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Investigation and Study of the Potential Energy and Energy Cost Savings of Ground Source Heat Pump Systems Used in Cold-Climate Regions of the U.S.

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ABSTRACT

A Ground Source Heat Pump (GSHP) system has the potential for reducing CO_2 emission and fossil fuel consumption. The high heating efficiency of a typical GSHP system compared to conventional heating devices, such as gas-fired furnaces or boilers, makes it more attractive in cold-climate regions, e.g., the areas of the northern Great Plains in the U.S. However, many factors determine the performance of GSHP systems, e.g., control strategy, part/full-load efficiency, the age of the system, whether or not regular maintenance services are provided, etc., any of which could have significant impacts on the normal operation of existing GSHP systems and the achievement of expected energy and energy cost savings. Therefore, the objective of this paper is to further investigate and evaluate the potential energy and energy cost savings of existing GSHP systems currently used in cold-climate regions of the U.S., i.e., the areas of the northern Great Plains. After the comprehensive investigations and simulations of eight existing buildings, the results indicate that the energy savings of these investigated buildings range from 8% to 46% compared to conventional

HVAC (Heating, Ventilation, and Air Conditioning) systems. The corresponding energy cost savings, however, is relatively low (with a range between -12% and 42%), due to the extremely low natural gas price in these regions. Additionally, the result of a linear regression analysis indicates that a higher site EUI (Energy Use Intensity) may result in lower energy savings for buildings equiped with GSHP systems and located in these regions.

KEYWORDS: Ground source heat pump, GSHP, Building energy savings, Building energy cost savings, EUI, Cold climate

1. INTRODUCTION

Ground Source Heat Pump (GSHP) systems take advantage of the undisturbed ground temperatures (typically in the range of 7.2 – 10 ºC in the northern regions of the U.S. (ASHRAE 2015)), rejecting building heat into the ground during summer and conversely extracting heat from the ground to provide the heating effect to buildings during winter. By using GSHP systems, the energy savings and the reduction of the greenhouse gas emissions are significant compared to conventional HVAC (Heating, Ventilation, and Air Conditioning) systems that typically use air-cooled condensing units/chillers and natural gas furnaces/boilers to provide cooling and heating effects to buildings/houses (ASHRAE 2015; Lorraine 2007; Grandstrand et al. 2011; Kavanaugh and Rafferty 2014). The possible energy savings of GSHP systems can be as high as 60% for high-efficiency GSHPs (Goetzler et al. 2009). The major energy savings for GSHP systems typically come from the high Coefficient of Performance (COP), especially when the system is in heating mode (Lorraine 2007). A GSHP system typically has a COP of approximately 3-4 or even greater, which is about 3-4 times higher than that of, e.g., a condensing boiler that usually has an efficiency of around 90-95%, i.e., 0.9-0.95 COP. This is one of the major reasons why GSHP systems have superior performance during winter (especially when not considering the intermittent use of auxiliary electric resistance heating) compared to conventional heating devices, such as boilers or furnaces (Healy and Ugursal 1997; Ozgener Hepbasli 2005; Bakirci 2010; Ozyurt and Ekinci 2011).

Research has been done by people focusing on the use of GSHP systems in cold climates mainly due to their attractive feature of high operational efficiency for heating, compared to other conventional systems. Healy and Ugursal (1997) investigated the impact of system parameters on GSHP performance through computer simulations. They further justified the superior performance of GSHP systems and demonstrated their economic feasibility in cold-climate applications, compared to conventional HVAC systems. Bakirci in 2010 evaluated the performance of a GSHP system equipped with a ground heat exchanger with a series piping circuit, where the working fluid is circulated through each borehole one after another, in a cold-climate region through experiments and measurements, and the results indicate that the average heating COP and the overall COP during the coldest months in that region with this type of GSHP system are 3.0 and 2.6, respectively. Another experimental study was conducted by Ozyurt and Ekinci in 2011 to justify the use of a GSHP system for residential heating in a cold-climate region in Europe with decent heating COPs. More measurements and simulations were carried out by Flaga-Maryanczyk et al. (2014), who established a validated Computational Fluid Dynamics (CFD) model to evaluate the performance of a GSHP used for a passive house ventilation heating in winter. Research in regard to applying GSHP systems in cold-climate regions also focuses on the use of multi-source heat pump systems, such as the combination of solar and geothermal heat (Ozgener 2010; Bakirci et al. 2011). According to the literature review, it is noticed that the prior research and studies emphasized the developments, measurements, and simulations of different types of GSHP systems at different cold-climate regions. Nevertheless, studies of existing GSHP systems currently used in buildings located in cold-climate regions, in terms of system operational performance as well as potential energy and energy cost savings, are limited. The operation of an existing GSHP system may be different from a system established and studied in a lab for experimental purposes and could be influenced by many factors, such as

- if the design and selection of the GSHP system are reasonable (no over- or under- sizing) and if the system is able to meet the heating and cooling loads of the entire facility,
- if the control strategies are appropriate for the building usage without significant energy waste caused by improper control sequence,
- if the selection and control strategies of water pumps are appropriate for the use of GSHP system to avoid excessive pump energy consumption,
- if there are defective parts and/or poor quality of system installations that could result in significant unnecessary energy consumption,
- if the major equipment, such as heat pump units, are too old to maintain high efficiency,

- if regular maintenance services are missing, which causes additional energy usage.

