# Residential Ground Source Heat Pump Study:

## A Comprehensive Assessment of Performance, Emissions, and Economics

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Prepared by: University of Minnesota, Cold Climate Housing Program

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**Prepared by:**
Patrick Huelman, Cold Climate Housing Coordinator & Principal Investigator
Tom Schirber, CCH Fellow & Project Manager
Garrett Mosiman, CSBR Senior Research Fellow
Rolf Jacobson, CSBR Research Fellow
Timothy Smith, Professor & Director of NorthStar Initiative for Sustainable Enterprise
Mo Li, Graduate Research Assistant

**University of Minnesota**
**Department of Bioproducts and Biosystems Engineering, Cold Climate Housing Unit**
203 Kaufert Lab, 2004 Folwell Ave.
St. Paul, MN, 55101
Phone (612) 624-1286)
Website (http://bbe.umn.edu/research/building-systems/cold-climate-housing)
Project Contact (Pat Huelman)
Contract Number: B44645

**Prepared for Minnesota Department of Commerce, Division of Energy Resources**
Mike Rothman, Commissioner, Department of Commerce
Bill Grant, Deputy Commissioner, Department of Commerce, Division of Energy Resources
Laura Silver, Project Manager
651-539-1873
laura.silver@state.mn.us

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# Abstract

This project conducted in situ performance measurements of residential ground source heat pump (GSHP) systems in Minnesota to better characterize their energy savings, emission reductions, and life-cycle costs. The intensive field performance assessment provided a basis for the direct comparison of the GSHP system to more traditional heating and cooling systems in Minnesota homes using an accepted energy software model. Additional software tools were used to further evaluate and compare overall emissions and life-cycle costs. In total, the project provides broad energy and environmental data that can inform appropriate financial and policy incentives to overcome existing barriers and hurdles to market acceptance of GSHP systems in Minnesota.

The study was divided into three distinct, but interdependent components: a) an in-field, real-time performance monitoring of GSHP systems, b) modeling of GSHP system for comparison to more traditional gas-fired forced air (GFA) heating and air-conditioning systems, and c) a broad environmental and policy assessment of the GSHP technology.

On average, the field study showed that GSHP systems are operating near or above their rated COPs. However, the seasonal system COPs from the field study were somewhat lower due to loop field and pump impacts. These measured system COPs were carefully analyzed to guide the energy modeling analysis. In all cases, modeled GSHP systems reduced site energy consumption compared to GFA-based systems. However, with the current electricity grid carbon emissions profile and common utility rate structures, the GSHP systems did not compare as favorably in terms of source energy, $CO_2$ emissions, or yearly operating costs.

At 2015 fuel and electricity rates, most GSHP systems had higher operational energy costs compared to natural gas heating with typical air-conditioning. However, the GSHP systems did show considerable operational cost savings when compared to propane heating with typical air-conditioning. Due to the low efficiency of converting thermal energy to electricity and the heavy reliance on coal as a power source, carbon emissions and source energy use generally increased for GSHP systems compared to more traditional gas forced air heating with air conditioning systems. However, these emission rates are changing rapidly as utilities add more natural gas, wind power, and solar production to their fuel mix.

The life-cycle assessment model results showed that the vast majority of $CO_2$ emissions over a 20 year life span are due to operational emissions (annual heating and cooling energy consumption). Typically 5% or less of total life-cycle emissions were embodied in the equipment, transportation, and installation of the systems. As expected, GSHP systems had greater embodied impacts than GFA-based systems due to installation of the loop fields. Since operating emissions were generally higher, GSHP systems showed negative emissions savings over their life-cycle in nearly all cases.

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# Executive Summary

## Research Question

This project was designed to improve our understanding of residential ground source heat pump (GSHP) system performance in Minnesota. Using measured in-field performance data, these systems were modeled for comparison to more traditional gas-fired forced air (GFA) heating and conventional air-conditioning (AC) systems for energy consumption, emissions produced, and cost of operation for the homeowner.

## Study Participants

The original project sample was to come from the State of Minnesota GSHP rebate recipients. Qualifying geothermal heat pump systems properly installed after December 31, 2008 were eligible for 30% of the installed cost without a cap, as provided under the American Recovery and Reinvestment Tax Act of 2009 (ARRA). This was intended to provide a high-quality set of application data, including system sizing calculations, loop field details, and installation costs that would support the research outcomes. However, this pool failed to get enough participants that met the study criteria and secondly, the self-reported information from the rebate forms was highly variable, missing, or of suspect value in many cases. To address these issues, additional units were added to the study, including several with fossil-fueled back-up heat sources. All GSHP installations assessed in this study, except for four new homes, were for retrofits to existing residential heating systems.

**KEY TAKEAWAYS**

- Previous in situ studies, especially for a cold climate, have been fairly limited in number. This study increases the confidence of the in situ COP by carefully monitoring 37 sites of varying housing types (age, construction, efficiencies) and system types across several geographical locations in a cold-climate.
- Modeling of GSHP systems in Minnesota showed negative emissions savings over their life cycle in nearly all cases. This was based on 2005 emission data available at the time of the analysis. These numbers have changed and further improvements to reduce the source energy and carbon intensity of the electrical grid could change the climate impacts of residential GSHP systems in Minnesota.
- Energy cost results suggested that yearly savings are possible compared to low efficiency GFA-systems installed in houses with high heating and cooling loads. However, presumably, these houses could see similar cost (and emissions) benefits by tackling common insulation, air sealing, and conventional mechanical system upgrades at a lower cost of implementation.
- In out-state areas without natural gas service, GSHP systems offer substantial cost savings in nearly every case. Furthermore, they offer significantly improved energy cost stability compared to propane-fired systems, which have been subject to volatile fuel prices in the last several years.
- In this set of single family homes, cooling use was infrequent and those systems that included a desuperheater had limited summer operation. This type of operation is likely to limit savings from these systems. For systems which have a larger cooling load, these operational changes with the inclusion of a desuperheater would likely increase the overall efficiency and potential savings for the GSHP system
- On average, the field study confirmed that GSHP systems are operating near or above rated COPs. However, results also indicate a wide variation in performance, which means that some homeowners receive systems that perform significantly worse than expected.

## Methodology

The study was divided into three distinct, but interdependent components: an in-field performance monitoring of GSHP systems, modeling of GSHP systems for comparison to more traditional gas forced air heating and air-conditioning systems, and a broad environmental and policy assessment of the GSHP technology.

## Results

The in situ monitoring of 37 GSHP systems in Minnesota required the vast majority of the project's resources. Despite various problems with hardware installation and the gathering of reliable data, the rich data set allowed for determination of the in situ coefficient of performance (COP) performance of these systems.

Energy simulation modeling compared the performance of the ground source heat pump systems to more traditional GFA and AC systems. This was rather straightforward; however, for consistency and broader application, assumptions had to be made including a range of house characteristics (loads and efficiencies). This modeling provided site and source energy consumption for each configuration, along with $CO_2$ emissions and annual energy costs.

The Policy, Environmental, Social, and Technology (PEST) study went even further to assess the life-cycle energy, emissions, and costs of the GSHP systems. This broad assessment takes a much larger view of the environmental inputs and outputs of GSHP and traditional systems to provide a longer term view of their overall impacts.

## Analysis and Discussion

This study brings new information and insights into a broader statewide conversation on residential GSHP systems. It will help guide statewide policies regarding GSHP systems, enable utilities to see where residential GSHP systems fit in their Conservation Improvement Program (CIP) program portfolios, and provide more detailed performance information to assist consumers interested in purchasing GSHP systems.

## Field Study of GSHP Performance

On average, the field study showed that GSHP systems are operating near or above their rated coefficients of performance (COP). Even when the additional energy for the loop field pumps is included, COPs remain close to expectations. Items of concern include a wide variation in performance, which means that some homeowners receive systems that perform significantly worse than expected. Also, cooling use is infrequent in this set of single family homes, limiting the potential savings provided by desuperheaters and likely leading to lower ground temperatures in the fall since the loop field is not being "recharged" with waste heat from the house during the summer. Seasonal system COPs from the field study were used directly in the energy modeling analysis.

## Modeled Comparison of GSHP and GFA Systems

In all cases, modeled GSHP systems reduced site energy consumption compared to GFA-based systems with air conditioning (AC). However, with the current carbon profile of the electricity grid and common utility rate structures, the GSHPs did not compare as favorably in terms of source energy savings, $CO_2$ emissions, or yearly operating costs.

Energy cost results suggested that yearly savings are possible compared to low efficiency GFA-systems installed in houses with high heating and cooling loads. But, presumably, existing houses (and some new ones) could see similar cost (and emissions) benefits with a lower cost of implementation by tackling common insulation, air sealing, and conventional mechanical system upgrades. Yearly energy costs increased in all cases compared to high efficiency (90AFUE) furnaces installed in well-insulated homes meeting 2015 MN energy code. However, in outstate areas without access to natural gas, modeled energy cost savings with the GSHP compared to propane-fired GFA systems were very significant – in the range of $700 to more than $3000 per year. With these savings, a reasonable payback for GSHP installations may be possible depending on the cost of installation.

$CO_2$ emissions typically increased by 5-30% even with higher performing GSHP systems (operating at the 75th percentile in the field study). Conclusions from a 20 year life cycle analysis were similar. Future improvements to reduce the source energy and carbon intensity of the electrical grid could change the current impacts of residential GSHP systems in Minnesota, but would require a reduction in the current $CO_2$ emission rate of 40–45%.

## Political, Economic, Social and Technological (PEST)

Under Minnesota's mandated energy efficiency standard, (Minnesota Statutes 216B.241), nearly all electric utilities in the state of Minnesota offer incentives through their CIP portfolios for installing and/or operating GSHP systems to replace electric resistance heat. Installation incentives are generally in the range of several hundred dollars per ton of capacity, commonly less than 10% of the installation cost. Operational incentives are also typically available through special rate programs such as dual fuel, off-peak, or interruptible service.

These programs have been justified under the assumption that GSHP systems save energy similar to other conservation improvements. This study showed that GSHP systems do save energy from a site energy perspective. However, comparing electrical energy obtained from the grid to fossil fuels burned on site for heat does not clearly illustrate the whole story. Therefore, a comparison of source energy is an important consideration. Currently in the northern MISO region, the largest share of electricity is still generated using coal and transmission losses are significant. While the use of renewables and especially wind power has been increasing rapidly in recent years, grid electricity in this region still has 5 times the $CO_2$ emissions per unit of energy than that of natural gas or propane burned onsite.

For a good picture of the emissions comparison between GFA-based systems and GSHPs, a detailed life cycle analysis (LCA) was performed using GaBi 5 software. The functional unit of this analysis was defined as the equipment and operational energy necessary to provide space heating and cooling as well as water heating to a single family home in the Minnesota climate over the course of 20 years. $CO_2$ emissions of all the material components of both GFA and

GSHP equipment were included along with $CO_2$ emissions involved in transportation and installation of the GFA and GSHP equipment (including the loop field for the GSHP system). These emissions were added to the yearly operating emissions from the energy modeling analysis.

LCA model results showed that the vast majority of $CO_2$ emissions over a 20 year life span are due to operational emissions (annual heating and cooling energy consumption). Typically 5% or less of total life cycle emissions were embodied in the equipment, transportation, and installation of the systems. As expected, GSHP systems had greater embodied impacts than GFA-based systems due to installation of the loop fields. Since operating emissions were also generally higher, GSHP systems showed negative emissions savings over their life cycle in nearly all cases.

## Recommendations

While this study is a large advancement to our knowledge of the performance of ground source heat pump systems in Minnesota, there remain some unanswered questions and research opportunities.

It is clear that there are significant differences in the COPs of the installed systems that we monitored. Further research might be able to identify key design and installation practices that would ensure a higher operational COP. Clearly the GSHP systems with very high COPs will show improved energy savings, reduced emissions, and lower operational costs.

Another interesting observation was the wide range of back-up heating approaches. Originally the study was designed to select homes with GSHP systems that had no back-up or only electric resistance back-up for peak heating loads. Despite our best efforts to use only those GSHP systems with no or electric-only auxiliary (or back-up) heating, this simply wasn't possible. Many GSHP systems were being added to existing gas forced-air systems and others chose to install fossil-fueled supplemental heating to take advantage of off-peak and dual-fuel rate incentives. There was a wide variety of back-up heating options used in the systems studied ranging from no back-up at all to electric resistance only to fossil-fueled furnaces and fireplaces. On average, for those systems with electric auxiliary heating, it was used only 3% of the heating run time. This and other backup heating measures ensured that adding them to the GSHP system had a small impact on the overall in situ COP measurements. It would have been useful to determine how system sizing and control strategies might impact back-up heating needs, as well as general GSHP operation, emissions, efficiency, and cost; but unfortunately this was beyond the scope of this study.

One surprising observation was the limited cooling hours for many of the systems. This affects the opportunity for energy savings in several ways. First, GSHP systems will usually outperform standard air-source air-conditioning systems. While increased AC use does raise the absolute energy used and utility cost, it would show better energy savings and emission reductions for the GSHP systems. A second component is that during cooling mode, heat is placed back into the loop field. This can provide a warmer incoming water temperature in the fall and early winter to further increase the heating COP. Also summer cooling using a GSHP with a desuperheater can provide very inexpensive water heating and increased overall savings

for the GSHP system. But again many systems did not use a desuperheater and many systems that did include this technology had limited summer operation.

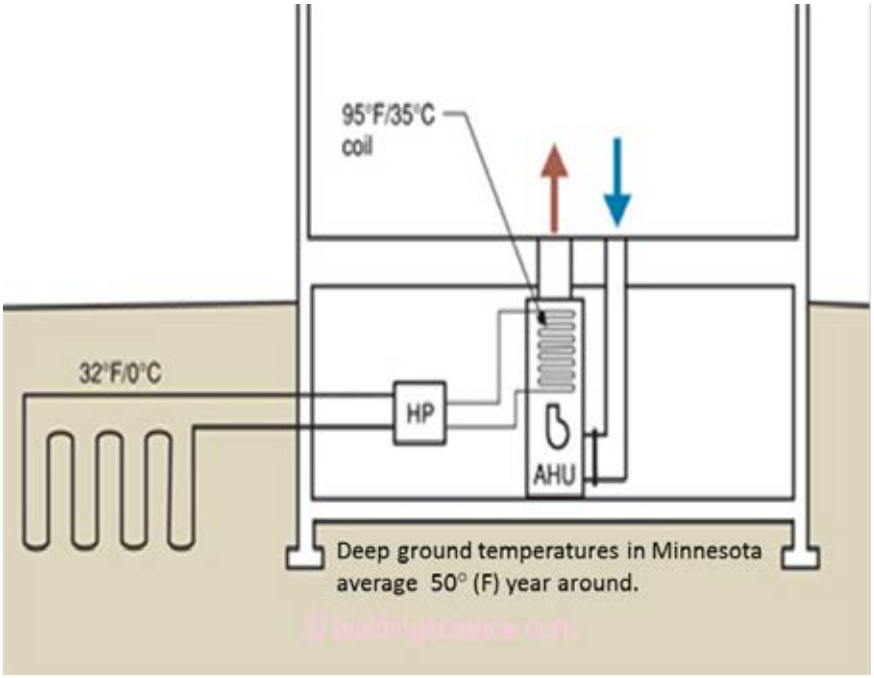
Finally, this study did not attempt to track time of day usage, which may be of interest to utilities and provide some changes to the emissions and cost profiles. This would require a much more in-depth look at both system and occupant behaviors as well as a much finer-grained modeling approach.

# Background

## Ground Source Heat Pump Technology

Today there is considerable interest in new heating and cooling technologies and systems that might provide significant efficiency or environmental gains over our more traditional equipment. This study is focused on the in situ performance of residential (3 to 5 ton) ground source heat pump (GSHP) systems (Figure 1) in Minnesota.

Figure 1: Graphic depicting a basic installed GSHP system




A water/anti-freeze solution is pumped through the ground. Using a heat pump, heat is extracted from the ground in winter and transferred to the house. In summer, the heat pump is reversed to extract heat from the house and transfer it to the ground.

In order to obtain accurate, whole system in situ COPs we measured the total energy consumed (electrical or kWh) and the number of Btus (heat) produced or extracted. When heating in the winter, we measured the Btus produced for heat. In the summer we measured the Btus removed or extracted from the house for cooling. A Btu meter and a small temperature sensor are the two devices that calculate the amount of Btus exchanged by the fluid flowing through the ground in a thin plastic pipe called the "loop line." The word "loop" refers to a single pipe that is sealed and carries water and antifreeze through ground, through the heat pump, and back to the ground again. The heap pump is the point at which Btus (heat) is transferred into or out of the house. The loop line is general buried in the ground six to eight feet below the surface for horizontal loop piping and 200 feet or more for vertical wells. The length of pipe for each house is determined by the calculated thermal load of the house and the capacity of the heat pump.

The rest of the equipment making up the GSHP system is powered by electricity. Devices measuring kWh consumption are attached to each electrical component in the system. All piping stays well below the frost line where the ground is normally (prior to installing the

GSHP) around 45 to 50 degrees Fahrenheit. For heating, the fluid passes through the heat pump which extracts Btus (heat) from the fluid and transfers the heat to the home space. For cooling, the process works in reverse by removing Btus from the house and moving that heat into the ground. Figure 1 shows the loop field pipes attached to the heat pump unit. One side of the loop pipe carries fluid flowing from the ground and the other side carries fluid flowing back to the ground and the cycle or looping continues as long the loop pump is running.

## Research Need

Previous research on the performance and implication of GSHP systems has been primarily limited to modeled results using literature values or engineering judgment for the coefficients of performance (COP). While some installed systems have had in situ measurements, in cold climates they have generally been very limited in number or were for customized systems that could not be extrapolated to a broader population of systems. This study was designed to increase the confidence of the in situ COP by carefully monitoring 37 houses of varying types (age, construction, efficiencies) across several geographical locations.

This research was attempting to close two specific gaps. First, it is important to determine how these systems actually perform in real Minnesota houses. Second, using these measured performance values, how do these systems compare to more traditional gas forced-air (GFA) heating and cooling systems. While that second step had to be completed using modeling due to cost constraints, it does provide a basis for evaluating this technology for energy, emissions, and cost benefits. The last step was conducted to provide an even broader view of the environmental life-cycle costs for these systems in order to guide future policies related to this technology.

It is recognized that the GSHP systems can be much more expensive to purchase and install than GFA systems. As a result it was important to develop quantitative indicators of any energy, emissions, or cost savings for policy makers, industry supporters, and consumers.

# Overall Project Design

This project was deliberately broken into three separate parts:

1. Field Study
2. Modeled Performance Comparison
3. Economics and Policy Analysis

The first component was specifically designed to assess how GSHP systems are performing in Minnesota. A detailed data collection effort was used to determine that actual operating (or in situ) energy performance of a significant sample of these systems in Minnesota homes. Originally, the study was developed to use the criteria and data from the State's GSHP rebate program to create the sample set. However, due to the lack of all-electric GSHP systems, lack of a reliable internet connection, and poor participation rates, additional units were added to the study, including several with fossil-fueled back-up heat sources.

The second component was designed to answer the more pressing question of how these systems compare to more traditional systems with gas forced air heating and central air-conditioning. Due to cost of a comparable in situ field study of the traditional heating and cooling systems – which have already been more carefully characterized in the literature – a modeling approach was used. The in situ data and subsequent analysis was used to determine a realistic installed COP for each GSHP system and that was compared to the more established heating and cooling systems across a wide spectrum of house types (efficiencies and size of loads). In general, this method was designed to help provide consumers with a comparative benchmark for selecting a heating and cooling system for their home.

The last component was intended to provide a larger environmental perspective of GSHP and GFA with AC systems. It included environmental life cycle costs of all inputs and outputs. Each of these components were designed to help inform both policy-level and consumer-level decisions.

# Field Study of In Situ Performance of GSHP Systems

## Introduction

The State of Minnesota administered a GSHP rebate program from 2008-2009 with American Recovery and Reinvestment Act (ARRA) funding. There were about 250 applicants that received rebates and installed GSHP systems. In 2010 we were able to use the list of rebate recipients to begin recruiting potential study participants. The goal was to recruit 40 homes to participate. The original hope was to recruit homeowners that had not yet installed systems and used only electric back-up heat, no fossil fuel for heating energy. That way our study could begin data collection with consistent system status. We wanted GSHP systems that were to be installed soon because we wanted the system contractors to install a Btu meter and temp sensor in the ground loop tubes, a task that only they could perform to maintain their warranty. Secondly, we wanted electric back up heating only, or no fossil fuel back up because we could only monitor back-up heating strips installed with the system. We did not have available methods to measure gas, propane, oil, or wood consumption. If there was no fossil fuel back up, we could consistently monitor electricity consumption without unmeasurable influence of fossil fuel heating. Based on the rebate list we received from the State, system installation dates indicated there were 130 applicants who had not yet installed their systems. It seemed realistic that we could find 40 homes that met the two criteria above.

## Field Study Methodology

This project began with a field study designed to assess the in situ performance of ground source heat pump systems in Minnesota. There is more than one way to measure the in situ performance of a heat pump system. While the overall metric of energy output divided by energy input is pretty straight forward, there are several approaches that can be used. The energy inputs are all electric and fairly easy to identify and measure. The energy output to the home can be measured in three basic ways. The first is to measure its energy performance within the refrigerant loop. While this can be very accurate using quality monitoring devices in the lab, it is very expensive and difficult to do in the field, and would require invasive sensors that would likely void equipment warranties. A second approach that is commonly used is to measure the change in enthalpy across the heat pump unit. This requires very precise measurement of the air flow and temperature rise within the air side of the system. Accurate airflow measurements can be difficult in the field and get even more challenging in two stage and variable speed units. The third approach is to carefully measure the energy removed or added to the ground loop beyond the house boundary. This represents the energy added to the system and can be more easily measured with a flow meter, the change in temperature between the incoming and outgoing fluid, and the specific heat of the heat transfer fluid. We chose the third option as it would be more reliable for in-field measurement. Once the energy extracted or sent to the loop is determined it can be combined with the electrical energy used in the system and the total energy output of the system can be derived.

As part of the study, several different COP values were monitored and subsequently calculated. This is controlled by electrical energy inputs which are added to the energy derived from the loop field.

- Compressor COP
- Compressor + Loop Pump COP
- Total System COP

Challenges here include many key variables in GSHP system design and installation that impacts the in situ performance. According to the literature two significant variables are the unit and loop field sizing, and the in situ ground conditions surrounding the loop field. Unfortunately the sizing and loop field data was not clearly provided by the applicants for the State rebate funds. And furthermore, we had to select homes that did not participate in that program. Also there was insufficient information to determine if the systems were installed as originally designed. So we are not able to comment on the impact of those variables on overall system performance. Distribution fan energy was measured, but it was difficult to know how to fairly use it. While it clearly is part of the system energy inputs, all forced-air system have some fan distribution energy requirements.

# Implementation Steps

## *Participation Recruitment*

As we began mapping homes and tracking potential study participants that fit with selection criteria, we soon found there were fewer ideal homes than we expected. We started trying to find systems without fossil fuel back up (electric backup only) heat and newly installed in the home. We soon learned that out of the 250 participant list, we would not find 40 systems to meet our criteria. So we then opened our search up to potential participants outside of the rebate program. The main reason for disqualifying was not due to our criteria, but rejection from uninterested homeowners. The second largest group that fell out of the list was those with significant fossil fuel use.

Before a homeowner's system was selected we first checked if the system had been installed yet and then screened the home against the five questions in the Participant System Selection Criteria section. Our original assumption was there would be enough all-electric homes, homes without additional fuel sources, to meet our goal of forty homes. If so, we could easily measure all consumption. There was no simple way to measure fossil fuel which, if large amounts were consumed, would greatly affect the COP of the GSHP system. If gas, oil, propane, or wood was used as back up fuel, we interviewed the homeowners regarding their homes' consumption rates. From there we determined a threshold of fossil fuel back-up that would minimally impact the COP.

We asked for monthly gas bills, propane tank delivery amounts, or cords of wood, etc. to determine fossil fuel use amounts. If consumption was minimal (we discussed case by case), then they were asked to participate in the study. For fireplace wood burning we asked how many times per year they burned wood. We allowed "occasional" (6 times per year) users to participate. If they burned wood every week, they would be eliminated and so on.

The primary reason a high number of GSHP systems used fossil fuel backup is due to participation in dual fuel programs offered by utilities. If the GSHP system has a non-electric back up heat source the utility provider can curtail the electricity for the heat pump during peak load times in exchange for a discounted electrical rate. This leads to another way that fossil fuel can be a measurement problem which happens when the fossil fuel is heating the house due to curtailment and the heat pump stops operating. If the heat pump stopped returning very cold fluid to the earth, it would promote a temperature increase of the earth, making the extraction of Btu's from the earth somewhat "easier" for the heat pump in the heating season and would also contribute to a false higher COP.

Minnesota Power helped find homeowners through their newly developed list of qualified GSHP installers. We were able to find four GSHP installers that helped us recruit additional participants.

Our final resource for finding participant was to expand acceptance of non-new construction homes. We asked all our installers for GSHP systems that had been running for no more than two years. This group helped us acquire 37[1] participants (four were new construction, 33 were retrofits). Table 1 below gives a profile of the entire sample with location and system details.

Table 1: Site Information

| Site Number | County | System Capacity | Loop Type | Loop Description | Backup Fuel |
|---|---|---|---|---|---|
| 1 | Ramsey | 4 tons | Vertical | 3 x 180" D | Electric |
| 2 | Dakota | 3 tons | Horizontal | 3 x 200' L | Gas |
| 3 | Hennepin | 4 tons | Vertical | 4 x 180' D | Gas |
| 4 | Sherburne | 4 tons | Vertical | 4 x 250'D | Propane |
| 5 (New const) | St. Louis | 4 tons | Horizontal | 3200 ' slinky | Wood |
| 6 (New const) | Carver | 5 tons | Horizontal | 5 loops, 12' D | Propane |
| 7 | Ramsey | 3 tons | Vertical | 3x 200' D | Electric |
| 8 | Lake | 4 tons | Horizontal | 5 x 800' L | Wood |
| 9 | St. Louis | 4 tons | Horizontal | 4 loops, slinky | Wood |
| 10 | Stearns | 5 tons | Vertical | 5 x 250' D | Propane |

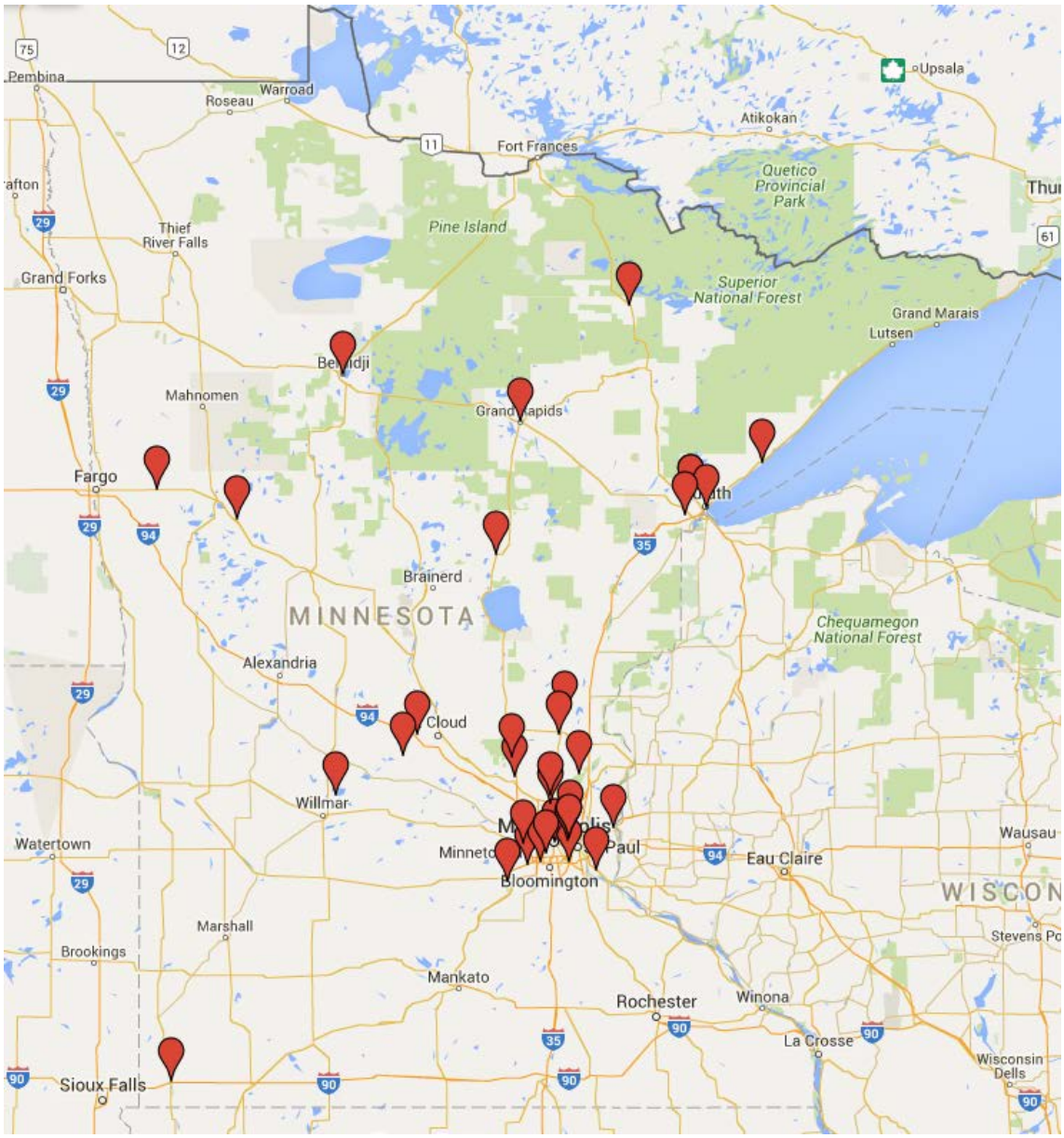
[1] While we initially recruited 37 participants, one site was eventually dropped from the study because the homeowner needed to exit due to personal matters, leaving a total of 36 sites that provided the data for the study.

| Site Number | County | System Capacity | Loop Type | Loop Description | Backup Fuel |
|---|---|---|---|---|---|
| 11 | Ramsey | 4 tons | Vertical | 4 x 180′ D | Electric |
| 12 | Isanti | 5 tons | Horizontal | 6 x 205′ D | Electric |
| 13 | Itasca | 4 tons | Horizontal | Slinky | Electric |
| *14 (Removed)* | | | | | |
| 15 | Ramsey | 5 tons | Vertical | 8 x 140′ D | Gas |
| 16 | St. Louis | 5 tons | Horizontal | 3000′ slinky | Electric |
| 17 | Washington | 4 tons | Vertical | | Gas |
| 18 | Anoka | 4 tons | Vertical | 150′ D | Gas |
| 19 | Anoka | 5 tons | Horizontal | 5 loops, 8′ D | Gas |
| 20 | Aitkin | 5 tons | Horizontal | 5 x 250′L | Propane |
| 21 | Hennepin | 5.5 tons | Horizontal | 4 loops, 8′ D | Gas |
| 22 | Hennepin | 4 tons | Horizontal | 4 loops, 600′ L sl. | Gas |
| 23 (New const) | Hennepin | 5 tons | Vertical | 6 x 180′ D | Gas |
| 24 | St. Louis | 4 tons | Horizontal | 4 x 125′ L slinky | Electric |
| 25 | Becker | 5 tons | Vertical | 5 x 200′ D | Electric |
| 26 | Clay | 4 tons | Vertical | 4 x 180′ D | Propane |
| 27 | Anoka | 5 tons | Vertical | 5 x 180′ | Gas |
| 28 (New const) | Stearns | 5 tons | Horizontal | 5 x 800′ slinky | Propane |
| 29 | Kandiyohi | 4 tons | Vertical | 4 x 200′ D | Electric |
| 30 | Beltrami | 5.5 tons | Vertical | 5 x 120′ D | Electric |
| 31 | Hennepin | 4 tons | Vertical | 4 x 175′ D | Gas |
| 32 | Sherburne | 3 tons | Horizontal | 1200′ HDPE | Propane |
| 33 | Isanti | 4 tons | Horizontal | 4 x 240′ L | Wood |
| 34 | Rock | 4 tons | Horizontal | 5 x 800′ L | Propane |
| 35 | Aitkin | 4 tons | Horizontal | 5 x 250′ L | Electric |
| 36 | St. Louis | 4 tons | Horizontal | 4000′ slinky | Electric |
| 37 | Ramsey | 4 tons | Vertical | 5 x 120′ D | Gas |

We attempted to obtain accurate loop field design details. With the records we could track down there were some loop field details still missing. However this information did not affect the COP calculation. Even though right sizing of loop line size contributes to the performance of the system and its resulting COP, the data calculations could determine the COP without loop field details. We left the loop information in Table 1 to show the variable types of loop fields.

Figure 2 below shows the location in Minnesota of the 37 GSHP study sites.

Figure 2: GSHP Study Site Locations




## *Participant System Specifications*

Once the agreements were in place with all of the homeowners, we now had to install Btu meters in 90% of the participant's operating systems. This created a shortage of potentially ideal

participants that had not yet installed systems. In order to increase the pool of potential study participants it was determined we would need to use installed systems. However, this meant the original contractor would be required to cut into the system's ground loop piping to install a Btu meter and temp sensor. Only the original installer could alter the operating system in order to maintain the warranty and reduce liability issues. This also promoted a good working relationship between the homeowner and the installer. "Cut-in" Btu meters would require more funding to pay the contractors to install these devices. There would also be an additional trip to the house and a significant amount of time to manage the "cut-in" operation.

We now completely altered our original parameters to include systems that used minimal back up fossil fuel and that had Btu meters and temp sensor added after the system was running (see Figure 3 and Figure 4).

## Participant System Selection Criteria

The following criteria list was designed to select potential homeowners, to ensure optimal data collection and appropriate candidate selection.

1. *Maximum of 5.5 tons capacity.* – this is the maximum size allowed by rebate program.

2. *One heat pump feeding one loop field design.* – occasionally a system might be designed with multiple heat pumps for better zone control, or to have multiple loop fields for larger capacity systems. These situations would have been almost impossible to measure for energy efficiency so we only allowed the most common configuration of 1 heat pump and fed by 1 loop field.

