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INVESTIGATION AND EVALUATION OF A HORIZONTALLY BORED GEOTHERMAL HEAT PUMP SYSTEM USED IN THE COLD CLIMATE OF THE U.S.

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ABSTRACT

Geothermal Heat Pump (GHP) systems equipped with horizontally bored underground pipes are a variant of a conventional horizontal closed-loop GHP system. The development of this type of system benefits from a horizontal drilling technique that allows the installation of horizontal heat exchangers in the deeper ground at different layers. Like a vertical closed-loop system, the horizontal boreholes are typically grouted in order to enhance the heat transfer performance. This type of system is less disturbed by outdoor weather compared to conventional horizontal closed-loop systems and thus may have higher cooling and heating capacities for larger building applications. Although horizontally bored GHP systems have their own advantages, this type system is not as widely used as conventional vertical or horizontal closed-loop systems, especially in cold-climate regions of the U.S. This paper aims to investigate and evaluate a horizontally bored underground GHP system currently used in an airport terminal located in Grand Forks in North Dakota (Climate Zone 7). This study includes a detailed description regarding this airport facility and an in-depth building energy simulation performed by using the commercial energy simulation software packages, Trane Trace 700 and GLHEPro 5.0. The models used in the simulation have been calibrated by using actual utility bills. The results indicate that the potential energy savings of this building are 17% compared to a conventional HVAC system. However, the corresponding energy cost savings are -7%, due to the extremely low natural gas price in this cold-climate region compared to electricity.

INTRODUCTION

Unlike conventional vertical or horizontal closed-loop Geothermal Heat Pump (GHP) systems, a horizontally bored GHP system can be considered as a variant of a conventional horizontal closed-loop GHP system. The development and application of this type of system benefit from the Horizontal Directional Drilling (HDD) method (Remund and Carda 2009; Beier and Holloway 2015) that allows the installation of horizontal heat exchangers (U-tubes) in a deeper ground compared to horizontal trenches. The pipes of a horizontally bored GHP system are typically installed in grouted horizontal boreholes located in the deep ground (usually between 30 and 50 feet) at different layers. This type of system is less disturbed by outdoor weather compared to conventional trenched horizontal closed-loop systems and thus may have higher cooling and heating capacities for larger building applications (Kavanaugh and Rafferty 2014).

Due to the annual temperature and moisture content variations are close to deep-earth values, the design lengths of this type of ground loop are near those for conventional vertical GHP systems (ASHRAE 2015; Kavanaugh and Rafferty 2014, Yu and Olson 2018). Therefore, this type of GHP system can be also regarded as an intermediate system between conventional vertical and horizontal closed-loop GHP systems. It is able to be installed under existing building structures, driveways, etc. without disturbing them. References and useful resources about this type of underground loop, however, are insufficient (Wiryadinata 2015; Yu et al. 2017), especially in consideration of a detailed design guideline and case studies of this type of system used in different climate zones for various building types. Without this information, designers, engineers, and building owners would have less confidence in the design and use of this kind of system, which thus limits its wide application in the U.S., even though its advantages are apparent.

Therefore, this paper investigates and evaluates a horizontally bored underground GHP system currently used in an airport terminal located in Grand Forks in North Dakota (Climate Zone 7). The primary objectives of the paper are to, as a case study, review and demonstrate the feasibility and operational performance of this type of system used in cold-climate regions of the U.S., as well as quantify and justify the energy and energy cost savings of this facility. It is also intended to provide a useful reference to designers, engineers, and/or building owners in order to increase their confidence in using horizontally bored GHP systems, especially in cold climate regions of the U.S., where unexpected issues for GHP system may occur, such as frozen pipes, less heat from the ground for the first winter, underground thermal imbalance, etc. (Meyer et al. 2011).

BUILDING BACKGROUND

The Grand Forks Airport International Terminal (Figure 1) is located in Grand Forks, North Dakota, and was built in 2011. This building has an area of about 53,548 ft^2 having 48 rooms with the full occupancy of 808. This facility was initially designed to use a vertical closed-loop GHP system (96 boreholes with the depth of about 200 feet) to provide space heating and cooling. A horizontally bored underground heat exchanger, however, was planned for use after finding the unusually high water table during construction. Auxiliary heating devices are used, including gas-fired unit heaters and a hot water floor radiation system. Other features include two Dedicated Outdoor Air Systems (DOASs) with heat pump cooling and heating modes that connect to the ground loop with other heat pump units, Variable Speed Drive (VSD) water pumps and fans, occupancy and daylighting sensors, Building Automation System (BAS), etc. This building achieved the LEED Silver certification in 2013 and was one of only five international airport terminals that achieved LEED certification in the U.S. as of 2013. Table 1 summarizes the building information.