Any of these factors could have significant impacts on the normal operation of existing GSHP systems as well as the achievement of expected energy and energy cost savings. Additionally, the large potential of GSHPs for energy savings in heating mode could be greatly reduced, e.g., in the buildings located in a cold-climate region, such as the regions in the Climate Zone 6 or 7 of the U.S. (defined in ASHRAE 2007) with a relatively long winter. Some of these buildings may still require cooling instead of heating during winter seasons, especially for commercial buildings, such as offices, schools, colleges, etc., due to the large amount of heat generated by equipment (computers, printers, etc.), people, and lighting systems, and/or the installation of a large number of south-facing windows.

Therefore, the study described in this paper aims to investigate and evaluate the existing GSHP systems used in buildings located in cold-climate regions of the U.S., i.e., the areas of the northern Great Plains (specifically in the state of North Dakota with the Climate Zone 6 and 7) through on-site investigations and computer simulations, in order to find out whether these systems are operating as anticipated and designed, and to identify the potential energy and energy cost savings of these buildings compared to conventional HVAC systems. The results of these studies are important because they may provide references for the application of GSHP systems in the areas of the northern Great Plains in the U.S. and help establish the confidence of design teams and the acceptance of potential end users.

2. INVESTIGATION AND STUDY

In this study, in-depth investigations and simulations of 8 existing buildings were conducted. These buildings include 4 college buildings, 1 church, 2 commercial buildings, and 1 public building, which are located in different cities in the state of North Dakota (Climate Zone 6 and 7). The basic building information is shown in Table 1 (with the numbering of buildings from 1 to 8).

The investigations involved on-site visits and the acquiring, from building owners and/or design companies, of the basic building and system information including building type, building floor area, the ages of building and HVAC system, the number of boreholes/wells, as well as the detailed building information, such as design plans/drawings (architectural, mechanical, electrical, etc.) and/or specifications, the annual utility bills, and the design documents, i.e., the Owner's Project Requirements (OPR), the Basis Of Design (BOD), and the installation and operations manuals. The mechanical system parameters of these studied buildings are summarized in Table 2, including GSHP system type, the number of boreholes, borehole depth, borehole separation distance, borehole length, borehole length per ton, GSHP water flow rate per ton, the types of ground-loop/building-loop pumps, the number of ground-loop circuits, and the number of heat pump units. Since each borehole of all the vertical and horizontal GSHP 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 pipe length per ton are a factor of 2 larger than the corresponding borehole length and borehole length per ton, respectively, for each system.

3. COMPUTER SIMULATION

The goal of this study is to identify potential energy and energy cost savings of the existing GSHP systems compared to conventional HVAC systems. To do so, two simulation models are established for each building listed in Table 1, i.e., Model One and Model Two (Figure 1). Model One represents the simulation model for the existing building and reflects the actual condition and usage of the GSHP system. Model Two is a modified simulation model based on Model One. The purpose of Model Two is to establish a simulation model that may reflect the usage of a conventional HVAC system, instead of a GSHP system, in the existing building. In other words, it is to simulate the situation where the question will be answered, i.e., "What would the corresponding energy consumption and energy expenses be, if the virtual conventional systems were installed and used in the first place in those investigated buildings (Table 1), instead of the GSHP systems?" Therefore, in Model Two, the basic building conditions and parameters, such as construction materials, people, lighting, and equipment schedules, infiltration rates, light power density, etc., should be kept the same as those in Model One; whereas only the HVAC system is changed from the GSHP to a conventional system defined in the ASHRAE Standard 90.1 – Appendix G (the publication year of the code/standard depends on where the building is located and which corresponding building code is applied). Appendix G in the ASHRAE 90.1 Standard (e.g. ASHRARE 2007) describes the Performance Rating Method that is typically used for rating the energy efficiency of building designs that exceed the requirements of this ASHRAE standard. Table 3 shows the conventional HVAC systems used for Model Two in each building. Please note that this Performance Rating Method was only used to determine the conventional HVAC system for Model Two. This is different from using the Performance Rating Method to perform a whole building energy simulation, e.g., for pursuing LEED (Leadership in Energy and Environmental Design) building credits/certification (LEED 2009), where the baseline energy simulation model has to be established exactly in compliance with the requirements of this Performance Rating Method, i.e., all building parameters for the baseline model, such as the building construction, interior and exterior light power densities, mechanical systems, etc., should exactly follow this standard, rather than using the actual data.

In order to improve the accuracy and reliability of the simulations, especially to determine some of the common building parameters that are used in both Model One and Two but difficult to know or determine, such as infiltration rates, occupancy/lighting/equipment schedules, etc., a model calibration was conducted for each building. In this process, Model One is calibrated against the actual monthly energy usage and/or energy cost of the existing buildings by adjusting these parameters (Figure 1) to achieve a good agreement between the actual utility data and the simulated results. The energy usage/cost were obtained from utility bills provided by building owners. If necessary, some of these parameters were further confirmed with building owners or operators. The calibration process can also be seen as the process of fine-tuning the model inputs in order for the actual data to match those simulated using the simulation model and to ensure the "goodness-of-fit". According to ASHRAE Guideline 14 (2002), Model One will be considered as a calibrated model if the errors between monitored and simulated data are within the allowable limits of Mean Bias Error (MBE) (Equation 1) and Coefficient of Variation of Root Mean Square Error (CVRMSE) (Equation 2).

$$\mathrm{MBE} = \frac{\sum_{i=1}^{12}(S_i - M_i)}{\sum_{i=1}^{12} M_i} \times 100\% \quad (1)$$

$$\mathrm{CVRMSE} = \frac{\sqrt{\frac{\sum_{i=1}^{12}(S_i - M_i)^2}{12}}}{\frac{\sum_{i=1}^{12} M_i}{12}} \times 100\% \quad (2)$$

where S_i represents the simulated result per month; M_i represents the actual/measured data per month; and i represents the time interval, i.e., month.