3. *Minimal back up heating fuel. Back up heat. What type? Utility program? How much*? We discussed directly with the homeowners what type and how much back up heating fuel they used. Their responses helped us determine on a case-by-case basis which systems used minimal fossil fuel. (*Explanation:* The participant selection goal was to find all homes without fossil fuel back up. We wanted all electric so we could easily measure kWh. Our data gathering package was unable to measure fossil fuel consumption and therefore we were not able to identify fossil fuel energy used in COP calculations. We only found 12 all electric homes. That left 24 homes with fossil fuel backup [20 gas/propane and 4 – wood]. Minimal use of wood or gas backup would have a negligible effect on Btus production. Minimal wood use was 1-2 uses per month. Gas/propane use was considered minimal if backup heat kicked on when outdoor temp reach 0° F, or if the house was on a "peak load" utility program).

4. *System used for both heating and cooling*. The two key COPs we needed to calculate were winter and summer, or seasonal. The data are very different for each season and we needed both for a good average comparison. If the homeowner planned on not using air conditioning in the summer, the data would be incomplete.

5. *Able to maintain a working internet connection*. This was critical in order to gather accurate energy data. If the homeowner said they would disconnect or turn off their system for travel or other reasons, the data would be incomplete.

## Selection of Monitoring Package

The goal of the study was to determine the in situ efficiency or coefficient of performance (COP) for the GSHP system as a whole. To make this calculation the monitoring package had to determine how much electricity (kWh) the system consumed and how many Btus the system produced and used. The simple equation to determine this is total kWhs plus total Btus divided by total Btus. Therefore the monitoring package required devices that measured all kWhs consumed as well as all the Btus that were produced and consumed.

In Table 2: System Equipment and Data Source the Data Source refers to the source from which data can be gathered. The instruments are the devices installed by technicians in each house that measure the data. The meters calculate units of electricity, air or liquid temperature, run time, and liquid flow rate. These instruments convert the calculated data to units of energy that are placed in the COP equation.

Table 2: System Equipment and Data Source

| Data Source | Instrument | Unit |
|---|---|---|
| Loop field energy | Btu Meter & Temp Sensor | Btu |
| Compressor | kWh Meter | kWh |
| Loop pump | kWh Meter | kWh |
| Air handler Blower | kWh Meter | kWh |
| Desuperheater | kWh Meter | kWh |
| Buffer Tank | kWh Meter | kWh |
| Plenum Coil | kWh Meter | kWh |
| Inside Temp | Temp Sensor | ˚F |
| Outside Temp | Temp Sensor | ˚F |
| Plenum Temp | Temp Sensor | ˚F |

The Btu meter is different from the kWh meters in that it measures Btu production and consumption. It measures extraction of Btus from the earth (heating) as it warms the fluid traveling through the loop piping. The Btu meter measures liquid flow rate, and the liquid temperature going in the house as well as exiting the house. The heat pump extracts the Btus form the loop liquid and transfers it into the house.

The basic monitoring package was designed to accurately collect the data in real time to derive whole system, in situ COPs. Electric consumption was measured with kWh meters. Heat transfer was measured with a Btu meter and temp sensor. During the heating season, we measured the Btus extracted from the loop field and delivered to the house for heat. In the

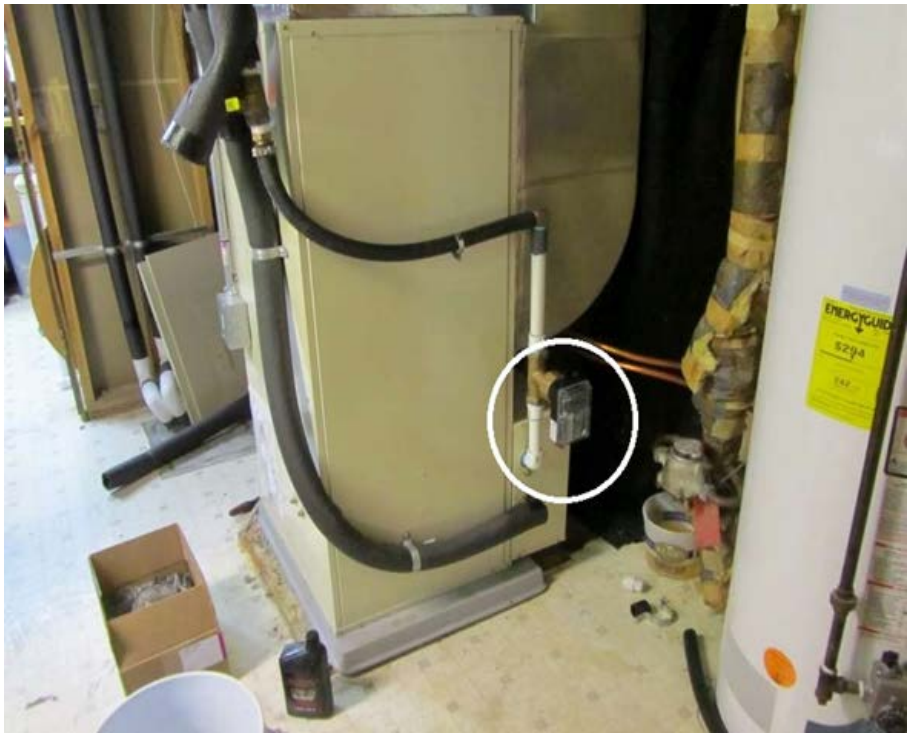
cooling season, we measured the Btus removed or extracted from the house and deposited in the loop field.

The original intent was to install meters in the loop line as the system was installed. This would simplify the process for the installer by eliminating another trip and recharging the system. However we found only four systems that were newly installed enabling the Btu meter to be installed along with the GSHP system. The rest were "cut in" to the loop line (see Figure 3 and Figure 4). The "cut in" approach took much more time, but worked well.

Figure 3: Heat pump before Btu meter installed. Black pipes carry fluid to the ground.

Table 2: System Equipment and Data Source shows the loop line in and line out as originally installed by contractor. Figure 4 shows a Btu meter and temp sensor (white circle) which were cut into the incoming loop line and installed on the heap pump. The second temp sensor (not shown) is cut into the outgoing loop line to measure the change in temperature after heat pump extracts the Btus from the liquid. By measuring the fluid flow and the temperature difference (delta) between the fluid coming into the house and leaving the house, we could calculate the Btu's that were added or removed from the loop by the heat pump.

Figure 4: Heat Pump with Btu meter Installed



## Instrumentation Design

To measure kWh expended, the monitoring package of several kWh meters to measure the kWh consumption of different components of the GHSP system were pre-assembled in the shop and tested before installation in the field. Sometimes due to variety in the layout of each system in the home, some changes to the package configuration had to be made in the home.

The Btu meter was installed by the GSHP contractor to maintain operational continuity and not violate the warranty. It was installed prior to the other electrical monitoring devices enabling the technicians to make a single trip. Each installer designed their meter cut-in and installation approach. The two reasons for this were a) there was varying accessibility to the pipes due to their location, and b) installers had different protocols for purging air after opening and closing the loop pipe. Because of this, the cost of meter installations varied considerably for the 37 homes.

## Software and Programming

We used Talon™ software as a SCADA platform to manage the data transferred from the instruments at each house. This software was located on our server that resided at System One in St. Paul. The Talon ™ software can deliver data in a number of formats, provide updates, and report problems.

The technicians at System One made the final connection for the data to flow smoothly for several years. Also, if data problems surfaced during normal operation, they performed troubleshooting procedures to resolve the issues.

For accurate calculation of kWs consumed by the system the software settings accounted for different back up heat sources, i.e. electric heat verses fossil fuel. The software was configured to calculate electrical energy and Btus added or removed from the loop field in 15 minute increments. This setting was determined to provide enough data for calculations but not over complicate the process. Data acquisition from all sites was underway as of October 31, 2013.

### Early Data Acquisition

Careful analysis of reports weekly helped to determine if all systems were sending data properly. The technicians noticed early on some vulnerabilities that were corrected including:

- Homeowners inadvertently turning off their modems and routers.
- Several power outages related to storms and other causes
- Programming (software) glitches that caused false time segments
- Programming (factory) for some devices could only be detected in the field

Along with combing through the spread sheets to find and solve bad data occurrences, we improved trouble shooting by implementing better communication with all homeowners via email and phone. Secondly, an email "quick warning" of outages detection system was activated in the software to daily notify technicians. Vigilance early on helped the team find glitches in the software settings as well as the calculation formulas.

# Configure and Installation

## *Instrumentation Package*

At each home technicians designed the installation of the device monitoring package as needed. Some of the design work done in the shop was adjusted in the field. Some of the installation protocols had to be determined once the crew arrived at the house. The key components were placed in a locked metal box (Figure 5) that was mounted in a convenient place near the heat pump equipment and all of the wiring from the sensors and meters were connected within this box. The technicians had to determine the optimal wiring approach and test the instrumentation package through the home's computer router. Ultimately we learned that a separate router in each house would address the problems with homeowners turning off or changing routers.

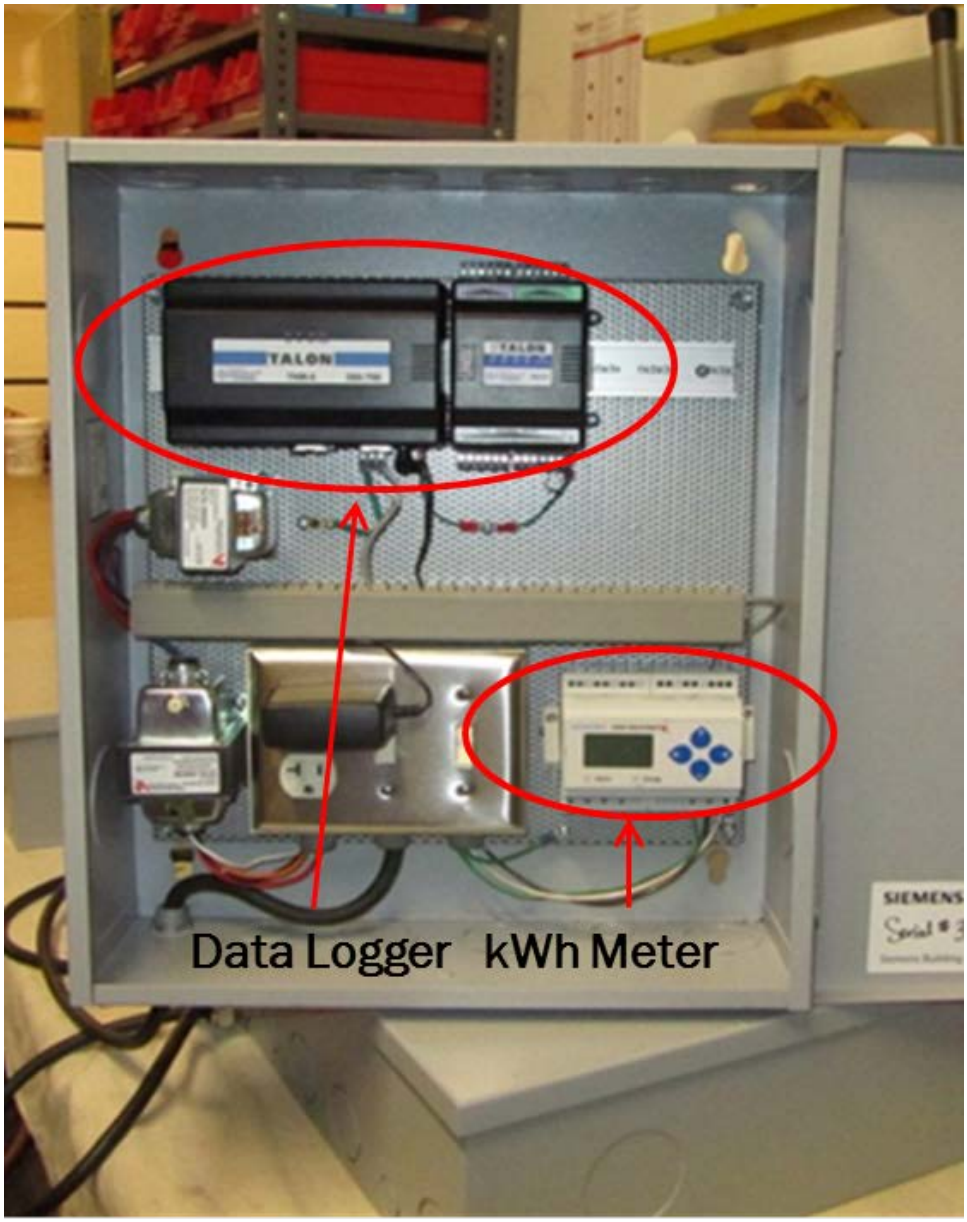
Each router configuration was addressed singularly and adapted to each computer connection and internet provider. Table 3 contains the specified equipment, software and other components that were purchased to build the monitoring packages.

Table 3: Ground source Heat Pump Study Monitoring and Control Equipment

| Equipment Item | Vendor | Item # | Purpose |
|---|---|---|---|
| AX Workbench Software (attached to data server – full data management) | Siemens | Talon™ Workstation AX | Data gathering |
| On site Network Manager (Embedded server platform for data logging and connection to internet) | Siemens | TNM2 Talon | Data gathering |
| Router with power supply | ASUS | RT-N10+ | Data gathering |
| 16 I/0 Module | Siemens | TNM2 Talon | Electric data |
| AX Modbus RTU RS485 | Siemens | TNM2 Talon | Electric data |
| Power and energy meter | Veris | E50 Series | Electric data |
| Current Transformers-Split Core | Magnalab | SCT-0750 Series | Electric data |
| BTU Meter | Veris/ Badger | Series 380 | Btu data |
| Stainless Steel Insertion Well | Siemens | QAE Series | Btu data |
| Control Transformers Dual Hub/Circuit Breaker | Veris | X Series | Electric data |
| Outside Temp Sensor | Veris | TO Series | Electric data |
| Space Temp Sensor | Veris | TW Series | Electric data |

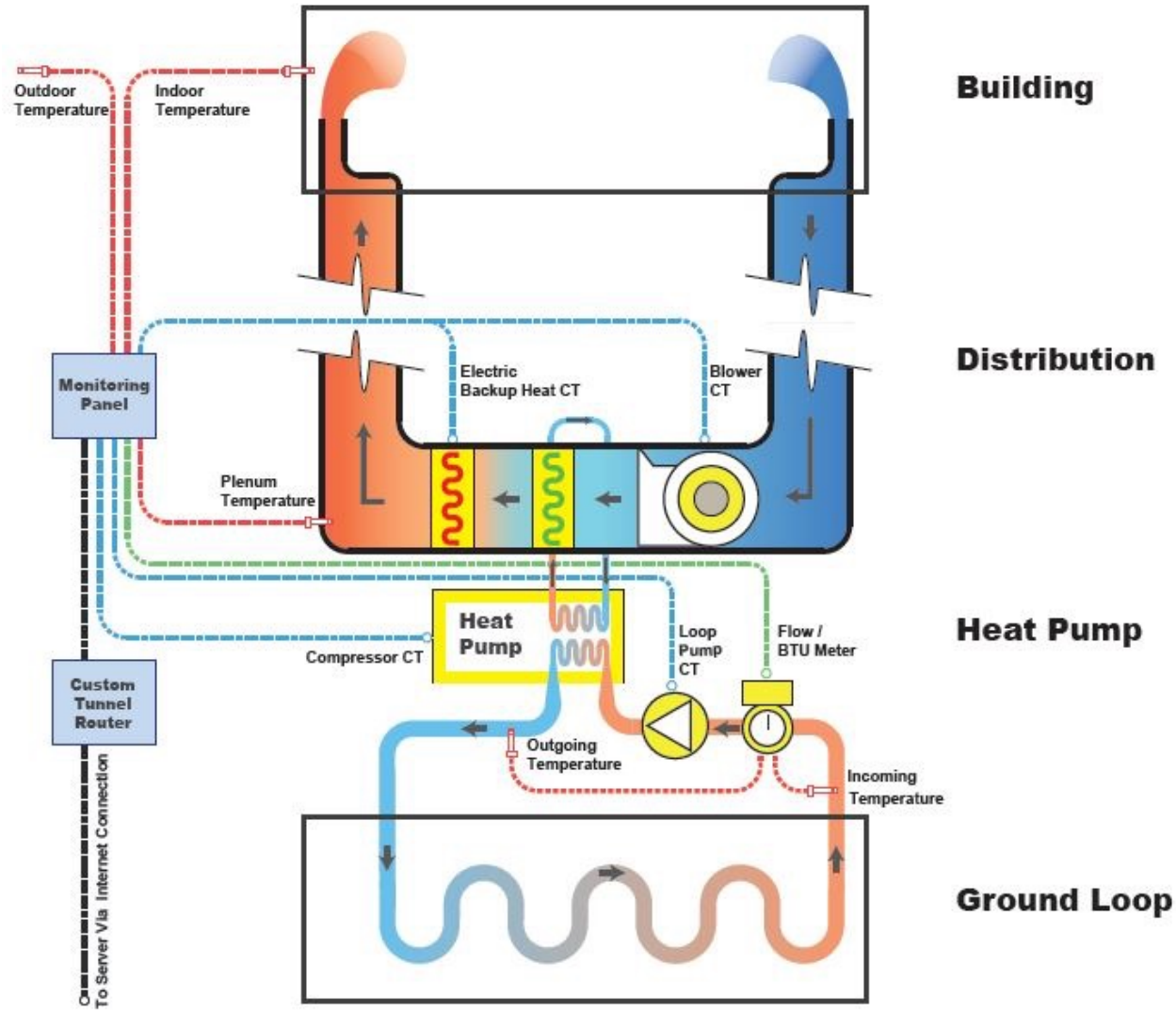
Figure 5shows the metal lock box that contains the Data logger/controller which receives Modbus data from the kWh meter and BTU meter; temperature data from plenum, inside and outside temp sensors; and electrical current readings from electric backup plenum heater and desuperheater pump. Modbus data is a protocol which defines a Protocol Data Unit (PDU). The PDU is independent of the underlying communication layers from the devices. The kWh meter (Figure 5) measures electrical energy consumed by compressor, blower, and loop pumps connected by Current Transformers (CT's). The CT transforms voltage to regulate power with device connections.

Figure 5: Electronic control box installed in each house




All data was gathered from the sensors and meters and managed by a data logger in the electrical panel. The data logger would then transport the data through the homeowner's internet connection to a server at System One in St Paul. The complete wiring diagram shown in Figure 6 depicts the wire connections and sequence relative to the main or Monitoring Panel, which then was managed by the router and uploaded to the main server.

Figure 6: Wiring diagram for monitoring devices.




## *Internet Connection Protocols*

Using the homeowner's router and internet connection proved to be problematic. There were several types of internet connections (e.g., high speed cable, DSL, satellite) and it was difficult to find an invulnerable and replicable method of connecting our monitoring equipment to the internet in each house. The best approach utilized a different type of router which was programmed with a Virtual Private Network or (VPN) approach using SSH tunneling which creates a secure connection between a local computer and remote machine or server. This process "tunnels" through the home firewall and basically ignores changes the homeowner might make to their internet setup. The router had specific firmware installed to make it all work. The best part of this approach was that each router was programmed at the warehouse and installed in a few minutes at each home. All original routers were replaced with this process.

# Software Design and Trouble Shooting

## *Server Selection*

As the instrumentation package was being designed, the next step was to select the appropriate server to handle the data and in a manner that would allow some adjustment for each home system to ensure equivalent data from each home was gathered for analysis. Once the monitoring package was field tested and acceptable, a uniform monitoring package and data collection software platform was developed. This process continued while the final participants were being recruited. The package had to be ready for installation as home systems were selected.

A simple calculation made by University IT staff found the server did not have to be very fast or very large. A normal desk top computer would almost suffice. The data coming from GSHP systems would be a comparatively small number of bytes at preset time intervals. So collection of the information and storing it is a relatively small task. Our main concern was that the server would have to run every day, all day and we wanted to make sure it was durable, had minimal maintenance, and some redundancy with key components that could fail. So we chose to move up a class from the desk top computer to a small office server.

University IT staff had four recommendations:

1. Server class: designed to run nonstop. We chose the server class
2. Redundant Array of Inexpensive Disks (RAID) The RAID Configuration was originally RAID 1 in our quote. RAID 1 is a pair of mirrored drives. Data can be written or retrieved from either disk. The University only uses RAID 5. It has three drives operating independently and if one crashes a new primary takes over and the third becomes back-up which results in no down time. We chose RAID 5 because it is more durable.
3. For servers running 24/7 they recommend a redundant power supply. If there is a surge or failure, the other power supply kicks in seamlessly. We chose a redundant power supply.
4. Standard current operating system ease of use. We would primarily use Microsoft Excel and occasionally Microsoft Word. We also needed a current operating system for internet browsers and in case there was a need for more software. We chose Windows 7 and Microsoft Office from the University licenses. It was convenient and free.

Prior to deciding on the server specifications above we briefly considered an alternative. The University leases a large amount of space on third party servers which can be used by any University department or program. We were told these large server entities claim excellent security and safety. University IT suggested we could down load our GSHP system data to this "virtual server."

We decided against it because our research technicians would have to go through extra steps to get into the server to do software design and troubleshooting work. This virtual server set-up work would be more difficult and less accurate than with the hardware server. An example is all computing tasks would be handled through a secondary connection called a "remote

desktop." This is less flexible, thus less effective than having the software live at the engineer's desk. It was thought that a stand-alone server, which could be accessed directly by the project technicians and software engineer for real time diagnostics would work better. Additionally, the set up and customization for each home would be cumbersome communicating through a third party server. Also, hands on communication with the technicians in the field would be necessary to solve potential problems instantly as the equipment is being installed in the field.

# Data Analysis and Results

## *Technicians and Automated Data Stability*

The primary goal of the data collection and analysis portion of the project was to arrive at seasonal coefficient of performance (COP) values for use in energy modeling comparisons with traditional HVAC systems. The daunting monitoring process was complex and took a long time. The key elements really were the two technical subcontractors who were able to design and install the monitoring packages and accurately manage the data collection so the data technicians could build the COP calculations. They were also able to program notification of data flow interruptions. This was critical for consistent collection of accurate data which also provided security regarding the process.

Installed monitoring systems in each house were sending data to a server that was programmed and maintained by one of our subcontractors in St Paul. System One, a subsidiary of Peoples Electric, stayed in contact with monitoring equipment installation technician, CR-BPS of Duluth, MN. The installing technician also had a backup copy of the server software and could see what the home systems were sending to the server. This subcontractor could spot-check for outages and errors. Also, most outages could be reset automatically by an internal device in each home's system within 24 hours. If the outage lasted 48 hours a phone call and email was sent to the homeowner. Someone in the home would sometimes inadvertently turn off the router or possibly a breaker. If this was the case the homeowner could remedy the problem. Otherwise a home visit was required.

## *Raw Data Acquisition*

Data were logged in 15-minute increments. It was determined that this fine level of granularity was not necessary for meaningful analysis, and served to unnecessarily increase the size of analysis files.

Data from each house was transferred via internet connection. Beginning in July 2013, weekly data files were sent via email to the University of Minnesota. The data were presented in .csv file format, with data from five houses in each file. Files comprised one month of data, with data from the previous month being sent on the first Sunday after the end of that month.

Microsoft Excel was chosen as a platform for data manipulation and analysis. A database solution was also considered, but rejected due to cost.

The data were processed by System One Control in Saint Paul Minnesota.

## Data Processing

In general, five types of data were collected. These are:

- Runtime (RT): This is the amount of time, in minutes, that a piece of equipment was drawing electrical energy. Runtimes are generally not used directly in calculations. Runtimes are reported by kWh meters.
- Kilowatt hours (kWh): kWh is a measure of the amount of electrical energy consumed by a device in a given hour.
- Heating/Cooling Mode (Htg/Clg Mode): Determining whether a component was operating during heating or cooling mode was an attempt to differentiate between times when the system is providing or extracting heat from the house. We calculated this value based on whether or not the compressor had run in a given time interval, and if so the difference in loop fluid temperature across the heat pump compressor was used to determine whether the unit was heating or cooling. Especially during hours with low runtimes, this column routinely mistook heating for cooling, or vice-versa. Therefore other methods were developed to identify heating vs. cooling.
- British Thermal Units (Btu): Btu data directly from the Btu meter populated the "Loop Btu Meter" column. Because of the design of the meter, reporting intervals often spanned multiple hours (and often days) of actual operation. This meant that it was impossible to calculate COP at the hourly or daily time scale. For this reason, a calculation was used to provide finer, 15-minute (converted to 1-hour) data on Btu rate. This calculation relied on flow rate and the change in temperature of the loop fluid across the heat pump compressor to calculate Btu delivery over smaller time increments. Spot checks of the meter data vs. the calculated data suggested the two were generally in good alignment in most houses. Heating Energy and Cooling Energy were allocated based on the Htg/Clg Mode status, which was not reliable as previously mentioned.
- Temperatures: Temperatures were measured at multiple locations:
    - Entering and leaving loop fluid (Local and Remote sensors. These sensors were not connected to data loggers consistently, so in some cases "local" was entering and in others leaving).
    - Air plenum discharge point
    - Indoor air (sensors were sometimes placed by necessity in areas that did not closely track conditions at typical occupied spaces, but were not critical to our calculations)
    - Outdoor air (some sensors were placed by necessity in direct sunlight, skewing the readings, though not critical to our calculations)

As received, raw data were not able to be used directly because of a few factors:

- Raw data was collected at 15-minute intervals; one-hour intervals were desired for analysis.
- Five houses per file made house-by-house analysis difficult.

- Data column headings were created according to the logic of sensor placement. In turn, the data were reported alphabetically, and were therefore not grouped in meaningful ways. In addition, column heading titles were confusing in many cases.
- Errors in the data were present, including Btu meter rollover errors - "rogue" timestamps (additional rows) inserted at random spots, and occasional jumps in Btu meter readings of 100 million.

For these reasons, a "transformer" spreadsheet was developed. This transformer spreadsheet performed several operations:

- Reordered columns to group like outputs (e.g. kWh consumption, runtimes, and temperatures), and renamed column headings
- Combined four fifteen-minute recording increments into a single 1-hour increment.
- Allowed for the discovery of the errors mentioned above.

In practice, data entries for a single house were copied and pasted into the transformer spreadsheet. The resultant converted data were then copied from the transformer spreadsheet and pasted into individual sheets in the final analysis spreadsheets. Data column headings from the raw and converted data, along with units of measurement and conversion method from 15-minute to 1-hour interval are shown in Table 4.

Table 4: Raw and Converted Data Headings, with Units and Conversion Method

| | | | | Conversion Method (15-minute data to 1-hour data) | | | | Data use category | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Measure Type** | **Final Data Heading Titles** | **Units** | **Instrument** | **Sum of four 15- minute readings** | **Subtraction (last 15 minute reading - first 15 minute reading** | **Average of four 15- minute averages** | **Instantaneous reading from the last 15-minute interval in a given hour** | **Used to calculate key COP value** | **Used to calculate non-key COP value** | **Used for data quality checks** | **Not used** |
| Runtime | Heat Pump Compressor RT | Minutes | kWh meter | x | | | | | | | x |
| | Loop Pump RT | Minutes | kWh meter | x | | | | | | x | |
| | Aux Duct Heater RT | Minutes | kWh meter | x | | | | | | | x |
| | Circulation Fan RT | Minutes | kWh meter | x | | | | | | | x |
| | Desuperheater RT | Minutes | kWh meter | x | | | | | | | x |
| | Auxiliary Pump 1 RT | Minutes | kWh meter | x | | | | | | | x |
| | Auxiliary Pump 2 RT | Minutes | kWh meter | x | | | | | | | x |
| Electrical Energy | Heat Pump Compressor kWh | kWh | kWh meter | x | | | | x | | | |
| | Loop Pump kWh | kWh | kWh meter | x | | | | x | | | |
| | Aux Duct Heater kWh | kWh | kWh meter | x | | | | | x | | |
| | Circulation Fan kWh | kWh | kWh meter | x | | | | | x | | |
| | Desuperheater kWh | kWh | kWh meter | x | | | | | x | | |
| | Auxiliary Pump 1 kWh | kWh | kWh meter | x | | | | | x | | |
| | Auxiliary Pump 2 kWh | kWh | kWh meter | x | | | | | x | | |
| Miscellaneous | Htg/Clg Mode | N/A | Calculated | | | | x | | | | x |

| | | | | Conversion Method (15-minute data to 1-hour data) | | | | Data use category | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Measure Type** | **Final Data Heading Titles** | **Units** | **Instrument** | **Sum of four 15- minute readings** | **Subtraction (last 15 minute reading - first 15 minute reading** | **Average of four 15- minute averages** | **Instantaneous reading from the last 15-minute interval in a given hour** | **Used to calculate key COP value** | **Used to calculate non-key COP value** | **Used for data quality checks** | **Not used** |
| Thermal Energy | Loop Btu Meter | Btu | Btu meter & temp. sensor | | x | | | x | | | |
| | Energy Calc - Instantaneous | Btu | Btu meter & temp. sensor | x | | | | | | | x |
| | Energy Calc - 60 Min | Btu | Btu meter & temp. sensor | | x | | | x | | | |
| | Heating Energy | Btu | Calculated | | x | | | | | | x |
| | Cooling Energy | Btu | Calculated | | x | | | | | | x |
| Flow Rate | Flow Rate Instantaneous | Gallons /Minute | Btu meter | | | | x | | | | x |
| | Flow Rate 60 Min Ave | Gallons /Minute | Btu meter | | | x | | | | | x |
| Temperature | Local Sensor Instantaneous | Degrees F | Temperature sensor | | | | x | | | | x |
| | Local Sensor 60 Min Ave | Degrees F | Temperature sensor | | | x | | | | x | |
| | Remote Sensor Instantaneous | Degrees F | Temperature sensor | | | | x | | | | x |
| | Remote Sensor 60 Min Ave | Degrees F | Temperature sensor | | | x | | | | x | |
| | Plenum Temp Instantaneous | Degrees F | Temperature sensor | | | | x | | | | x |
| | Plenum Temp 60 Min Ave | Degrees F | Temperature sensor | | | x | | | | x | |
| | Room Temp Instantaneous | Degrees F | Temperature sensor | | | | x | | | | x |

| | | | | Conversion Method (15-minute data to 1-hour data) | | | | Data use category | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Measure Type** | **Final Data Heading Titles** | **Units** | **Instrument** | **Sum of four 15- minute readings** | **Subtraction (last 15 minute reading - first 15 minute reading** | **Average of four 15- minute averages** | **Instantaneous reading from the last 15-minute interval in a given hour** | **Used to calculate key COP value** | **Used to calculate non-key COP value** | **Used for data quality checks** | **Not used** |
| | Room Temp 60 Min Ave | Degrees F | Temperature sensor | | | x | | | | x | |
| | Outdoor Temp 60 Min Ave | Degrees F | Temperature sensor | | | x | | | | x | |

Btu data required modification because Btu meter readings assumed water as a heat transfer medium, while installed systems were known to use a variety of admixtures to prevent freezing. A correction factor was implemented to accommodate specific heat capacities of actual loop fluids. Initially a "stand-in" value of 0.835 (representative of a 20% propylene glycol solution) was used to enable preliminary COP calculations that would be closer to actual performance. Additional columns were created to modify these imported data for calculations as shown in Table 5.

Table 5: Modified Data Calculations

| **Additional Column Heading** | **Description** |
|---|---|
| Loop Fluid Correction | 0.835 was used as a stand-in. Actual values were substituted for each system following project closeout and fluid testing. |
| Loop Field Delta 60 Min Ave | Difference in temperature between incoming and outgoing loop fluid |
| Corrected Loop Btus | Measured Btu modified by the loop fluid correction factor |
| Corrected Energy Calc (Btu) | Calculated Btu modified by the loop fluid correction factor |
| Corrected Heating Energy (Btu) | Calculated Btu modified by the loop fluid correction factor |
| Corrected Cooling Energy (Btu) | Calculated Btu modified by the loop fluid correction factor |

More columns were added to record the conversion of kWh energy consumption by individual devices to Btus in order to enable simple COP calculations. (Btus delivered could have been converted to kWh as well.)

- Heat Pump Compressor Btu
- Loop Pump Btu
- Aux Duct Heater Btu
- Circulation Fan Btu
- Desuperheater Btu
- Auxiliary--Pump 1 Btu
- Auxiliary--Pump 2 Btu

Finally, a series of COP calculations for several combinations of devices were made at the hourly, weekly, monthly, and seasonal time scales. Initially these COP calculations were made using the heating COP calculation {(energy delivered from the loop + energy consumed by the device(s) / energy consumed by the device(s)}. Final seasonal COP values used for energy modeling used cooling and / or heating calculations as appropriate. The combinations for which COP values were calculated are:

- Compressor
- Compressor + Loop Pump
- Compressor + Loop Pump + Auxiliary Heater
- Compressor + Loop Pump + Circulation Fan
- Compressor + Loop Pump + Auxiliary Heater + Circulation Fan
- Compressor + Loop Pump + Auxiliary Heater + Circulation Fan + Other devices (Whole System COP)

## *Final COP Calculations*

During the decommissioning process, a small sample of the loop fluid was obtained from each of the GSHP systems. The specific heat of each of the samples was measured by Dynalene Laboratory Services using Differential Scanning Calorimetry test standards. These measured specific heat capacity values were inserted into the appropriate set of house data, replacing the stand-in value that had been previously used. Actual values for thermal energy transported by the system were then obtained.

Since the primary goal of the data collection and analysis portion project was to arrive at seasonal-COP values for use in energy modeling comparisons with traditional HVAC systems, it was necessary to determine the specific dates when heating seasons and cooling seasons began. The calculation for COP for heating and cooling differs for the two modes (see below).

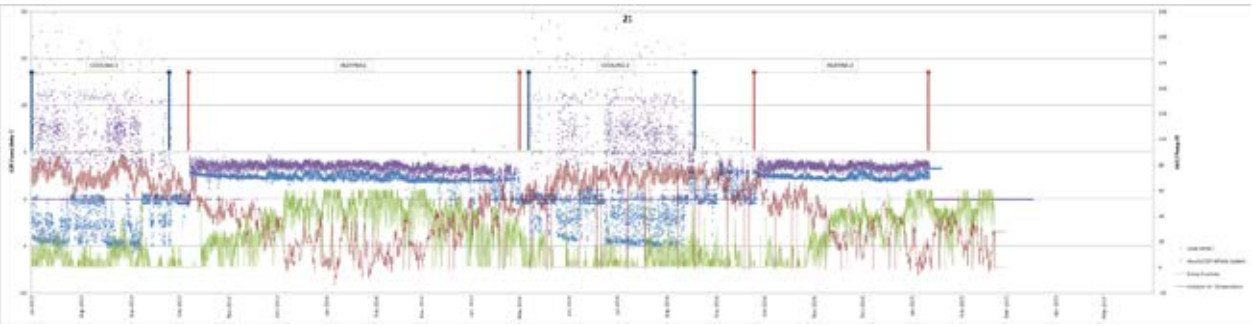
As described previously, an initial attempt was made to automate the determination of heating vs. cooling operation. However this automated method was susceptible to erroneous conclusions due to low hourly runtimes that did not present a clear signal in loop fluid temperature difference across the compressor. Therefore, we developed graphs that could be used to make the determination of whether the system was in heating mode or cooling mode.

