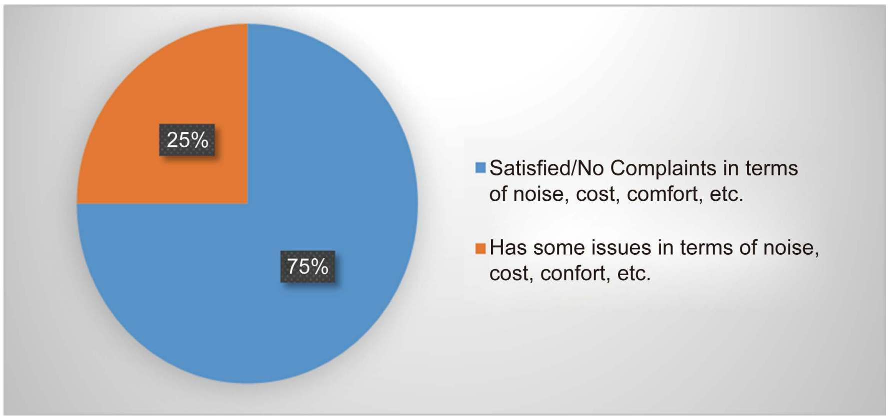

Figure 6. Survey result for noise, cost and comfort.

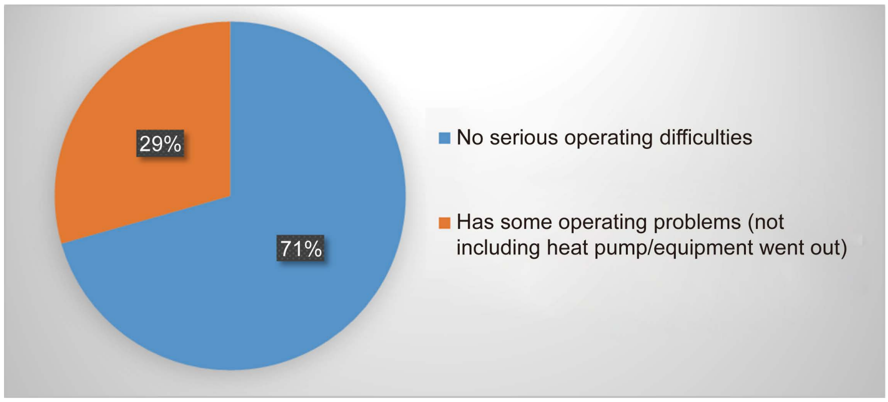

Figure 7. Survey result for operating difficulties.

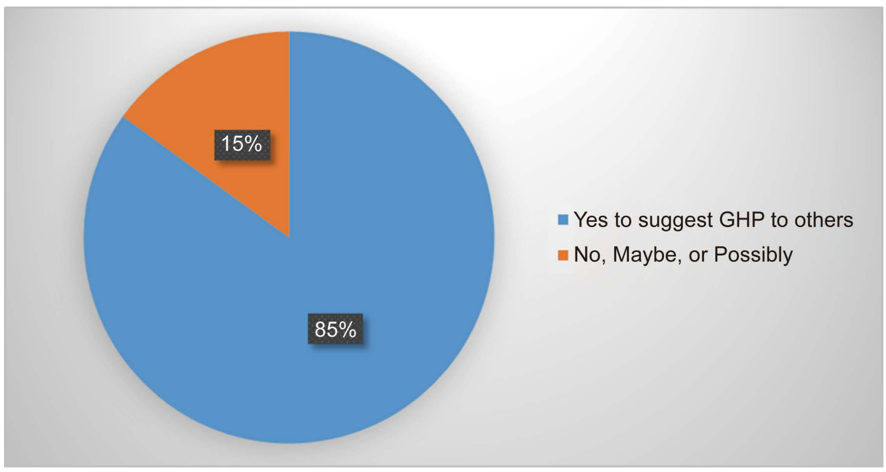

Figure 8. Survey result for suggesting GHP to others.

- Simultaneous heating and cooling may exist in a large open space that is served by two or more heat pump units with more than one thermostat.
- In a cold-climate region, heat pump units are sized based on heating loads due to a cold winter, which may cause the oversizing for cooling coils and overcooling.
- Heat pump replacement costs are expensive.