Figure 1: Grand Forks Airport International Terminal (Source: http://gfkairport.com/)

Table 1 Building Information

Building Name	Grand Forks Airport International Terminal
Building Location	Grand Forks, North Dakota
Building Type	Public/Commercial Building
Building Construction Year	2011
Building Total Area (ft^2)	53,548
Total Number of Floor	Above ground: 2
LEED Building	Yes - Silver

SYSTEM DESCRIPTION

In the Grand Forks Airport International Terminal building, 33 water-to-air heat pump units are used to condition the indoor occupied spaces. Another water-to-water heat pump is used only to provide the heating effect to the large open space – the main entrance lobby with a hot water floor radiation system. Two DOASs are used to provide necessary ventilation (total 6,355 cfm). Ducts from these two units are tied to each heat pump to supply fresh air to each occupied space. Energy recovery wheels are equipped in these two DOASs respectively to exchange the heat between the exhaust and outdoor intake air. These DOASs are in the heat pump mode, which are connected to and share the same ground loops with other heat pump units. These heat pump units have the rated efficiencies between 8.9 ~ 12.3 EER for cooling and 2.6 ~ 3.7 COP for heating. Heat rejection and extraction take place through 16 horizontal boreholes that are buried underground with the depth of 25 feet and 40 feet (two layers) below the ground surface with a minimum separation distance of about 20 feet, as shown in Figure 2. The length of each horizontal borehole is 500 feet. Water in both of the ground and building loops is circulated between them through four VSD pumps (two for the ground loop and the other two for the building loop). The GHP information is summarized in Table 2.

Table 2 GHP Information

HVAC/GHP Installation Year	2011
Installation Type	New
GHP system type	Horizontally bored closed loop
Number of Boreholes for Horizontal GHP	16
Borehole Depth (ft)	25 and 40
Borehole Separation Distance (ft)	20
Borehole Length (ft)	500/each Total 8,000
Underground Pipe Length (ft)	16,000
Borehole Length per ton (ft/ton)	83
Underground Pipe Length per ton (ft/ton)	166
GHP water flow rate per ton (gpm/ton)	2.3
Number of Heat Pump Units	Water-to-Air Heat Pump: 33 Water-to-Water Heat Pump (Heating Only): 1 DOAS - Heat Pump: 2
Total Capacity of Heat Pump Units (tons)	96
Total Capacity of the entire HVAC System (tons)	96
Rated Heat Pump Efficiency Range	Cooling: 8.9~12.3 EER Heating: 2.6~3.7 COP