These graphs included four variables:

- Hourly COP (purple)
- Loop delta T across the compressor (blue)
- Outdoor air temperature (red)
- Pump runtime (proxy for system operation) (green)

An example four-variable graph is shown in Figure 7 below. Graphs for each house are in Appendix A.

Figure 7: Four-variable graph used to determine heating and cooling seasons.



The four-variable graphs include nearly two years of data, beginning in July 2013 and ending in May 2015. In this series of graphs, whole-system hourly COP appears as a purple dot. In many cases these dots cluster to form a narrow band, which closely aligns with longer-term (weekly and monthly) COP calculations. This is especially true during sustained periods of heating. Loop delta-T appears as blue dots. Similar to COP, periods of sustained operation (especially heating) tend to cause hourly values to cluster in a narrow band. Outdoor air temperature (OAT) can be seen as a red line. This is intended to function as a secondary check on the heating vs. cooling determination. Pump runtime is shown as a green line. This was used as a proxy to indicate system operation.

Typically the "signal" that differentiates heating from cooling operation is a fairly clear one. In Figure 7, COP values are high but are quite scattered along the y-axis (COPs are highly variable). During the two periods of highest summer OAT, there do appear to be two slightly denser regions centered around COP=7. These denser regions also correspond to periods with higher pump runtime. Meanwhile, loop delta-T shows a strong negative signal during periods when the system is running. During periods of no runtime, loop delta-T drifts to zero. This is because both loop fluid temperature sensors are inside the house, so both approach indoor air conditions when fluid is not circulating.

Beginning in the first part of October 2013, the COP and delta-T data shift significantly, indicating heating operation. The strongest indication is a shift in loop delta-T from negative to positive. This indicates that heat is being extracted from, rather than added to, the loop fluid. Note that sensors at the home are often reversed, so the direction (positive vs. negative) of the delta-T is not meaningful, while a switch from one to the other is meaningful. At the same time, COP values cluster, at a lower value than for the cooling season. As OAT begins to decline in the month, pump runtime begins to increase. Ultimately, during the first part of December, hours with 60-minute runtime (continuous operation) begin to appear. Toward the end of the heating season as OAT rises, pump runtime begins to decline. Also, during periods of time

when OAT is higher, loop delta-T drifts toward 0, as does COP, indicating periods of system inactivity.

The period beginning in mid-August 2014 and ending in mid-September 2014 is not included in either a heating season or cooling season. This is because mixed heating and cooling are indicated, chiefly by use of the loop delta-T and COP data.

Graphs for each house were analyzed in a similar fashion to make determinations when heating and cooling seasons began and ended. The length of these seasons is indicated on the graphs by the red and blue vertical arrows to each graph, indicating each season as long as possible without including periods of mixed (heating and cooling) operation.

The heating and cooling seasons that were determined for each house were used to calculate seasonal COP values for each season. Two general equations were used: one for heating and one for cooling. This is necessary because electrical energy consumed by devices inside the home release heat equivalent to their energy consumption. In the winter when heating is required, this is beneficial and results in a COP for a piece of equipment (fan, pump, etc.) of 1. In the summer it detracts from system performance, since the added heat needs to be removed by the system. The two general equations are:

**Heating:**

(Energy delivered from the loop (Btu) + Electrical energy consumed (Btu)) ÷ Electrical energy consumed (Btu)

**Cooling:**

(Energy extracted from the house (Btu) – Electrical energy consumed (Btu)) ÷ Electrical energy consumed (Btu)

Energy delivered from the loop and energy extracted from the house are both values either taken directly from the Btu meter, or from the finer-grained "Energy Calc" value. Electrical energy is the sum of kWh consumption of all the devices under consideration for a particular COP calculation (e.g. compressor only, compressor + loop pump, and whole-system). The result is that COP values generally decrease as more devices are included in the calculation.

## *Fan-Only Runtime Elimination*

In the examination of these graphs as well as the original data, it was determined that many of the houses run the fan in the air handler constantly, or nearly so. Running air handler fans continuously is a strategy that is commonly used to reduce differences in temperature between living spaces or zones. This energy use would have appeared in all COP calculations that included fan energy. We determined that this variable would be eliminated to enable direct comparison between systems, both those that did and those that did not run circulation fans constantly. In order to ensure that COP calculations were not skewed by fan-only operation (which is not intended as a direct space-conditioning strategy), a logic argument was implemented to eliminate fan energy from COP calculations at all hours when the compressor was not running

## *Derivation of COP values for energy and environmental modeling*

It was determined that the "Compressor + Loop Pump" COP values would be used as energy model inputs in subsequent modeling operations. Compressor + Loop Pump COP values for each house were calculated for each heating and cooling season. For houses with sufficient data, this resulted in two cooling seasons and two heating seasons. In addition, COP was calculated based on data obtained directly from the Btu meter, as well as the calculated value derived from loop delta-T and flow rate, thus generating two sets of four analogous seasonal COP calculations (two heating and two cooling each for Btu meter and calculated Btu data). Therefore for houses with two years of good quality data, eight COP numbers were generated.

Due to a variety of issues with sensor calibration, data transmission, data loss, and data translation, some data were found to be incorrect or absent. In some houses, COP derived directly from Btu meter data deviated significantly from that derived from the calculated Btu values (See Data Processing section above for a discussion about the difference between Btu meter data and calculated Btu data). In these cases, the hourly data were examined directly and a determination was made to eliminate one or more sets of COP values. Houses 10, 14, and 29 were eliminated from the pool due to persistent data quality issues. Table 6 lists the collected seasonal data from each system first by the Btu meter then secondly by calculations. The white or blank cells in the table show where data was missing or corrupted.

Table 6: Data used for COP calculations

| House Number | Seasonal Meter COP | | | | Seasonal Calculated COP | | | |
|---|---|---|---|---|---|---|---|---|
| | Cooling 1 | Heating 1 | Cooling 2 | Heating 2 | Cooling 1 | Heating 1 | Cooling 2 | Heating 2 |
| 1 | | X | X | X | | X | X | X |
| 2 | X | | X | X | X | X | X | X |
| 3 | X | X | X | X | X | X | X | X |
| 4 | X | X | X | | X | X | X | |
| 5 | X | X | X | X | X | X | X | X |
| 6 | X | X | | X | X | X | | X |
| 7 | X | X | X | X | X | X | X | X |
| 8 | | X | X | X | X | X | X | X |
| 9 | X | X | | X | X | X | X | X |
| 10 | | | | | | | | |
| 11 | X | X | X | X | | X | X | X |
| 12 | | X | X | X | | X | X | X |
| 13 | X | X | X | X | X | X | X | X |
| 14 | | | | | | | | |

| House Number | Seasonal Meter COP | | | | Seasonal Calculated COP | | | |
|---|---|---|---|---|---|---|---|---|
| | Cooling 1 | Heating 1 | Cooling 2 | Heating 2 | Cooling 1 | Heating 1 | Cooling 2 | Heating 2 |
| 15 | X | X | X | X | X | X | X | X |
| 16 | X | X | X | X | X | X | X | X |
| 17 | X | X | X | X | X | X | X | X |
| 18 | X | X | X | X | X | X | X | X |
| 19 | X | X | X | X | X | X | X | X |
| 20 | X | X | X | | X | X | X | |
| 21 | X | X | X | X | X | X | X | X |
| 22 | X | X | X | X | X | X | X | X |
| 23 | | | X | X | | | X | X |
| 24 | | | X | X | | | X | X |
| 25 | X | X | X | X | X | X | X | X |
| 26 | X | X | X | X | X | X | X | X |
| 27 | X | X | | X | X | X | | X |
| 28 | | X | | X | X | X | X | X |
| 29 | | | | | | | | |
| 30 | | X | X | X | X | X | X | X |
| 31 | X | X | X | X | X | X | X | X |
| 32 | X | X | X | X | X | X | X | X |
| 33 | X | X | X | X | X | X | X | X |
| 34 | X | X | X | X | X | X | X | X |
| 35 | X | X | X | X | X | X | X | X |
| 36 | | X | X | X | X | X | X | X |
| 37 | X | X | X | X | X | X | X | X |

Figure 8: Heating Season COP

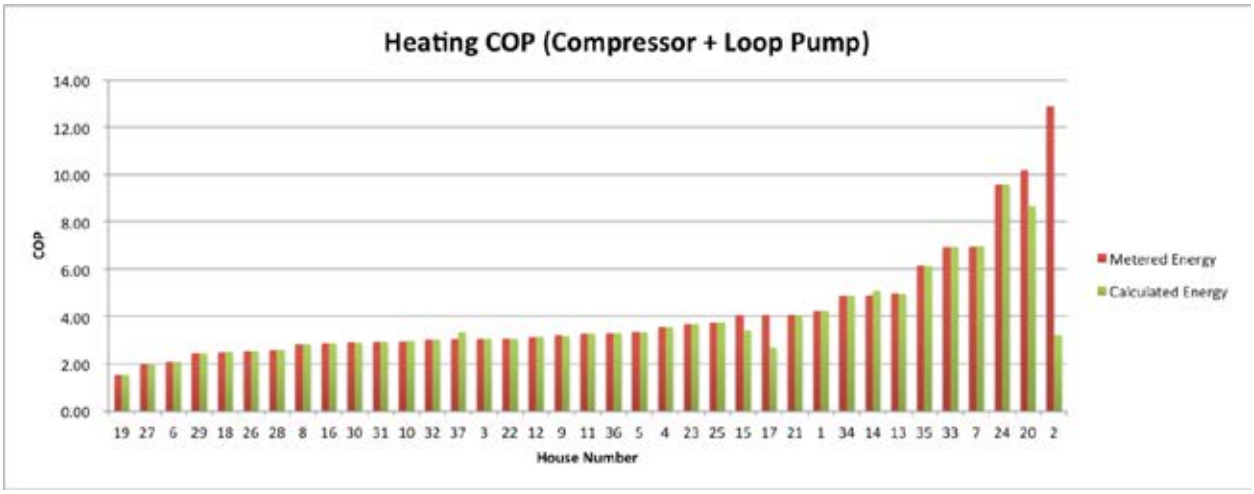



Figure 9: Cooling Season COP

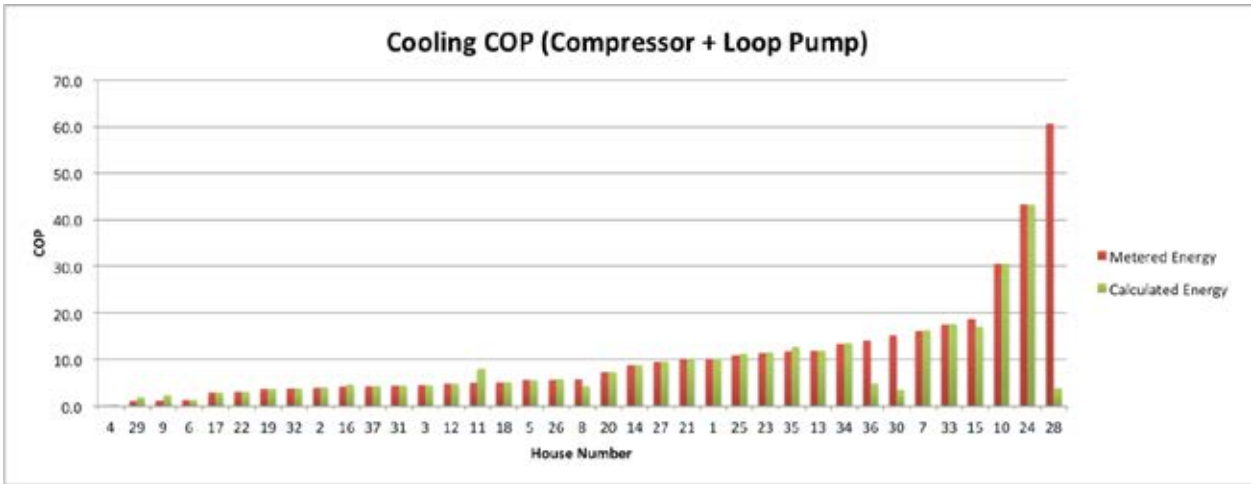



Table 7: Final COP Values

| | Heating COP | Cooling COP |
|---|---|---|
| Minimum Value | 1.51 | 0.23 |
| 25th Percentile | 2.88 | 3.91 |
| Median | 3.19 | 5.20 |
| 75th Percentile | 3.75 | 10.13 |
| Maximum Value | 7.19 | 23.44 |

For all acceptable data sets, the two heating seasons and two cooling seasons were averaged to generate a single heating and cooling meter-based and calculation-based COP. Figure 8 and Figure 9 show the Compressor + Loop Pump heating and cooling COPs for each house ranked

from low to high COP values. From The final set of data, three values were chosen to use in later modeling exercises: 25th percentile, median (50th percentile), and 75th percentile. After the elimination of unreliable data sets, the meter-based and calculation-based COP series were identical. COP values obtained from the study homes are shown in Table 7.

### *"All Systems" COP*

Absolute thermal loads satisfied by heat pump systems in the study likely vary widely due to factors such as house size, thermal efficiency of the building shell, etc. For this reason, houses with low loads and performance at the extreme ends of the sample (high or low COP values) could skew the averages. In order to examine the question of "average" performance in a different way in order to reduce the impact of such houses, we derived an "all systems" Compressor + Loop Pump COP. To do this, all energy delivered in all the houses, and all electrical energy consumed by all the houses, was added up. COP values were then calculated from these cumulative energy tallies. For the Compressor + Loop Pump, all system COPs were 3.43 in heating, and 5.10 in cooling. These values are within seven percent of the median heating COP, and within two percent of the median cooling COP of the entire population listed in Table 7

### *Electric Resistance Backup Energy*

We determined that we needed an assessment of heating energy provided by electric resistance in the study homes for modeling purposes. This measured value would be used to replace the default backup energy use assumed by the energy modeling software. There are eleven houses in the study which use electric resistance elements for backup heating when the heat pump is incapable of meeting the heating load due to extremely cold weather (high heating demand), low incoming fluid temperatures, or both. Of those, ten had data of sufficient quality to perform the analysis.

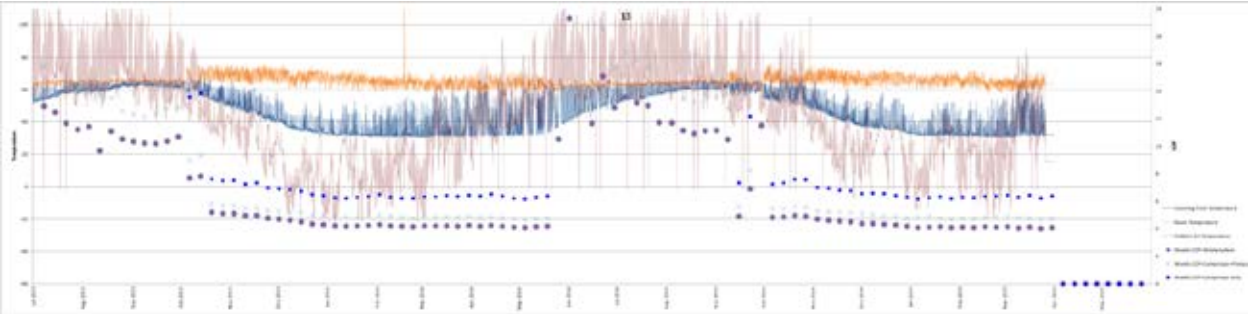
To arrive at a final number for backup energy use to apply to GSHP systems in the energy model, heating energy delivered by electric resistance backup was compared to total heating energy delivered by the system in houses and seasons where electric backup was used. The calculation revealed that approximately three percent of all heating energy was provided by electric resistance heat.

## Additional Research Questions

### *COP and incoming loop fluid temperature*

We made the hypothesis that COP would decrease during the heating season as heat was extracted from the earth, causing incoming fluid temperatures to decline. In order to visualize this phenomenon, a series of six-variable graphs was generated. Figure 10 shows an example of these graphs; graphs for all the houses can be found in Appendix B.

Figure 10: Six-variable graph used to examine the relationship of incoming fluid temperature to weekly COP



The graph includes the following six variables:

- Outdoor air temperature or OAT (red line)
- Incoming fluid temperature or EFT (blue line)
- Indoor air temperature (orange line)
- Weekly compressor-only COP (dark blue squares)
- Weekly compressor + loop pump COP (light blue X)
- Weekly whole-system COP (purple circles)

We chose weekly timescale for COP reporting to reduce the effect of outliers caused by short runtimes. For example, in Figure 7, which uses an hourly time scale for COP, COP calculations are reported even for very short hourly runtimes. During these conditions entering loop fluid temperatures may not reach a steady state reflecting actual loop field temperatures. Therefore COP during these periods of short runtime may be deceptively low or high. Since short runtime hours are represented in the same fashion as long runtime hours, the results can be confusing when COP values shift significantly.

Figure 10 shows approximately two years of data. The OAT line may be used as a reference to quickly identify warmer and cooler periods. In addition, COP increases during cooling seasons, a trait that is common to many of the houses in the study. The entering fluid temperature (EFT) shows clear evidence of cooling over time as the heating season progresses. Like many houses in this study, the fluid temperature seems to stabilize at a minimum low temperature. In this case fluid temperature stabilized at approximately 32°F. In many other houses, incoming water temperatures dropped below this temperature, into the low- to mid- 20s°F range. There is no apparent consistent relationship between EFT and OAT (as a proxy for heating operation). In most cases EFTs decline fairly rapidly at a rate similar to the decline in OAT in the fall. During the coldest months, decline in EFT slows, no longer declining at a rate similar to OAT. In some cases it seems to reach equilibrium, stabilizing at a fairly constant minimum temperature. In others it continues to decline until the weather begins to warm. In some houses the variation in EFT over the heating and cooling seasons is fairly large, in others smaller (ranging from approximately 20°F to 50°F).

Figure 10 indeed shows a decline in COP at all scales (compressor, compressor + loop pump, and whole-system) as incoming fluid temperature declines in the fall. Once the incoming fluid reaches its apparent equilibrium low temperature, COP values stabilize and remain stable for the remainder of the heating season. The reduction in COP from the beginning to the end of the heating season is not trivial. In this case, compressor-only COP drops from approximately 8 at

the beginning of the season to approximately 6.2 at the end of the season, a decline of 25 percent.

About 50 percent of the houses in this study show an apparent correlation between incoming fluid temperature and COP, especially when compressor-only COP is considered. Of the others, performance either does not appear to change much over the course of the heating season, or it changes in ways that are inconsistent with a strong relationship with incoming fluid temperature. It is unclear why some systems' performance is relatively strongly tied to incoming fluid temperature, while others are not. One possibility is that backup heat (especially use of gas, propane, or wood) was in intermittent use during the coldest part of the year, when EFT is also coldest. These fuel source consumption rates were not monitored during the study, so this use would be undetected in the current data set. Most of the systems that show little or no response of COP to EFT use backup heat sources other than electricity. However if compressor operation were suspended completely due to cold EFT while the air handler supplied heat (using gas, propane, or electricity), whole-system COP would be 1; this would also be the case if electrical backup heat were used continuously. This phenomenon is not seen in these systems.

## *Compressor COP at rated incoming fluid temperature*

We compared compressor-only COP to the COP listed in the manufacturers' specifications, as stated in manufacturer manuals. To do this, we calculated hourly compressor-only COP at times when the incoming fluid temperatures most closely matched those used for laboratory ratings (32°F for heating, 77°F for cooling), and when runtimes exceeded 50 minutes in that hour. These were then compared to specified performance data provided in manufacturer literature. We calculated the energy efficiency ratio (EER) for the cooling season by multiplying compressor only COP by 3.412 (Btu in 1 watt-hour).

Most houses saw significant hours of runtime during rated heating conditions (near 32°F entering fluid temperature (EFT)). However, only a limited number of houses had significant cooling operation at rated cooling conditions.

It is important to note that when manufacturers' specifications are developed other variables that influence the compressor COP are controlled in the laboratory, but are unknown or uncontrolled in the study data. Among these variables are air temperature change across the coil, entering air temperature, and refrigerant temperature change across the compressor.

Summary graphs of the results are provided in Figure 11 and Figure 12. These graphs show two results for each house: compressor COP (heating) or EER (cooling) during rated incoming loop fluid conditions, and percent deviation from rated COP or EER values

COP and values are calculated when systems run at least thirty minutes in an hour, and EFT is within ½°F of rating conditions (31.5°F to 32.5°F). Thirty-two houses are included in the heating analysis; five did not have data that met these criteria. Median compressor runtime on the 32 houses analyzed was 426 hours, with a minimum of 6 hours and a maximum of 1676 hours.

Because cooling operation near rated conditions was far more sporadic and limited than heating operation, the parameters were relaxed to enlarge the data set. EER values are calculated for hours when the compressor runs and EFT is within three degrees F of rating conditions (74°F to

80°F). Only 15 houses met these expanded criteria and are included in the analysis. Compressor runtime is substantially lower than that for heating, with a median of 13 hours, minimum of 1 hour, and maximum of 676 hours. Due to this limited data set these in situ observations are likely to be less meaningful than the heating observations.

Figure 11: Compressor-only heating COP at rated entering fluid temperature and percent deviation from rated COP.

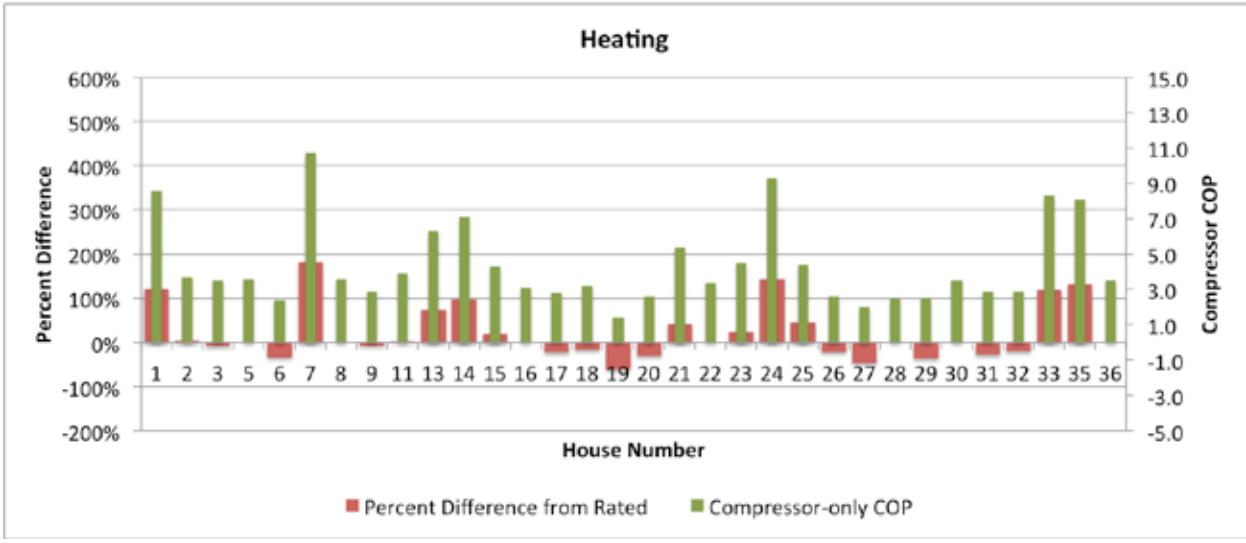
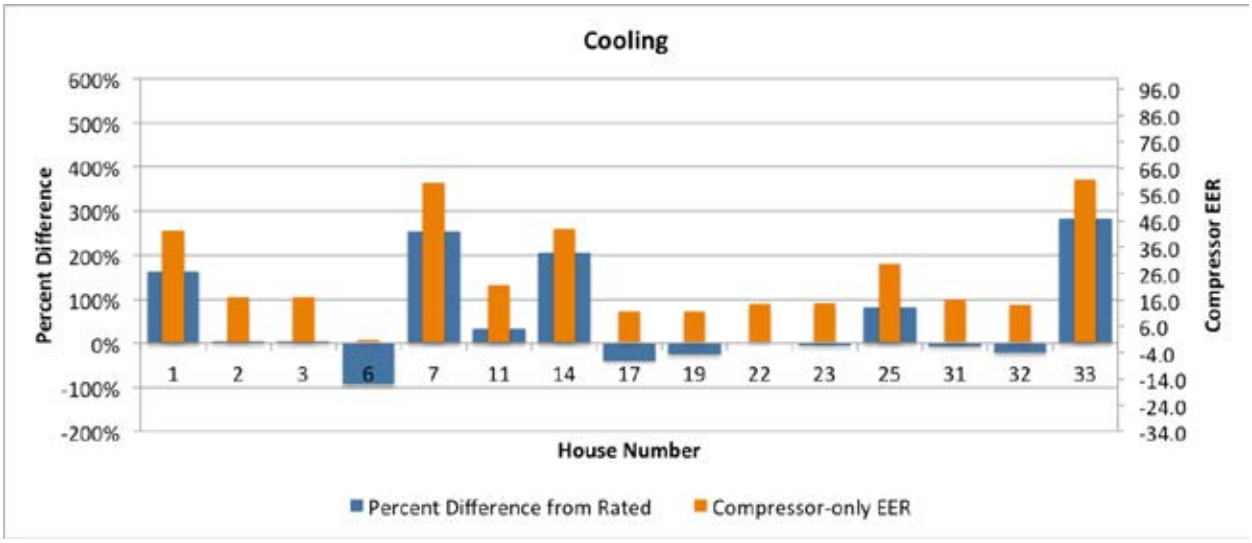



Figure 12: Compressor-only cooling EER at rated entering fluid temperature and percent deviation from rated EER.




# Concluding Remarks

In all but three houses, we collected of sufficient quality during the two-year data gathering period to determine in situ seasonal COP values. There was a wide variety of system performance as expressed by COP. Values during the heating season ranged from a low of 1.51 to a high of 7.19. Values during the cooling season were more divergent, ranging from 0.23 to

23.44. It should be noted that the amount of cooling seen in the study homes was very small compared to the amount of heating, and brief periods of operation may tend to skew the results. The median values derived for use in the energy model correlated closely to hypothetical "all systems" COPs that we calculated using cumulative energy delivery and electric consumption values for all systems in the study.

There is a meaningful correlation between incoming loop fluid temperature and COP in approximately half of the study homes, while the other half appear to operate at efficiencies that are independent of the incoming fluid temperature. Given that extracting heat from the loop field is thermodynamically less efficient as loop fluid temperatures decrease, the reason for a lack of correlation between the two variables for half the study homes is unclear, though it might be attributable to intermittent use of backup heating from gas, propane, or wood combustion. Further research would be required to determine the reasons these homes do not exhibit this expected behavior.

There were 32 houses (86 percent) with entering fluid temperature near rating conditions. Seven GSHP systems (22 percent of those appropriate for analysis) performed within ten percent of manufacturer-provided rated COP values during the heating seasons. Sixteen systems (50 percent) performed at or above rated COP values. Performance relative to rated values ranged from a low of 61 percent below to a high of 182 percent above rated COP. Houses with entering fluid temperatures near rating conditions for cooling were sparse, with only fifteen (41 percent) included in the analysis. In cooling, four systems (27 percent of those appropriate for analysis) were within ten percent of rated EER values, and eight (53 percent) performed at or above rated EER values. Measured performance ranged from a low of 93 percent below, to a high of 284 percent above rated EER.

# Modeled Performance Comparisons of Energy, Emissions, and Cost

## Modeling Methodology

While the field study was designed to find out how GSHP systems perform in the real world, the second part was to determine the impact of that performance. How GSHP systems work in an absolute sense is helpful to the designers and installers, but how they compare to other alternatives is important for policy makers and consumers. Since it was not possible to actually measure energy consumption and costs in the tested homes and then convert them to an alternative system to compare performance, we used a modeling approach.

The basic methodology involved establishing a set of model houses that represented a range of typical loads and efficiencies, and modeling and comparing the performance of those model homes using both a GSHP system and a more traditional GFA heating system with central air-conditioning. The characteristics of the GSHP systems were based on our field results. The GFA system with central air conditioning was considered the "base case" against which the GSHP systems were compared.

There were challenges with this approach, and an "apples to apples" comparison with the more traditional GFA heating system with central air-conditioning was harder to complete than originally anticipated. Physically there are some important differences in these systems:

1. The GSHP can also provide hot water with the use of a desuperheater. A desuperheater was used in 62% of the monitored homes.
2. The GSHP system has a lower delivery temperature compared to a forced-air furnace. In general this requires a higher airflow rate which subsequently increases fan power and electrical consumption. This requires some accommodation to fairly compare their side-by-side performance.
3. Most GFA heating system with central air-conditioning are oversized to reliably meet heating and cooling loads at or even beyond peak conditions. However, most GSHP systems use a back-up or auxiliary heating system to meet peak winter loads. This back-up energy must be properly accounted for in the side-by-side comparisons since gas furnaces generally don't require it.
4. Finally, an accurate cost comparison from the consumer perspective is heavily dependent on fuel source availability, as well as the particular cost structure for electricity.

## Energy Modeling Approach

The overall goal of the energy modeling was to systematically compare the performance of GSHP systems to more conventional GFA-based systems using a set of standardized model houses.

By using energy modeling and standardizing the model houses, variables can be controlled to ensure as close to an "apples to apples" comparison as possible between GSHP equipment and other HVAC equipment. For example, using energy modeling and a consistent set of standardized test homes, heating and cooling equipment can be tasked with meeting the exact same space heating and cooling demands. Another major goal was to base the energy modeling on "real-world" COP data. To that end, GSHP system COP values were taken from actual performance in the field study, rather than relying on manufacturer's test data or estimates. A range of these values were used in the GSHP energy models to indicate the likely spread in performance and energy savings.

We developed 9 model houses using 3 different house sizes and 3 different levels of home energy efficiency. This allowed us to compare the benefits of a GSHP system in a wide variety of installation scenarios, from old houses to new houses and house sizes from 2000 to 4000 square feet. The 9 model houses are shown in the matrix in Table 8.

Table 8: Model house matrix with installation scenario and case number.

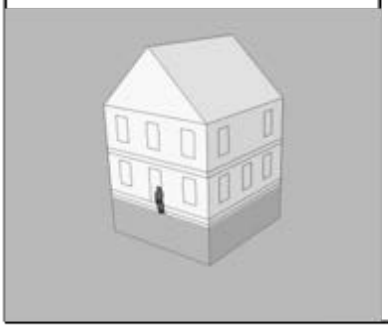
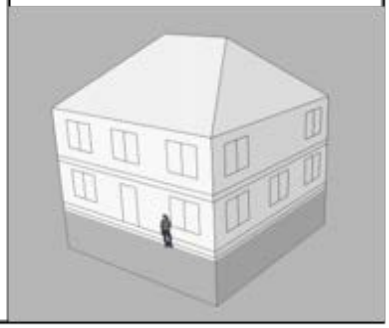
| | | **Home Energy Efficiency** | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| | | Pre-energy code | 1980's energy code | 2015 energy code |
| **Home Size** | 2000 sf (small) | 1 | 4 | 7 |
| | 3000 sf (medium) | 2 | 5 | 8 |
| | 4000 sf (large) | 3 | 6 | 9 |

For conciseness, "Pre-energy code," and "1980's energy code," and "2015 MN energy code" will be referred to as "low," "medium," and "high" efficiency homes. The specific assumptions regarding insulation levels, equipment efficiencies, ventilation levels, etc., for each of these levels of home efficiency will be discussed in detail in following paragraphs. Likewise, the 2000sf, 3000sf, and 4000sf house sizes will be referred to as "small," medium," and "large."

## *Model Home Characteristics*

In Figure 13 we based the characteristics of the 3 house sizes on a 2-story, detached single family home with a finished basement. A square footprint was used for each house to standardize the enclosure surface area calculations. The window to floor area ratio was also standardized at 0.15, resulting in 300sf of window area for the 2000sf house, 450sf of window area for the 3000sf house, and 600sf of window area for the 4000sf house. The window area was distributed equally on all four facades. Bedroom count varied from 3 bedrooms for the small house, 4 bedrooms for the medium house, and 5 bedrooms for the large house. The number of bedrooms was used to determine mechanical ventilation rates.

Figure 13: Characteristics and house size–small, medium and large

| 2000 sf house | 3000 sf house | 4000 sf house |
|---|---|---|
| 26' x 26'<br><br>3-bed, 2-story with conditioned basement<br><br>0.15 window to floor area ratio<br>300 sf window area equally distributed | 31.5' x 31.5'<br><br>4-bed, 2-story with conditioned basement<br><br>0.15 window to floor area ratio<br>450 sf window area equally distributed | 36.5' x 36.5'<br><br>5-bed, 2-story with conditioned basement<br><br>0.15 window to floor area ratio<br>600 sf window area equally distributed |
|  | |  |

## *Model Home Characteristics, GFA cases*

We made a number of assumptions regarding the 3 energy efficiency levels of the model homes. The high efficiency house was assumed to meet the prescriptive requirements of the 2015 MN energy code and/or 2012 IECC. This level of home efficiency could be expected for all new single family homes built in Minnesota. For all house sizes, a window to floor area ratio of 0.15 was selected to maximize heat loss from the windows and represent a "worst case" scenario with the highest heat load. This tended to maximize the energy savings from GSHP systems. We assumed an air infiltration rate of 3.0 air changes per hour at 50Pa test pressure (ACH@50Pa) for the high efficiency house which similarly maximized heat loss and energy savings from GSHP systems. Most new homes in MN are more air tight than this. Balanced, mechanical ventilation is required with the 2015 MN energy code. The vast majority of builders are currently meeting this requirement with either heat recovery or energy recovery ventilators (HRVs or ERVs). We assumed an ERV with sensible heat recovery efficiency of 60%. This efficiency level is on the low to middle end of the spectrum for ERVs available in today's market. We assumed a 90 AFUE furnace and 13 SEER air conditioner which are required to meet the 2012 IECC for a high efficiency home. Table 9 lists the energy performance characteristics of high efficiency houses, as specified in 2015 Minnesota Energy Code and 2012 IECC.