The calibration results of all these 8 buildings are shown in Figure 2, where the solid lines represent actual utility data (monitored data) and dash lines represent simulated results/data. Table 4 shows the corresponding results of MBE and CVRMSE for each building.

As shown in Table 4 and Figure 2, several models were calibrated based on energy usage, while other models were based on energy cost, depending on the availability of the provided utility data from the building owners. Additionally, as shown in Figure 2, electricity is the only energy source for Building 3, 4, and 7, due to the use of GSHP systems for space heating and cooling without fossil fuel. For Building 5, the natural gas consumption of this building was not given by the building owner, but was estimated by using the computer model, and therefore only the electricity calibration result of this building is shown in Figure 2 and Table 4. As shown in Table 4, the MBE value for each building is within the acceptable limit, i.e., ±5%, and the CVRMSEs are within the acceptable limit of 15%, as described in ASHRAE Guideline 14 (2002) for monthly calibration type. These results indicate the successful establishments of calibrated simulation models for these eight buildings, which can be then used to identify the building energy and energy cost savings. The utility rates for electricity and natural gas used in the simulation models were determined based on the actual utility bills and are represented in the form of yearly average, e.g., 8.85 cents per kWh for electricity and $0.45 per therm for natural gas for Building 1.

The simulations were accomplished by using the software packages of Trane Trace 700 (Trane 2015) coupled with GLHEPRO (IGSHPA 2016). Trane Trace 700 is a commercial simulation tool for whole building energy analysis and load estimation, in which various HVAC systems can be selected and defined, including heat pump system, chilled beam system, Variable Air Volume (VAV) system, and other typical mechanical systems. GLHEPRO can be used to design and simulate ground loop heat exchangers. The integration of Trane Trace 700 with GLHEPRO allows users to accurately simulate and estimate the energy consumption related to GSHP systems.

4. RESULTS AND DISCUSSIONS

Specifically, this paper includes the case studies of 8 existing buildings that are located in cold-climate regions of the U.S. (North Dakota) and equipped with GSHP systems. The results of these 8 case studies are summarized below.

4.1 GSHP Parameters

Most of the investigated GSHP systems were installed in the past 15 years (Table 1). The average age of these 8 investigated GSHP systems is about 8 years old, which is close to the middle of the lifespan of a typical heat pump unit. A GSHP system with this age is appropriate for this study since it is not either too old or young and can effectively reflect the operational performance of a typical GSHP system.

Unsurprisingly, most of the investigated GSHP systems are vertical closed-loop systems, which are obviously the most common systems used in these regions and indicate that they are the reliable GSHP systems for local designers/engineers. A horizontally bored closed-loop GSHP system was installed in one of the commercial buildings (Building 6). In fact, this building was originally designed to use a vertical closed-loop GSHP system (96 boreholes with the depth of about 61 meters) to provide space heating and cooling. This new type of horizontal borehole, however, was planned for use after finding an unusually high water table during construction.

The number of vertical boreholes of these investigated GSHP systems varies from 18 to 130 (not including the horizontal boreholes) (Table 2 and 5). Larger buildings usually require more heating and cooling effects from underground boreholes. The horizontally bored pipe system has 16 horizontal boreholes that are buried underground with a very long borehole length (152.4 meters for each).

Borehole depth is a critical parameter when designing a GSHP system. Typically, the thermal behavior of the deeper ground is less disturbed and influenced by outside weather conditions, and therefore the deeper a borehole is, the higher capacity a GSHP system can usually reach when other GSHP parameters are not changed, such as the underground heat exchanger length, borehole separation distance, etc. The average borehole depth of these 8 investigated GSHP systems is about 65.5±11.5 meters (not including the horizontal boreholes), which is common in these northern areas of the U.S. considering the local geologic formation. Typically, the borehole depth for a vertical closed-loop GSHP system can be between 15.2 and 137.2 meters or even more, according to the different references (Egg et al., 2013; Kavanaugh and Rafferty, 2014; ASHRAE, 2015). The horizontally bored pipe system of Building 6 was buried underground with a depth of 7.6 meters and 12.2 meters with two layers below the ground surface.

The minimum suggested borehole separation distance is 6.1 meters when loops are placed in a grid pattern, whereas a 4.6 meters separation might be used if annual heat flow is nearly balanced underground (ASHRAE, 2015). The average borehole separation distance of all the vertical GSHP system investigated in these cold-climate regions is 4.4±0.6 meters with the range between 3 and 4.6 meters, which indicates the shorter separation distance than the suggested 6.1 meters and a possibility of Ground Temperature Penalty (Kavanaugh and Rafferty 2014) that might occur in the future, even though currently no issues regarding warm/cold ground or low heat pump efficiency are reported by the building owners.

Although borehole length is a critical parameter that represents the total length of all the boreholes used in a GSHP system, the parameter of borehole length per ton is usually more meaningful and useful. The typical borehole length per ton is between 12.9 and 21.4 meters/kW, and the corresponding underground pipe length per ton is between 25.7 and 42.9 meters/kW when designing a single U-tube vertical GSHP system. The average design values of these two parameters for these investigated vertical GSHP systems are 19.7±6 and 39.4±12 meters/kW, respectively, both of which can be useful for the local designers and engineers as a reference when designing a GSHP system in these cold-climate regions of the U.S.