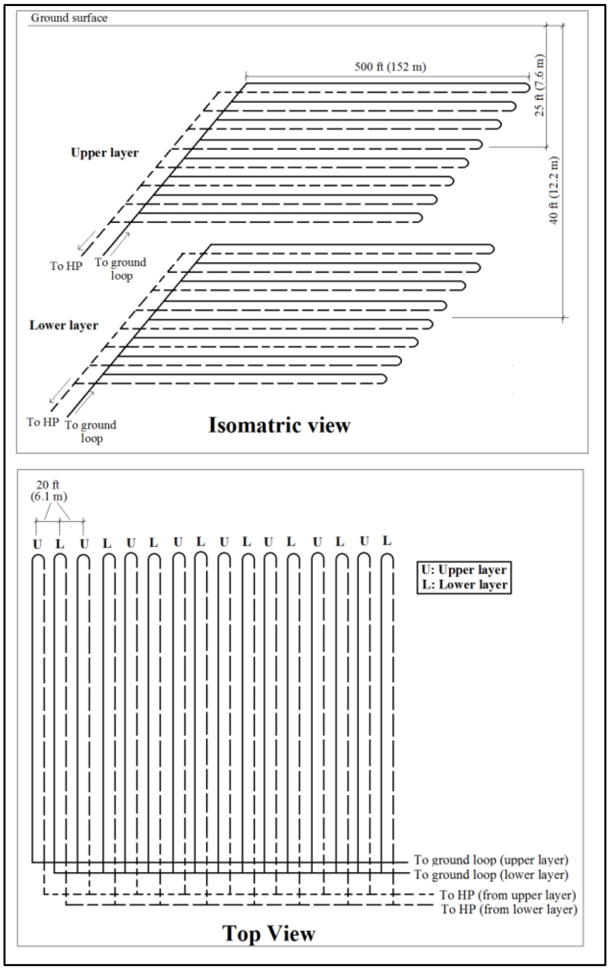

Figure 2 Well field circuits

SYSTEM PERFORMANCE

The actual monthly energy cost for natural gas and electricity (between July 2016 and June 2017 for 12 months) of the Grand Forks Airport International Terminal building is displayed in Figure 3 with the total cost of $112,768.73 per year ($109,163.31 for electricity and $3,605.42 for natural gas), i.e. $2.11/ft^2/yr.

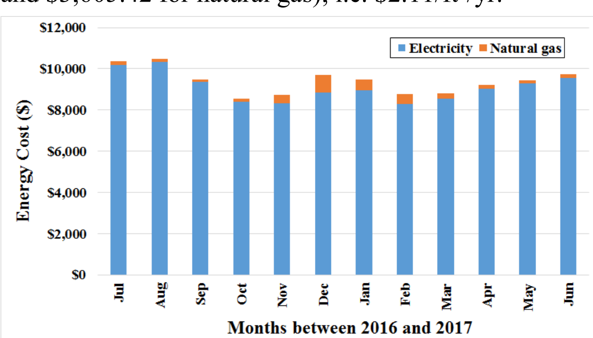

Figure 3 Monthly energy cost between 2016 and 2017

In order to determine the potential energy and energy cost savings between the existing building equipped with a GHP system (Model I) and an identical building but equipped with an imaginary conventional HVAC system (Model II), an energy simulation model was established by using the commercial energy simulation software packages, Trane Trace 700 and GLHEPro 5.0, which are coupled together. The building load profile generated in Trace 700 is input into the GLHEPro, where the Free-Placement Finite Line Source (FPFLS) Model is used to define the horizontally-drilled boreholes, in order to generate an idf file that will be imported back to the Trace 700 model to provide a detail geothermal loop description.

In order to improve the accuracy and reliability of the simulations, primarily to determine some of the typical building parameters that are used in both Model I and II but are difficult to know or identify, such as infiltration rates, occupancy, lighting, and equipment schedules, etc., a model calibration was conducted for this building. In this process, Model I is calibrated against the actual monthly energy usage and cost of the existing building by adjusting these parameters to achieve a good agreement (a "goodness-of-fit") between the actual utility data and the simulated results. For example, Figure 4 shows the occupancy schedules used in the model after the calibration. This parameter is one of the most critical parameters in the model calibration since people typically contribute to the significant internal loads for the HVAC system in this type of facility (an airport terminal).

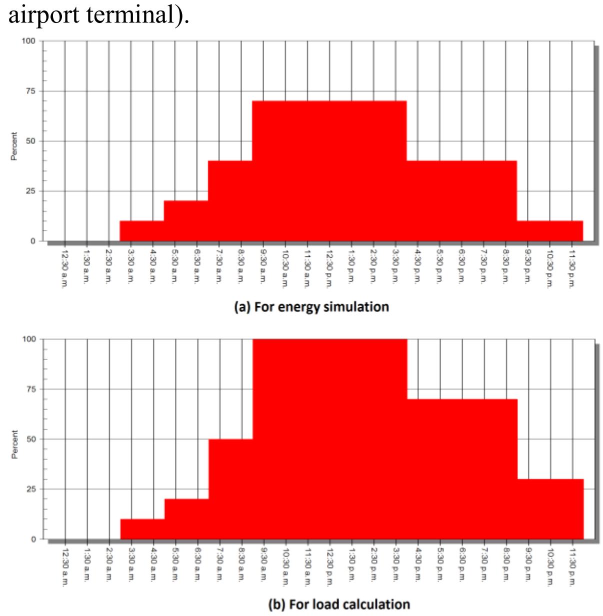

Figure 4 Occupancy schedules after calibration

According to ASHRAE Guideline 14 (2002), Model I 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).

