Heat pump system assessment for a groundwater-source municipal drinking water utility

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ABSTRACT

Compared to a conventional heating, ventilation, and air conditioning (HVAC) system, a groundwater source heat pump (GSHP) system should have lower operating costs and greenhouse gas emissions, providing economic and environmental advantages for a ground water-based municipal water utility. This paper describes a test of that hypothesis, involving simulations and evaluations of the economic performance of the above two systems for a model office building in five major U.S. climate zones. The cost-benefit analysis suggests that a GSHP system in climate zone 5 (Chicago-region) has the best return on investment, whereas climate zone 2 (Phoenix-region) is not economically promising. Relative to a conventional HVAC system, the GSHP system has lower carbon emissions in each of the five climate zones, with the greatest reduction of carbon emissions occurring in climate zone 5 (Chicago-region).

Key words: groundwater source heat pump, climate zone, HVAC, water utility, cost-benefit analysis, greenhouse gas emission
Studies of groundwater source heat pumps (GSHPs) are available, but only a few of investigations focused on the effect of climate zones, and we are not aware of any studies specifically related to the assessment of GSHP for water utility. A ground water-based municipal water utility has existing subterranean pipe network, which should provide economic advantage over conventional HVACs. This paper describes a test of that hypothesis, involving simulations and evaluations of the economic performance of the above two systems for a model office building in five major U.S. climate zones.
BUILDINGS account for about 40% of worldwide energy consumption, much more than what is used, for example, in transportation [1]. The U.S. Energy Information Administration (USEIA) recently predicted that energy consumed by buildings would increase to around 50% of total energy use by 2030 [2]. In the United States, buildings accounted for around 47% of total energy consumption in 2010, with 41% for operations and 6% for construction [2]. Cooling and heating account for more than 40% of operations energy use in residential buildings; the amount was about 27% in commercial buildings in 2009. Therefore, heating, ventilation, and air conditioning (HVAC) systems play an important role in determining energy efficiency in buildings.

A heat pump (HP) can transfer thermal energy from a source (such as air, water, or the ground) to a building in winter, and in the opposite direction in summer. Relative to conventional HVAC systems, an HP system offers several potential advantages including decreased space needs, higher efficiency, and lower maintenance costs [3]. The ratio of heating or cooling provided to the amount of work required in the transfer process, is the coefficient of performance (COP); a higher COP value implies a higher energy efficiency HP system [4].

Ground source heat pumps (GSHP), which take advantage of the heat capacity of soil or groundwater, are recognized as energy-efficient and environmentally-friendly HVAC systems [5,6]. The USEPA [7] compared the performance of GSHPs with many conventional HVAC systems, and concluded that the GSHPs had the lowest CO₂ emissions and the lowest overall environmental cost. After more than 20 years development of conventional HVAC systems and GSHPs, in general, GSHPs remain superior to conventional HVAC systems. For example, Wang [8] used building energy modeling to compare energy consumption for GSHP and variable refrigerant flow (VRF – a relatively advanced conventional HVAC system) systems. He reported
that annual electricity consumption for GSHP systems was always lower in the three climate zones he studied. Because of these advantages, GSHP applications have increased rapidly in recent years. For example, Lund et al. [9] reported that over one million GSHP systems were installed worldwide in 2008, and that the annual growth rate was about 10%. Kim and Nam [10] mentioned that the number of GSHP installations in Korea increased almost 100% from 2005 to 2011.

There are also potential barriers that can discourage adoption of GSHP systems, such as initial cost and the lack of an experienced designer [11]. For example, conventional GSHP systems require a subterranean pipe network. Costs associated with drilling, grouting, heat exchangers, wells, and pumps typically account for at least 50% of the total project capital costs [12]. Furthermore, GSHP systems can have higher-than-expected operating costs when the real system efficiency is lower than the labeled factory COP [11]. Puttagunta et al. [13] reported that because circulating fluid through ground-loop requires a substantial amount of energy, the working COP is low relative to the factory COP. It can also be important to have accurate water quality information to ensure that system components are compatible with existing water conditions, so potential problems associated with biofouling, scaling, or corrosion can be avoided [14].

Considering these potential advantages and disadvantages, municipal drinking water facilities that rely on groundwater sources would seem to be good candidates for GSHP applications. At a groundwater treatment facility, a GSHP system can transfer heat from/to the drinking water supply through a heat exchanger (Figure 1). Because a groundwater supply is already part of the process, there is no need for an additional subterranean pipe network; and the related initial and operation costs of the GSHP system can be reduced.