Central loop GSHP systems, as defined in Kavanaugh and Rafferty 2014, are used in all these buildings, most of which are equipped with differential pressure-controlled VSD pumps (Table 2), except Building 3, 4, and 5 that are using multiple central constant speed inline pumps for water circulation in the underground loops. The numbers of ground-loop circuits used in these buildings are also shown in Table 2. The typical design water flow rate in a vertical GSHP system is between 0.045 and 0.054 L/s/kW (Kavanaugh and Rafferty 2014). The average water flow rate per ton of the investigated vertical GSHP systems is 0.062±0.017 L/s/kW (with a range between 0.043 and 0.097 L/s/kW), which is more than the upper level of the typical values. This may indicate the oversizing of the water flow rate in the underground loops in several investigated buildings. The oversizing may result in higher pump power and unnecessary operational costs. Table 5 summarizes the average values of the mechanical parameters mentioned above. These average values are useful especially for local designers and engineers, as a reference, when designing a vertical GSHP system in a cold-climate region of the U.S., such as North Dakota.

4.2 Building Energy Simulation

In order to determine the potential energy and energy cost savings between the actual building with a GSHP system and a similar building with a conventional HVAC system, an energy simulation (Model One and Model Two as shown in Figure 1) was established for each target building, where Model One represents the simulation model calibrated against the actual utility bills, and therefore the results of it for each building are the same or very close to the actual utility data, in terms of energy consumption and/or energy cost. Table 6 shows the site EUI (Energy Use Intensity), the energy cost density, and the corresponding potential energy and energy cost savings of each building (for the year of 2016). Figure 3 and 4 show the comparisons of the site EUIs and energy cost densities, respectively.

The conventional system shown in Table 6 for each target building was determined according to the ASHRAE Standard 90.1 – Appendix G or depending on the actual building situation (Table 3). For example, the conventional system for Building 4 was determined based on the previous HVAC system used before the installation of a GSHP system for this retrofit project, and for Building 1 (an addition to an existing building as shown in Table 1), the conventional system was determined based on the system currently used in the existing building.

As shown in Table 6 and Figures 3 & 4, the average energy cost density of these 8 buildings is about $14.32±3.95/m^2/yr, which is lower than the average energy cost density of the buildings equipped with the conventional HVAC systems ($16.58±4.26/m^2/yr). Regardless of the different types of buildings, these average cost densities may be used as a reference for local building owners who would like to use GSHP systems in their buildings but are not aware of the approximate building energy costs. Compared to the conventional systems, the energy savings range from 8% to 46%, due to the use of high-performance GSHP systems. The energy cost savings, however, is not as high as the identified energy savings with a range between -12% and 42%. For example, the energy savings for the college building (Building 1) is about 14%, but the energy cost savings is only 5%. For the church building (Building 5), 46% energy savings is achieved, but it only has the energy cost savings of about 2%. The same conclusion can be drawn for the commercial and public buildings (Building 6 and 8). Table 7 summarizes the average values of the energy and energy cost savings mentioned above.

The difference between these two savings is mainly caused by the extremely low utility rate for natural gas compared to electricity in the regions investigated. The average natural gas price for the year of 2016 in North Dakota is $0.526 per therm, while the yearly average price of electricity is 8.96 cents per kWh (EIA 2017). To compare these two utility prices, the

$0.526 per therm for natural gas, when converted to the same energy unit for electricity, is equivalent to about 1.8 cents per kWh. This is about 1/5 of the electricity price.

In order to find the potential relationship between the energy usage and/or energy/energy cost savings identified and the GSHP parameters described above, a linear regression analysis was performed. The results of the regression analysis contribute to finding the correlations and deriving meaningful relationships for the GSHP systems used in the investigated regions in the U.S. The correlation and relationship found through the regression analysis are summarized in Table 8 and Figure 5.

As shown in Table 8, the regression analysis demonstrates a medium to strong correlation between Site EUI and Energy Savings (Figure 5), which indicates that for a building located in this investigated regions of the U.S. and equipped with a GSHP system, a higher site EUI may result in lower energy savings when comparing it to a conventional HVAC system. This may indicate that in cold-climate regions of the U.S., like North Dakota, the use of GSHP system in a building that typically has a relatively high site EUI, such as a building for college/university, convenience store, restaurant, residential care facility, etc. (refer to the U.S. National Median Reference Values in Star, 2014), could be not cost-effective, due to the relatively low energy savings compared to buildings typically with smaller site EUIs, such as office buildings, churches, etc. (Star, 2014) .

5. CONCLUSIONS AND FUTURE WORK

By using geothermal energy, GSHP systems have a large potential for building energy savings and CO_2 emissions reduction. However, many factors determine the performance of GSHP systems, such as control strategy, part/full-load efficiency, the age of the system, whether or not regular maintenance services are provided, etc. Any of these factors could have significant impacts on the normal operation of GSHP systems and the achievement of expected energy and energy cost savings. The objective of this paper is to study and evaluate the operational performance of existing GSHP systems currently used in buildings located in cold-climate regions of the U.S., i.e., the areas of the northern Great Plains (specifically in the state of North Dakota).

In this study, onsite investigations and computer simulations of 8 existing buildings were carried out, including 4 college buildings, 1 church, 2 commercial buildings, and 1 public building. The conclusions of this study are listed below.

- The energy savings of these 8 existing buildings range from 8% to 46%, compared to conventional HVAC systems, which demonstrates the performance and the achievement of energy savings of the existing GSHP systems used in the cold-climate regions investigated. The corresponding energy cost savings, however, is relatively low (with a range between -12% and 42%), due to the extremely low natural gas price in these cold-climate regions of the U.S. The low energy cost savings may cause the loss of attraction of building owners/developers to GSHP systems, who would rather consider to 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 governments about energy efficiency and environmental protection.