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

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

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.

Figure 5~8 show the calibration results, i.e., the comparison between the simulated energy usage/cost and the actual utility use/cost between July 2016 and June 2017.

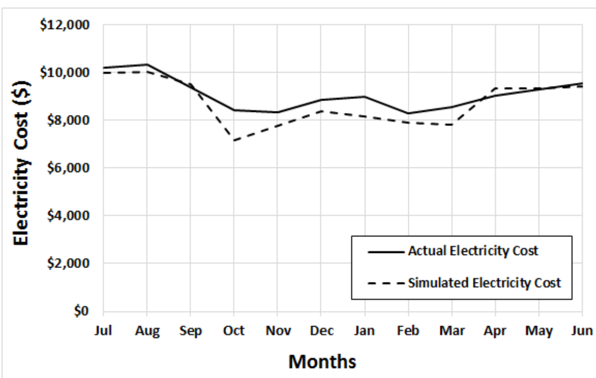

Figure 5 Electricity cost comparison

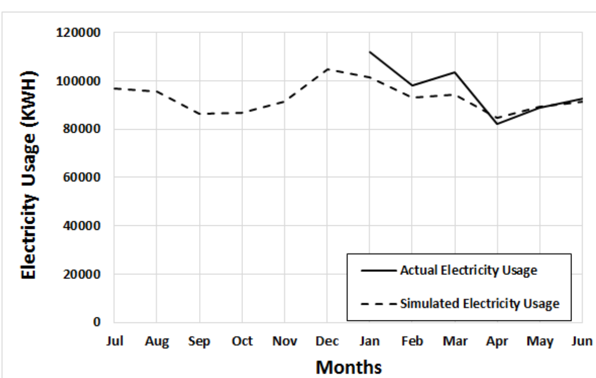

Figure 6 Electricity usage comparison

In Figure 6, the actual electricity usage data between July 2016 and December 2016 are missing and thus are not shown in this figure. Therefore, they were not used in the calibration process to determine the MBE and CVRMSE values, due to the limited utility data provided by the building owner of this facility. In other words, only the electricity usage data for the six months (January ~ June) in 2017 were used in the model calibration.

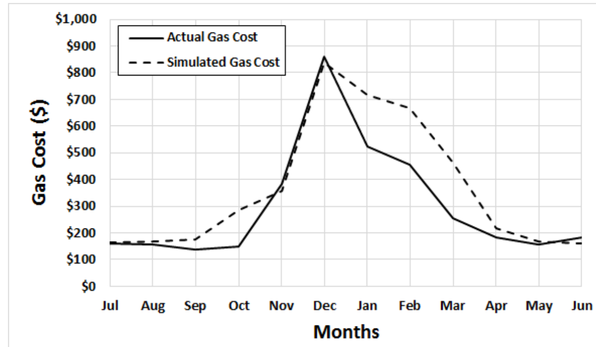

Figure 7 Natural gas cost comparison

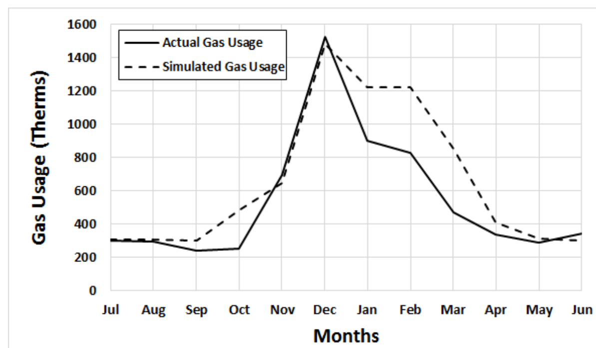

Figure 8 Natural gas usage comparison

As shown in Figure 7 and 8, the simulated natural gas cost and usage do not match well with the actual natural gas utility data. This also can be seen in Table 3, where the calibration results in terms of the MBE and CVRMSE values of Model I are shown. It is clear to see that for electricity (energy usage/cost) both of the MBE and CVRMSE values are within the acceptable limits (±5% for MBE and 15% for CVRMSE) according to the ASHRAE Guideline 14 (2002). However, the MBE and CVRMSE values for natural gas are not within these limits. After the careful analysis, the reason for the mismatching of natural gas was found, which is due to the use of the TMY3 (Typical Meteorological Year 3) weather data in the simulation. The actual weather in Grand Forks during the simulation period (between July 2016 and June 2017) is much different from the TMY3, especially during the heating season, as shown in Figure 9 that compares these two weather data (the hourly TMY3 data vs. the actual daily weather data) for outdoor dry-bulb air temperatures. The dry bulb air temperatures used in the simulation (TMY3) are much lower than the actual weather condition, as shown in Figure 9, which is one of the primary reasons that cause the higher natural gas usage and cost (Figure 7 and 8) as well as the higher MBE and CVRMSE values for natural gas (Table 3).