Two factors that are important to consider include local climate and sources of electricity, in terms of their influence on the performance efficiency and carbon emissions of any HVAC system.
For example, the US Department of Defense (USDOD) [15] conducted field studies to assess the applicability and cost effectiveness of conventional GSHPs at DOD facilities in all seven climate zones. USDOD has been installing GSHP systems since the late 1980s, and operated more than 52,000 tons of GSHP systems by 2007; the capacity of a GSHP for a single family home is commonly from two to four tons. In their report, they concluded that GSHP systems were unlikely to be cost effective in cold climates. It is also important to keep in mind that sources of electricity generation by states are different, and different sources have different carbon emissions. In this paper, carbon emission estimates for HVAC systems in different climate zones will be discussed in the methodology section, which also includes descriptions of the HVAC systems model, the simulated office building at the utility, and the cost-benefit analysis.

**METHODOLOGY**

In this study, AutoDesk® Revit® [16] was used for the design and simulation of the office building. Heating and cooling demands of the simulated building in five different climate zones were estimated with Sefaira [17], a building performance analysis software program. The design and analysis compared a conventional HVAC system and a GSHP for the simulated building, including energy consumption and operational costs. Greenhouse gas emissions based on energy consumption and the local sources of electricity were also considered. Assumptions used in this study include:

- Relative to the capacity of the groundwater treatment facility, the GSHP system is small and has an insignificant effect on the temperature of the water supplied to the distribution system.
- A 2.8°C temperature difference is typical for a heat exchanger between the groundwater loop and building loop in a GSHP system, and the required groundwater flowrate is usually below 0.05
L/s/kW [18]. In this study, the maximum capacity of the GSHP system is about 130 kW so the required flowrate is only 6.5 L/s. Assuming a per capita water use rate of 379 L/d, the flowrate through that loop equals the amount of water supplied for a community of 1482 people. In other words, the 2.8°C temperature change should be insignificant for all but the smallest utilities.

- Water quality has no effect on the GSHP system, and the GSHP has no effect on water quality. Gravity-film heat exchangers [19] or shell-and-tube heat exchangers [20] can be used to eliminate direct contact between groundwater and refrigerant.
- All building characteristics remained the same at each location
- Maintenance costs of conventional HVAC systems remained the same at each location

**Conventional HVAC system selection**

The conventional HAVC selected for comparison purposes was based on the California Energy Commission (CEC) [21] suggestion, which is appropriate for a small office building (typically three floors or less and smaller than 2323 m²). The CEC [21] suggested that variable air volume (VAV) system is a common and efficient HVAC system used in small offices and commercial type buildings. The VAV is the typical HVAC system in office buildings [22]. The VAV system is also the default HVAC system in Revit version 2016 for small office buildings. As a result, a VAV system was used as the conventional HVAC system to do a comparison study.

**US Climate zones**

There are seven major climate zones in the United States, as described in the 2009 International Energy Conservation Code [23]. Climate and weather data from five of these climate zones (2~6)
were used in this study, covering most of the area (Figure 2) and population in the U.S. These five climate zones were classified as hot (2), middle (3, 4, and 5) or cold (6) climates. Each of the five selected climate zones (Figure 2) is identified by a major city; climate data for that city were obtained from AutoDesk® Revit® [16] based on data from the National Oceanic and Atmospheric Administration. Identifying a region with a city name does not imply that specific city is appropriate for a GSHP application. For example, although there are groundwater-based municipal water utilities in NE Illinois, the City of Chicago relies exclusively on Lake Michigan as the source of municipal water. (Temperatures of the deeper source water in Lake Michigan are relatively constant, a water-source heat pump could be economically viable, but that system is not the subject of this paper).

**Simulated building**

The simulated building was a 1000 m$^2$, one-story office building with a floor-to-roof height of 4 m, created using AutoDesk® Revit® [16] (Figure 3). The building faced north and windows accounted for approximately 14% of the total area of the building’s facade. The roof was flat, the roof type was metal deck, and the wall type was concrete block. These materials, from the default configuration in Revit, are based on ASHRAE Standard 90.1-2010 [24]. These building characteristics were the same at each location; only the climate conditions changed.

Energy analysis of the building envelope was performed with the aid of the Sefaira software program [17]. Internal heat gain depends on internal loads such as lighting power density and occupant density. Internal conditions and thermal transmittance of the building elements (Table 1) were based on default values in the Sefaira system; these default values meet the baseline of ASHRAE Standard 90.1-2010 [24].
Cost-benefit analysis

Initial, operation, and maintenance costs were considered in determining the economic performance of the HVAC systems. Simulations of the annual energy cost, as well as design cooling and heating capacity of two HVAC systems were based on the design comfort zone temperature, the climate conditions, and the building information.