- On average, the design water flow rates per ton (0.062±0.017 L/s/kW with a range between 0.043 and 0.097 L/s/kW) for the vertical underground loops of the investigated GSHP systems are more than the upper level of the typical values (0.045~0.054 L/s/kW). This may indicate the oversizing of water flow rate in the ground loops, which may result in higher pump power and increased operational costs.

- The result of a linear regression analysis demontrates a medium to strong correlation between Site EUI and Energy Savings Percentage, which indicates that a higher site EUI may result in lower energy savings when comparing two systems in a builing, i.e., a GSHP system and a conventional HVAC system. Therefore, in the cold-climate regions of the U.S., like North Dakota, a GSHP system is probably not suitable and cost effective for a building with a higher site EUI, such as college/university buildings, restaurant, etc., compared to buildings typically with relatively low site EUIs, such as office buildings, churches, etc.

- In these northern regions of the U.S., most of the studied buildings are equipped with vertical closed-loop GSHP systems, which indicates the high acceptance of this type of system by the local building owners, end users, and designers/engineers, compared to other types of GSHP systems. Additionally, the average values for borehole depth, borehole separation distance, borehole length per ton, and underground pipe length per ton mentioned in Table 5 can be conisdered as references for local designers/engineers/building owners, when designing a GSHP system in these cold-climate regions of the U.S., espcially in the state of North Dakota.

- This study also demonstrates the successful installation and use of a horizontally bored closed-loop GSHP system in a cold-climate region of the U.S. It was a substitute for a vertical closed-loop GSHP system after finding an unusually high water table during construction.

- A combination of computer models using Trane Trace 700 integrated with GLHEPRO demonstrates the capability and reliability of this integrated model in the simulation of GSHP systems.

In this study, the sample size, i.e., the total number of the investigated buildings in these regions is not too large, and the number of the factors considered in the regression analysis is also limited. More comprehensive work is still needed in the future in order to get more scientific results, e.g., to enlarge the sample size by investigating more buildings with GSHP systems. Broader studies and investigations will be performed as well, which are intended to cover other different climate-zone 6 and/or 7 areas in the U.S., where a different utility rate structure is used compared to the ones for the northern Great Plains region. This will give a more comprehensive result regarding the usage of GSHP systems in the northern regions of the U.S.