Table 3 Calibration result

		Electricity (E)	Natural Gas (NG)	Total (E+NG)
MBE (%)	Energy	-3.96%	21.15%	1.59%
	Cost	-4.12%	24.34%	-3.30%
CVRMSE (%)	Energy	6.35%	36.75%	3.18%
	Cost	6.15%	36.84%	5.16%

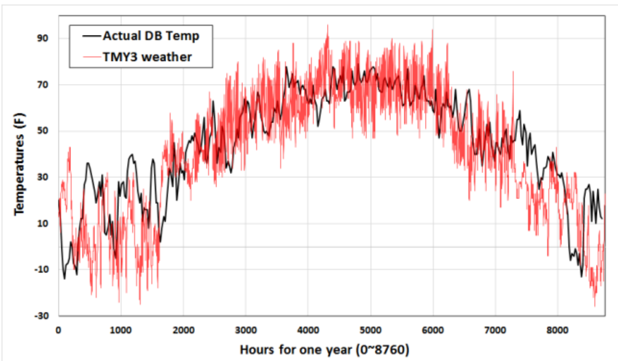

Figure 9 Weather data comparison

Although the MBE and CVRMSE values for natural gas are not within the required limits, Model I in this paper can be still regarded as a calibrated model (or near calibrated model) to be used to determine the potential energy and energy cost savings, due to the fact that the majority of energy consumed by this building is electricity (as shown in Figure 3), while natural gas only accounts for 3.2% of the total utility cost. Furthermore, the MBE and CVRMSE values for the total energy usage and cost (electricity + natural gas) are within the limits, as shown in Table 3 and Figure 10 and 11. Again, in Figure 11, only 6-month data were displayed and used in the MBE and CVRMSE calculations due to the limited utility data provided by the building owner.

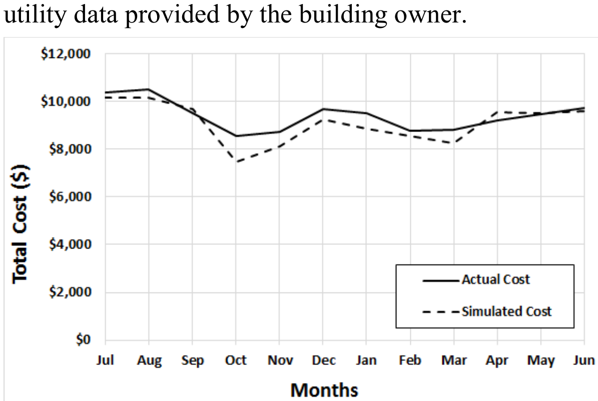

Figure 10 Total utility cost comparison

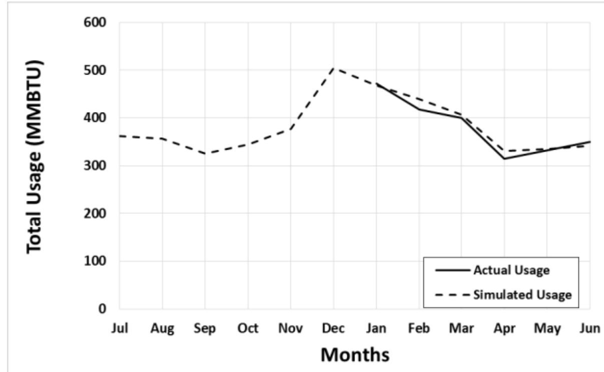

Figure 11 Total utility usage comparison

In fact, the supply and return water temperatures to or from the ground loops also show a good agreement between the measured hourly data provided by the building owner and the simulated results obtained from Model I. Figure 12 and 13 show this comparison in terms of supply or return water temperatures to or from the ground loop over two days (between 7/31/2017 and 8/1/2017). The corresponding MBE and CVRMSE values are MBE = -1.39% and CVRMSE = 1.00% for supply water temperatures, and MBE = 1.57% and CVRMSE = 0.90% for return water temperatures. These hourly simulation data were extracted from Trace 700 by using the small application, “t700prof”, which is located in the folder where the Trace 700 is installed. “t700prof” allows users to look at more detailed simulation results through the Trace 700 Visualizer.