Table 9: Energy performance characteristics of high efficiency house

| High efficiency (2015 MN Energy Code) | Values | Notes |
|---|---|---|
| Ceiling R-value | 50.0 | 2015 MN Energy Code |
| Wall R-value | 21.0 | 2015 MN Energy Code |
| Rim joist R-value | 21.0 | same as wall |
| Basement Wall R-value | 15.0 | 2015 MN Energy Code |
| Slab R-value | 10.0 | 2015 MN Energy Code |
| Fenestration U-factor (area-weighted avg.) | 0.32 | 2015 MN Energy Code |
| Fenestration SHGC (area-weighted avg.) | 0.26 | approx. industry average |
| Airtightness (ACH@50Pa) | 3.0 | 2015 MN Energy Code |
| Window-to-Floor Area Ratio | 0.15 | 2012 IECC max |
| Furnace AFUE | 90 | 2012 IECC |
| Air Conditioner SEER | 13.0 | 2012 IECC |
| DHW ER | 0.62 | 2012 IECC, 2015 NAECA |
| Ventilation Rate (cfm, continuous) | 55,75,95 | 2015 MN Energy Code (2000/3000/4000sf) |
| Sensible Recovery Efficiency (%) | 60.0 | HRV (w separate kitchen fan) |
| Duct location | | conditioned space |
| Lighting CFL percentage | 80% | |

We modeled the medium efficiency house based on the MN energy code in place during the 1980's. Building shell R-values were slightly lower than the high efficiency house. Window performance was significantly worse than the high efficiency house and was matched to industry averages for vinyl framed windows with double clear glass (no low-e glass) in use at the time. We estimated airtightness at 5, 4, and 3 ACH@50Pa for 2000, 3000, and 4000sf homes respectively. Air tightness scores in terms of ACH generally improve as house size increases because larger houses enclose more volume with comparatively less surface area, resulting in less air leakage through the enclosure per unit of volume. We assumed a 50cfm bathroom fan was used for mechanical ventilation. One hour of use per day was afforded for each bedroom, so bath fans in larger houses had longer runtimes. No heat recovery was assumed for ventilation air. We assumed an 80 AFUE furnace and a 10 SEER air conditioner for the medium efficiency home. This level of efficiency assumes a likely replacement of the original space conditioning equipment with a standard efficiency GFA at some point in the 25-35 years since construction. Table 10 lists energy performance characteristics of high efficiency houses, as specified in 1980's Minnesota Energy Code.

Table 10: Energy performance characteristics of medium efficiency house

| Med. efficiency (1980's MN Energy Code) | Values | Notes |
|---|---|---|
| Ceiling R-value | 38.0 | |
| Wall R-value | 19.0 | |
| Rim joist R-value | 13.0 | |
| Basement Wall R-value | 10.0 | |
| Slab R-value | 10.0 | |
| Fenestration U-factor (area-weighted avg.) | 0.46 | double clear vinyl (REM Rate library) |
| Fenestration SHGC (area-weighted avg.) | 0.57 | double clear vinyl (REM Rate library) |
| Airtightness (ACH@50Pa) | 5,4,3 | (est. rates 2000sf, 3000sf, 4000sf) |
| Window-to-Floor Area Ratio | 0.15 | |
| Furnace AFUE | 80 | |
| Air Conditioner SEER | 10.0 | |
| DHW ER | 0.56 | |
| Ventilation Rate (cfm, runtime) | 50, 3/4/5hr | exhaust only (2000/3000/4000sf) |
| Sensible Recovery Efficiency (%) | 0.0 | no recovery |
| Duct location | | conditioned space |
| Lighting CFL percentage | 50% | |

The low efficiency house shown in Table 11 required the greatest number of assumptions regarding its energy efficiency because there was no energy code in place to stipulate minimum levels of performance. We assumed some level of insulation retrofit was likely, so while insulation levels are considerably lower than the medium and high efficiency houses, the house is still fairly well insulated. We assumed 2x 4 wall construction filled with blown-in insulation at R-11, the roof insulation at R-24, and basement walls insulated to R-5, representing a full or partial basement finishing project. Windows are single pane but are retrofitted with exterior storm windows, significantly improving U-values. We estimated airtightness at 7, 6, and 5 ACH@50Pa for 2000, 3000, and 4000sf houses respectively. These values represent typical levels of airtightness for homes built before air sealing practices were widely established through building codes. We assumed a 70 AFUE furnace. As of 1992, federal regulations have required a minimum 78 AFUE in all states, so this level of performance implies a low-efficiency furnace that is more than 23 years old. We assumed a SEER 9 air conditioner representing the lowest efficiency central air conditioner likely to still be in use. Mechanical ventilation assumptions are the same as for the mid-efficiency house since most old houses have been retrofitted with bath fans.

Table 11: Energy performance characteristics of low efficiency house

| Low efficiency (Pre-Energy Code) | Values | Notes |
|---|---|---|
| Ceiling R-value | 24.0 | 7 inches cellulose |
| Wall R-value | 11.0 | insulated 2x4 wall |
| Rim joist R-value | 11.0 | same as wall |
| Basement Wall R-value | 5.0 | 1 inch interior foam board |
| Slab R-value | 0.0 | carpeted slab |
| Fenestration U-factor (area-weighted avg.) | 0.67 | Single wood frame w storm (REM Rate lib.) |
| Fenestration SHGC (area-weighted avg.) | 0.65 | Single wood frame w storm (REM Rate lib.) |
| Airtightness (ACH@50Pa) | 7,6,5 | (est. rates 2000sf, 3000sf, 4000sf) |
| Window-to-Floor Area Ratio | 0.15 | same as other models |
| Furnace AFUE | 70 | Gas Furn Pre 1987 (REM Rate library) |
| Air Conditioner SEER | 9.0 | Cent AC Pre 1987 (REM Rate library) |
| DHW ER | 0.55 | Gas Stor 1984-87 (REM Rate library) |
| Ventilation Rate (cfm, runtime) | 50, 3/4/5hr | exhaust only (2000/3000/4000sf) |
| Sensible Recovery Efficiency (%) | 0.0 | no recovery |
| Duct location | | conditioned space |
| Lighting CFL percentage | 50% | |

## *Model Home Characteristics, GSHP cases*

To develop the model houses with GSHP systems, the model houses' shape and enclosure characteristics were unchanged but the mechanical systems (heating, cooling, and domestic hot water) were changed. For the purposes of energy modeling, we assumed the GSHP model houses were all-electric. That is, all the combustion equipment was removed from the model homes and replaced with electric options. This decision followed results from the field study which found that almost half of the homes in the study did not have propane or natural gas service. The fuel-fired furnace and central air conditioner was replaced with an electric GSHP system. Backup heating was provided by electric resistance (such as electric baseboard heaters). The fuel-fired water heater was also replaced with an electric resistance water heater of the same storage capacity. We assumed that electric water heaters in the low and mid-efficiency houses met the old National Appliance Energy Conservation Act (NAECA) requirements which mandated 0.92EF for electric water heaters with 40 gallons of storage. Electric water heaters for the high efficiency model houses met the new 2015 NAECA requirements mandating 0.95EF for all units with storage capacity of 50 gallons or less. We assumed that the GSHP system delivered heating and cooling via forced air through a central circulation fan and system of

ductwork, in the same fashion as the GFA system with central air conditioner. No attempt was made to investigate or compare radiant heat systems.

As discussed in the field study section, GSHP systems performed at a wide range of in situ COPs. One of the main goals of this research was to use these measured COPs in the energy modeling process, rather than relying on estimates or manufacturer's COP data at test conditions. To this end, we used the field study data to provide a range of COPs for the GSHP model houses. Each of the 9 model houses described above was modeled 4 times, once each with low, medium, and high COPs, and once assuming GFA equipment. Therefore, a total of 27 GSHP energy models were run, and savings compared to the 9 corresponding GFA base cases. The COP values taken from field data were "system level" COPs including energy use from loop field pumps, but not the circulation fan for heat distribution through the ductwork. This topic will be discussed in greater detail below.

System COP values used in the energy models for low, medium, and high efficiency levels were taken from Table 7. We used the first quartile for the low efficiency house, the second quartile (or median) for the medium efficiency house, and the third quartile for the high efficiency house. The first quartile is the COP value halfway between the median (middle) value and the smallest value. 25% of values are lower, and 75% of values are higher. The second quartile is the median. 50% of values are lower, and 50% are higher. The third quartile is the COP value halfway between the median and the highest value. 75% of values are lower, and 25% of values are higher. Matching Table 7, we used separate COPs for the heating season and cooling season. For each efficiency level we used the corresponding seasonal COP regardless of whether those COPs actually occurred in the same house. For example, in the low efficiency model house, we used the first quartile of all the heating COP values and the first quartile of all the cooling COP values. The COP values used in the model houses are shown in Table 12 below.

Table 12: GSHP efficiency levels used in energy modeling, derived from field data.

| GSHP Efficiency | heating COP | cooling COP |
|---|---|---|
| Low COP (1st quartile in field data) | 2.9 | 3.9 |
| Med. COP (2nd quartile/median in field data) | 3.2 | 5.2 |
| High COP (3rd quartile in field data) | 3.8 | 10.1 |

## GFA efficiency assumptions

Ideally, COP values taken from GSHP systems operating in the field should be used in the energy models in conjunction with AFUE values taken from GFA units operating in the field. While this research effort did not have the funding to conduct a similar study of GFA units and their operating efficiency under "real-world" conditions, some previous research was available. A research study performed by the Partnership for Advanced Residential Retrofit (PARR) and published in 2013 looked at a dozen residential furnaces and used both field measurements and lab testing to determine their efficiency (Brand, 2013, p.112).That study tested a range of older furnace models with AFUEs in the 60's to the 90's. PARR found that while the steady state efficiency under field conditions was on average 6% lower than stated, the AFUE (a measure of overall or annual efficiency) was extremely close and in some cases greater than the

manufacturer-reported AFUE. Based on the results of PARR's study, we feel comfortable making the assumption that the AFUE values used in our energy modeling analysis come quite close to the actual performance of furnaces with the same stated AFUE.

## GSHP COP Inputs in REM Rate

REM Rate provides a number of specific inputs for GSHP systems including circulation fan energy, pump energy (for the ground loop field), COP, heating/cooling capacity, and inputs specific to the type of ground loop. The impact on energy use outputs of some of these inputs cannot be easily traced. The ground loop field in particular is considered a "black box" in which inputs have unknown impacts on the final energy use of the GSHP system. Therefore, the GSHP modeling strategy was carefully determined in coordination with REM Rate support staff to minimize elements that might have unintended or unknown effects on energy use outputs.

With guidance from REM Rate staff, two "open loop" GSHP systems were entered to model each GSHP case. One unit was assigned to the cooling load and given the appropriate cooling COP, depending on case and efficiency. The other was assigned to the heating load and given a separate heating COP. In REM Rate, the open loop system replaces the ground loop inputs with a straightforward COP calculation, eliminating the "black box" ground loop algorithms entirely. That is, it uses the entered COP directly to calculate the heating or cooling energy and resulting energy consumption. This was verified with a series of test cases confirming that in REM Rate the heating energy supplied (i.e., annual load) divided by heating energy consumption equaled the COP as long as pump and system fan energy was set to 0. To include the effects of the system fan and ground loop pump, the system fan energy was added back in after an independent calculation (discussed in more detail below), while the pump energy was included in the COP. Therefore, the COP values from the field data that were used for energy modeling included pump energy, but not fan energy.

## Fan Energy Inputs in REM Rate

Calculating fan energy was particularly problematic for several reasons. First, fan energy is not consistent from GSHP to GFA systems. Fan energy is dependent on supply air temperatures, or the temperature of the air that is distributed from the furnace or GSHP to heat the house. As supply air temperature drops, the amount of air supplied must increase proportionally to meet the same heat load or demand. In general, as the efficiency of the heating equipment increases, the supply air temperature goes down. Thus, high efficiency condensing furnaces with relatively low supply air temperatures require more air flow and therefore more fan energy consumption than low efficiency furnaces with much hotter supply air. GSHPs typically output temperatures even lower than condensing furnaces, so air flow and fan energy consumption is proportionally greater.

Second, REM Rate's default fan energy for both GFA and GSHP systems appeared suspect. A sizeable number of test runs of varying system efficiency (both COP and AFUE), as well as capacity, revealed some strange patterns in fan energy consumption that could not be justified. Fan energy consumption taken from test simulations showed that REM Rate's default fan energy increased as expected with larger capacity equipment, but steadily decreased as furnace efficiency improved. In general, this runs counter to expected results. Strangely, default fan energy for GSHP systems did increase, but jumped to 3-4x higher than comparably sized GFAs

- well beyond what could be expected. The use of ECM motors for high efficiency heating equipment (both GSHPs and condensing furnaces) could help drop fan energy despite the need for higher air flow rates, but the point at which ECMs were introduced in the range of furnace efficiencies and fan energies tested in REM Rate could not be found. In addition, it did not appear that higher efficiency ECM motors were assumed for the GSHP systems tested in REM Rate since fan energy increased so dramatically.

For these reasons, REM Rate's default fan energies for GFA and GSHP systems were not used, and a separate calculation was made to estimate fan energy. For simplicity, higher efficiency ECM motors were not considered, and all fan motors were assumed to operate at the same efficiency. This improved the consistency of the comparison between high and low efficiency furnaces as well as GSHPs. With the additional assumption that both GSHP and GFA duct systems operate under consistent static pressures and similar run times, and that heating capacities are matched, the calculation of fan energy becomes simply proportional to supply air temperatures. These were taken from recent research conducted by the Center for Energy and Environment and the Partnership for Advanced Residential Retrofit. (Brand, 2013)

Table 13: Assumed supply air temperatures for fan energy calculations

| Heating equipment | Assumed Supply Air Temp | Source | Resulting fan energy factor |
|---|---|---|---|
| 70 AFUE GFA | 140°F | CEE, PARR (upper end of range) | 0.86 |
| 80 AFUE GFA | 130°F | CEE, PARR (lower end of range) | 1.0 (base case) |
| 90 AFUE GFA | 115°F | CEE, PARR (lower end of range) | 1.32 |
| GSHP (high, med, low COPs) | 95°F | Field data, average heating supply air temp | 2.3 |

This matrix (Table 13) shows the various combinations of size and efficiency of the nine model houses used for the energy modeling analysis. All the fan energies for heating equipment (both GSHP systems and GFA systems) at various capacities could then be calculated based on the difference of their output temperatures and given a specific starting point or starting fan energy. This starting point was selected for each of the cases as REM Rate's default fan energy for an 80 AFUE furnace of the same capacity. This point was selected under the assumption that REM Rate's default fan energy data was most accurate at the standard efficiency level of 80 AFUE. The difference in fan energy caused by the supply air temperature difference is summarized by the fan energy factor, noted above in Table 13. Thus, a 70 AFUE furnace was assigned a fan energy factor equal to 0.86x the default fan energy of an equal capacity 80 AFUE furnace. GSHP systems were assigned a fan energy factor equal to 2.3x the default fan energy of an equal capacity 80 AFUE furnace, and so on. These calculated fan energy factors were entered in the REM Rate input screen for either the GSHP or GFA system in replacement of the default fan energy.

## Mechanical System Capacity and Backup Assumptions

Selecting appropriate capacities for GSHP and GFA equipment also required some additional assumptions. While GFA equipment is generally oversized to ensure that heat loads are met at or beyond design conditions and provide some extra capacity to "catch up" after thermostat setbacks, GSHP equipment is not. Rather, GSHP systems are usually paired with backup systems that can provide some additional heating when necessary. The reason for this is expense. While it's relatively inexpensive to upgrade a furnace from 48 kBTU/hr to 60 kBTU/hr, the equivalent step in a GSHP system installation requires 25% more excavation, tubing, and fluid; a larger loop field pump; and a larger capacity heat pump. Therefore, it's generally cheaper to provide the additional capacity with backup heat sources such as electric resistance baseboards or heating elements within the heat pump.

Based on these assumptions, GFA systems were sized with capacities equal to 1.25x the REM Rate -calculated design heat load of the house. This is likely a conservative estimate as many installers prefer to oversize their equipment by an even larger factor. GSHP systems for the same case (therefore, same design heat load) were sized with capacities exactly equal to the design heat load. The largest repercussion of this decision was on fan energy. GFA fan energy was therefore based on a capacity that was 1.25x greater than otherwise needed, increasing fan energy consumption. In comparison, GSHP system fan energy was based on a smaller capacity for the same house and heat load, reducing fan energy consumption. Thus, while GSHP cases still had larger fan energy consumption overall than GFA cases, the difference was reduced. Normally, some of this difference would be "earned back" by the GFA system as its larger capacity would enable it to run less frequently than the matching GSHP system. We made no attempt to account for this dynamic, and therefore provided a slight benefit to the GSHP system.

However, the GSHP cases were paired with a backup heating system which was not present in the GFA cases. This backup system had to be electric resistance since GSHP cases were electric-only. To provide a solid basis for backup heating system estimates, we used data from the field study to calculate the percentage of heat load met through backup heating sources. Of the homes that had backup heating systems and used it, an average 3% of the heating load was met with backup. While the large majority of homes in the field had some form of backup heat, more than 50% met that need through another fuel source such as propane, natural gas, or even wood. While electric resistance is cheap to install, it is costly in terms of source energy consumption (energy consumed at the power plant) and ongoing energy costs. Requiring GSHP cases in the energy modeling study to use electric resistance backup increased source energy consumption and cost slightly compared to the alternatives with fuel-fired backup.

## Design Heating and Cooling Loads

Once the energy models were set up, REM Rate calculated the design heating and cooling loads, or peak heating and cooling demand for each of the 9 model houses. These values are typically used to size the heating or cooling capacity of the equipment. It was important that for each of the model houses, the peak loads could be met by GSHP equipment capacities within the range of those used in the field study. Originally, we planned to take this a step further and use "average" COP values taken only from GSHP equipment in the field study that actually matched or came close to the peak loads in the energy models. However, we determined that

there were not a sufficient number of GSHP systems in the field study to calculate separate average COPs for these subsets. Rather, values from the entire range of GSHP systems in the field study were used to find the 1st, 2nd, and 3rd quartiles, and these values were applied in the energy models regardless of the capacity of the GSHP system, or peak heating or cooling demand.

Peak heating loads were always larger than peak cooling loads, and the largest peak heating load - found for case #3, the low efficiency 4000sf house - was greater than 90 kBTU/hr. The largest capacity GSHP in the field study was a 6 ton unit, at 72 kBTU/hr. Due to this mismatch between the sizes of the GSHP systems in the field study and the required capacity for case #3, this scenario was dropped from further study.

## *Fuel Cost Assumptions*

Determining reasonable fuel costs (electricity, propane, and natural gas) to use for an energy cost comparison was another challenge.

Electric rates in particular were difficult to determine. We chose a selection of utilities from the greater metro area - Dakota Electric Association, Connexus, and Xcel Energy – and one utility from outstate – Minnesota Power –for electric rate and rate program analysis. While most customers with GSHP systems are allowed to purchase electric power at discounted rates, these programs vary in type and level of discount. "Interruptible," "off peak," and "dual fuel" programs exist in various forms for all of these utilities. The exact rate program used by customers with GSHP systems was often too dependent on additional factors to determine with confidence. Therefore, we examined rate cards for each of these utilities and recorded the electric rates that customers with GSHP systems would be eligible for, as well as standard rates.

This task was compounded by the fact that rates frequently differ by season, and many of the special rates available for GSHP systems offered discounts only for heating energy. Therefore, rough seasonal averages were calculated by combining these discount programs together. Across these various programs and utilities, the average discounted winter heating rate was found to be approximately 5 cents per kWh. There was not a consistently discounted summer cooling rate that could be applied to GSHP systems in particular. Therefore, the summer rate for GSHP cooling energy was assigned the average standard summer rate. This rate was approximately 10 cents per kWh, and was used for both GSHP and GFA systems. The average standard winter rate used for GFA systems was approximately 9 cents per kWh.

Since the previous analysis provided cost information only for the volumetric (i.e. per kWh) component of utility rates, we needed to develop a method for estimating the additional cost charges (i.e. taxes, fuel cost surcharges, and fees). Utilities declined to give average values for these additional charges since they can fluctuate month to month based on the cost of power, and from location to location based on local taxes and fees. We did have access to actual Xcel bills, and these additional surcharges - with the notable exception of the basic monthly service charge - were averaged for the most recent 12 months (September 2014 – August 2015). The average of these additional surcharges, fees, and taxes was between 5 and 6 cents per kWh. Therefore, we added 5 cents per kWh to the seasonal averages discussed in the preceding paragraph.

There tends to be greater price volatility in natural gas and propane prices than in electric power prices. For this reason, we calculated a long-term 5-year average for the state of Minnesota based on average monthly prices reported by the EIA. These averages were used to calculate space and water heating costs for the GFA systems of $1.00 per therm for natural gas and $2.00 per gallon for propane.

All of these costs, as well as their conversion to $/MMBtu of energy, are shown in Table 14, Table 15 and Table 16. These costs were to develop the cost analysis and cost savings reported in the energy modeling results section. Only costs for space heating, space cooling, and water heating were included. Appliances, plug loads, and lighting were not included in the cost analysis since they did not vary from a particular GSHP case to its corresponding GFA case.

Table 14: Energy costs for GFA system with central AC, basic electric and natural gas service.

| Energy Type | Rate | Units | Time of Year | Source | $/MMBtu |
|---|---|---|---|---|---|
| cooling energy charge | 0.15 | $/kWh | June - Sep | 2015 MN utility avg. (inc. surcharges) | $43.96 |
| heating fan energy charge | 0.14 | $/kWh | Oct - May | 2015 MN utility avg. (inc. surcharges) | $41.03 |
| nat. gas (water/space heat) | 1.00 | ($/therm) | whole year | EIA 5yr avg for MN ('10-'15) | $10.00 |

Table 15: Energy costs for GFA system with central AC, basic electric and propane service.

| Energy Type | Rate | Units | Time of Year | Source | $/MMBtu |
|---|---|---|---|---|---|
| cooling energy charge | 0.15 | $/kWh | June - Sep | 2015 MN utility avg. (inc. surcharges) | $43.96 |
| heating fan energy charge | 0.14 | $/kWh | Oct - May | 2015 MN utility avg. (inc. surcharges) | $41.03 |
| propane (water/space heat) | 2.00 | ($/gallon) | whole year | EIA 5yr avg for MN ('10-'15) | $21.90 |

Table 16: Energy costs for GSHP system, electric-only specialized rate structure (dual fuel/off peak/etc.)

| Energy Type | Rate | Units | Time of Year | Source | $/MMBtu |
|---|---|---|---|---|---|
| cooling energy charge | 0.15 | $/kWh | June - Sep | 2015 MN utility avg. (inc. surcharges) | $43.96 |
| heating energy charge | 0.10 | $/kWh | Oct - May | 2015 MN utility avg. (inc. surcharges) | $29.31 |
| water heating | 0.117 | $/kWh | whole year | (weighted avg. of above) | $34.19 |

## Energy Modeling Results

Simulation results follow:

Note that case 3 (4000 sf low efficiency house) was removed from the analysis since the required design heat load was well outside the capacity range of the GSHP systems in the monitoring study and therefore relevant field data for COPs was unavailable.

The following Tables (Table 17, Table 18, Table 19, Table 20, Table 21, Table 22, Table 23, and Table 24) show the modeling results for several home size and energy use comparisons for GSHP and GFA systems. Table 17 through Table 20 lay out the heating and cooling energy consumption comparison. Table 21 and Table 22 compare the site and source consumption for the three house models. Table 23 shows the energy cost comparison for the houses, and Table 24 displays the comparative amounts of $CO_2$ emissions for the different houses.

Table 17: GFA with central AC energy model results

| | | Design load (kBtu/hr) | | Annual load (MMBtu/yr) | | |
|---|---|---|---|---|---|---|
| House Description | Case | heating | cooling | heating | cooling | water heating |
| 2000sf, low efficiency | 1.0 | 56.2 | 24.7 | 100.8 | 17.1 | 15.9 |
| 3000sf, low efficiency | 2.0 | 74.7 | 34.1 | 132.4 | 24.6 | 18.3 |
| 2000sf, mid efficiency | 4.0 | 38.0 | 20.1 | 61.4 | 17.1 | 16.8 |
| 3000sf, mid efficiency | 5.0 | 49.8 | 27.6 | 79.0 | 24.6 | 19.2 |
| 4000sf, mid efficiency | 6.0 | 59.0 | 34.5 | 91.1 | 32.5 | 22.0 |
| 2000sf, high efficiency | 7.0 | 30.2 | 14.7 | 49.3 | 11.0 | 16.0 |
| 3000sf high efficiency | 8.0 | 41.7 | 20.5 | 68.9 | 14.9 | 18.5 |
| 4000sf, high efficiency | 9.0 | 51.8 | 25.9 | 85.5 | 18.9 | 20.9 |

| | | Annual Energy Consumption (MMBtu/yr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| House Description | Case | heating total | heating total, no fan (gas) | heating fan only (elec) | cooling (elec) | water heating (gas) | lights + app (elec) | total energy | total energy (gas) | total energy (elec) | total kBTU/sf |
| 2000sf, low efficiency | 1.0 | 146.4 | 143.9 | 2.5 | 6.6 | 22.7 | 24.0 | 199.6 | 166.6 | 33.1 | 99.8 |
| 3000sf, low efficiency | 2.0 | 192.3 | 189.2 | 3.1 | 9.5 | 26.1 | 30.5 | 258.3 | 215.3 | 43.1 | 86.1 |
| 2000sf, mid efficiency | 4.0 | 78.9 | 76.8 | 2.1 | 6.0 | 22.1 | 24.0 | 130.9 | 98.9 | 32.1 | 65.5 |
| 3000sf, mid efficiency | 5.0 | 101.3 | 98.7 | 2.6 | 8.6 | 25.2 | 30.5 | 165.6 | 123.9 | 41.7 | 55.2 |
| 4000sf, mid efficiency | 6.0 | 116.8 | 113.9 | 2.9 | 11.4 | 28.2 | 37.0 | 193.3 | 142.1 | 51.3 | 48.3 |
| 2000sf, high efficiency | 7.0 | 57.0 | 54.7 | 2.3 | 3.0 | 20.1 | 23.9 | 104.0 | 74.8 | 26.2 | 52.0 |
| 3000sf high efficiency | 8.0 | 79.5 | 76.6 | 2.9 | 4.1 | 23.1 | 30.3 | 137.0 | 99.7 | 33.2 | 45.7 |
| 4000sf, high efficiency | 9.0 | 98.6 | 95.0 | 3.6 | 5.3 | 26.1 | 36.7 | 166.6 | 121.1 | 40.3 | 41.7 |

Table 18 GSHP (low COP–heating COP 2.9, cooling COP 3.9) energy model results

| | | Design load (kBtu/hr) | | Annual load (MMBtu/yr) | | |
|---|---|---|---|---|---|---|
| House Description | Case | heating | cooling | heating | cooling | water heating |
| 2000sf, low efficiency | 56.2 | 24.7 | 100.8 | 17.1 | 13.6 | 56.2 |
| 3000sf, low efficiency | 74.7 | 34.1 | 132.4 | 24.6 | 16.0 | 74.7 |
| 2000sf, mid efficiency | 38.0 | 20.1 | 61.4 | 17.1 | 13.6 | 38.0 |
| 3000sf, mid efficiency | 49.8 | 27.6 | 79.0 | 24.6 | 16.0 | 49.8 |
| 4000sf, mid efficiency | 59.0 | 34.5 | 91.1 | 32.5 | 18.5 | 59.0 |
| 2000sf, high efficiency | 30.2 | 14.7 | 49.3 | 11.0 | 13.3 | 30.2 |
| 3000sf high efficiency | 41.7 | 20.5 | 68.9 | 14.9 | 15.7 | 41.7 |
| 4000sf, high efficiency | 51.8 | 25.9 | 85.5 | 18.9 | 18.1 | 51.8 |

| | | Annual Energy Consumption (MMBtu/yr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| House Description | Case | heating total | heating total, no fan (gas) | heating fan only (elec) | cooling (elec) | water heating (gas) | lights + app (elec) | total energy | total energy (gas) | total energy (elec) | total kBTU/sf |
| 2000sf, low efficiency | 1.0 | 42.1 | 36.7 | 5.4 | 3.1 | 13.9 | 24.0 | 83.1 | 0.0 | 83.1 | 41.6 |
| 3000sf, low efficiency | 2.0 | 55.3 | 48.3 | 7.0 | 4.3 | 16.4 | 30.5 | 106.5 | 0.0 | 106.5 | 35.5 |
| 2000sf, mid efficiency | 4.0 | 26.4 | 22.4 | 4.0 | 2.8 | 13.9 | 24.0 | 67.1 | 0.0 | 67.1 | 33.5 |
| 3000sf, mid efficiency | 5.0 | 33.8 | 28.8 | 5.0 | 3.9 | 16.4 | 30.5 | 84.6 | 0.0 | 84.6 | 28.2 |
| 4000sf, mid efficiency | 6.0 | 38.9 | 33.2 | 5.7 | 5.0 | 18.8 | 37.0 | 99.7 | 0.0 | 99.7 | 24.9 |
| 2000sf, high efficiency | 7.0 | 21.3 | 18.0 | 3.3 | 2.0 | 13.5 | 23.9 | 60.7 | 0.0 | 60.7 | 30.4 |
| 3000sf high efficiency | 8.0 | 29.4 | 25.1 | 4.3 | 2.6 | 16.0 | 30.3 | 78.3 | 0.0 | 78.3 | 26.1 |
| 4000sf, high efficiency | 9.0 | 36.3 | 31.2 | 5.1 | 3.2 | 18.5 | 36.7 | 94.7 | 0.0 | 94.7 | 23.7 |

Table 19: GSHP (mid COP - heating COP 3.2, cooling COP 5.2) energy model results

| | | Design load (kBtu/hr) | | Annual load (MMBtu/yr) | | |
|---|---|---|---|---|---|---|
| House Description | Case | heating | cooling | heating | cooling | water heating |
| 2000sf, low efficiency | 1.0 | 56.2 | 24.7 | 100.8 | 17.1 | 13.6 |
| 3000sf, low efficiency | 2.0 | 74.7 | 34.1 | 132.4 | 24.6 | 16.0 |
| 2000sf, mid efficiency | 4.0 | 38.0 | 20.1 | 61.4 | 17.1 | 13.6 |
| 3000sf, mid efficiency | 5.0 | 49.8 | 27.6 | 79.0 | 24.6 | 16.0 |
| 4000sf, mid efficiency | 6.0 | 59.0 | 34.5 | 91.1 | 32.5 | 18.5 |
| 2000sf, high efficiency | 7.0 | 30.2 | 14.7 | 49.3 | 11.0 | 13.3 |
| 3000sf high efficiency | 8.0 | 41.7 | 20.5 | 68.9 | 14.9 | 15.7 |
| 4000sf, high efficiency | 9.0 | 51.8 | 25.9 | 85.5 | 18.9 | 18.1 |

| | | Annual Energy Consumption (MMBtu/yr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| House Description | Case | heating total | heating total, no fan (gas) | heating fan only (elec) | cooling (elec) | water heating (gas) | lights + app (elec) | total energy | total energy (gas) | total energy (elec) | total kBTU/sf |
| 2000sf, low efficiency | 1.0 | 39.0 | 33.6 | 5.4 | 2.7 | 13.9 | 24.0 | 79.6 | 0.0 | 79.6 | 39.8 |
| 3000sf, low efficiency | 2.0 | 51.1 | 44.1 | 7.0 | 3.7 | 16.4 | 30.5 | 101.7 | 0.0 | 101.7 | 33.9 |
| 2000sf, mid efficiency | 4.0 | 24.5 | 20.5 | 4.0 | 2.4 | 13.9 | 24.0 | 64.8 | 0.0 | 64.8 | 32.4 |
| 3000sf, mid efficiency | 5.0 | 31.3 | 26.3 | 5.0 | 3.3 | 16.4 | 30.5 | 81.5 | 0.0 | 81.5 | 27.2 |
| 4000sf, mid efficiency | 6.0 | 36.0 | 30.3 | 5.7 | 4.2 | 18.8 | 37.0 | 96.0 | 0.0 | 96.0 | 24.0 |
| 2000sf, high efficiency | 7.0 | 19.7 | 16.4 | 3.3 | 1.7 | 13.5 | 23.9 | 58.8 | 0.0 | 58.8 | 29.4 |
| 3000sf high efficiency | 8.0 | 27.3 | 23.0 | 4.3 | 2.2 | 16.0 | 30.3 | 75.8 | 0.0 | 75.8 | 25.3 |
| 4000sf, high efficiency | 9.0 | 33.6 | 28.5 | 5.1 | 2.8 | 18.5 | 36.7 | 91.6 | 0.0 | 91.6 | 22.9 |

Table 20: GSHP (high COP - heating COP 3.8, cooling COP 10.1) energy model results.

| | | Design load (kBtu/hr) | | Annual load (MMBtu/yr) | | |
|---|---|---|---|---|---|---|
| House Description | Case | heating | cooling | heating | cooling | water heating |
| 2000sf, low efficiency | 1.0 | 56.2 | 24.7 | 100.8 | 17.1 | 13.6 |
| 3000sf, low efficiency | 2.0 | 74.7 | 34.1 | 132.4 | 24.6 | 16.0 |
| 2000sf, mid efficiency | 4.0 | 38.0 | 20.1 | 61.4 | 17.1 | 13.6 |
| 3000sf, mid efficiency | 5.0 | 49.8 | 27.6 | 79.0 | 24.6 | 16.0 |
| 4000sf, mid efficiency | 6.0 | 59.0 | 34.5 | 91.1 | 32.5 | 18.5 |
| 2000sf, high efficiency | 7.0 | 30.2 | 14.7 | 49.3 | 11.0 | 13.3 |
| 3000sf high efficiency | 8.0 | 41.7 | 20.5 | 68.9 | 14.9 | 15.7 |
| 4000sf, high efficiency | 9.0 | 51.8 | 25.9 | 85.5 | 18.9 | 18.1 |

| | | Annual Energy Consumption (MMBtu/yr) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| House Description | Case | heating total | heating total, no fan (gas) | heating fan only (elec) | cooling (elec) | water heating (gas) | lights + app (elec) | total energy | total energy (gas) | total energy (elec) | total kBTU/sf |
| 2000sf, low efficiency | 1.0 | 34.1 | 28.7 | 5.4 | 2.1 | 13.9 | 24.0 | 74.1 | 0.0 | 74.1 | 37.1 |
| 3000sf, low efficiency | 2.0 | 44.8 | 37.8 | 7.0 | 2.9 | 16.4 | 30.5 | 94.6 | 0.0 | 94.6 | 31.5 |
| 2000sf, mid efficiency | 4.0 | 21.5 | 17.5 | 4.0 | 1.8 | 13.9 | 24.0 | 61.2 | 0.0 | 61.2 | 30.6 |
| 3000sf, mid efficiency | 5.0 | 27.5 | 22.5 | 5.0 | 2.5 | 16.4 | 30.5 | 76.9 | 0.0 | 76.9 | 25.6 |
| 4000sf, mid efficiency | 6.0 | 31.7 | 26.0 | 5.7 | 3.1 | 18.8 | 37.0 | 90.6 | 0.0 | 90.6 | 22.6 |
| 2000sf, high efficiency | 7.0 | 17.4 | 14.1 | 3.3 | 1.3 | 13.5 | 23.9 | 56.1 | 0.0 | 56.1 | 28.1 |
| 3000sf high efficiency | 8.0 | 24.0 | 19.7 | 4.3 | 1.8 | 16.0 | 30.3 | 72.1 | 0.0 | 72.1 | 24.0 |
| 4000sf, high efficiency | 9.0 | 29.5 | 24.4 | 5.1 | 2.2 | 18.5 | 36.7 | 86.9 | 0.0 | 86.9 | 21.7 |

## Selected Results

Table 21: Site energy consumption comparison, MMBtu/yr.