Initial and maintenance costs of VAV and GSHP systems were based on NRC [18] and CEC [21]. Specifically, according to the CEC [21], the initial cost of a VAV central plant system typically depends primarily on the floor area of the building. In this study, the initial cost of the VAV/central plant was estimated as $17 per square meter at all locations [21]. As noted earlier, in this GSHP application there is no need for well pumps or ground loop pipes; as a result, relative to a conventional GSHP system, a GSHP application at a groundwater treatment utility has about a 50% savings [12,18]. Initial costs were limited to medium efficiency heat pumps (COP for heating = 3.2; COP for cooling = 4.5), circulating pumps, heat exchanger, fitting and valves, and personnel training.

NRC [18] provided the ranges of cost for different parts of a GSHP system; in this study that information was used to estimate the initial cost of a GSHP for a water treatment plant. Unfortunately, these data provide only a range of costs so the mean and standard deviation are unknowns.

Relative to conventional HVAC systems, GSHP systems typically have lower maintenance costs. NRC [18] suggested the savings for an office building amount to $1 per square meter per year, for a total savings of $1000 each year for our test building. In this analysis, these maintenance costs were the same in each climate zone.
Local electricity costs must be known to estimate operation costs of the HVAC systems in the different climate zones. Annual average electricity prices were adopted from USEIA [25]; in city regions, New York has the highest electricity price ($0.144/kWh) and Burlington has the second highest price ($0.143) whereas the prices in Atlanta and Chicago are much lower at $0.089 and $0.091, respectively. Phoenix has a medium price at around $0.10.

Two parameters used to assess the feasibility of the project were the simple payback period and internal rate of return (IRR). The analysis considered initial and operating costs, as well as depreciation and inflation factors. Values of inflation (3%) and energy escalation rates (2%) were based on ten years (2005-2015) of inflation data [26]. In their analysis, the USDOD [15] assumed an economic life for their HP system of 20 years and that same time frame was adopted for this study.

**Carbon emissions**

GHG emissions analysis involved three steps. First, emissions associated with each fuel source (natural gas, nuclear, or coal) were assessed. Second, total emissions for each electricity mix were calculated for each state. Third, emissions for the conventional HVAC system and the proposed GSHP system were calculated.

Fuel-source emissions estimates were based on a World Nuclear Association (WNA) [27] report, a review of lifecycle GHG emissions for typical electricity generation sources compiled from 83 studies (Figure 4). The variance of a generation source stems from different definitions of lifecycle and different scopes of research. For example, some studies considered waste management in the GHG emission calculation while the others did not. Nevertheless, coal, oil, and natural gas are the three top sources that are responsible for high GHG emissions, and even their lowest values are
higher than all sources except solar. The large variance in solar sources seems to be exceptional, perhaps due to rapid development in technology for solar energy generation. GHG emissions can differ from state-to-state because electricity generation sources differ among the states. Based on data from USEIA [28], for example, 49% of the electricity generated in Illinois comes from nuclear power plants, whereas the contribution from nuclear power in Vermont is insignificant (Figure 5). Considering the GHG emission rates for different types of generation sources (Figure 4), Arizona, Georgia, and Illinois have larger potential for GHG emissions because they heavily rely on coal and natural gas.

In general, the cost-benefit analysis used electricity price, climate and groundwater temperature data for each city, and the carbon emission analysis used state electricity generation by sources data. Results presented below are identified by city-regions.

RESULTS AND DISCUSSION

Load calculation

Estimated peak cooling loads are substantially higher than peak heating loads in all zones except for the Burlington-region (climate zone 6) where the peak loads are similar (Figure 6). With increasing latitude, peak heating loads increase gradually, and peak cooling loads decrease. These peak cooling or heating loads have a significant effect on the heating and cooling capacity, as can be seen in the section on cost analysis.

Initial costs

The initial cost of a GSHP system is largely determined by the design cooling or heating capacity, which depends on the peak heating and cooling loads for the climate zone. The total installed cost
also included a 25% contingency for unforeseen expenses throughout the project [18]. Among the five test locations, the Atlanta-region (climate zone 3) has the lowest average initial costs, followed by the Chicago- and Burlington-regions (Figure 7). The Phoenix-region has the highest initial cost estimate, ranging from a minimum of $57,000 to a maximum of $80,000. The ranges of initial costs were derived from the variance of different parts of the heat pump system [18].