FIGURES AND TABLES

Figure 1. Computer simulation procedure

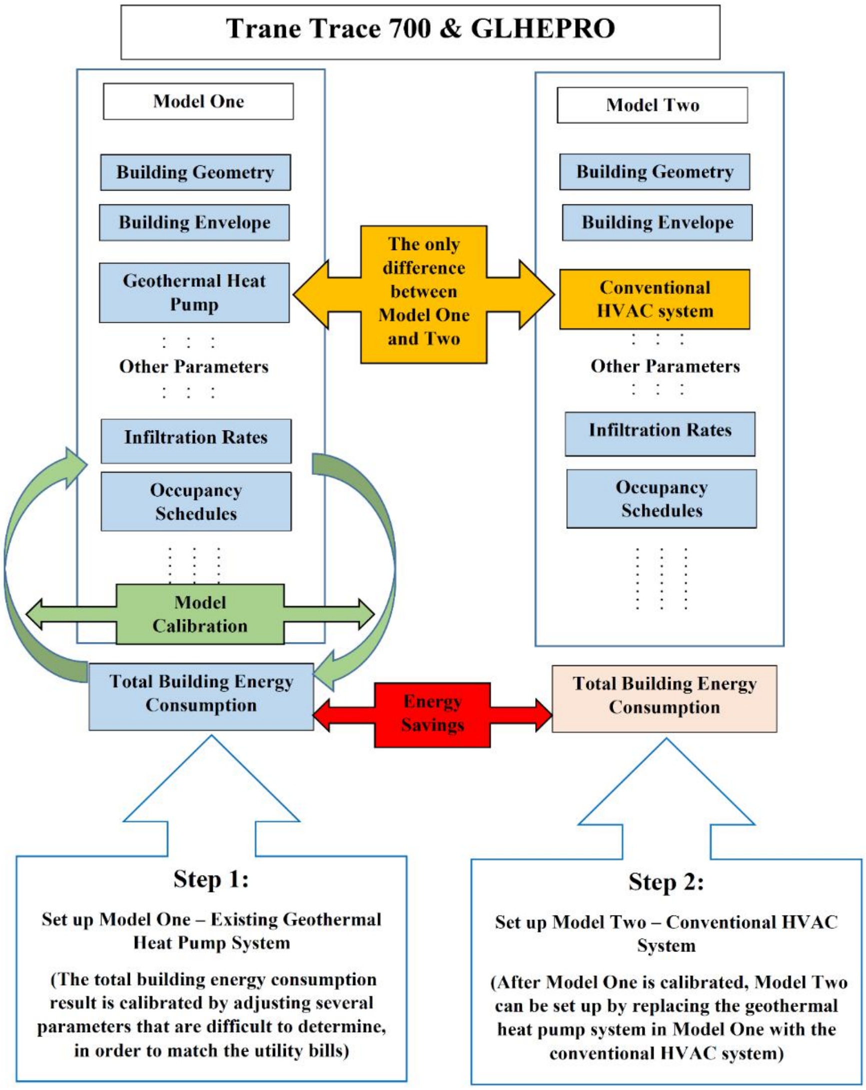

Figure 2. Model calibration results

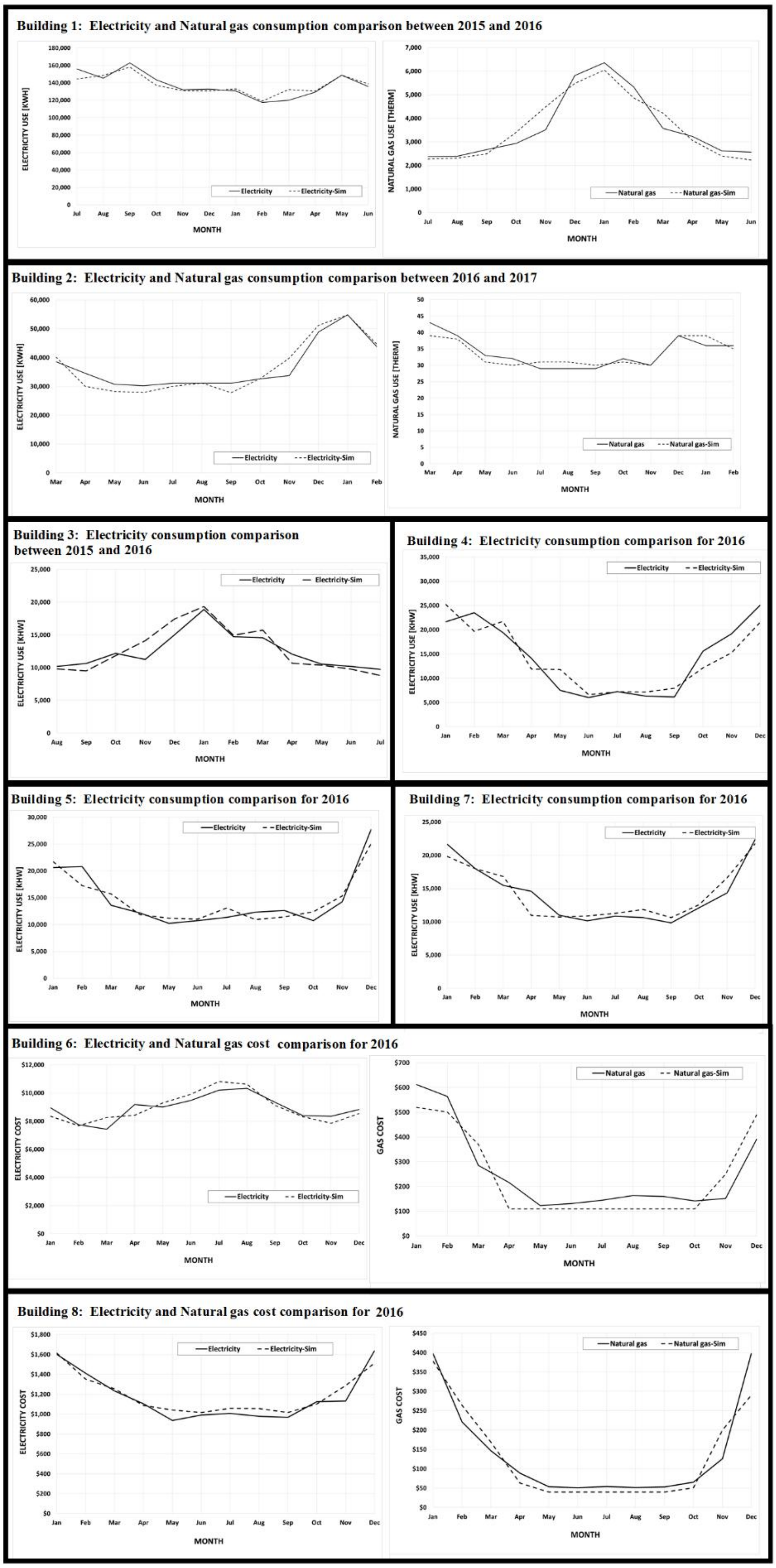

Figure 3. Site EUI comparison for the year of 2016

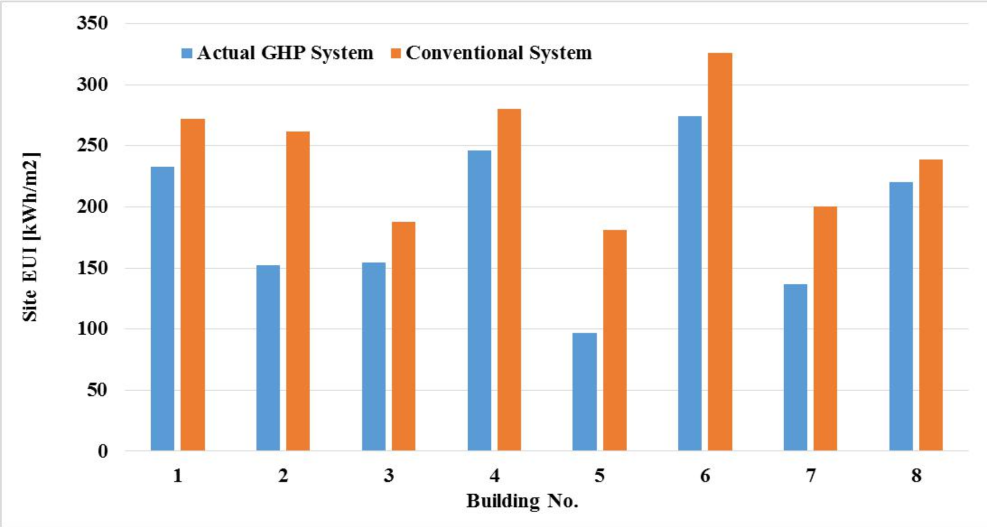

Figure 4. Energy cost density comparison for the year of 2016

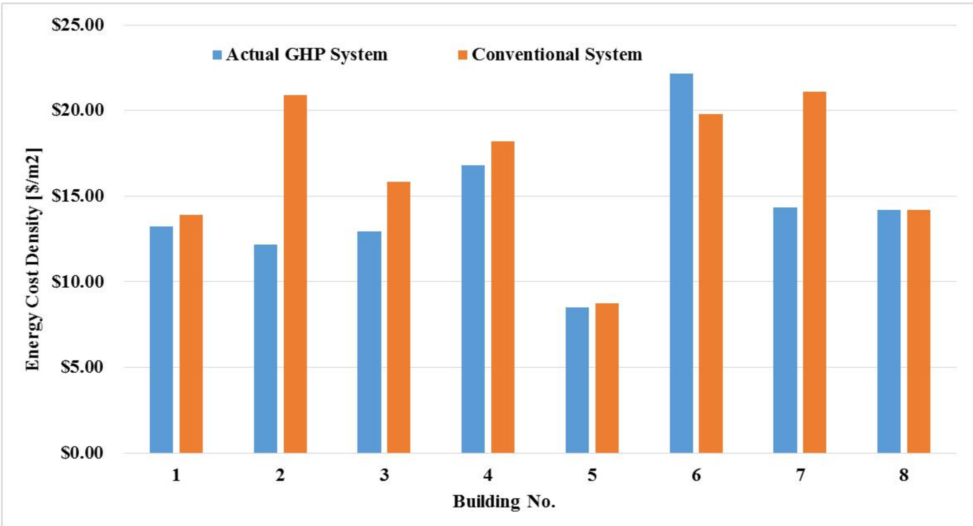

Figure 5. Linear regression analysis between Site EUI and Energy Savings

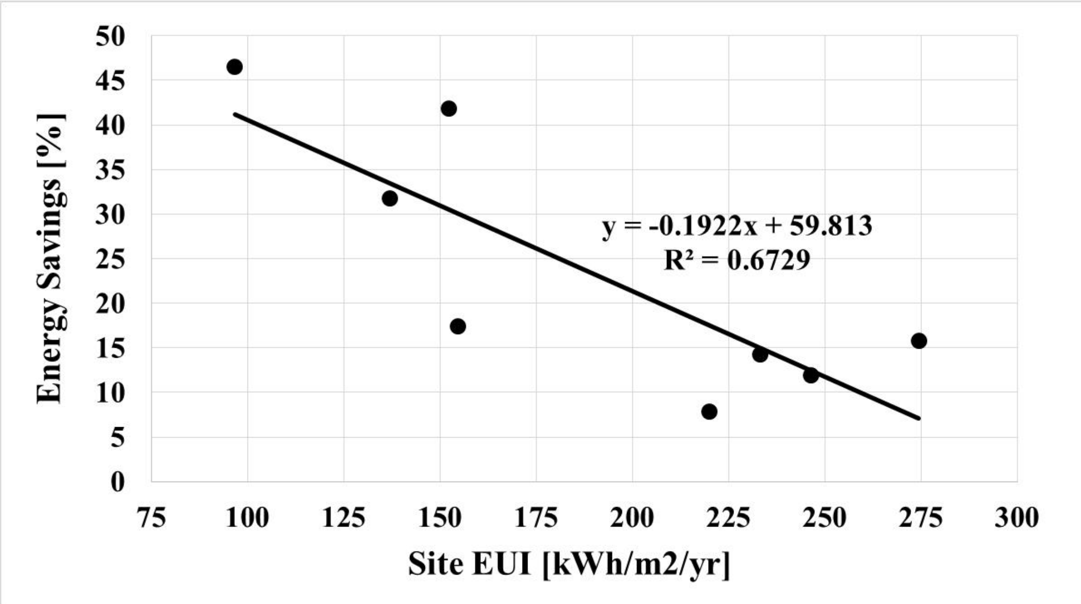

Table 1. Basic building information

Building Number	Location in North Dakota	Building Type	Building Total Area [m^2]	Total Number of Floor	GSHP Installation Year	GSHP Installation Type
1	Fargo	College	12542	Above ground: 6 Below ground: 1	2009	New for the addition
2	Bismarck	College	2973	Above ground: 2	2010	New
3	Dickinson	College/Office	970	Above ground: 2	2006	New
4	Langdon	College/Office	697	Above ground: 1 + Mezzanine	2010	Retrofit/Upgrade
5	Minot	Church	2230	Above ground: 1 + Mezzanine	2006	New