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | 199.6 | 130.9 | 104.0 | 258.3 | 165.6 | 137.0 | 193.3 | 166.6 |
| GSHP low COP | 83.1 | 67.1 | 60.7 | 106.5 | 84.6 | 78.3 | 99.7 | 94.7 |
| GSHP med. COP | 79.6 | 64.8 | 58.8 | 101.7 | 81.5 | 75.8 | 96.0 | 91.6 |
| GSHP high COP | 74.1 | 61.2 | 56.1 | 94.6 | 76.9 | 72.1 | 90.6 | 86.9 |

Table 22: Source energy consumption comparison, MMBtu/yr., source energy factors elec. = 3.15, natural gas = 1.09, propane = 1.15

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) nat. gas | 285.9 | 208.9 | 164.1 | 370.4 | 266.4 | 213.3 | 316.5 | 258.9 |
| Base case (GFA w/AC) propane | 295.9 | 214.9 | 168.6 | 383.4 | 273.8 | 219.2 | 325.0 | 266.2 |
| GSHP low COP | 261.9 | 211.3 | 191.3 | 335.4 | 266.3 | 246.7 | 314.0 | 298.4 |
| GSHP med. COP | 250.9 | 204.1 | 185.3 | 320.2 | 256.6 | 238.8 | 302.3 | 288.6 |
| GSHP high COP | 233.5 | 192.7 | 176.8 | 297.9 | 242.1 | 227.1 | 285.3 | 273.8 |

Table 23: Energy cost comparison, $/yr.

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) nat. gas | $2,059 | $1,339 | $974 | $2,698 | $1,724 | $1,296 | $2,041 | $1,592 |
| Base case (GFA w/AC) propane | $4,041 | $2,516 | $1,864 | $5,259 | $3,198 | $2,482 | $3,732 | $3,033 |
| GSHP low COP | $1,847 | $1,372 | $1,175 | $2,370 | $1,721 | $1,523 | $2,002 | $1,838 |
| GSHP med. COP | $1,738 | $1,298 | $1,115 | $2,220 | $1,622 | $1,444 | $1,882 | $1,741 |
| GSHP high COP | $1,568 | $1,184 | $1,030 | $2,000 | $1,475 | $1,330 | $1,708 | $1,594 |

Table 24: $CO_2$ emissions comparison, lbs/yr.

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) nat. gas | 37,298 | 28,783 | 22,794 | 48,374 | 36,851 | 29,464 | 44,118 | 35,774 |
| Base case (GFA w/AC) propane | 40,548 | 30,712 | 24,254 | 52,574 | 39,268 | 31,409 | 46,890 | 38,137 |
| GSHP low COP | 44,346 | 35,786 | 32,398 | 56,790 | 45,101 | 41,771 | 53,171 | 50,523 |
| GSHP med. COP | 42,480 | 34,559 | 31,385 | 54,229 | 43,447 | 40,438 | 51,197 | 48,869 |
| GSHP high COP | 39,546 | 32,638 | 29,944 | 50,442 | 40,994 | 38,464 | 48,317 | 46,362 |

# Energy Modeling Discussion

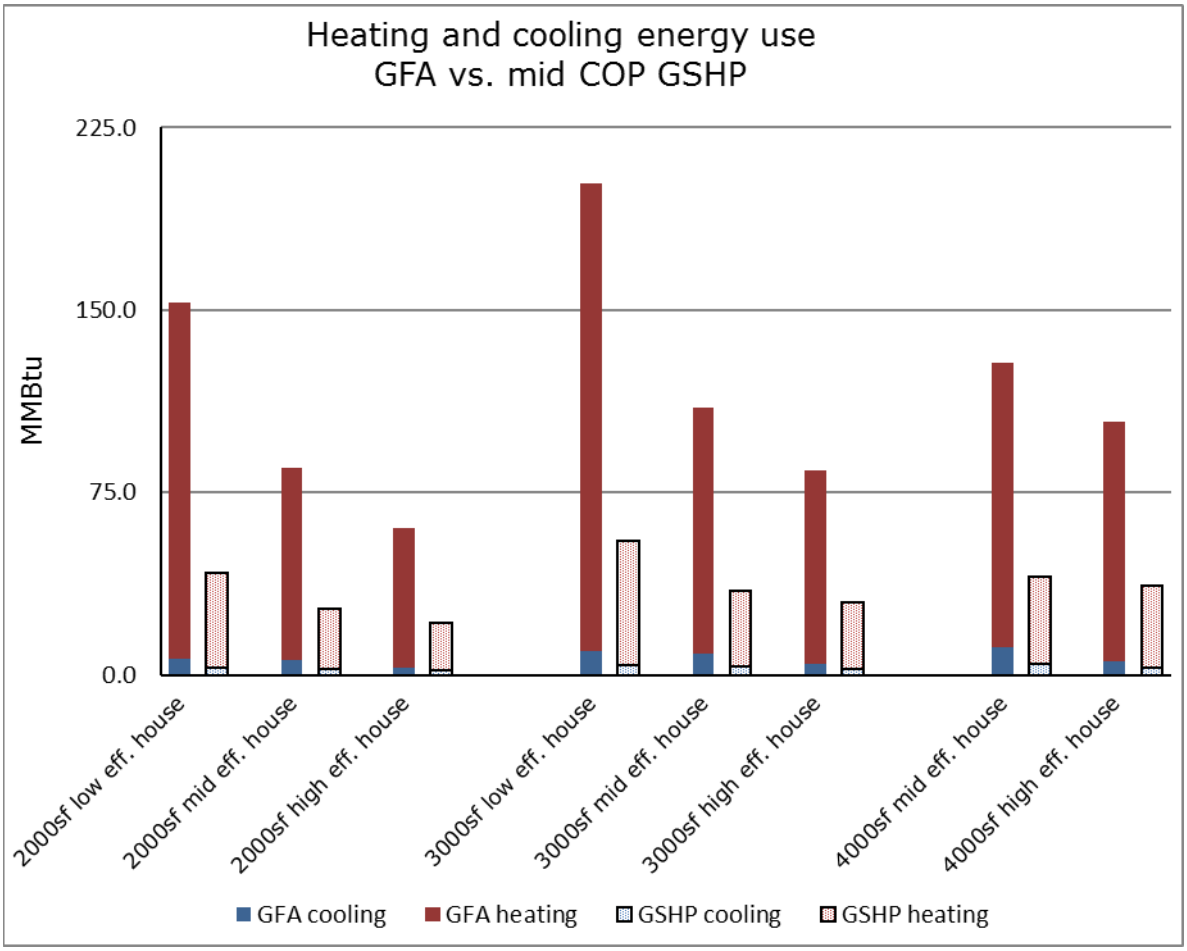
## *Site Energy Use*

Energy modeling results show that residential GSHP systems save significant amounts of site heating energy and can reduce cooling energy and domestic hot water energy use as well. By far, the majority of savings come from reduced heating energy in a typical Minnesota climate.

Figure 14, Table 17 suggests that the amount of heating energy used for a traditional GFA system is roughly 10 – 20x greater than the amount of cooling energy consumed. This impacts the benefits of residential GSHP systems in this climate because they typically operate at highest COP and greatest efficiency during the cooling cycle, but are unable to generate large energy savings during the summer months simply because cooling energy consumption is so small. Some GSHP systems in the field study never operated in cooling mode, and many others operated very infrequently. These results are supported by the energy modeling study.

Although not as efficient in heating mode as in cooling, GSHP systems are still several times more efficient than GFA heating systems, and this provides a significant reduction in site heating energy consumption. Low efficiency homes and large homes requiring large amounts of space heating offer the chance for greater savings. That is, the larger the heating load, the larger the possible savings. Conversely, as homes become smaller and more efficient, the heat load shrinks as does the possible energy savings. This relationship can be seen clearly in Figure 14. The smallest energy savings are afforded by the 2000sf high efficiency house matching the 2015 MN energy code. The greatest energy savings are afforded by the 3000sf low efficiency house.

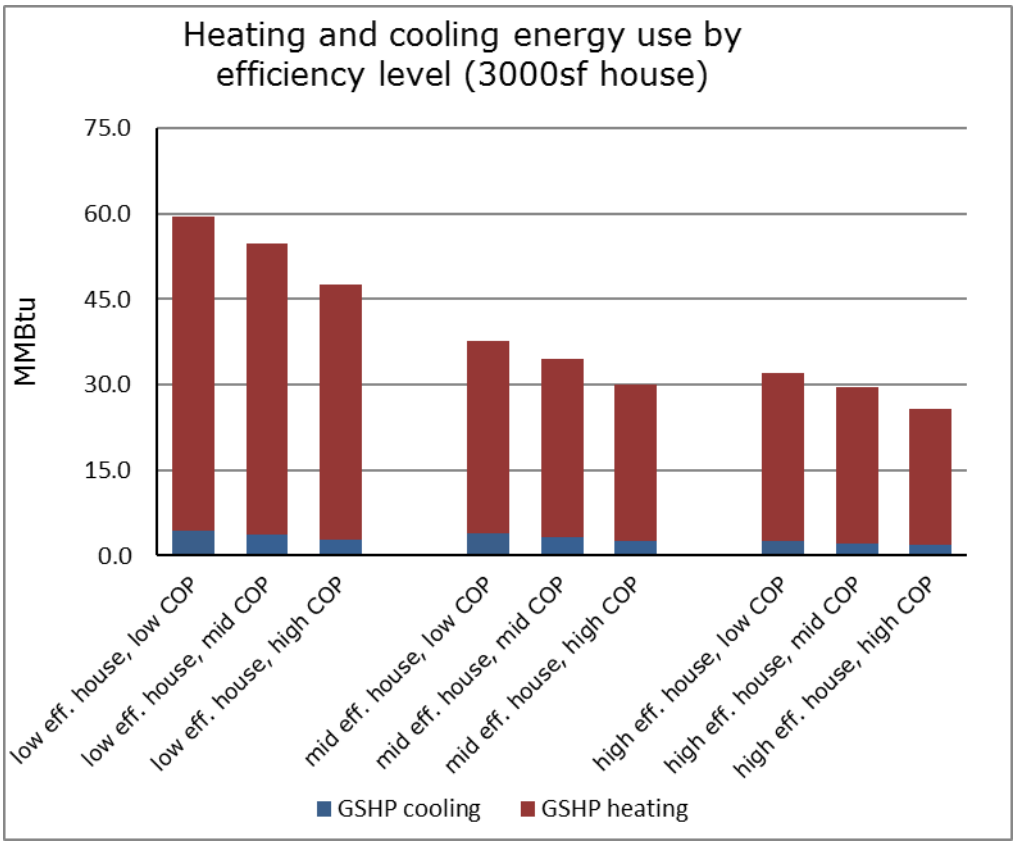
Figure 14: Heating + cooling energy use/year for GFA vs. GSHP-based system with mid-level COP.




GSHP efficiency also impacted energy use. As expected, GSHP systems with low COPs (2.9 heating COP, 3.9 cooling COP) resulted in higher energy use compared to systems with high

COP (3.8 heating COP, 10.1 cooling COP), but the difference was relatively small, especially for high efficiency houses built to the 2015 MN energy code. For example, the difference between low COP and high COP GSHP systems for the 3000sf high efficiency house amounted to approximately 6MMBtu/yr. This relationship can be seen in Figure 15. Again, the greatest impact on heating and cooling energy use due to improved GSHP efficiency can be found for the low efficiency houses, where savings greater than 10MMBtu/year are possible.

Figure 15: Heating + cooling energy use/year for 3000sf house, arranged by house and GSHP efficiency.




In terms of total site energy use measured at the house (Figure 16), savings afforded by a GSHP system were significant for all cases. Savings of over 100 MMBtu/yr. were found for the highest energy use cases (2000 and 3000sf low efficiency houses), and were still close to 50 MMBtu/yr. for the lowest energy use cases (2000 and 3000sf high efficiency houses). Percentage savings compared to the base case GFA-systems were typically 60% for low efficiency homes, 50% for mid efficiency homes, and 40% for high efficiency homes. However, as Figure 16 shows, the amount of electricity used in houses with GSHP systems is typically twice that of houses with more traditional GFA systems. This dynamic has implications for both energy costs and source energy. Table 25 summarizes site energy savings of GSHP systems.

Figure 16: Site energy use for GFA vs. GSHP-based system with mid-level COP

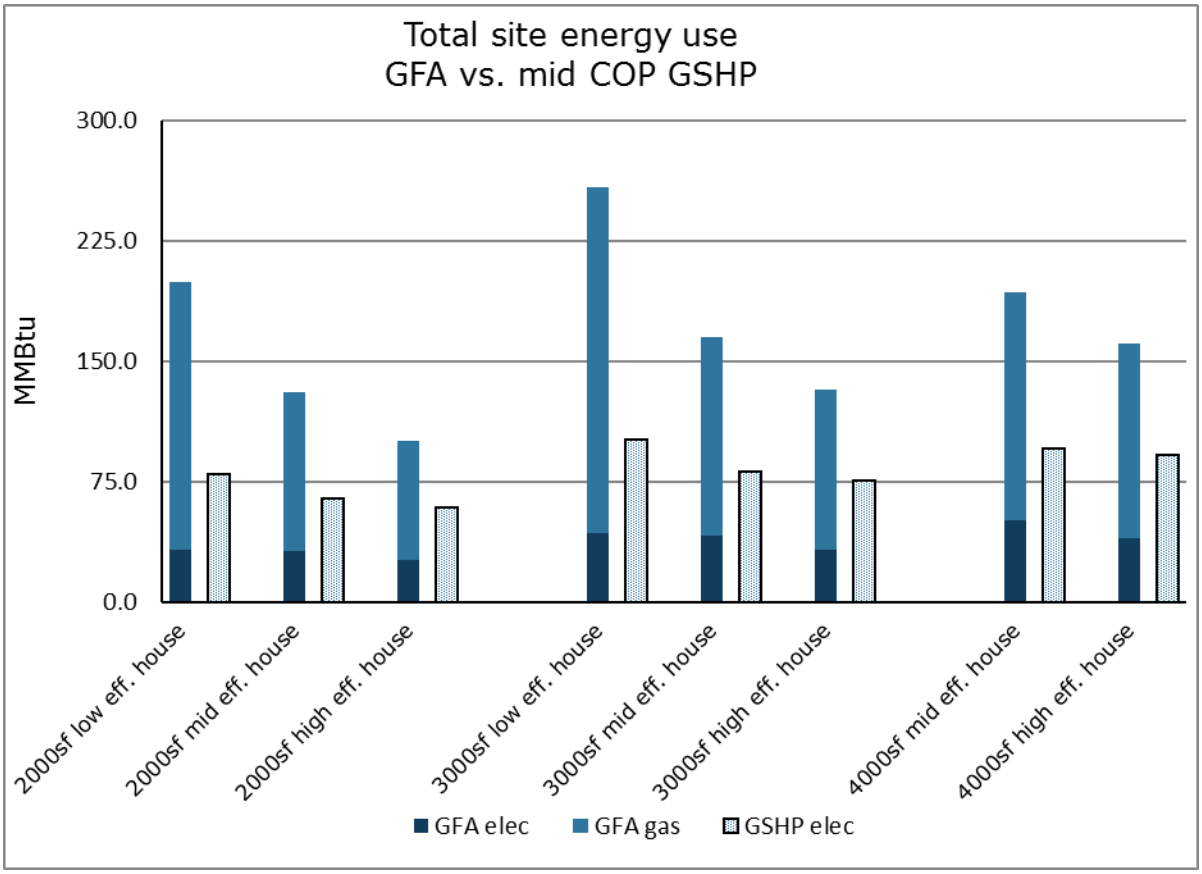



Table 25: Site energy savings, MMBtu/yr.

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | 116.5 | 63.8 | 43.3 | 151.8 | 81.0 | 58.7 | 93.6 | 71.9 |
| GSHP med. COP | 120.0 | 66.1 | 45.2 | 156.6 | 84.1 | 61.2 | 97.3 | 75.0 |
| GSHP high COP | 125.5 | 69.7 | 47.9 | 163.7 | 88.7 | 64.9 | 102.7 | 79.7 |

## Source Energy Use

Source energy is a measure of the true energy that was consumed to provide the heating, cooling, or other service demanded on site, at the house. It is common to think of site energy as the energy metered at the house, while source energy is the energy consumed at the power plant. Thus, source energy accounts for losses in the conversion of thermal energy to electrical energy at a fuel-fired power plant, as well as losses incurred through transmission and transformation of that electrical energy. For example, typically it takes around 3 units of coal or natural gas energy to provide 1 unit of electrical energy to a house. Thus, the "source energy factor" for electricity is generally around 3. If that natural gas was instead burned at the house in a furnace to create heat, those losses incurred in converting thermal energy to electrical energy and transporting that energy can be avoided. Thus, for natural gas burned in a furnace, the source energy factor is generally close to 1. The source energy factor for natural gas and propane is not exactly 1 because some fuel is lost to flaring, spills, and gas leaks during pumping, transportation, and storage. Table 26 shows the source energy factors for grid electricity, natural gas, and propane assumed for source energy calculations.

The national average source energy factors used in this report were calculated in American National Standards Institute (ANSI) standard 105-2014 and represent the most recent, standardized calculation available.

Table 26: Source energy factors

| **Source energy factors** | | **referenced source** |
|---|---|---|
| grid electricity | 3.15 | ANSI Std. 105-2014 (national avg.) |
| natural gas burned in combustion appliance | 1.09 | ANSI Std. 105-2014 (national avg.) |
| LP burned in combustion appliance | 1.15 | ANSI Std. 105-2014 (national avg.) |

Considering source energy (Table 22), residential GSHP systems generally provide significant savings only in cases where they are replacing inefficient GFA systems and air conditioners. These cases are represented by the low efficiency cases, with a 70 AFUE furnace and 9 SEER air conditioner. For the mid-efficiency cases with an 80 AFUE furnace and 10 SEER air conditioner, replacement with a GSHP system achieved source energy savings only when the installation achieved mid to high COPs, and in many cases these savings were quite small. Figure 17 compares source energy consumption of the GSHP with mid-level COP to a natural gas-fires system. For high efficiency cases, such as those built to 2015 MN energy code, even high COP GSHP systems (3.8 heating COP, 10.1 cooling COP) failed to achieve source energy savings. These results are due primarily to the use of grid electricity with a high source energy factor for GSHP systems. As mentioned previously, houses with GSHP systems typically had twice the electrical consumption compared to houses with GFA-based systems with central air conditioners. Although propane has a slightly higher source energy factor than natural gas the comparison to GSHP systems does not change significantly. Results of this analysis are shown in Figure 17, Table 27 and Table 28. Note that negative savings shown in Figure 17represent an increase in source energy use for the GSHP systems compared to GFA systems.

Figure 17: Source energy use for GFA vs. GSHP-based system with mid-level COP

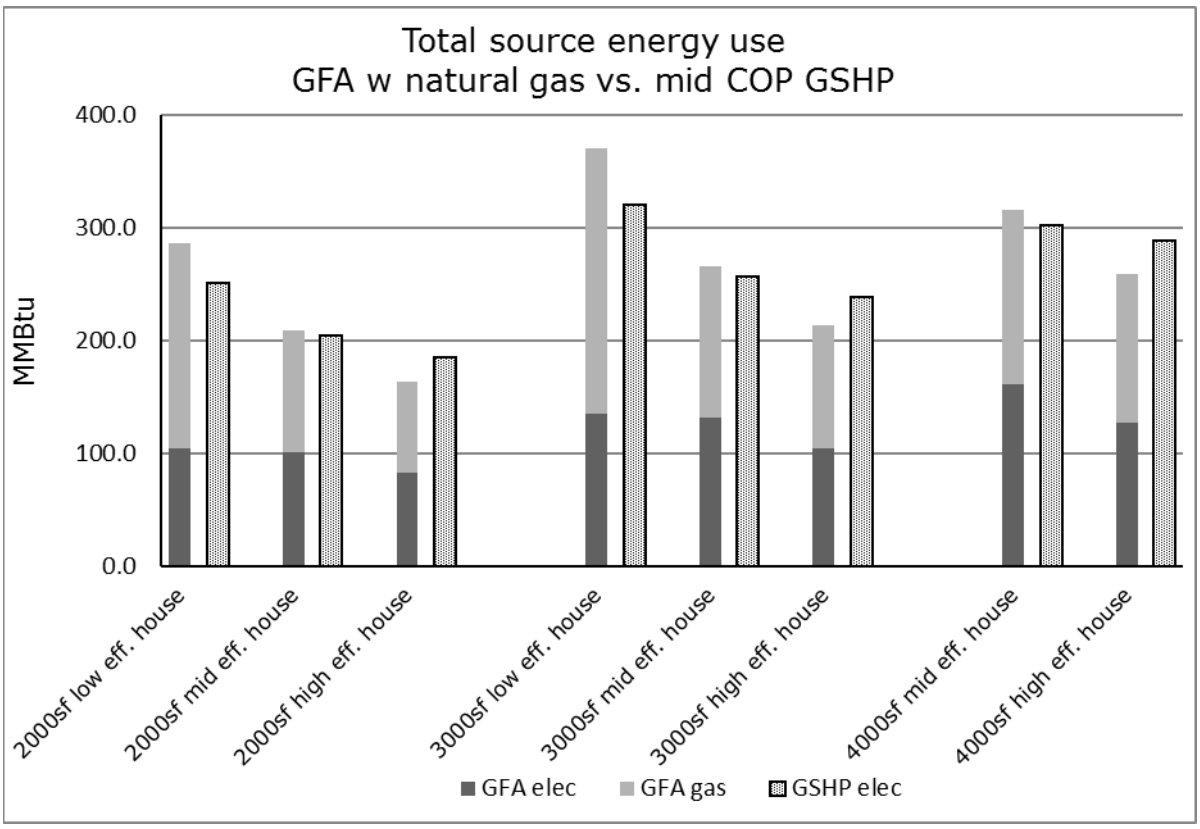



Table 27: Source energy savings for GSHP compared to natural gas-fired GFA system, MMBtu/yr
(Negative numbers indicate GSHP systems increase source energy)

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) nat. gas | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | 23.1 | -3.2 | -28.2 | 34.1 | -0.8 | -34.7 | 1.5 | -40.9 |
| GSHP med. COP | 34.3 | 4.2 | -22.2 | 49.4 | 9.1 | -26.7 | 13.3 | -31.0 |
| GSHP high COP | 51.9 | 15.7 | -13.5 | 72.1 | 23.8 | -14.8 | 30.6 | -16.0 |

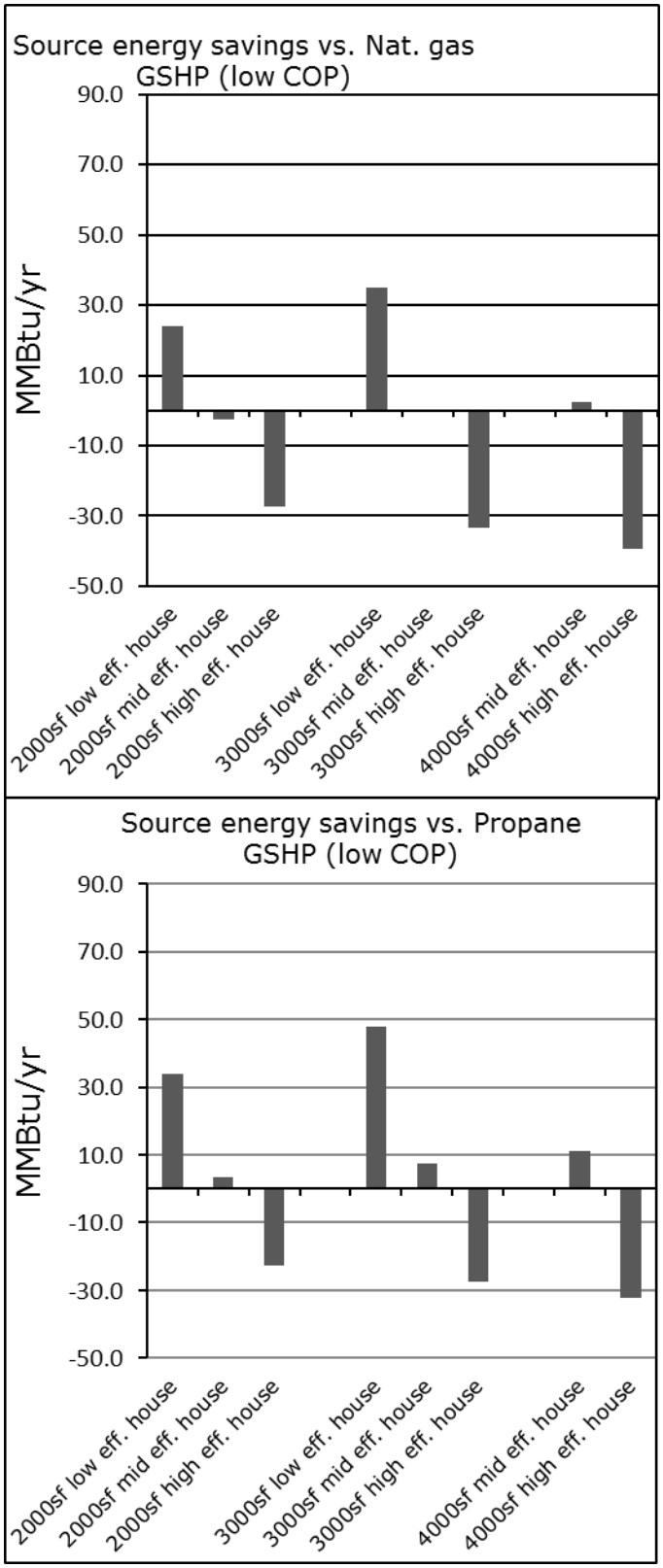
Table 28: Source energy savings for GSHP compared to propane-fired GFA system, MMBtu/yr
(Negative numbers indicate GSHP systems increase source energy)

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) propane | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | 34.0 | 3.5 | -22.8 | 48.0 | 7.5 | -27.4 | 11.0 | -32.1 |
| GSHP med. COP | 45.0 | 10.8 | -16.8 | 63.1 | 17.3 | -19.6 | 22.7 | -22.4 |
| GSHP high COP | 62.3 | 22.1 | -8.3 | 85.5 | 31.8 | -7.9 | 39.7 | -7.6 |

The following three sets of figures display the results in Table 27 and Table 28 in graphical format. The first pair of graphs (Figure 18) displays the source energy savings for GSHP systems with low COP, the second pair of graphs (Figure 19) displays the savings for GSHP systems with medium COP, and the last pair of graphs (Figure 20) displays the savings for GSHP systems with high COP. In each pair, the top graph shows savings compared to natural gas-fired GFA systems and the bottom graph shows savings compared to propane-fired GFA systems.

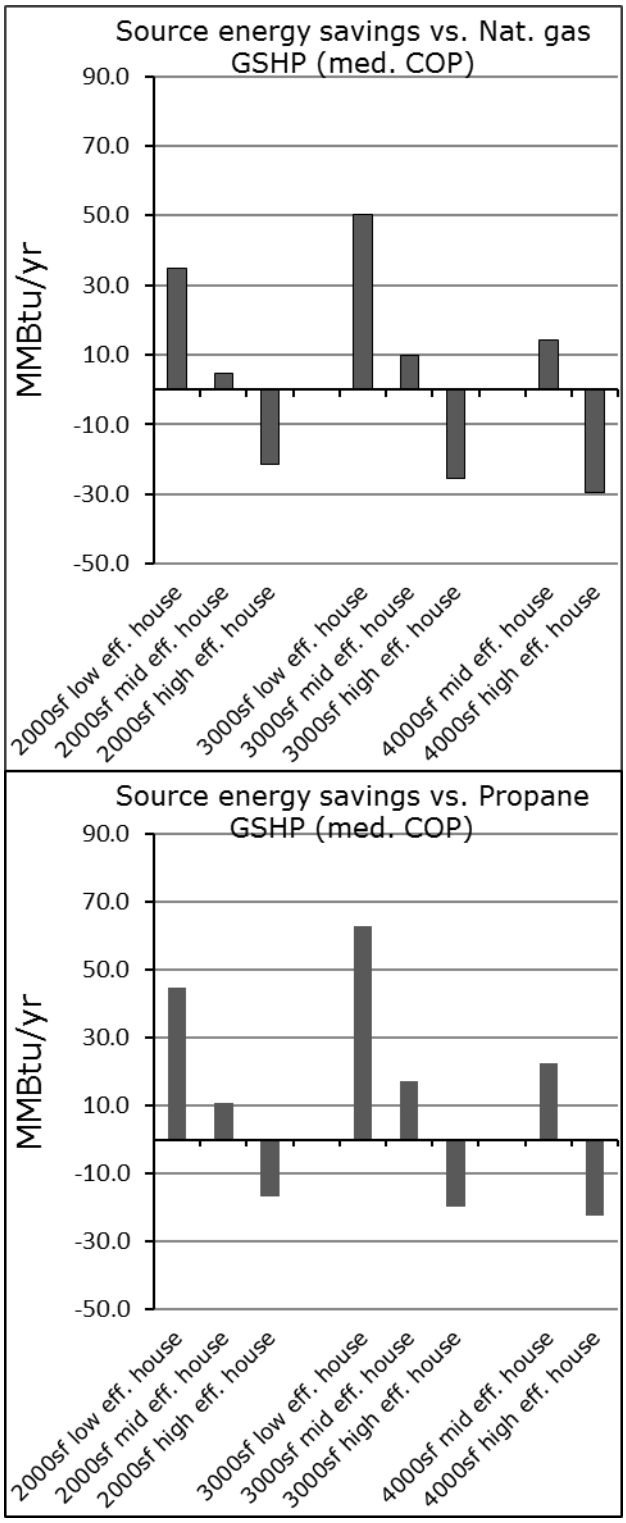
At low system COPs, GSHPs achieved significant source energy savings only when replacing low efficiency combustion appliances and central air conditioners (Figure 18, Table 18).

Figure 18: Source energy savings for GSHP -based system with low COP



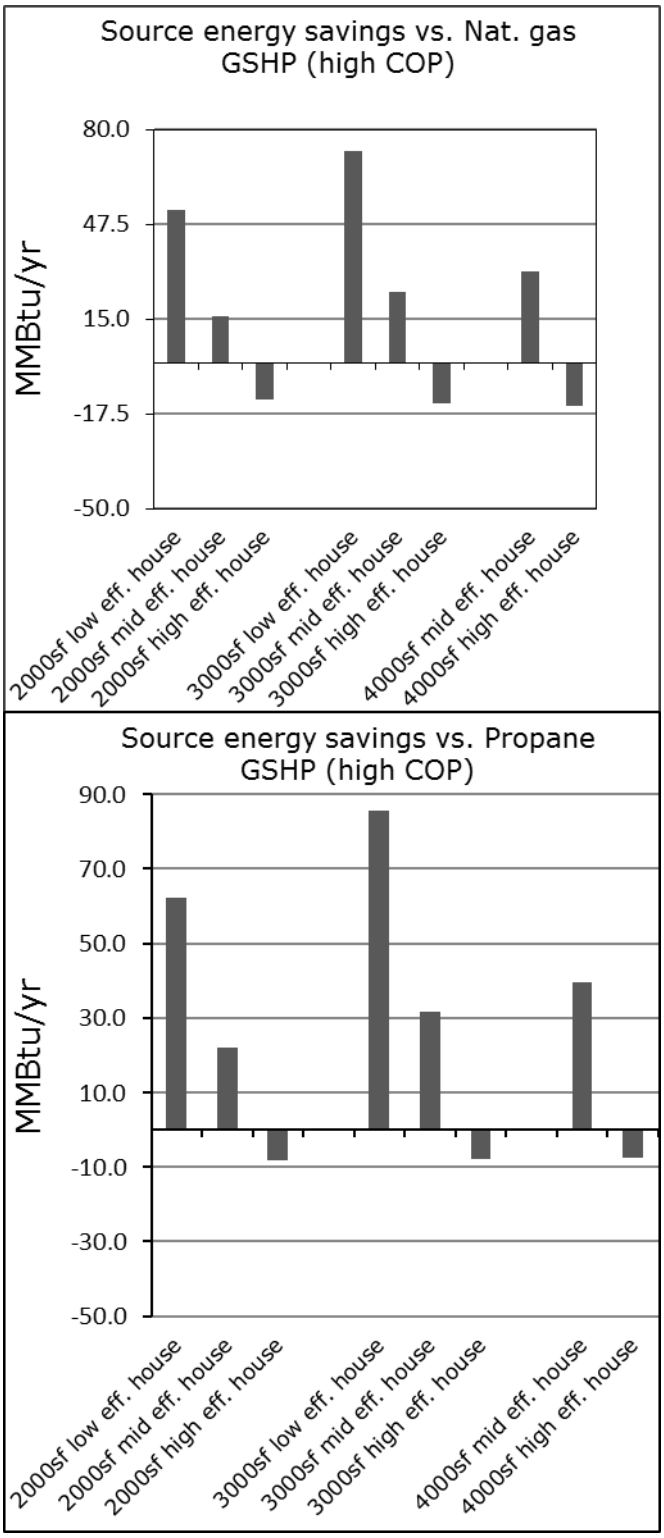
At medium system COPs, GSHPs generally achieved significant source energy savings only when replacing low efficiency combustion appliances and central air conditioners (Figure 19, Table 19).

Figure 19: Source energy savings for GSHP -based system with medium COP



At high system COPs, GSHPs achieved significant source energy savings for homes with low to medium efficiency equipment. (Figure 20, Table 20)

Figure 20: Source energy savings for GSHP -based system with high COP.