- Slow response of the GHP system to the change of building cooling/heating loads.
- The difficulties for the geothermal system to initially start up during the first winter, due to the absence of a backup heating system and that the underground region had not absorbed enough building heat during the summer period.
- The antifreeze used in old heat pump systems might be corrosive, which may cause environmental issues.
- GHP systems are not appropriate for all the buildings in cold-climate regions. It depends on the application and scale of the project and what other heating systems are available. Geothermal energy can be a great choice in the right scenario.
- Incentives can help to reduce the high installation costs of GHP systems.
- Supplemental/backup heating for GHP systems seems necessary in cold-climate regions.

4. Conclusions

In this study, onsite surveys and investigations of 24 buildings were carried out. These investigated buildings located in the cold-climate regions of the US include 9 college buildings, 6 school buildings, 2 churches, 3 commercial buildings, 2 public buildings, and 2 residential buildings. The conclusions of this study are listed below.

- Currently, one of the biggest barriers to the wide application of GHP system in the investigated regions of the US is the high capital and/or replacement cost. Reduction of capital costs and improvement of cost effectiveness of installing and using this type of system are the keys. Financial support from local governments and/or utility companies would give a much needed shot in the arm to the popularity of GHP systems in the cold-climate regions of the US.
- The major reasons for installing geothermal systems include "lower cooling and heating bills", "energy efficiency", and "environmental concerns". Although some of the building owners expressed more concerns about energy and environment, instead of "money", these building owners are limited to non-profit organizations, such as colleges or schools. "Lower cooling and heating bills" is still the top concern for commercial building owners.
- For these 24 buildings, 75% of the building owners are very satisfied with their GHP systems in terms of noise, cost, and indoor comfort; about 71% of the investigated GHP systems have not had serious operating difficulties; and more than 85% of the respondents would suggest this type of system to other people. These survey results indicate the reliability and applicability of GHP systems in the cold-climate regions of the US as well as the potential for a broader statewide/nationwide application.
- Compared to the national median of energy use and energy cost of typical buildings of the same type nationwide, the overall performance of the actual

GHP systems used in the cold-climate regions is slightly better, *i.e.* about 7.2% energy savings and 6.1% energy cost savings on average. The relatively low energy and energy cost savings compared to similar buildings nationwide may cause the loss of attraction of building owners/developers to GHP systems, who would rather use conventional HVAC systems that usually have low capital costs but consume more energy and fossil fuels. This will be against the original intention of the state or local governments about energy efficiency and environmental protection.

- Compared to other buildings, higher energy and energy cost savings were achieved by the college and commercial buildings investigated, which may indicate that the more often and heavier a GHP system is used, the more energy and energy cost savings would be achieved. Therefore, in cold-climate regions, a GHP system would be more suitable and attractive for use in college or commercial buildings than schools or churches.
- On average, the design water flow rate per kW (total cooling capacity), *i.e.* 3.7 L/min/kW with a range between 2.3 and 5.8, for the ground loops of the investigated GHP systems is slightly more than the upper level of the typical values (2.7 - 3.2 L/min/kW). This may indicate the oversizing of water flow rate in ground loops, which may result in higher pump power and increased operational costs.
- In the cold-climate regions of the US, the issues regarding warm ground and high return water temperatures do exist. One of these investigated systems (Building 2 - a cooling-dominated building) had already encountered a serious operating issue, *i.e.* high return water temperatures (warm ground) and low cooling capacities, due to the unbalanced cooling and heating loads, a shorter borehole separation distance, the low thermal conductivity of the grout material, and/or an insufficient underground heat exchanger length.
- In these northern regions of the US, on average, the depth of GHP boreholes is typically about 61 meters below the ground surface, due to the local geologic formations and the relatively high water table. Additionally, test wells before the installation of a GHP system are suggested, which are not only able to test the thermal performance of the underground region, but also to ensure how deep the geothermal loops can go and the depth of the water table in that region.
- Supplemental/backup heating for GHP systems is suggested and sometimes necessary, especially for the initial startup during the first and/or unexpectedly cold winters in cold-climate regions, but unfortunately, most of the investigated GHP systems used in the cold-climate regions are not equipped with any supplemental heating devices (regardless of unit heaters used in heating-only spaces).

In this study, 24 buildings have been investigated through onsite surveys and questionnaires, but not all the necessary information was collected or provided by building owners, which limited the number of buildings for in-depth analysis. Therefore, future work is needed in these unexplored research areas. Additionally, more buildings, especially residential buildings or single houses, could be studied to enhance the statewide/nationwide influence and engagement of this study.

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