6	Grand Forks	Commercial/Airport Terminal	4970	Above ground: 2	2011	New

Table 1. Basic building information						
Building Number	Location in North Dakota	Building Type	Building Total Area [m^2]	Total Number of Floor	GSHP Installation Year	GSHP Installation Type
7	Grand Forks	Commercial/Office	1254	Above ground: 2	2012	New
8	Fargo	Public/Fire Station	1115	Above ground: 1 + Mezzanine	2009	New

Table 2. Building GSHP system summary										
Bldg. NO.	GSHP system type*	NO. of Bore-holes	Borehole Depth [m]	Borehole Separation Distance [m]	Borehole Length [m]	Borehole Length per ton [m/kW]	GSHP water flow rate per ton [L/s/kW]	Ground/Building Loop Pump**	NO. of Ground-Loop Circuits	NO. of HP Units***
1	VCL	120	62	4.6	7425	23.14	0.081	GL:DPVSD BL:N/A	5	WAHP: 53 WWHP: 3
2	VCL	130	91	4.6	11887	30.94	0.097	GL:DPVSD BL:DPVSD	13	WAHP: 41
3	VCL	30	61	4.6	1829	17.14	0.063	GL:CS Pump BL:DPVSD	3	WAHP: 12
4	VCL	26	61	3.0~4.6	1585	19.20	0.065	GL:CS Pump BL: N/A	2	WAHP: 7
5	VCL	48	61	4.6	2926	16.45	0.056	GL:CS Pump BL: N/A	4	WAHP: 13 WWHP: 1