The above discussions indicate that Model I in this case study can be considered as a calibrated (or near calibrated) model and is able to be used to estimate and determine the potential (normalized) energy and energy cost savings of this building using the GHP system.

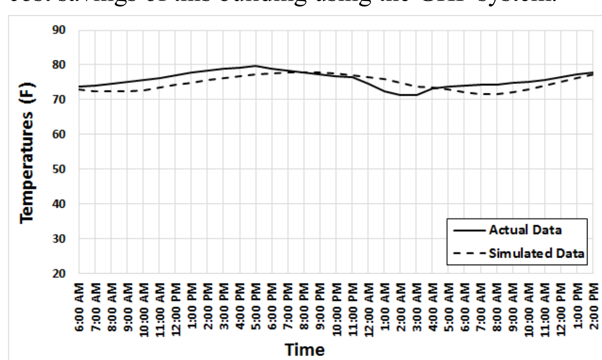

Figure 12 Supply water temperatures to the ground loop (between 7/31/2017 and 8/1/2017)

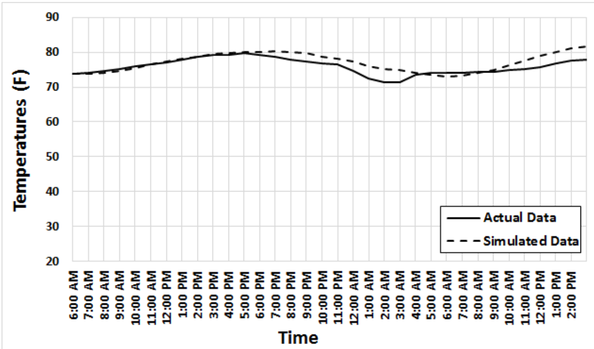

Figure 13 Return water temperatures from the ground loop (between 7/31/2017 and 8/1/2017)

To identify the building energy savings, the baseline model (Mode II) for an identical building but equipped with an imaginary conventional HVAC system was established based on the ASHRAE Standard 90.1 – Appendix G, as shown in Table 4. Please note that in the model with the conventional HVAC system, only the description of the mechanical system complies with the ASHRAE 90.1 (Appendix G). Other building parameters, such as building wall and roof constructions, lighting power density of each space, etc., were not altered (these parameters are kept same between Model I and II). It is intended to answer this question, "What would the corresponding energy consumption and energy expenses be if the imaginary conventional HVAC system (the system for Model II) were installed and used in the first place in the existing building instead of the GHP system?" This is different from using the Appendix G to perform a whole building energy simulation, e.g., for pursuing LEED (Leadership in Energy and Environmental Design) building credits/certification, where the baseline energy simulation model has to be established exactly in compliance with the requirements of Appendix G, i.e., all building parameters for the baseline model, including the building construction, interior and exterior light power densities, mechanical systems, etc., should exactly follow this standard.

Table 4 Model I and II

Model I	**Model II**
Geothermal heat pump systems as designed	Packaged rooftop VAV with reheat, direct expansion (DX) cooling and hot-water fossil fuel boiler heating.

Once these simulation models (Model I and II) have been established successfully, the energy and energy cost savings can be identified, which are summarized below and also shown in Table 5.

- 17% of energy savings is achieved between the existing building and a baseline building equipped with a conventional HVAC system;
- The corresponding energy cost savings are -7%.

The inconsistency between these two savings is mainly caused by the extremely low utility rate for natural gas compared to electricity. For example, the average natural gas price for the year of 2016 in North Dakota is $0.526 per therm, while the average price for electricity is 8.96 cents per kWh (EIA 2018). To compare these two utility prices, the $0.526 per therm for natural gas was converted to the same energy unit for electricity, which is equivalent to about 1.8 cents per kWh. This is about 5 times less than the electricity price.