## Energy Cost

Energy cost savings afforded by GSHP systems are highly dependent on special electric rates offered to customers using heat pumps or other specialized electric heating equipment. Usually these electric rates cut the base price of electricity used by the GSHP unit by a half or more. After various surcharges and taxes are added, the price is about 2/3 of the normal rate. These prices are generally offered through "dual fuel", "off peak," or "demand controlled" programs which allow the utility some control over when the electric heating appliances are used. These rates were discussed in the Energy Modeling Approach, Fuel Cost Assumptions section and the values used for energy cost calculations are referenced in Table 14 and Table 15. These values are the basis for all the cost conclusions discussed in this section. If readers wish to calculate cost savings based on their own individual utility rates and fuel cost assumptions, we have provided calculation charts in Appendix B.

As long as GSHP system owners can take advantage of these reduced electric rates, GSHP systems do offer energy cost savings compared to homes with low efficiency natural gas-fired GFA systems (Table 29). These savings are commonly in the range of $200 - $500 per year. If the GSHP operates at high efficiency (at the 75th percentile or better compared to GSHP systems in the field study) these savings may be increased to $500 - $700 per year. Large houses with more heating and cooling energy consumption offer the chance for greater energy cost savings. GSHP systems offer significant cost savings over mid-efficiency natural gas-fired GFA systems only when the GHSP system performs at high efficiency. Even high efficiency GSHP systems do not offer energy cost savings compared to high efficiency GFA-based systems that are installed in homes meeting current energy codes.

While energy cost savings offered by GSHP systems may be significant in some cases, they may or may not achieve acceptable payback periods for homeowners, depending on the highly variable cost of GSHP installation. These savings are also highly dependent on utility programs that lower the cost of electricity used by the GSHP. Without these programs, energy costs for GSHP owners would likely double, and savings compared to GFA-based systems would be eliminated.

Table 29: Energy cost savings compared to natural gas-fired GFA system, $/yr

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) nat. gas | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | $212 | -$33 | -$201 | $328 | $2 | -$227 | $39 | -$246 |
| GSHP med. COP | $321 | $40 | -$141 | $478 | $102 | -$148 | $159 | -$149 |
| GSHP high COP | $491 | $155 | -$56 | $698 | $249 | -$34 | $334 | -$3 |

(See Table 13: Assumed supply air temperatures for fan energy calculations for assumed utility rates.)

Some additional considerations may also play a role in homeowner decisions regarding energy costs. For example, GSHP systems are often installed in rural areas without access to natural gas. In those locations, heating alternatives include electric-resistance based heating – which would be roughly three times more expensive than GSHP based heating – or propane-fired combustion equipment. The price of propane is often unpredictable and can become extremely expensive during times of high demand. In these cases, a GSHP installation can dramatically reduce yearly energy costs while providing a high level of cost consistency. Consistency alone can be an important benefit for families with limited savings or discretionary funds.

Recently, propane prices have been significantly higher than natural gas, averaging roughly two times the cost per MMBtu. For this reason, GSHP systems offer considerably larger savings in areas that do not have access to natural gas. Even compared to high efficiency GFA systems in homes meeting current energy codes, savings are frequently more than $1000 per year (Table 30).

Table 30: Energy cost savings compared to propane-fired GFA system, $/yr

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) propane | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | $2,194 | $1,144 | $689 | $2,890 | $1,476 | $959 | $1,730 | $1,195 |
| GSHP med. COP | $2,303 | $1,217 | $749 | $3,039 | $1,576 | $1,038 | $1,850 | $1,292 |
| GSHP high COP | $2,473 | $1,331 | $834 | $3,259 | $1,723 | $1,153 | $2,024 | $1,438 |

(Reference Table 13: Assumed supply air temperatures for fan energy calculations-14 for assumed utility rates)

The following three sets of figures display the results in Table 29 and Table 30 in graphical format. The first pair of graphs (Figure 21) displays the energy cost savings for GSHP systems with low COP, the second pair of graphs (Figure 22) displays the savings for GSHP systems with medium COP, and the last pair of graphs (Figure 23) displays the savings for GSHP systems with high COP. In each pair, the top graph shows savings compared to natural gas-fired GFA systems and the bottom graph shows savings compared to propane-fired GFA systems.

Figure 21: Energy cost savings for GSHP-based systems, with low COP

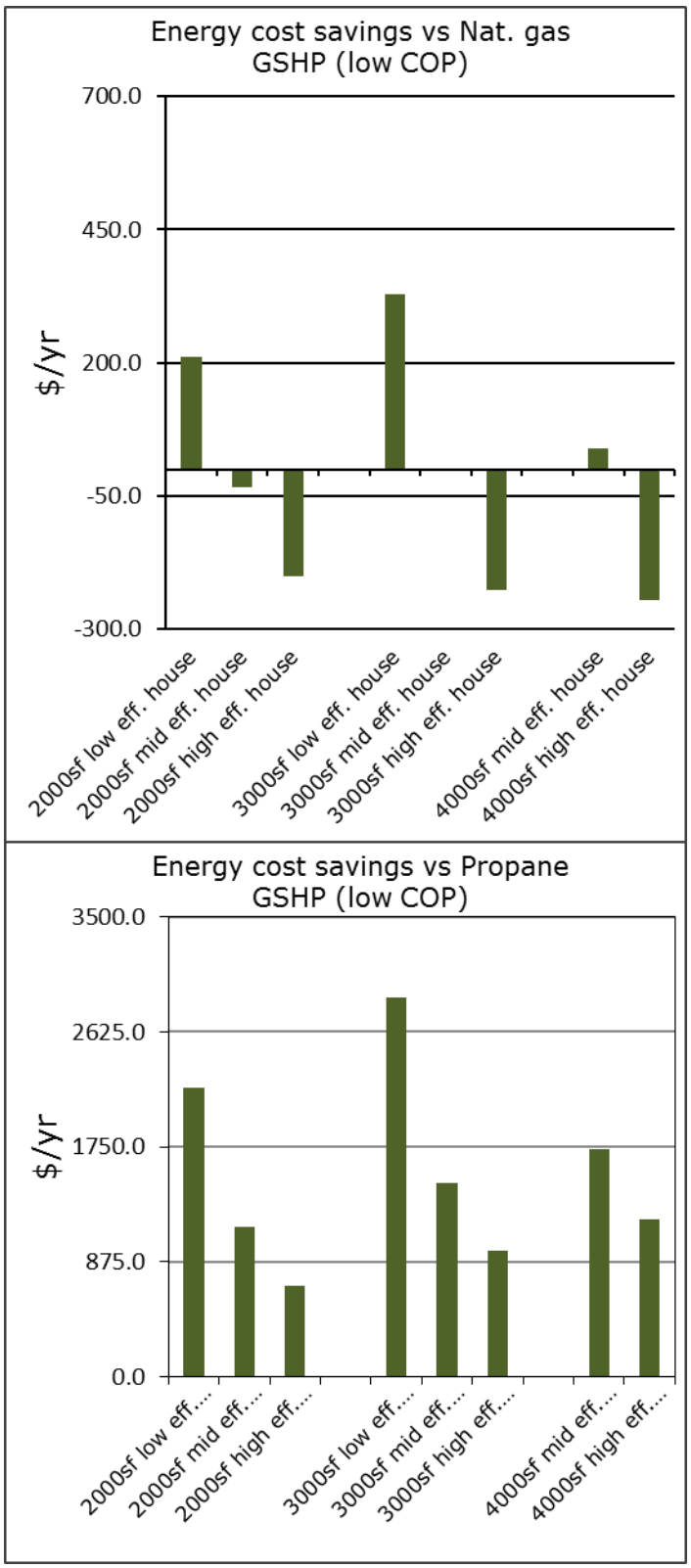


Figure 22: Energy cost savings for GSHP-based systems, with medium COP

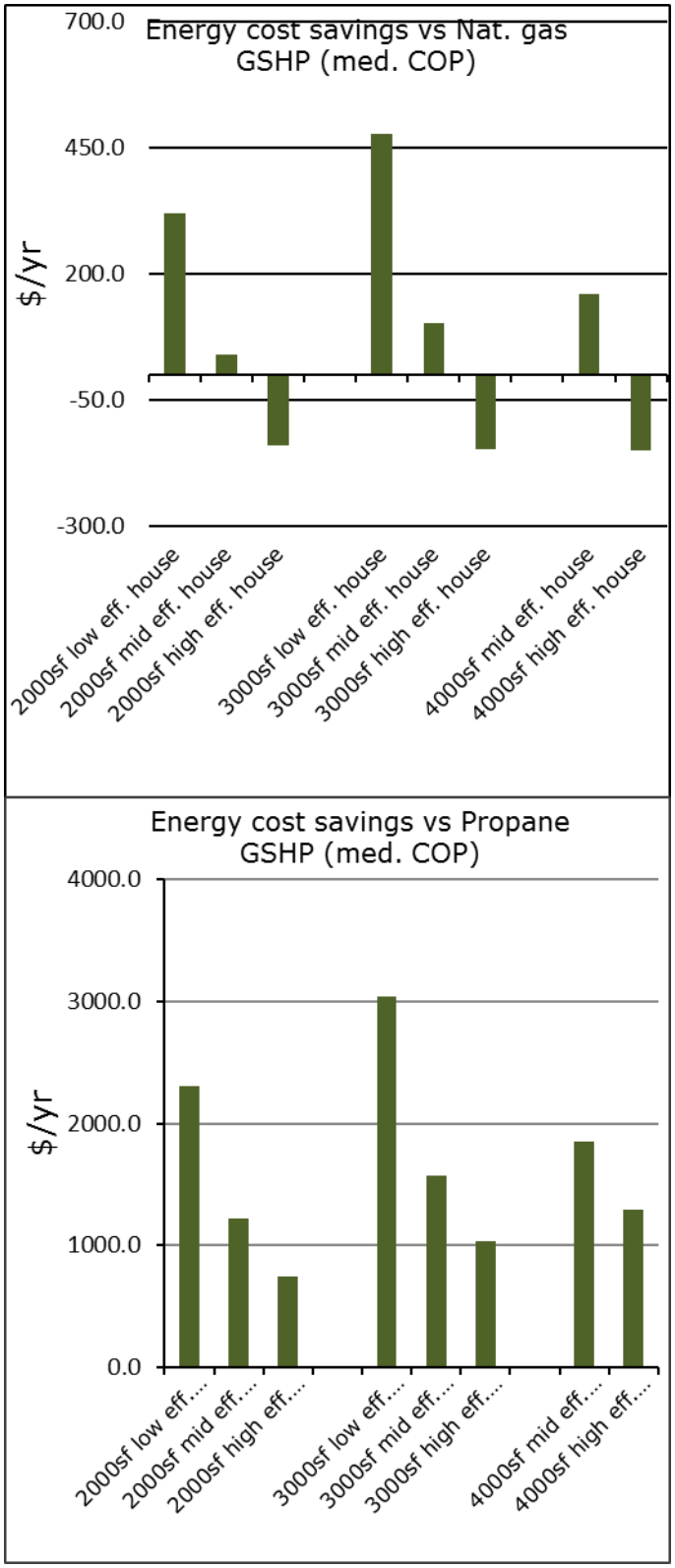
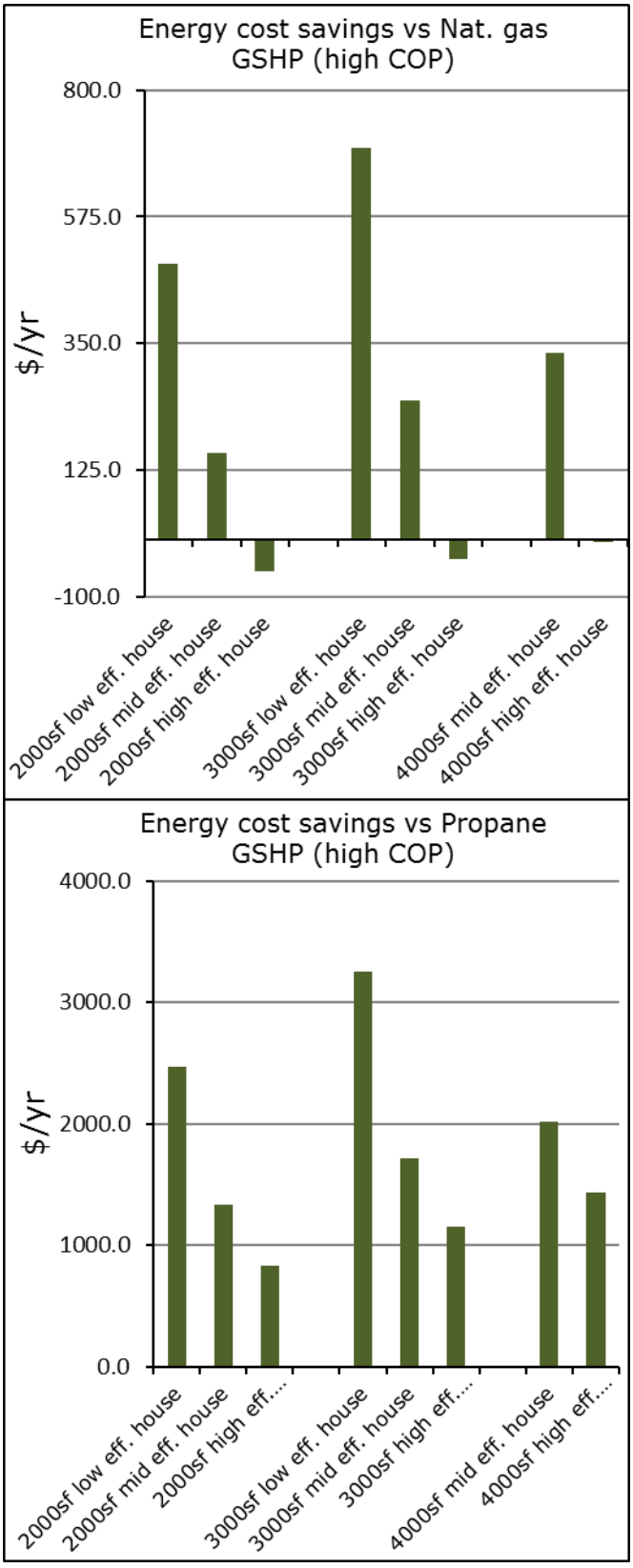


Figure 23: Energy cost savings for GSHP-based systems, with high COP



## Carbon Dioxide Emissions

Carbon dioxide ($CO_2$) emissions are an important component of GSHP systems' impact on the environment. $CO_2$ is a "greenhouse gas" that is emitted as a primary combustion by-product when fossil fuels are burned. It can be an indicator of other air pollutants as well, such as NOx, SOx, particulates, and mercury. That is, higher $CO_2$ emissions are often tied to higher emissions of these other pollutants. However, for the purposes of this report, we chose to track emissions in terms of $CO_2$ only.

Different types of fossil fuel are "dirtier" or "cleaner" depending on how much $CO_2$ and other pollutants they release into the air during combustion. Natural gas and propane are relatively "clean" fuels, as they emit very low levels of dangerous pollutants like particulates and mercury, as well as lower levels of $CO_2$. Coal releases significantly larger quantities of all these pollutants when burned. Electricity used on site (to run GSHP equipment for example) could be considered a clean energy source as there are no combustion or combustion by-products introduced into the home. However, the fossil fuels used to generate electricity at the power plant do release $CO_2$ and, because so much of this thermal energy is lost in conversion to electricity, grid electricity has a very high $CO_2$ emissions factor (roughly five times greater than natural gas). Moreover, a large percentage of electricity used in Minnesota still comes from coal, which has significantly higher $CO_2$ emissions than natural gas or propane that might be burned in a furnace or water heater on site.

The source emission factor for electricity is calculated using the current "fuel mix" or ratio of different fossil fuels and other energy sources used to generate the electricity used in Minnesota. Table 31 shows the source emissions factors for grid electricity, natural gas, and propane assumed for $CO_2$ emissions calculations. Renewable energy like wind power or solar power has essentially no $CO_2$ emissions. As the fuel mix used to generate electricity changes away from coal towards more renewable energy and/or lower emissions fuels such as natural gas, electricity's $CO_2$ emission factor will decline. Emissions factors for natural gas and propane burned on site are somewhat easier to calculate, and standardized factors for these fuels are provided by the US Energy Information Administration (EIA). The specific source emissions factors used in this report were provided by the State of Minnesota's Pollution Control Agency (PCA).

Table 31: Source emissions factors

| Energy Type | Rate | Units | Source | lbs $CO_2$/MMBtu |
|---|---|---|---|---|
| electricity | 1.82 | lbs $CO_2$/kWh | MN PCA (from 2005 eGrid MROW) | 533.4 |
| natural gas | 11.79 | lbs $CO_2$/therm | US EIA Form EIA-1605 Instructions "Voluntary Reporting of Greenhouse Gases", 2010 | 117.9 |
| propane | 12.55 | lbs $CO_2$/gallon | US EIA Form EIA-1605 Instructions "Voluntary Reporting of Greenhouse Gases", 2010 | 137.4 |

In general, an analysis of the results from Table 24 shows that GSHP systems do not provide $CO_2$ emissions savings. This is true for both the comparison to natural gas-fired and propane-

fired GFA systems. The one exception in this comparison is for low-efficiency propane-fired GFA systems, in which case a small amount of $CO_2$ savings are possible, provided the GSHP achieves better-than average performance. Similar to the analysis of source energy, the reason for this lack of savings is due to the GSHP's use of grid electricity, and its high CO2 emission factor. If the GSHP used electricity primarily from a renewable source on site, or the $CO_2$ emissions rate of grid electricity was decreased, GSHP systems would provide savings. For comparison with Table 31: Source emissions factors, at an emissions factor around 1.2 lbs $CO_2$/kWh (380 lbs $CO_2$/MMBtu), mid-COP GSHP systems could begin to provide $CO_2$ savings compared to medium efficiency houses with GFA systems (built to 1980's energy code). It would require an emissions rate of less than 1 lb $CO_2$/kWh (290 lbs $CO_2$/MMBtu) for mid-COP GSHP systems to break even with high efficiency houses with GFA systems (built to 2015 MN energy code). This would require cutting the emissions factor used in this report by 45%. Test cases for source emissions savings are shown in Table 32and Table 33. In Figure 24 source emissions for a medium COP GSHP system are compared to a natural gas-fired GFA system.

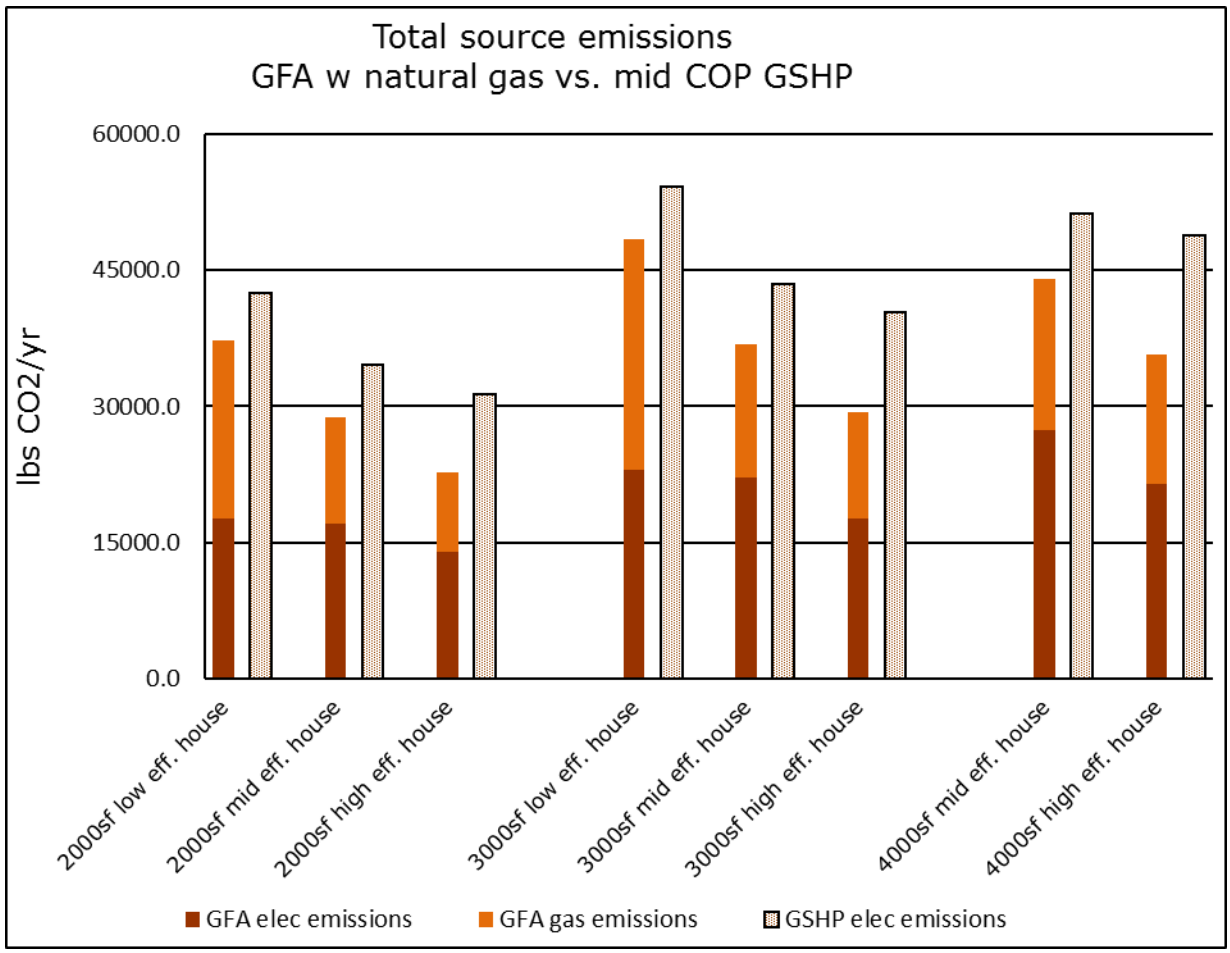
Table 32: Source emissions savings compared to natural gas-fired GFA system, lbs $CO_2$/yr (Negative numbers indicate GSHP systems increase $CO_2$ emissions)

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) nat. gas | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | -7048 | -7003 | -9604 | -8416 | -8250 | -12307 | -9053 | -14749 |
| GSHP med. COP | -5181 | -5776 | -8590 | -5856 | -6596 | -10974 | -7079 | -13095 |
| GSHP high COP | -2248 | -3856 | -7150 | -2068 | -4143 | -9000 | -4199 | -10588 |

Table 33: Source emissions savings compared to propane-fired GFA system, lbs $CO_2$/yr (Negative numbers indicate GSHP systems increase $CO_2$ emissions)

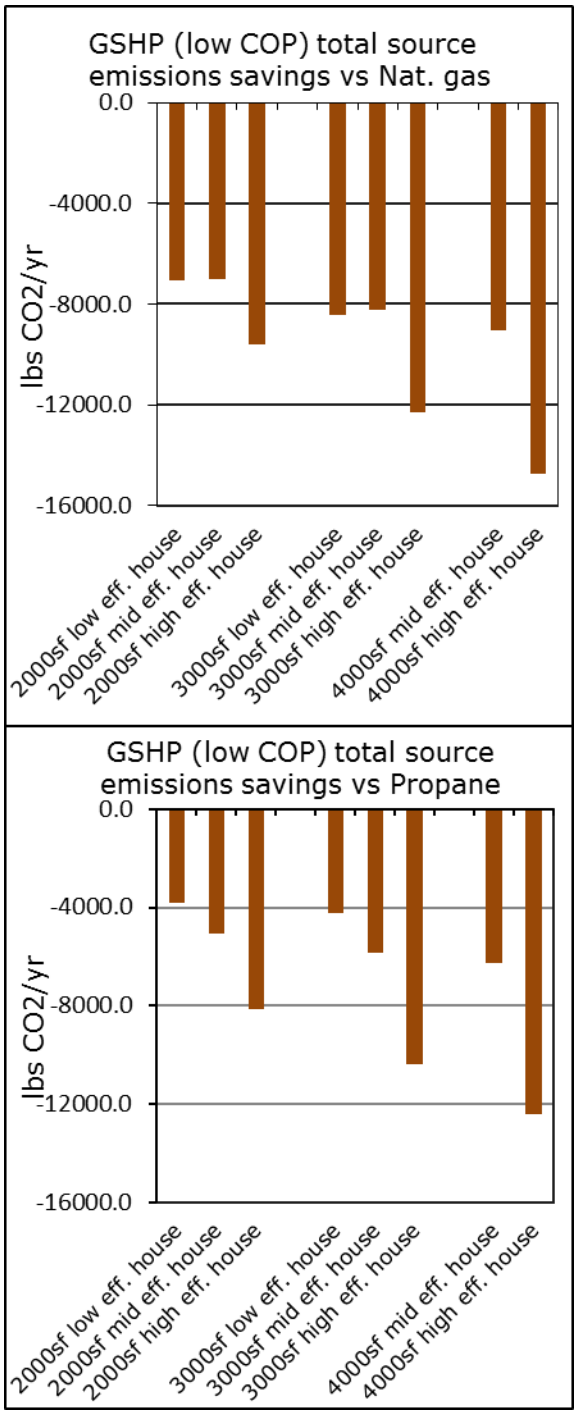
| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) propane | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | -3798 | -5073 | -8145 | -4216 | -5833 | -10362 | -6281 | -12386 |
| GSHP med. COP | -1931 | -3846 | -7131 | -1655 | -4179 | -9029 | -4307 | -10732 |
| GSHP high COP | 1003 | -1926 | -5691 | 2132 | -1725 | -7055 | -1427 | -8225 |

Figure 24: Source emissions for GFA vs. GSHP-based system with medium COP.



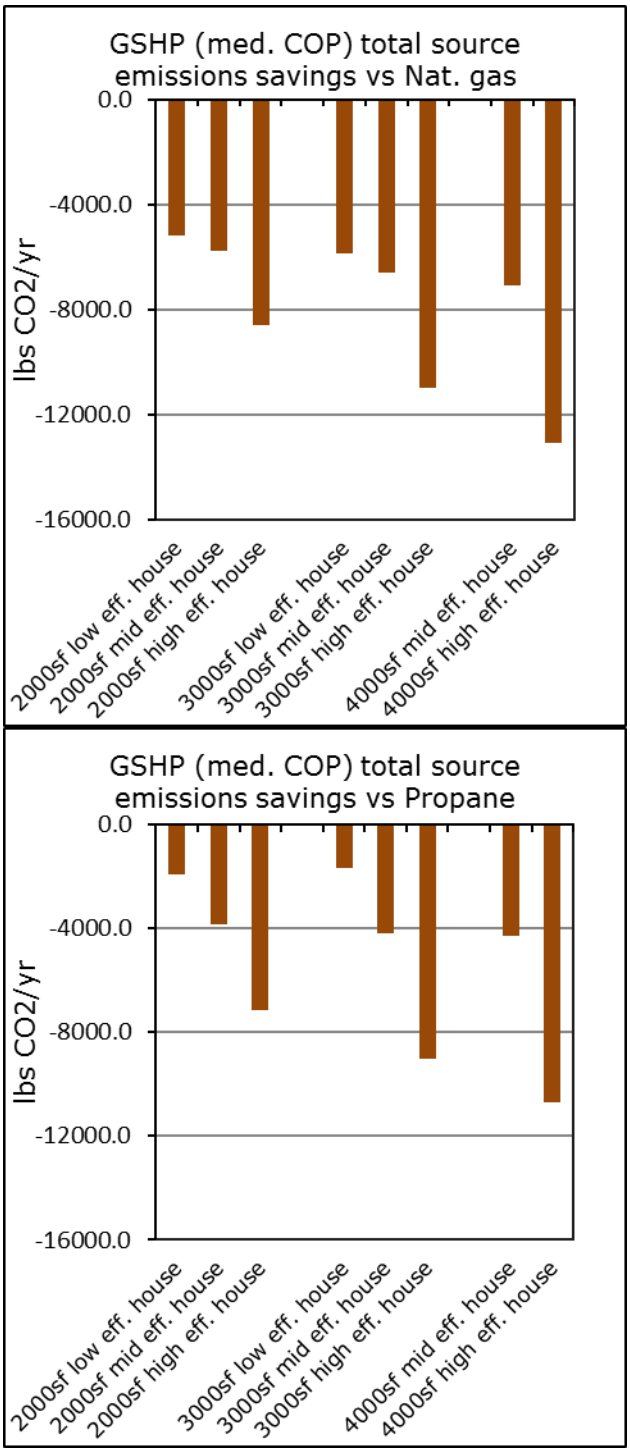
At low system COPs, GSHPs powered with grid electricity offer no $CO_2$ emissions savings. They typically increase $CO_2$ emissions by 20-40%, frequently by more than 8000 lbs/yr compared to natural gas-fired GFA systems (Figure 25).

Figure 25: Source emissions savings ($CO_2$) for GSHP-based systems, with low COP. (Negative numbers indicate $CO_2$ increase.)



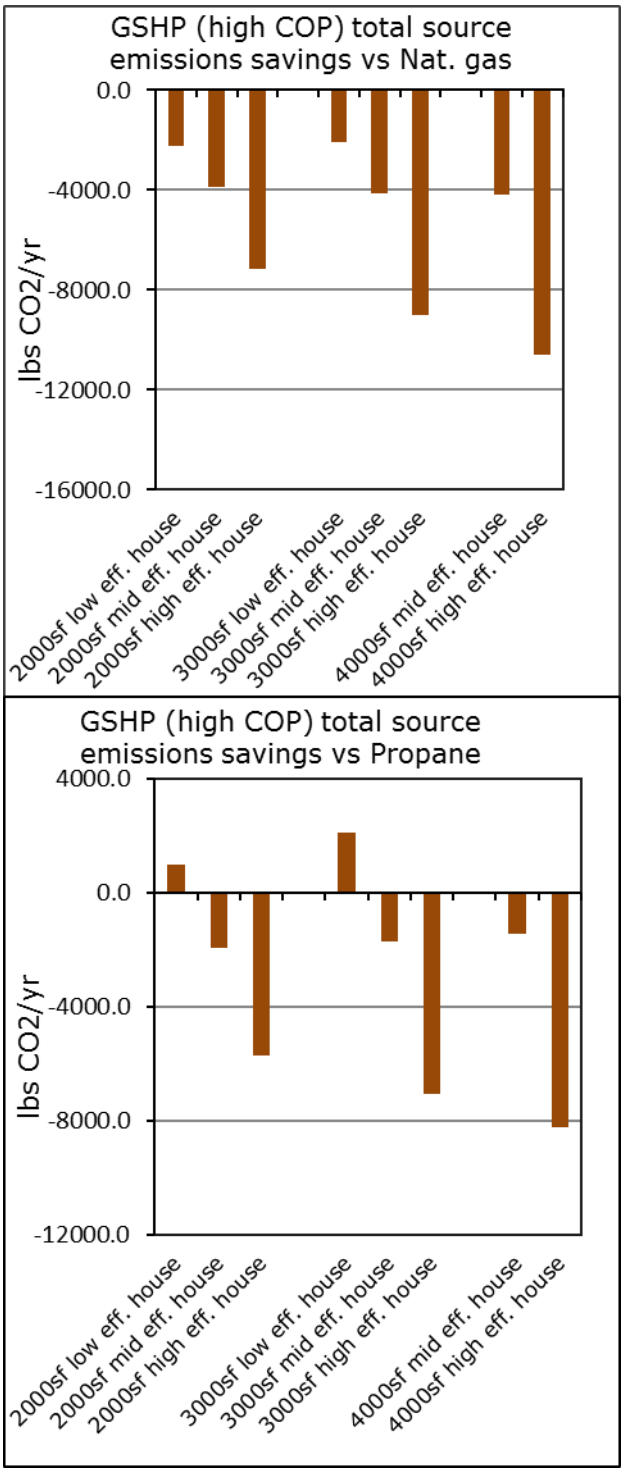
At medium system COPs, GSHPs powered with grid electricity offer no $CO_2$ emissions savings. They typically increase $CO_2$ emissions by 15-35%, frequently by more than 6000 lbs/yr compared to natural gas-fired GFA systems (Figure 26).

Figure 26: Source emissions savings ($CO_2$) for GSHP-based systems, with medium COP. (Negative numbers indicate $CO_2$ increase.)



At high system COPs, GSHP systems powered with grid electricity offer no or limited $CO_2$ emissions savings. They typically increase $CO_2$ emissions by 5-30%, frequently by 4000 lbs/yr or more compared to natural gas-fired GFA systems (Figure 27).

Figure 27: Source emissions savings ($CO_2$) for GSHP-based systems, with high COP. (Negative numbers indicate $CO_2$ increase.)



## *Impact of Desuperheaters*

An important factor to consider in the comparison of GSHP and GFA systems is the ability of GSHPs to supplement the domestic hot water heater with the use of a desuperheater. To determine whether desuperheaters provide sizeable energy, emissions, and cost savings within the larger framework of GSHP systems, we performed a side study of the technology using energy modeling. The intention of the side study was not to precisely determine savings but rather use an industry-accepted energy modeling tool to generate a reasonable range of savings that could be expected.

Energy savings from a desuperheater are highly dependent on climate, and are greatest in cooling-dominated climates. An early study done by Oak Ridge National Laboratories found that desuperheaters could provide nearly 2x more energy savings in hot, humid climates than in cold climates such as Minneapolis/St. Paul. (Olszewski, 1983). In practice, energy savings from desuperheaters in cold climates may be even lower than estimated in this study since many people in Minnesota choose not to use an air conditioner (or use it sparingly) in the summer.

When in cooling mode, the GSHP system can move waste heat extracted from the house into the domestic hot water, saving energy and reducing water heating costs. When in heating mode the GSHP can also provide domestic hot water but in this scenario there is no "free heat" available from the house. Instead, the GSHP provides heat primarily from the ground, which would otherwise go towards heating the house. Nonetheless, there can still be energy and cost savings, especially if the alternative is electric resistance water heating. This is because the GSHP/desuperheater provides heat at a COP greater than 1, while electric resistance heating in a domestic hot water tank has a COP of slightly less than 1. Desuperheaters are not stand-alone water heating systems. They must be paired with a more conventional water heater such as an electric or fuel-fired tank capable of meeting all the domestic hot water loads when the GSHP system is not running. The larger the share of hot water provided by the desuperheater, the greater the potential energy and cost savings.