**Operation costs**

Reflecting the regional energy costs (Figure 8), the Chicago-region enjoys the largest energy savings, approximately $5,000, whereas the annual savings for the New York-region is only $2,900. The Chicago-region has the largest annual saving due to the high conventional HVAC operating cost. Considering electricity and maintenance costs, compared to a conventional HVAC system, the GSHP system can save 15 to 18% on the annual operating costs.

**Cost-benefit analysis results**

Comparing simple payback periods among the different climate zones, the Chicago-region has the shortest payback period, and the Phoenix-region has the longest (Figure 9). Assuming a 20-year economic life for a GSHP system at a drinking water plant, compared to conventional HVAC systems GSHP systems are cost-effective for climate zones 2 through 6. Relative to hot or cold climate zones, the middle climate zones (3, 4, and 5) have a more favorable economic analysis. Installations in the New York-region have longer payback periods because they have the lowest operation savings.

The average IRR for each city, which includes initial and operating costs and inflation, is positive (Figure 10). The average IRR for the Phoenix-region is close to 0% and the minimum rate is
negative, suggesting that a GSHP system is unlikely to be economically effective in climate zone 2. The Chicago-region has the highest economically promising performance for implementing the GSHP system at a groundwater utility.

**Greenhouse gas emissions**

A GSHP system in the Chicago-region leads to the greatest reduction in GHG emissions, about 35 tons of carbon emission per year (Figure 11). In contrast, renewable energy sources which have lower GHS emissions, are more common in the Burlington-region. As a result, the reduction in GHG emissions is relatively small (about three tons per year). Low GHG emission reductions in the New York-region reflect relatively small energy savings between GSHP and conventional HVAC systems. The relatively high GHG emission reduction in the Atlanta-region occurs mainly because 67% of its electricity is contributed from coal and natural gas.

**CONCLUSIONS**

Based on energy consumption, cost-benefit analysis, and greenhouse gas emission results, the conclusions from this work can be summarized as follows:

- Compared to a conventional HVAC system, a GSHP system for a groundwater drinking water treatment facility has lower annual energy consumption. The maximum payback time (12 years) for the GSHP installation is smaller than the expected life time of a conventional HVAC system, which is around 20 years.

- In the selected climate zones, the IRR analysis results showed that a groundwater source heat pump system installation in climate zone 2 is not economically favorable; installations in the four other climate zones are economically advantageous.
The greenhouse gas emission analysis, which considered both energy savings and the local energy sources, suggests that a GSHP can help to achieve carbon emission reduction goals. Benefits are greatest where more conventional energy sources, such as coal are used.

REFERENCES


16. Autodesk. (2015). Autodesk® Revit®, version 2016. Revit® is a building information modeling software package; the latest version is


Table 1. Internal conditions and thermal transmittance of the building elements [17].

<table>
<thead>
<tr>
<th>Building elements</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal conditions</strong></td>
<td></td>
</tr>
<tr>
<td>Occupant density (m²/people)</td>
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<tr>
<td>Infiltration (air changes per hour)</td>
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<tr>
<td>Equipment power density (W/m²)</td>
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</tr>
<tr>
<td>Light power density (W/m²)</td>
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<tr>
<td>Design temperature (°C)</td>
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<tr>
<td><strong>Thermal transmittance U-factor (W/m².K)</strong></td>
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<td>Glazing</td>
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<tr>
<td>Roof</td>
<td>0.27</td>
</tr>
<tr>
<td>Floor</td>
<td>0.36</td>
</tr>
</tbody>
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Figure 1. Heat pump system for a groundwater-source municipal drinking water utility.
Figure 2. Five city-regions selected from the seven climate zones (modified based on IECC [23]) for this study. Alaska, Hawaii, Guam, Puerto Rico, and the Virgin Islands are not shown here.

Figure 3. Floor plan and 3D view of the simulated office building.
Figure 4. High and low values of GHG emissions for eight typical electricity generation sources [27].
Figure 5. Net electricity generation sources in 2015 [28] for the five selected regions.
Figure 6. Peak cooling and heating loads of the simulated office building in the five city-regions.
Figure 7. Initial costs of the GSHP system for groundwater-source utilities in the five city-regions.
Figure 8. Comparison of annual operational costs between GSHPs and conventional HVACs in five city-regions.
Figure 9. Simple payback periods for a GSHP system at groundwater-source utilities in five city-regions.
Figure 10. The IRR for a GSHP system at a groundwater-source utility in five city-regions.
Figure 11. Effect of GSHP systems on GHG emissions in the five city-regions.