Therefore, even though the existing GHP system (Model I) consumes less energy, its energy cost is higher than the baseline system (Model II), as shown in Table 5, since the conventional HVAC system primarily uses natural gas (gas-fired boiler) to provide heating effect, while the existing geothermal system uses electricity (heat pumps).

Table 5 Energy Performance Comparison

	Actual GHP System (Model I)		ASHRAE Conventional System (Model II)
	Actual Utilities	Simulated	Simulated
Electricity Usage (kwh/yr)	577,200 (half year data)*	1,116,109	930,064
Electricity Cost ($/yr)	109,163.31	104,667.49	88,766.02
Natural Gas Usage (therm/yr)	6481	7,852	23,686
Natural Gas Cost ($/yr)	3,605.42	4374.77	13,213.99
Actual Site Energy Usage (MMBTU/yr)	2,946.1 (with half year electricity data)*	4,590.6	5,541.5
Total Actual Energy Cost ($/yr)	112,768.73	109,042.26**	101,980.01**
Actual Site EUI (kBtu/ft^2/yr)	55.0 (with half year electricity data)*	85.7	103.5
Energy Savings Compared to Conventional System	17%		
Energy Cost Savings Compared to Conventional System	-7%		

* With six-month electricity data only between January and June in 2017
** Determined by using the actual electricity and natural gas rates for the building.

CONCLUSION

This paper has described a horizontally bored underground GHP system currently used in an airport terminal located in Grand Forks in North Dakota. It includes a detailed description regarding this airport facility and a whole building energy simulation performed by using the commercial energy simulation software packages, Trane Trace 700 and GLHEPro 5.0. The models used in the simulation have been sufficiently calibrated by using the actual monthly utility bills in consideration of the calibration results shown above, even though the actual electricity usage data between July 2016 and December 2016 were missing and not used in the calibration process. The primary objectives of the paper are, as a case study, to review and demonstrate the feasibility and operational performance of the horizontally bored underground GHP system used in the cold-climate region of the U.S., as well as quantify and justify the energy and energy cost savings of this facility.

The conclusions of this study are listed below.

- No serious complaint from the building owner/operator has been received regarding the GHP system used in this airport terminal, which, to some extent, demonstrates the feasibility and reliability of using this type of GHP system in the cold-climate region of the U.S. This provides a useful reference for designers, engineers, and/or building owners in this region for the sake of increasing their confidence in using horizontally bored GHP systems.
- The potential energy savings for this facility using the horizontally bored underground GHP system for space heating and cooling is 17% compared to a conventional HVAC system, while the corresponding energy cost savings has not be identified (-7%), due to the extremely low utility rate for natural gas compared to electricity. This is one of the barriers to the wide application of GHP system in North Dakota or probably other cold-climate regions of the U.S., due to a relatively high capital cost and low/no energy cost savings, which may cause a long payback period.
- The combined use of Trace 700 and GLHEPro 5.0 is able to provide reliable simulation results for a horizontally bored underground GHP system. Especially, the new feature - Free-Placement Finite Line Source (FPFLS) Model added in the new version (5.0) of GLHEPro, which allows the accurate definition of horizontally-drilled boreholes. Furthermore, the use of the auxiliary application "t700prof" in the Trace 700 installation folder allows the user to extract/output more detailed hourly simulation data for advanced simulations and calibrations.
- The use of the Typical Meteorological Year (TMY) weather data may result in non-compliance results in building energy model calibration due to the inconsistency between the actual weather conditions and the TMY data. It is suggested to use real hourly weather data, if they are possible to be collected, which may help to reduce the inconsistency in model calibration and improve model reliability. Although this study used the TMY3 weather data in the model calibration and the subsequent saving estimations, real weather data will be collected and attempted in the future study.

In this study, the HVAC system described in the ASHRAE 90.1 - Appendix G (consuming electricity for cooling and natural gas for heating) was used as the baseline system to identify the energy and energy cost savings. Additional studies, however, are needed in the future, for example, the economic feasibility analysis of this type of GHP system used in cold-climate regions in the U.S. when comparing it to an air-source heat pump system that, like a GHP system, is also consuming electricity for both cooling and heating. This allows a more objective evaluation and "apple to apple" comparison by minimizing/avoiding the influence of different energy sources.

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