In Minnesota climates, most residential GSHP systems operate in cooling mode relatively infrequently, limiting the energy and cost savings available from the use of a desuperheater. Despite this, 62% of GSHP systems in the field study incorporated a desuperheater. The exact savings available from a desuperheater are often difficult to estimate because they strongly depend on operation of the GSHP in cooling mode. As seen in the field study, many Minnesotans choose not to use the cooling mode on their GSHP or do so infrequently. This means that desuperheater savings vary greatly depending on individual preferences and choices and may not often match their potential or predicted savings.

To sidestep this issue and quantify the expected impacts from desuperheater use in a Minneapolis/St. Paul climate, we performed a side-study of GSHP systems incorporating desuperheaters. This side study was based on energy modeling results only because there was not enough data collected in the field study to pinpoint desuperheater energy savings or efficiency. Therefore, unlike most of the results in the energy modeling section which are based on actual measurements of GSHP system efficiency, the results discussed in this side study are not based on field data. However, REM Rate is an industry-accepted energy modeling program which we deemed acceptable for providing a rough approximation of the energy impact of desuperheaters in this climate.

Energy modeling included the impact of desuperheaters operating in both the cooling and heating seasons. The GSHP systems operating at mid-level COPs were selected and modeled with desuperheaters for all house sizes and efficiency levels. REM Rate does not include detailed inputs for desuperheater systems. A simple check box is used to indicate that the GSHP system has a desuperheater. The program then calculates the estimated energy use for domestic hot water taking into account the efficiency of the GSHP unit and water heater, as well as tank size. We recalculated energy (site and source), energy cost, and $CO_2$ emissions savings compared to both natural gas and propane-based systems.

Based on energy modeling results, cooling season desuperheater use accounts for between 80 - 90% of the total energy savings offered by the desuperheater. This confirms the necessity of GSHP operation in the cooling season if significant energy savings are expected from the desuperheater. Model results show that desuperheaters do increase site energy savings compared to propane and natural gas-fired GFA-based systems. However, the savings are relatively small, amounting to 2-4% of the total site energy savings offered by the GSHP system. Total system source energy savings over natural gas and propane-fired GFA systems are smaller and in some cases negative compared to site energy savings. However, the source energy savings that can be attributed to the desuperheater alone are larger, because the desuperheater reduces the GSHP systems' reliance on electric resistance hot water tanks. With the addition of the desuperheater, modeled energy cost savings over natural gas-fired GFA systems increase slightly and more so for propane-fired GFA systems. $CO_2$ emissions savings over natural gas and propane-fired GFA systems are negative in almost all comparison cases and remain negative despite the addition of a desuperheater.

Energy model results show (Table 34) that desuperheaters do increase site energy savings compared to propane and natural gas-fired GFA-based systems. Savings due to the desuperheater alone range from 1.6 to 4.1 MMBtu/yr. depending on hot water load and efficiency of the hot water tank. This is a relatively small savings, amounting to 2-4% of the total site energy savings offered by the GSHP system. The impact of using a desuperheater is approximately half that of improving GSHP systems from mid to high COP.

Table 34: Site energy savings comparison, MMBtu/yr

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | 116.5 | 63.8 | 43.3 | 151.8 | 81.0 | 58.7 | 93.6 | 71.9 |
| GSHP med. COP | 120.0 | 66.1 | 45.2 | 156.6 | 84.1 | 61.2 | 97.3 | 75.0 |
| **GSHP med. COP w Desup.** | **122.6** | **68.6** | **46.8** | **160.1** | **87.5** | **63.4** | **101.4** | **77.8** |
| GSHP high COP | 125.5 | 69.7 | 47.9 | 163.7 | 88.7 | 64.9 | 102.7 | 79.7 |

Energy model results show (Table 35) that desuperheaters are expected to save 12-22% of domestic hot water energy use in a Minneapolis/St. Paul climate, again depending on the hot water load and efficiency of the hot water tank. The higher percentage savings correspond with larger hot water loads (larger home sizes) and lower efficiency tank water heaters.

Table 35: Domestic hot water energy (site), MMBtu/yr.

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Site energy savings due to desuperheater | 2.6 | 2.5 | 1.6 | 3.5 | 3.4 | 2.2 | 4.1 | 2.8 |
| DHW energy use w/out desuperheater (electric tank) | 13.9 | 13.9 | 13.5 | 16.4 | 16.4 | 16.0 | 18.8 | 18.5 |
| Percentage DHW energy savings | 18.7% | 18.0% | 11.9% | 21.3% | 20.7% | 13.8% | 21.8% | 15.1% |

Modelled source energy savings over natural gas and propane-fired GFA systems are smaller and in some cases negative compared to site energy savings. However, the source energy savings (Table 36) that can be attributed to the desuperheater alone are larger than the site energy savings discussed above. This is because the desuperheater reduces the GSHP systems' reliance on electric resistance hot water tanks – which consume a great deal of source energy. The desuperheater's additional source energy savings make up a significant portion of the total source energy savings offered in low and medium efficiency home cases. The impact of using a desuperheater is approximately half that of improving GSHP systems from mid to high COP. However, the addition of a desuperheater is not adequate to generate a net positive source energy savings for GSHP systems compared to fuel-fired GFA systems installed in new construction (Table 37).

Table 36: Source energy savings comparison (propane base case), MMBtu/yr.

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | 34.0 | 3.5 | -22.8 | 48.0 | 7.5 | -27.4 | 11.0 | -32.1 |
| GSHP med. COP | 45.0 | 10.8 | -16.8 | 63.1 | 17.3 | -19.6 | 22.7 | -22.4 |
| **GSHP med. COP w Desup.** | **53.2** | **18.6** | **-11.7** | **74.1** | **28.0** | **-12.6** | **35.6** | **-13.6** |
| GSHP high COP | 62.3 | 22.1 | -8.3 | 85.5 | 31.8 | -7.9 | 39.7 | -7.6 |
| Source energy savings due to addition of desuperheater | 8.2 | 7.9 | 5.0 | 11.0 | 10.7 | 6.9 | 12.9 | 8.8 |

Table 37: Source energy savings comparison (natural gas base case), MMBtu/yr.

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | 24.0 | -2.4 | -27.3 | 35.1 | 0.1 | -33.4 | 2.5 | -39.4 |
| GSHP med. COP | 35.0 | 4.8 | -21.3 | 50.2 | 9.8 | -25.5 | 14.1 | -29.6 |
| **GSHP med. COP w Desup.** | **43.2** | **12.7** | **-16.2** | **61.2** | **20.5** | **-18.6** | **27.1** | **-20.8** |
| GSHP high COP | 52.3 | 16.2 | -12.8 | 72.6 | 24.3 | -13.9 | 31.2 | -14.8 |
| Source energy savings due to addition of desuperheater | 8.2 | 7.9 | 5.0 | 11.0 | 10.7 | 6.9 | 12.9 | 8.8 |

Table 38 and Table 39 show modelled energy cost savings over natural gas-fired GFA systems increase slightly with the addition of a desuperheater. However, they remain negative compared to high-efficiency natural gas-fired GFA systems installed in new construction. Cost savings over propane-fired GFA systems are large and again increase slightly with the addition of a desuperheater.

Table 38: Energy Cost savings comparison (natural gas base case), $/yr.

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | $212 | -$33 | -$201 | $328 | $2 | -$227 | $39 | -$246 |
| GSHP med. COP | $321 | $40 | -$141 | $478 | $102 | -$148 | $159 | -$149 |
| **GSHP med. COP w Desup.** | **$410** | **$126** | **-$86** | **$597** | **$218** | **-$73** | **$299** | **-$53** |
| GSHP high COP | $491 | $155 | -$56 | $698 | $249 | -$34 | $334 | -$3 |
| Energy cost savings due to addition of desuperheater | $89 | $85 | $55 | $120 | $116 | $75 | $140 | $96 |

Table 39: Energy Cost savings comparison (propane base case), $/yr,

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | $2,194 | $1,144 | $689 | $2,890 | $1,476 | $959 | $1,730 | $1,195 |
| GSHP med. COP | $2,303 | $1,217 | $749 | $3,039 | $1,576 | $1,038 | $1,850 | $1,292 |
| **GSHP med. COP w Desup.** | **$2,392** | **$1,303** | **$804** | **$3,159** | **$1,692** | **$1,113** | **$1,990** | **$1,387** |
| GSHP high COP | $2,473 | $1,331 | $834 | $3,259 | $1,723 | $1,153 | $2,024 | $1,438 |
| Energy cost savings due to addition of desuperheater | $89 | $85 | $55 | $120 | $116 | $75 | $140 | $96 |

The modelled energy cost savings due to the addition of a desuperheater range from $55 to $140 per year (Table 38 and Table 39). They are the same for both natural gas and propane because the desuperheater in both sets of cases supplements the same electric tank water heater (assumed as part of the GSHP package).

$CO_2$ emissions savings over natural gas and propane-fired GFA systems are negative in almost all comparison cases and remain negative despite the addition of a desuperheater. According to modelling results, the addition of a desuperheater saves between 850 and 2,200 lbs $CO_2$/yr, which is significant but not large enough to generate net positive emissions savings for GSHP systems in most cases (Table 40 and Table 41.

Table 40: Source emissions savings comparison (natural gas base case), lbs, $CO_2$/yr,

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | -7048 | -7003 | -9604 | -8416 | -8250 | -12307 | -9053 | -14749 |
| GSHP med. COP | -5181 | -5776 | -8590 | -5856 | -6596 | -10974 | -7079 | -13095 |
| **GSHP med. COP w Desup.** | **-3795** | **-4442** | **-7737** | **-3989** | **-4783** | **-9800** | **-4892** | **-11601** |
| GSHP high COP | -2248 | -3856 | -7150 | -2068 | -4143 | -9000 | -4199 | -10588 |
| Emissions savings due to addition of desuperheater | 1387 | 1334 | 853 | 1867 | 1814 | 1174 | 2187 | 1494 |

Table 41: Source emissions savings comparison (propane base case), lbs $CO_2$/yr.

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| **Case #** | **1** | **4** | **7** | **2** | **5** | **8** | **6** | **9** |
| Base case (GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | -3798 | -5073 | -8145 | -4216 | -5833 | -10362 | -6281 | -12386 |
| GSHP med. COP | -1931 | -3846 | -7131 | -1655 | -4179 | -9029 | -4307 | -10732 |
| **GSHP med. COP w Desup.** | **-544** | **-2513** | **-6278** | **212** | **-2365** | **-7855** | **-2120** | **-9239** |
| GSHP high COP | 1003 | -1926 | -5691 | 2132 | -1725 | -7055 | -1427 | -8225 |
| Emissions savings due to addition of desuperheater | 1387 | 1334 | 853 | 1867 | 1814 | 1174 | 2187 | 1494 |

# Economics and Policy

## PEIT (Policy, Economy, Institution and Technology) Matrix

The PEIT matrix describes major factors from four categories that impact the deployment of residential GSHP systems in Minnesota, including regulatory and legal requirements (policy), economic factors that influence adoption (economics), institutional context for deployment (institutional), and technical factors that influence deployment. The matrix can help realize key barriers and opportunities for deployment of residential GSHP systems in Minnesota and provide guidance for stakeholders of the promotion of residential GSHP systems in Minnesota.

### *Political*

The line between designation of a technology as either "renewable" or "efficiency" is a blurry one. Traditionally, only renewable generation systems that produced electricity that could be metered were counted as renewable technologies. For this reason, residential ground source heat pumps (GSHPs) were traditionally designated as efficiency systems rather than renewable systems, because they do not generate electricity but rather use the earth's energy to reduce the amount of electricity needed to be purchased or otherwise generated. Additionally, residential GSHPs require electrical input to operate, making them seem more like traditional efficiency technologies. However, the GSHP industry has consistently maintained that residential GSHPs are a renewable resource because "the technology leverages renewable solar-derived heat stored in the ground and converts it into a useable form, namely building heating, and thus has the same net as other renewable energy systems such as solar thermal" (Williams, 2012)

Reflecting adoption of the GSHP industry perspective, GSHP systems are beginning to be recognized as renewable resources in some instances. For example, the federal Residential Renewable Energy Tax Credit includes GSHP systems among other more traditional renewable technologies, such as solar thermal, solar photovoltaic (PV), wind generation systems, and fuel cells that use renewable fuels (DSIRE, 2016). However, for GSHP systems to qualify for the federal residential tax credit, which reimburses residential property-owners for 30% of the cost of a renewable generation system, the system must be Energy-Star-rated, possibly implying that the system is being thought about as both an efficiency and renewable measure. Put another way, this may suggest that an Energy-Star-rated GSHP is being considered as an efficient form of energy generation by the federal government for the purposes of the Residential Renewable Credit (DSIRE, 2016).

To try to make the lines even clearer and on a wider scale, the Geothermal Exchange Organization (GEO) and GSHP manufacturers have been pushing for a more general federal declaration, rather than just the single inclusion under the Residential Renewable Credit, that GSHPs are renewable energy resources rather than efficiency improvements (ACHR News, 2014). GEO advocates argue that a federal definition would make it more likely that states would include GSHPs in their renewable portfolio standards (RPSs) rather than in their energy efficiency resource standards (EERSs), which matters because RPSs tend to be stronger and more ambitious than EERSs (ACHR News, 2014). While small in number, a few states do

already include GSHPs as part of their renewable portfolio requirements - including Maryland, New Hampshire, and Wisconsin (Williams, 2012).

Another important aspect of including GSHP systems in RPS requirements is how the renewable energy credits (RECs) for generation systems are assigned. For example, a utility only gets credit toward its RPS requirements for a PV system if it obtains both the electricity generated from a customer-sited PV system and the associated RECs. How RECs from customer-sited generation are assigned depends on the state, including how RECs are assigned for GSHPs in states that allow RECs for GSHP systems. Under current legislation in Minnesota, GSHP systems are not considered renewable energy.

While electric utilities have renewable energy requirements defined in Minnesota statute, GSHPs are not included in the definition of "renewable energy" in Minnesota statutes. According to Minnesota Statutes 216B.1691:

> "'eligible energy technology' means an energy technology that generates electricity from the following renewable energy sources: (1) solar; (2) wind; (3) hydroelectric with a capacity of less than 100 megawatts; (4) hydrogen, provided that after January 1, 2010, the hydrogen must be generated from the resources listed in this paragraph; or (5) biomass . . ."

Even if GSHPs were to be defined as renewable energy in statute, whether an electric utility could count electricity purchased from GSHPs as part of their renewable requirement is unclear. For types of energy classified as renewable energy, only some can be counted towards a utility's RPS requirements. For example, with solar energy systems, utilities receive credit for electricity purchased from customer-sited solar if the utility chooses to adopt a value of solar tariff (VOST) but not if they are purchasing the electricity through net metering. For Xcel community solar gardens that apply in 2017, the bill credit rate will be calculated using the Value of Solar methodology. For Xcel CSGs that were in development before 2017, customers can choose to be compensated using the applicable retail rate (ARR), under which the utility does not receive the RECs for the electricity generated and therefore cannot count that electricity towards their renewable electricity requirements; customers can also opt to receive an additional payment in exchange for the RECs associated with the electricity and therefore the utility can count the electricity generated toward their renewable requirements (Minnesota Public Utilities Commission, 2014). Based on this complicated scheme, it is hard to predict how RECs would be assigned in Minnesota were the legislation changed to allow GSHPs to count toward utility RPS requirements. One option would be to establish a thermal equivalent of 3.142 MMBtu/REC, with an approved process to measure or estimate Btus, and allow the utilities to propose GSHP incentive programs to procure RECS from GSHPs paired with renewable energy offsets for estimated lifetime electricity use.

Although GSHPs do not qualify as renewable technologies under Minnesota law, they do qualify as efficiency (or conservation) improvements that can be counted as such by utilities. Under Minn. Stat. § 216B.241, Xcel Energy is required to spend at least two percent of its annual gross operating revenues (GOR), and all other electric utilities in Minnesota are required to spend 1.5% of their GOR, on conservation improvement program (CIP) investments. In addition, each electric and natural gas utility is required to meet an energy savings goal of 1.5% of average retail sales. Utilities file their CIP plans with the Minnesota Department of Commerce's Division of Energy Resources for review and approval. As a result, the funds used

by utilities to issue rebates to their customers for installation of GSHPs to replace electric resistance heat can be counted as part of the utilities' energy savings and investment in conservation improvements.

Nearly every electric utility in Minnesota offers some form of a rebate for GSHP installation (see attached survey of Minnesota utility incentives for GSHPs). Despite the plethora of rebates and incentives offered by municipal utilities in Minnesota, however, some municipal utilities struggle to spend their required CIP expenditures every year because their customers are unaware of or are unwilling to make the effort needed to take advantage of such incentives. Some utilities have no minimum efficiency requirements for GSHPs, allowing customers to receive rebates for installing GSHP systems no matter how inefficient they are. If utilities were more easily able to encourage customer participation in CIP programs, they may be able to be more stringent in their rebate efficiency requirements.

## Economy

Rebates and financial incentives provided by federal and state government for residential GSHP systems are significant economic benefits for consumers who are considering whether to adopt such technology for space heating and cooling at home. The incentives can compensate the relatively high capital cost of GSHP systems and make GSHP systems cost-competitive in the market.

We evaluated the economic feasibility of the GSHP systems by calculating the present value (PV) of their total cost, including the capital cost (installation cost included), the maintenance cost, the operational cost, and the available rebates over a time horizon of 20 years (from 2015 to 2034). We used the following inputs and assumptions:

- U.S. dollars inflation rate of 1.99%, averaged from past five years 2010-2014 (InflationData.com, 2015)
- Estimates of the capital cost and the annual maintenance cost were obtained from the existing studies and manufacturer pricings (Kavanaugh, Gilbreah, & Kilpatrick, 1995) (Geothermal Systems, LLC, 2009) (Kleine, 2009) (Meyer, Pride, O'Toole, Craven, & Spencer, 2011) (EERE, US-DOE, 2011) (QualitySmith, 2012).
- Capital costs of individual components are from different years but all normalized to the year 2015.
- It was assumed that the annual maintenance costs of all GSHP systems are the same.
- The annual energy cost was estimated based on the annual energy use described in the Energy Modeling section in this study and the energy prices in Table 8, 9 and 10.
- For the financial incentives, a GFA system does not receive a rebate due to its COP of 90 and lower and SEER of 13 and lower, both of which are not high enough to be qualified for rebates.
- All GSHP systems obtained capital cost deduction by receiving the federal personal tax credit of 30% and a $400/ton rebate from Minnesota local utilities (DSIRE, 2012a) (EIA, 2010) (Minnesota Public Utilities Commission, 2012a) (Minnesota Public Utilities Commission, 2012b).

- In order to reflect the fluctuations of U.S. dollars over the life span (20 years) of the GSHP system, an upper annual U.S. dollar inflation rate of 3.16% and a lower annual fuel price escalation rate of 1.47% (U.S. EIA, 2015) were used.

Table 42, Table 43 and Figure 28 display the life cycle cost saving comparisons of gas-fired GFA to GSHP systems, whereas Table 44, Table 45 and Figure 29 display the life cycle cost saving comparisons of propane-fired GFA to GSHP systems.

Table 42: Life cycle cost savings compared to natural gas-fired GFA system (2015 U.S. dollars) (negative numbers indicate negative savings)

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| House efficiency | Low | Med. | High | Low | Med. | High | Med. | High |
| Base case (gas-fired GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | -$4,139 | -$8,835 | -$11,895 | -$1,585 | -$7,855 | -$11,954 | -$6,936 | -$11,931 |
| GSHP med. COP | -$2,329 | -$7,612 | -$10,893 | $910 | -$6,191 | -$10,633 | -$4,930 | -$10,317 |
| GSHP high COP | $508 | -$5,704 | -$9,474 | $4,579 | -$3,746 | -$8,725 | -$2,020 | -$7,871 |

Figure 28: Life cycle costs PV (present value) of natural gas-fired GFA and GSHP systems.

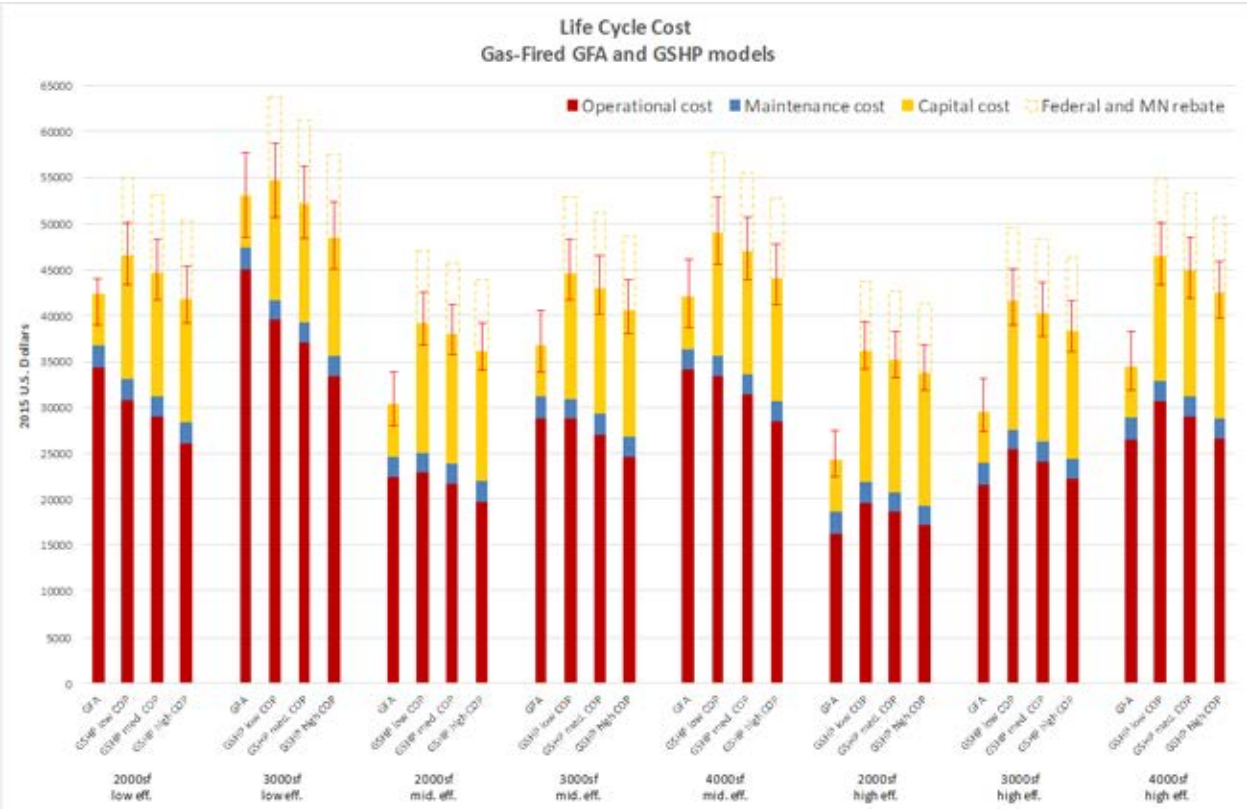


Table 43: Detailed costs and rebates of each natural gas-fired GFA and GSHP systems

| House | Description | Capital cost | Maintenance cost | Operational cost | Total cost | Federal rebate | MN utility based rebate | 20-year cost |
|---|---|---|---|---|---|---|---|---|
| 2000sf low eff. house | Gas-fired GFA | 5,634 | 2,357 | 34,360 | 42,351 | 0 | 0 | 42,351 |
| | GSHP low COP | 13,495 | 2,176 | 30,819 | 54,950 | 6,586 | 1,873 | 46,490 |
| | GSHP med. COP | 13,495 | 2,176 | 29,009 | 53,140 | 6,586 | 1,873 | 44,680 |
| | GSHP high COP | 13,495 | 2,176 | 26,172 | 50,302 | 6,586 | 1,873 | 41,843 |
| 3000sf low eff. house | Gas-fired GFA | 5,634 | 2,357 | 45,027 | 53,017 | 0 | 0 | 53,017 |
| | GSHP low COP | 12,878 | 2,176 | 39,548 | 63,679 | 6,586 | 2,490 | 54,602 |
| | GSHP med. COP | 12,878 | 2,176 | 37,053 | 61,184 | 6,586 | 2,490 | 52,108 |
| | GSHP high COP | 12,878 | 2,176 | 33,385 | 57,515 | 6,586 | 2,490 | 48,439 |
| 2000sf mid. eff. house | Gas-fired GFA | 5,634 | 2,357 | 22,347 | 30,338 | 0 | 0 | 30,338 |
| | GSHP low COP | 14,101 | 2,176 | 22,895 | 47,025 | 6,586 | 1,267 | 39,172 |
| | GSHP med. COP | 14,101 | 2,176 | 21,672 | 45,802 | 6,586 | 1,267 | 37,949 |
| | GSHP high COP | 14,101 | 2,176 | 19,764 | 43,894 | 6,586 | 1,267 | 36,042 |
| 3000sf mid. eff. house | Gas-fired GFA | 5,634 | 2,357 | 28,769 | 36,760 | 0 | 0 | 36,760 |
| | GSHP low COP | 13,708 | 2,176 | 28,731 | 52,861 | 6,586 | 1,660 | 44,615 |
| | GSHP med. COP | 13,708 | 2,176 | 27,067 | 51,198 | 6,586 | 1,660 | 42,952 |
| | GSHP high COP | 13,708 | 2,176 | 24,622 | 48,752 | 6,586 | 1,660 | 40,506 |
| 4000sf mid. eff. house | Gas-fired GFA | 5,634 | 2,357 | 34,067 | 42,057 | 0 | 0 | 42,057 |
| | GSHP low COP | 13,401 | 2,176 | 33,416 | 57,546 | 6,586 | 1,967 | 48,994 |
| | GSHP med. COP | 13,401 | 2,176 | 31,410 | 55,541 | 6,586 | 1,967 | 46,988 |
| | GSHP high COP | 13,401 | 2,176 | 28,500 | 52,630 | 6,586 | 1,967 | 44,077 |
| 2000sf high eff. house | Gas-fired GFA | 5,634 | 2,357 | 16,260 | 24,251 | 0 | 0 | 24,251 |
| | GSHP low COP | 14,361 | 2,176 | 19,609 | 43,739 | 6,586 | 1,007 | 36,146 |
| | GSHP med. COP | 14,361 | 2,176 | 18,606 | 42,737 | 6,586 | 1,007 | 35,144 |
| | GSHP high COP | 14,361 | 2,176 | 17,188 | 41,318 | 6,586 | 1,007 | 33,725 |
| 3000sf high eff. house | Gas-fired GFA | 5,634 | 2,357 | 21,634 | 29,625 | 0 | 0 | 29,625 |
| | GSHP low COP | 13,978 | 2,176 | 25,424 | 49,555 | 6,586 | 1,390 | 41,578 |
| | GSHP med. COP | 13,978 | 2,176 | 24,104 | 48,234 | 6,586 | 1,390 | 40,258 |
| | GSHP high COP | 13,978 | 2,176 | 22,196 | 46,326 | 6,586 | 1,390 | 38,350 |
| 4000sf high eff. house | Gas-fired GFA | 5,634 | 2,357 | 26,565 | 34,556 | 0 | 0 | 34,556 |
| | GSHP low COP | 13,641 | 2,176 | 30,670 | 54,800 | 6,586 | 1,727 | 46,487 |
| | GSHP med. COP | 13,641 | 2,176 | 29,056 | 53,186 | 6,586 | 1,727 | 44,873 |
| | GSHP high COP | 13,641 | 2,176 | 26,610 | 50,740 | 6,586 | 1,727 | 42,427 |

In general, the life-cycle (20 years) costs of all systems were found to range from $24,251 to $54,602 in 2015 U.S. dollars (Figure 28). Due to their high capital cost, the GSHP systems cannot provide economic savings compared to the gas-fired GFA systems in most model houses

described in the Energy Modeling section, even after receiving upfront rebates from federal and state sources (Table 34). Three exceptions are the high-COP GSHP system in the 2000sf low efficiency house (net saving of $508), the medium-COP GSHP system in the 3000sf low efficiency house (net saving of $910), and the high-COP GSHP system in the 3000sf low efficiency house (net saving of $4,579). GSHP systems can provide operational cost savings in the low and in most medium efficiency houses but not in the high efficiency houses. High and low life cycle cost of GSHP systems in all the model homes are shown in Figure 28. Error bars show the high and low life costs of all systems calculated using the upper U.S. dollar inflation rate of 3.16% and a lower annual fuel price escalation rate of 1.47% (InflationData.com, 2015) yielding an annual fuel price escalation rate of 0.98% and a lower annual fuel price escalation rate of 0.18% (U.S. EIA, 2015).

When the GFA systems use propane instead of natural gas, the life-cycle (20 years) costs of all systems were found to range from $33,725 to $95,779 in 2015 U.S. dollars (Figure 29). Due to propane's high price, the GSHP systems can achieve economic savings compared to the propane-fired GFA systems in all model houses described in the Energy Modeling section (Table 34).

Table 44: Life cycle cost savings compared to propane-fired GFA system (2015 U.S. dollars) (negative numbers indicate negative savings)

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| Base case (gas-fired GFA w/AC) | NA | NA | NA | NA | NA | NA | NA | NA |
| GSHP low COP | $28,949 | $10,808 | $29,61 | $41,176 | $16,753 | $7,848 | $21,287 | $12,121 |
| GSHP med. COP | $30,759 | $12,031 | $39,64 | $43,671 | $18,416 | $9,169 | $23,292 | $13,735 |
| GSHP high COP | $33,597 | $13,939 | $53,82 | $47,340 | $20,862 | $11,077 | $26,203 | $16,181 |

Figure 29: Life cycle costs PV (present value) of propane-fired GFA and GSHP systems.

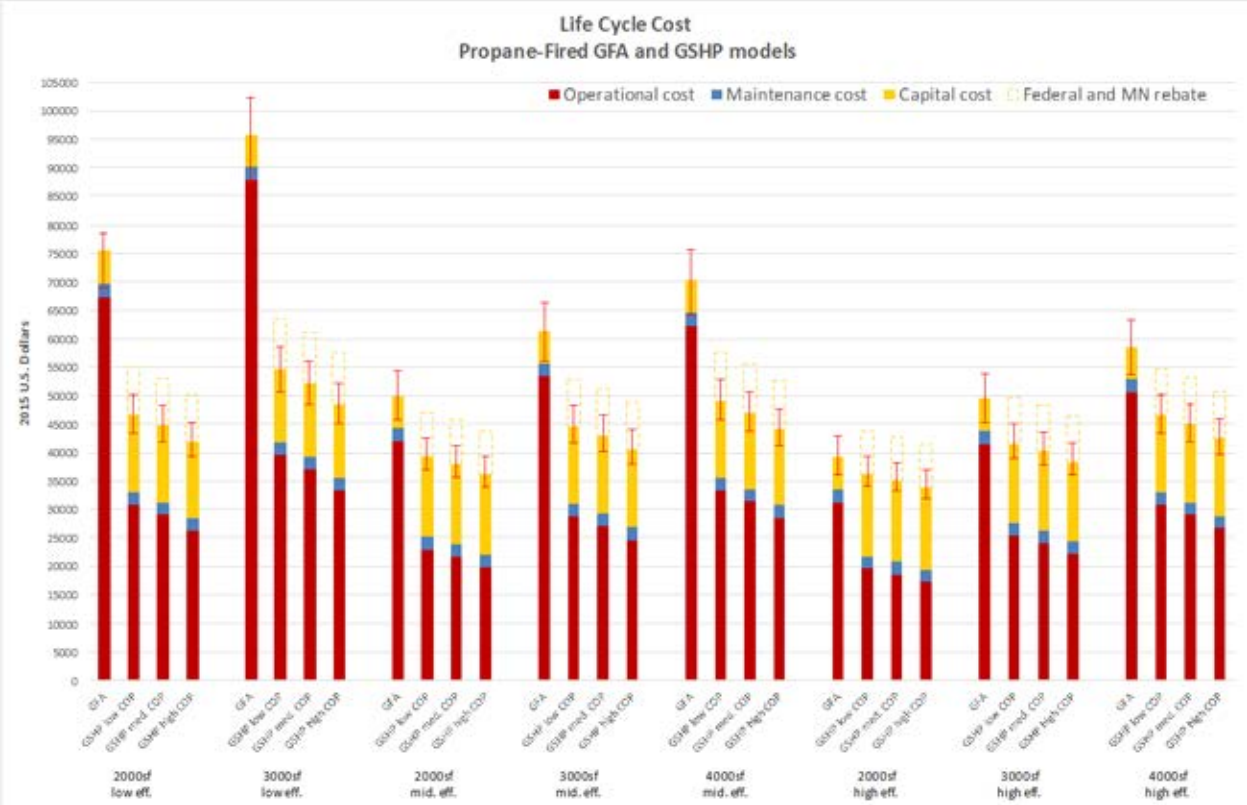


Table 45: Detailed costs and rebates of each propane-fired GFA and GSHP systems

| House | Description | Capital cost | Maintenance cost | Operational cost | Total cost | Federal rebate | MN utility based rebate | 20-year cost |
|---|---|---|---|---|---|---|---|---|
| 2000sf low eff. house | Gas-fired GFA | 5,634 | 2,357 | 67,449 | 75,440 | 0 | 0 | 75,440 |
| | GSHP low COP | 13,495 | 2,176 | 30,819 | 54,950 | 6,586 | 1,873 | 46,490 |
| | GSHP med. COP | 13,495 | 2,176 | 29,009 | 53,140 | 6,586 | 1,873 | 44,680 |
| | GSHP high COP | 13,495 | 2,176 | 26,172 | 50,302 | 6,586 | 1,873 | 41,843 |
| 3000sf low eff. house | Gas-fired GFA | 5,634 | 2,357 | 87,788 | 95,779 | 0 | 0 | 95,779 |
| | GSHP low COP | 12,878 | 2,176 | 39,548 | 63,679 | 6,586 | 2,490 | 54,602 |
| | GSHP med. COP | 12,878 | 2,176 | 37,053 | 61,184 | 6,586 | 2,490 | 52,108 |
| | GSHP high COP | 12,878 | 2,176 | 33,385 | 57,515 | 6,586 | 2,490 | 48,439 |
| 2000sf mid. eff. house | Gas-fired GFA | 5,634 | 2,357 | 41,989 | 49,980 | 0 | 0 | 49,980 |
| | GSHP low COP | 14,101 | 2,176 | 22,895 | 47,025 | 6,586 | 1,267 | 39,172 |
| | GSHP med. COP | 14,101 | 2,176 | 21,672 | 45,802 | 6,586 | 1,267 | 37,949 |
| | GSHP high COP | 14,101 | 2,176 | 19,764 | 43,894 | 6,586 | 1,267 | 36,042 |
| 3000sf mid. eff. house | Gas-fired GFA | 5,634 | 2,357 | 53,377 | 61,368 | 0 | 0 | 61,368 |
| | GSHP low COP | 13,708 | 2,176 | 28,731 | 52,861 | 6,586 | 1,660 | 44,615 |
| | GSHP med. COP | 13,708 | 2,176 | 27,067 | 51,198 | 6,586 | 1,660 | 42,952 |
| | GSHP high COP | 13,708 | 2,176 | 24,622 | 48,752 | 6,586 | 1,660 | 40,506 |
| 4000sf mid. eff. house | Gas-fired GFA | 5,634 | 2,357 | 62,289 | 70,280 | 0 | 0 | 70,280 |
| | GSHP low COP | 13,401 | 2,176 | 33,416 | 57,546 | 6,586 | 1,967 | 48,994 |
| | GSHP med. COP | 13,401 | 2,176 | 31,410 | 55,541 | 6,586 | 1,967 | 46,988 |
| | GSHP high COP | 13,401 | 2,176 | 28,500 | 52,630 | 6,586 | 1,967 | 44,077 |
| 2000sf high eff. house | Gas-fired GFA | 5,634 | 2,357 | 31,116 | 39,107 | 0 | 0 | 39,107 |
| | GSHP low COP | 14,361 | 2,176 | 19,609 | 43,739 | 6,586 | 1,007 | 36,146 |
| | GSHP med. COP | 14,361 | 2,176 | 18,606 | 42,737 | 6,586 | 1,007 | 35,144 |
| | GSHP high COP | 14,361 | 2,176 | 17,188 | 41,318 | 6,586 | 1,007 | 33,725 |
| 3000sf high eff. house | Gas-fired GFA | 5,634 | 2,357 | 41,436 | 49,426 | 0 | 0 | 49,426 |
| | GSHP low COP | 13,978 | 2,176 | 25,424 | 49,555 | 6,586 | 1,390 | 41,578 |
| | GSHP med. COP | 13,978 | 2,176 | 24,104 | 48,234 | 6,586 | 1,390 | 40,258 |
| | GSHP high COP | 13,978 | 2,176 | 22,196 | 46,326 | 6,586 | 1,390 | 38,350 |
| 4000sf high eff. house | Gas-fired GFA | 5,634 | 2,357 | 50,617 | 58,608 | 0 | 0 | 58,608 |
| | GSHP low COP | 13,641 | 2,176 | 30,670 | 54,800 | 6,586 | 1,727 | 46,487 |
| | GSHP med. COP | 13,641 | 2,176 | 29,056 | 53,186 | 6,586 | 1,727 | 44,873 |
| | GSHP high COP | 13,641 | 2,176 | 26,610 | 50,740 | 6,586 | 1,727 | 42,427 |

## *Technological*

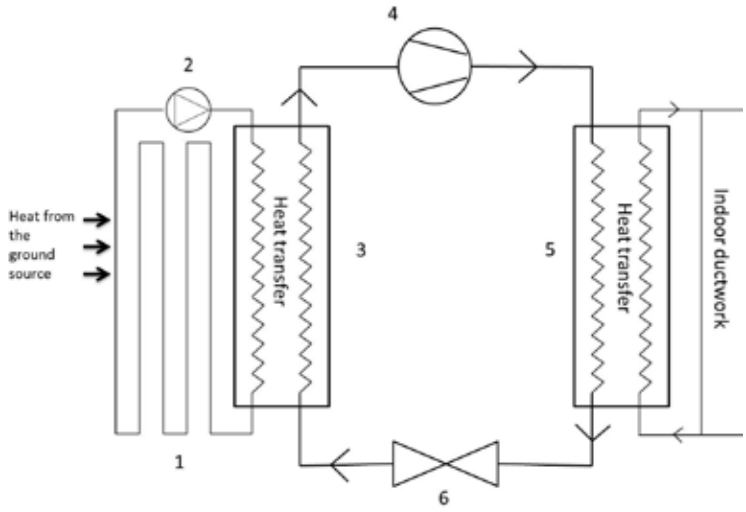
Unlike conventional GFA systems, GSHP systems avoid fossil fuels combustion at the residence by consuming electricity to extract and transport underground geothermal energy to provide heating and cooling service in residential buildings. Installation of residential GSHP systems, which can be completed in both new and existing houses, includes two parts: installing an outdoor underground loop system and an indoor heat pump unit with a circulating pump. The circulating pump propels an anti-freeze liquid (25% glycol and 75% water) to circulate in the loop system and draw geothermal energy from soil back to the heat pump. The heat pump then begins the refrigeration cycle, in which heat is moved from a lower-temperature location to another higher-temperature location via the refrigerant state change and circulation between liquid and gas. A heat exchanger and fan then deliver warmth or cold in the house through indoor ductwork.