Table 2. Building GSHP system summary										
Bldg. NO.	GSHP system type*	NO. of Bore-holes	Borehole Depth [m]	Borehole Separation Distance [m]	Borehole Length [m]	Borehole Length per ton [m/kW]	GSHP water flow rate per ton [L/s/kW]	Ground/Building Loop Pump**	NO. of Ground-Loop Circuits	NO. of HP Units***
6	HBCL	16	7.6 and 12.2	6.1	152/each Total 2438	7.11	0.041	GL:DPVSD BL:DPVSD	16	WAHP: 35 WWHP: 1
7	VCL	26	61	4.6	1585	12.08	0.043	GL:DPVSD BL:N/A	2	WAHP: 19 WWHP: 1
8	VCL	18	61	4.6	1097	19.03	0.067	GL:DPVSD BL:N/A	2	WAHP: 6 WWHP: 1

*VCL – Vertical Closed Loop; HBCL – Horizontally Bored Closed Loop

** GL: Ground Loop; BL: Building Loop; DPVSD - Differential Pressure-controlled Variable Speed Drive; CS - Constant Speed

***WAHP – Water-to-Air Heat Pump; WWHP – Water-to-Water Heat Pump

Table 3. Conventional systems used in whole building energy simulations	
Building	Conventional System

NO.	
1	Four-pipe fan coil system with chilled water chiller cooling and hot-water gas-fired boiler heating
2	Packaged rooftop VAV with PFP (Parallel Fan-Powered) boxes with direct expansion (DX) cooling and electric heating
3	Packaged rooftop heat pump with constant volume fan control, direct expansion (DX) cooling and electric heat pump heating.
4	Air-cooled condensing units with electric heat
5	Packaged rooftop air conditioner with constant volume fan control, direct expansion (DX) cooling and gas-fired furnace heating
6	Packaged rooftop VAV with reheat, direct expansion (DX) cooling and hot-water gas-fired boiler heating.
7	Packaged rooftop heat pump with constant volume fan control, direct expansion (DX) cooling and electric heat pump heating
8	Packaged rooftop air conditioner with constant volume fan control, direct expansion (DX) cooling and gas-fired furnace heating.

Table 4. Calibration results of MBE and CVRMSE

	MBE (%)		CVRMSE (%)	
	Electricity	Natural Gas	Electricity	Natural Gas
Building 1	-0.15%	-0.23%	4.07%	11.97%
Building 2	-0.64%	-0.74%	7.45%	5.71%
Building 3	1.56%	-	10.39%	-
Building 4	2.14%	-	14.66%	-
Building 5	-0.04%	-	11.84%	-
Building 6	-0.03%	-1.18%	5.35%	14.69%
Building 7	0.50%	-	10.49%	-
Building 8	1.93%	-5.00%	6.35%	14.89%

Table 5. Average of mechanical system parameters (not including horizontal boreholes)

	Average ± SD*	Range	Typical Value**
Borehole Depth [m]	65.5±11.5	61~91	15.2~137.2
Borehole Separation Distance [m]	4.4±0.6	3~4.6	6.1 or greater
Borehole Length per ton [m/kW]	19.7±6	12.08~30.94	12.9~21.4
Underground Pipe Length per ton for single U-tube configuration [m/kW]	39.4±12	24.16~61.88	25.7~42.9
GSHP water flow rate per ton [L/s/kW]	0.067±0.017	0.043~0.097	0.045~0.054

*SD – Standard Deviation

**for vertical closed-loop GSHP systems (Egg et al., 2013; Kavanaugh and Rafferty, 2014; and/or ASHRAE, 2015)

Table 6. Energy and energy cost information for the year of 2016

Bldg. NO.	Site EUI [kWh/m^2/yr]		Energy Cost Density [$/m^2/yr]		Energy Savings Compared to Conventional System	Energy Cost Savings Compared to Conventional System
	Actual GSHP System	Conventional System	Actual GSHP System	Conventional System		
1	233.1	272.2	$13.24	$13.89	14%	5%
2	152.4	261.8	$12.16	$20.88	42%	42%
3	154.6	187.4	$12.92	$15.82	17%	18%
4	246.4	279.8	$16.79	$18.19	12%	8%
5	96.8	181.1	$8.50	$8.72	46%	2%
6	274.4	325.9	$22.17	$19.81	16%	-12%
7	136.9	200.6	$14.32	$21.10	32%	32%
8	219.9	238.5	$14.21	$14.21	8%	0%

Table 7. Average of energy and energy cost savings		
	Average ± SD*	Range
Energy Cost Density - Actual GSHP System [$/m^2/yr]	$14.32±3.95	$8.50~22.17
Energy Cost Density - ASHRAE Conventional System [$/m^2/yr]	$16.58±4.26	$8.72~21.10
Range of Energy Savings Compared to Conventional System	8%~46%	
Range of Energy Cost Savings Compared to Conventional System	-12%~42%	

*SD – Standard Deviation

Table 8. Regression results						
Dependent Variable	Independent Variable	R	R Square	Standard Error	Correlation	Equation
Energy Savings [%]	Site EUI [kWh/m^2/yr]	0.82	0.673	9.03	Medium to Strong	Energy Savings [%] = 59.813 - 0.1922 EUI

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