The outdoor loop system consists of a series of small diameter HDPE (high-density polyethylene) pipes, usually the ¾ inch SDR-11AA ASTM D3035 HDPE, buried underground with an anti-freeze liquid, typically a glycol-water solution circulating in them. Closed and open systems are the two major types of outdoor loop systems applied in practice (Omer, 2006). To choose the right system for a specific residential installation, several factors need to be considered: geology and hydrogeology of the underground area, occupancy of the ground area, existence of potential heat sources like mines, and heating and cooling characteristics of the residential building (Omer, 2006). This study looks at the horizontal slinky loop and the vertical loop, which are the two most commonly used closed loop systems.

A ground source heat pump moves thermal energy against a thermal gradient at the expense of an external source of electricity. The pump usually includes an evaporator (refrigerant-to-water heat exchanger), a compressor, a condenser (refrigerant-to-air heat exchanger), and an expansion valve (Figure 30) (Rafferty, 2001) (Greening & Azapagic, 2012). In the heating season, the anti-freeze fluid flows from the outdoor loop system into the heat pump, carrying heat from underground. As it flows through the evaporator (a double-layer tube), liquid refrigerant inside the evaporator absorbs the heat and changes its state from liquid to gas. In the compressor, the gasified refrigerant is pressurized to raise its temperature to a high enough degree. After compression, the refrigerant loses its heat to the air in the condenser and returns to liquid. The warmed air is blown into indoor distribution system by a fan coil unit, while the liquid refrigerant flows back to the evaporator through the expansion valve and starts the next refrigeration cycle. In cooling season, the entire refrigeration cycle reverses: indoor air lowers indoor temperature by losing its heat to the refrigerant and eventually to the circulating fluid.

A circulating pump is a much smaller piece of equipment connected with the heat pump. It operates like a motor and powers the glycol-water solution to continuously circulate in the closed circuit consisting of the outdoor piping system and the heat pump.

Figure 30: A schematic of the ground source heat pump system




In Figure 30:

1. Outdoor loop system – heat collector;
2. Flow center – circulating pump;
3. Evaporator (refrigerant/water heat exchanger);
4. Compressor;
5. Condenser (refrigerant/air heat exchanger);
6. Expansion valve. Refrigerant circulates in it and provides heat cycle via change of state.

Source: Edited from the work by Greening & Azapagic (2007)

## Carbon Profile Life-Cycle-Assessment

We completed a life cycle assessment (LCA) method to evaluate the cradle-to-grave GWP (global warming potential) impact of the GFA systems and GSHP systems. The LCA method assesses environmental impacts associated with all life stages of a product<s lifespan from cradle to grave. The GWP impact is measured by the amount of heat that is trapped by greenhouse gases (GHG), namely carbon dioxide ($CO_2$), methane and nitrous oxides, in the atmosphere and is commonly represented using kg $CO_2$ equivalent. The LCA models were constructed in GaBi thinkstep software to accomplish the analysis on all the GFA and GSHP systems described in the Energy Modeling section. GaBi thinkstep software, developed by PE INTERNATIONAL, provides access to and use of Ecoinvent Integrated and Professional Extensions databases. Other data sources included GREET model 2015 by Argonne National Laboratory (Wang, GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model) 2015, 2015) and surveys with local residential GSHP system installers, such as Hass Geosystems Inc., Massmann Geothermal and Mechanical, and Summit Heating & Air Conditioning.

## *LCA Goal and scope definition*

### Goal of the study

LCA protocols are defined by ISO # and require that the following parameters included in defining the goal of a life cycle assessment:

- intended application
- reasons for carrying out the study
- intended audience, that is, to whom the results of the study are intended to be communicated
- whether the results are intended to be used in comparative assertions intended to be disclosed to the public (ISO, 2006b).

The intended application in the LCA component of this study was to assess life cycle GWP impacts (kg $CO_2$ equivalent) by each HVAC system. The reasons for carrying out this study comprised the recognition of the research gaps, including the lack of actual performance evaluations of the GSHP systems in real Minnesota houses and practical comparisons between the GSHP systems to the more traditional gas forced-air (GFA) heating and cooling systems, and the intention to approach a comprehensive life cycle assessment on carbon impacts of diverse residential GSHP systems in Minnesota.

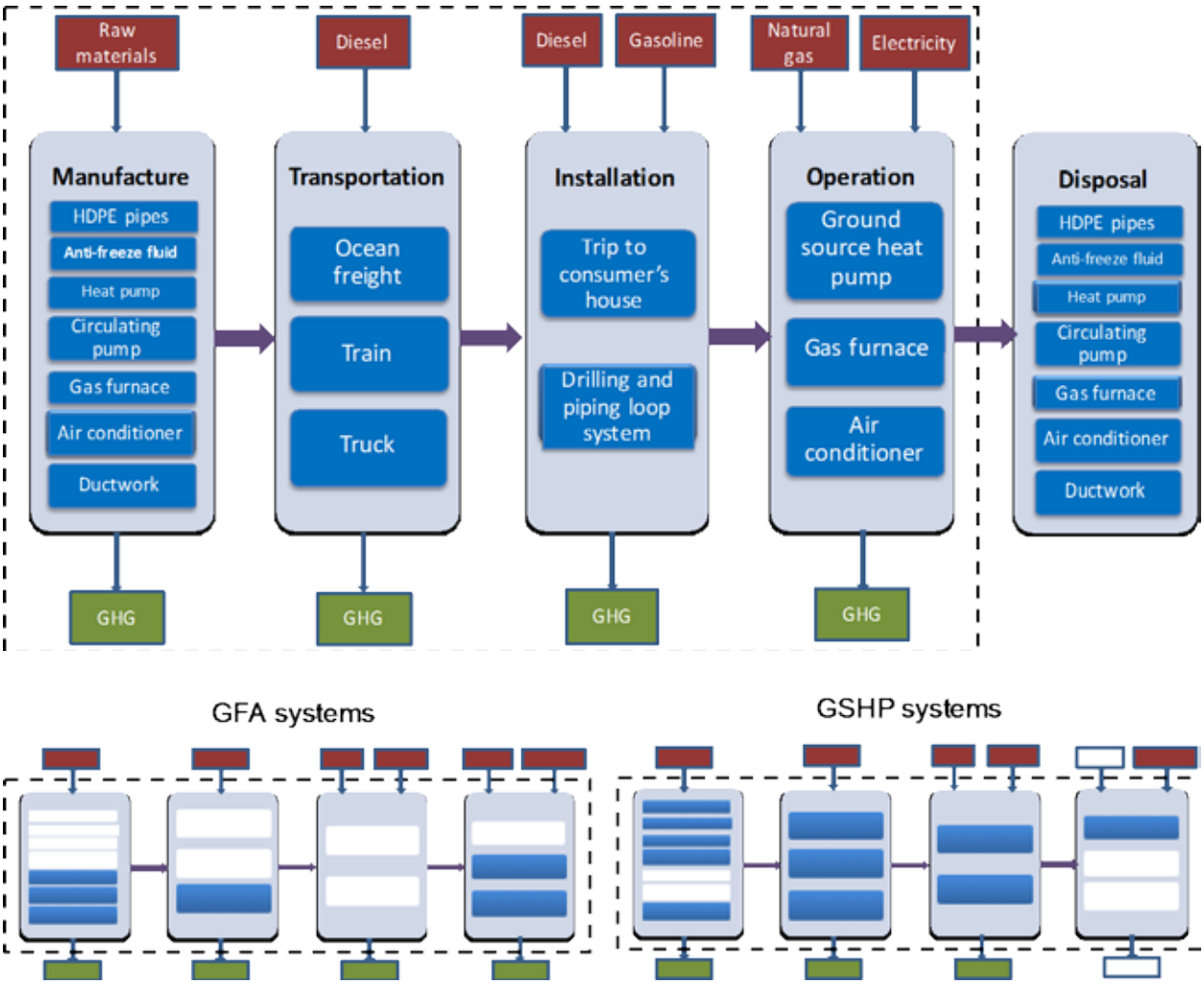
The intended audience will be utility demand-side management program administrators, state policy makers and regulators of demand-side management programs, and members of various aspects of the GSHP industry. The results will be disclosed to the public.

### Scope of the study

The scope of a life cycle assessment is defined by product systems, functions, and system boundaries. The relevant product systems are the residential GSHPs surveyed and monitored in this study.

Life stages of a typical product and details of all the GFA and GSHP systems helped make up the system boundary in this LCA study. An integrated illustration of the system boundary and life stages (manufacture, transportation, installation, and operation) of each system is shown in Figure 31, followed by a legend explaining the unique system boundary and specific components in each system. Overall inputs (materials and energy) and outputs (GHG) are displayed in Figure 31. For example, in the Operation stage, natural gas and electricity are the energy inputs and GHG are the outputs.

Figure 31: System boundary and life stages of residential HVAC systems




Based on the data sources in GaBi thinkstep software, certain independent processes have been aggregated accordingly. The extraction of raw materials is integrated with the manufacture life stage (the box with text "Manufacture" on the far left hand side in Figure 31 and simplified as inputs. The transportation stage represents the conveyance of the GSHP components from their manufacturers to local retailers then to consumers. The installation stage includes not only the construction of the GSHP system's loop field such as drilling, trenching, and laying the piping, but also the correlated vehicle trips and the associated GHG emissions. In the operation stage, annual electricity and natural gas consumption appear as inputs. Due to the absence of empirical data on the disposals of the GFA systems and GSHP systems, disposal is not included within the system boundary of this analysis.

## LCA functional unit

The functional unit is a key component of any life cycle assessment. It is a measure of the function of the studied systems. The functional unit must be consistent with the goal and scope of the study and provide a reference to which the input and output data are normalized (in a mathematical sense) (ISO, 2006b). In this study, the functions of the GSHP systems are to

provide space heating and cooling as well as associated water heating for residential houses in Minnesota. Therefore, the functional unit was defined to be 20 years of heating and cooling to maintain the domestic hot water supply and the indoor temperature at 68°F (20°C) and 75°F (24°C) in heating and cooling season, respectively.

## Overall system design

Based on practical conditions in Minnesota and existing studies (Greening & Azapagic, 2012) (Rey, et al., 2004) (Shah, Col Debella, & Ries, 2007), the GFA system LCA model includes the indoor equipment (i.e., the GFA furnace and the AC) and the indoor distribution ductwork; and the GSHP systems LCA models include the indoor heat pump and circulating pump, the indoor ductwork and the outdoor loop system.

## Loop system and anti-freeze liquid

As described in the Technological section, horizontal slinky and vertical loop systems were selected for this study. According to the survey conducted with the local installers, the GSHP industry accepts the 3/43/4the survey conducted as the most common pipe type used in both the loop systems and 25% as the volume proportion of glycol in the anti-freeze liquid. The lifetimes of the pipes and the anti-freeze liquid were estimated to be 70 years. The survey also showed that to support a 4-ton ground source heat pump, a total length of 2,400 feet of HDPE pipe is necessary to construct an outdoor loop field. We used the loop volume calculator by Hydro-Temp Corporation (2012) to provide parameters and custom calculations of the exact pipe type. It was assumed the HPDE pipes and glycol were manufactured in China and transported to Minneapolis, Minnesota, US.

## Ground source heat pump and circulating pump

Specifications of the heat pump models were adopted from models and findings in existing studies. A study by Roth North America (2011) included a 4-ton ground source heat pump with shipping weight of 240 kg (assumed net weight of 200 kg) and an estimated life of 35 years. A study by Greening and Azapagic (2012) included a ground source heat pump with a net weight of 132.8 kg and COP of 3.9 but size information (i.e. tonnage) was not provided. The total weight of 200 kg from the Roth North America study and the material specifications of the heat pump in the study by Greening and Azapagic (2012) were integrated to create a model of the targeted heat pump for this study. Due to different capacity and efficiency rates of the heat pump, specifications of the evaporator and the condenser heat exchangers change slightly because of their direct effects on the overall efficiency of the heat pump. Generally, the larger (heavier) the heat exchangers the more efficient the system becomes (National Air Warehouse, 2012), but their weight differences were not distinguished in this study due to lack of empirical references. Impacts of the weight differences might be considered minor and negligible in existing studies. Future work is recommended to investigate whether weight difference in different GSHP units impacts the results of a LCA analysis.

A circulating pump, also called a flow center, continuously circulates the glycol-water solution to in the closed circuit consisting of the loop field and the indoor heat pump. Compared to the heat pump, the circulating pump is a much smaller piece of equipment, which is commonly made of cast iron (BOSCH, 2012). Roth North America (2011) provides a flow center containing

double pumps, one type of circulating pump (two pumps side by side to handle greater load), weighs 19.1 kg (assumed net weight of 18 kg) and supports a 3.5- to 6-ton heat pump.

## Gas furnace, Air Conditioner and Ductwork

In this study, the gas furnace was designed to individually provide heating in the conventional GFA and AC system. The case study by Shah et al. (2007) provided inputs for a suitable gas furnace based on model number of 58DLA manufactured by Carrier Corporation (Carrier Corporation, 2006). Annual fuel utilization efficiency (AFUE) of that furnace was adjusted to 90% to meet the function simulation in this study. Other smaller fractions of material usages and energy usages during the assembly of the furnace, such as transportation of raw materials from mining origins to manufacturing factories, are not available in the study by Shah et al. (2007).

Similar to the gas furnace, the air conditioner used in this analysis was adopted from the case study by Shah et al. (2007), which is based on model number 24ACR3 manufactured by Carrier Corporation (Carrier Corporation, 2006). The seasonal energy efficiency ratio (SEER) of this unit is 13. Unlike the heat pump or the gas furnace, the air conditioner has a condenser located outside the house to extract air. The unit provides cooling to the house as the refrigerant absorbs heat from the air flowing through indoor ductwork. It was assumed that both the gas furnace and the air conditioner are manufactured in Mexico and transported to Minneapolis, Minnesota.

The indoor distribution system (ductwork) was adopted from Shah et al. (2007). All the GFA systems and GSHP systems were assumed to share the same indoor ductwork in the same house, which was designed for both heating and cooling services. Existence of the same ductwork helped simplify the comparison among all the GFA systems and GSHP systems. Material constituent of the ductwork is provided in Table 34 as well as the manufacturer information and transport method.

The heat pump also consumed energy during assembly: medium-voltage electricity 606.6 MJ and natural gas 1,575 MJ. Refrigerant R-134a was designed to be used in the heat pump and the air conditioner considering available data sources, its higher efficiency compared to refrigerant R-22, and the small proportion of refrigerant in the entire equipment unit. All equipment was transported from their origins (Table 46) to consumers' houses in Minneapolis, Minnesota.

Table 46: Summary of equipment specifications

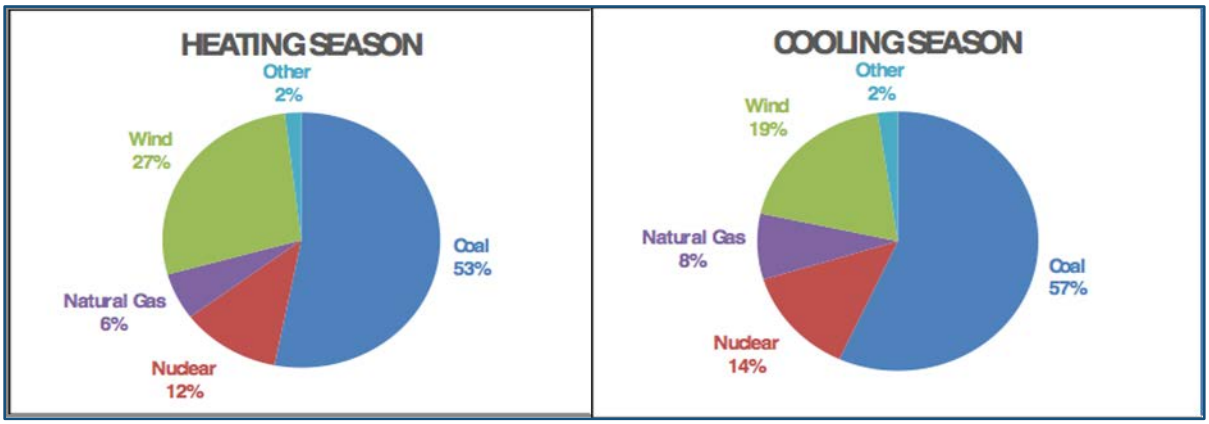
| Equipment | Material | Weight/kg | Manufacturer locations & transport methods |
|---|---|---|---|
| Heat pump | Low alloyed steel<br>Reinforcing steel<br>Copper<br>Elastomere<br>Polyvinylchloride<br>Lubricating oil<br>R-134a (refrigerant) | 30<br>112.5<br>33<br>15<br>1.5<br>2.55<br>4.64 | Roth North America, Watertown, New York, US<br>– Train: 1,800 km<br>– Truck: 57 km |
| HDPE pipe | High-density polyethylene | 174 | Tianjin Junxing Pipe Group Co., Ltd., Tianjin, China<br>– Ocean freight: 9,914 km<br>– Train: 2,700 km<br>– Truck: 93 km |
| Anti-freeze | Glycol (25% in volume) | 92.4 | Tianjin Jixin Industrial & Trade Co., Ltd., Tianjin, China<br>– Ocean freight: 9,914 km<br>– Train: 2,700 km<br>– Truck: 93 km |
| Circulating pump | Cast iron | 18 | Roth North America, Watertown, New York, US<br>– Train: 1,800 km<br>– Truck: 57 km |
| Gas furnace | Steel<br>Galvanized steel<br>Aluminum<br>Copper | 46<br>18<br>9<br>3 | Carrier Corporation, Monterrey, Nuevo León, Mexico<br>– Train: 2,300 km<br>– Truck: 20 km |
| Air conditioner | Steel<br>Galvanized steel<br>Aluminum<br>Copper<br>R-134a (refrigerant) | 78<br>35<br>17<br>17<br>6 | Carrier Corporation, Monterrey, Nuevo León, Mexico<br>– Train: 2,300 km<br>– Truck: 20 km |
| Ductwork | Galvanized steel | 265 | Minnesota, US<br>– Truck: 50 km |

## *Life Cycle Assessment Results*

Life cycle GWP impact (kg $CO_2$ equivalent) of the GFA systems and GSHP systems were calculated based on various data sources. Ecoinvent Integrated and Professional Extensions databases provided applicable data in most processes, including extractions of raw materials, refineries of primary products, and productions of secondary products. GREET model 2011 contributed to the transportation stage by providing data on GWP impact (kg $CO_2$ equivalent) from particular fuel combustion. The national electrical grid is managed by several regional system operators. Minnesota is located within northern portion of the Midcontinental Independent Transmission System Operator (MISO). We calculated the GWP impact (kg $CO_2$ equivalent) of direct electricity consumption by consumers by aggregating the GWP impact (kg $CO_2$ equivalent) of electric power generated and distributed in the MISO North Region based on the real-time generation fuel mix of heating and cooling seasons (Figure 32). We determined

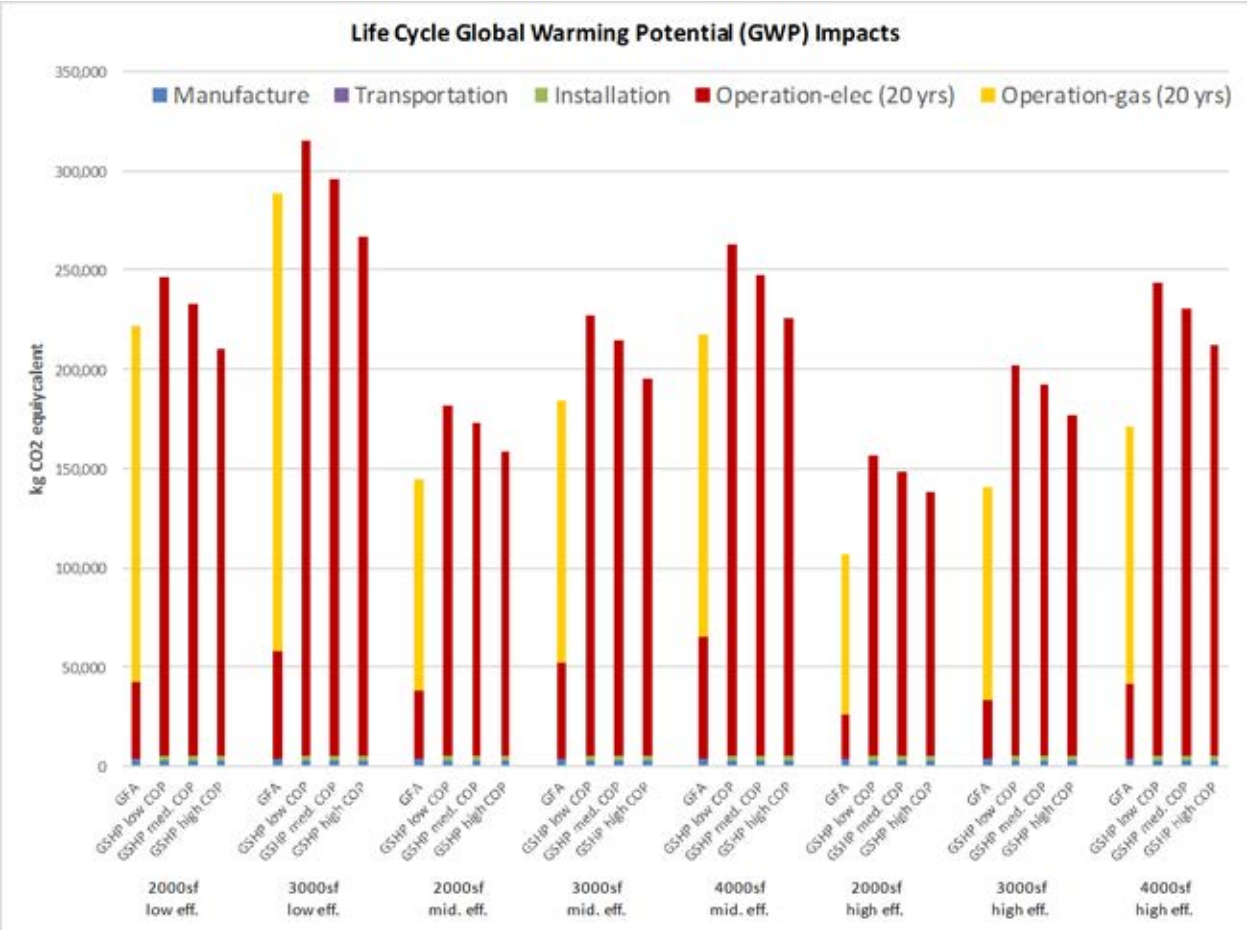
the seasonal fuel mixes by averaging the monthly fuel mixes of four heating months in 2015 (from Jan. to Apr.) and the monthly fuel mixes of four cooling months in 2015 (from May to August).

Figure 32: MISO (Midcontinental Independent Transmission System Operator) North Region real-time generation fuel mix in heating and cooling seasons.




Our LCA analysis finds that the GWP impacts of GSHP systems range from 106,194 to 315,564 kg $CO_2$ equivalent over the 20-year time horizon (Figure 33). The lower end of the ranges is associated with a GFA system installed in the 2000 sf high efficiency model house, while the higher end of the range is associated with a low-COP GSHP system installed in the 3000 sf low efficiency model house. The operation stage of all the heating systems dominates the GWP impacts compared to the other life stages. The life stage of transportation has the least GWP impact even though cargo weights and travel distances seem quite heavy and long, respectively. The reason for this lack of savings is because the electric power the GSHP systems use has high $CO_2$ emission factor. If the GSHP systems used electricity primarily from a renewable source like wind, which could decrease the $CO_2$ emissions rate of grid electricity, GSHP systems would provide savings. If the rate could decrease by 40%, GSHP systems would provide savings in all modeled houses.

Figure 33: Life cycle GHG emissions ($CO_2$ kg eq.) of gas-fired GFA and GSHP systems from material and energetic inputs perspective.




Our LCA analysis also found that most GSHP systems do not provide $CO_2$ (equivalent) savings over the 20-year time horizon compared to the GFA system installed in the same model house (Table 47). Two exceptions are high-COP GSHP system in 2000sf low efficiency house (net savings of 10,920 kg $CO_2$ equivalent) and the high-COP GSHP system in the 3000sf low efficiency house (net savings of 21,464 kg $CO_2$ equivalent).

Table 47: Life cycle GWP impacts (kg $CO_2$ equivalent) compared to natural gas-fired GFA system (the base case). (Negative numbers [brackets] indicate $CO_2$ increase determined by the actual GWP impacts of each system [brackets].)

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| Base case (GFA w/AC) | NA (221,229) | NA (288,605) | NA (144,428) | NA (184,683) | NA (217,726) | NA (106,194) | NA (140,137) | NA (171,172) |

| House size | Small (2000sf) | | | Medium (3000sf) | | | Large (4000sf) | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| GSHP low COP | -25,680 (246,910) | -37,777 (315,564) | -50,477 (182,205) | -26,959 (227,221) | -42,539 (262,821) | -62,197 (156,671) | -45,095 (202,334) | -72,138 (243,310) |
| GSHP med. COP | -11,443 (232,672) | -28,369 (296,018) | -42,717 (172,797) | -7,413 (214,518) | -29,835 (247,627) | -51,984 (148,911) | -29,901 (192,121) | -59,510 (230,682) |
| GSHP high COP | 10,920 (201,310) | -13,653 (267,141) | -31,699 (158,081) | 21,464 (195,701) | -11,018 (225,477) | -36,941 (137,893) | -7,750 (177,078) | -40,367 (211,539) |

When compared to propane-fired GFA systems, GSHP systems are found able to provide $CO_2$ (equivalent) savings over the 20-year time horizon in the 2000sf and 3000sf low-efficiency houses (Table 48). High-COP GSHP systems in the mid-sized houses can also achieve live-cycle $CO_2$ (equivalent) savings compared to propane-fired GFA systems. All other GSHP systems are not capable of saving life-cycle $CO_2$ (equivalent) compared to propane-fired GFA systems.

Figure 34: Life cycle GHG emissions ($CO_2$ kg eq.) of propane-fired GFA and GSHP systems from material and energetic inputs perspective.

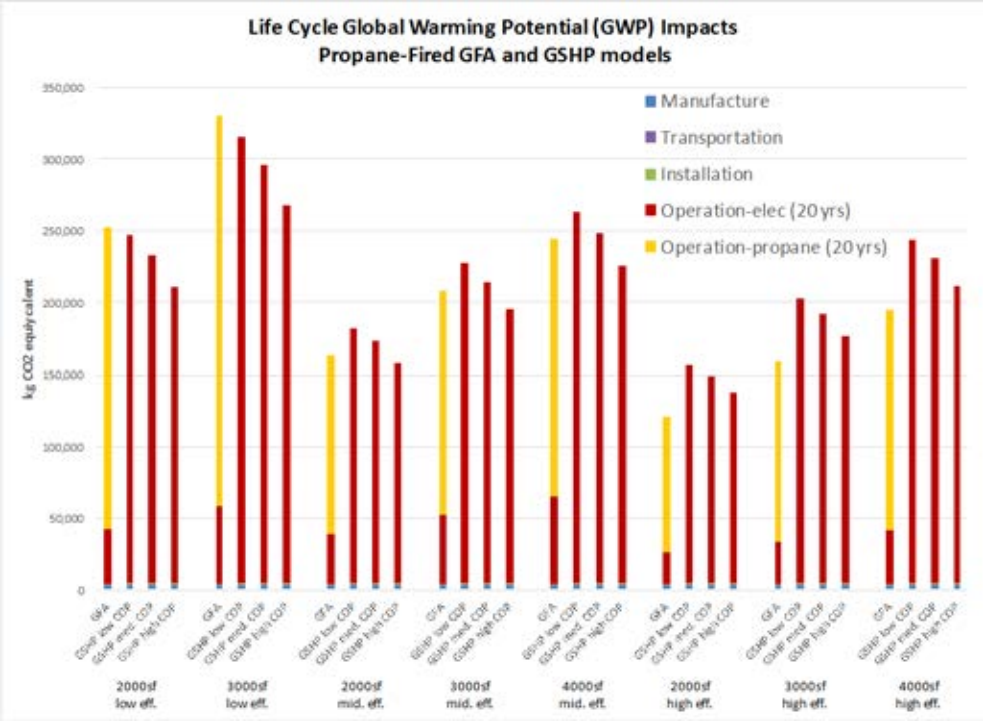


Table 48: Life cycle GWP impacts (kg $CO_2$ equivalent) compared to propane-fired GFA system (the base case). (Negative numbers indicate $CO_2$ increase determined by the actual GWP impacts of each system [brackets].)

| **House size** | **Small (2000sf)** | | | **Medium (3000sf)** | | | **Large (4000sf)** | |
|---|---|---|---|---|---|---|---|---|
| **House efficiency** | **Low** | **Med.** | **High** | **Low** | **Med.** | **High** | **Med.** | **High** |
| Base case (GFA w/AC) | NA (252,847) | NA (163,198) | NA (120,390) | NA (329,465) | NA (208,197) | NA (159,058) | NA (244,694) | NA (194,154) |
| GSHP low COP | 5,937 (246,910) | -19,008 (315,564) | -36,282 (182,205) | 13,901 (227,221) | -19,025 (262,821) | --43,276 (156,671) | -18,127 (202,334) | -49,155 (243,310) |
| GSHP med. COP | 20,175 (232,672) | -9,599 (296,018) | -28,521 (172,797) | 33,446 (214,518) | -6,321 (247,627) | -33,063 (148,911) | -2,933 (192,121) | -36,527 (230,682) |
| GSHP high COP | 42,537 (201,310) | 5,117 (267,141) | -17,503 (158,081) | 62,324 (195,701) | 12,496 (225,477) | -18,020 (137,893) | 19,217 (177,078) | -17,384 (211,539) |

# Results

This study provides new information and insights into the performance of Ground Source Heat Pump (GSHP) systems in Minnesota. The field study (discussed in the Field Study of In -Situ Performance of GSHP Systems section) monitored 37 systems for actual real-time, in situ energy performance to determine the operational coefficient of performance (COP). These COPs were used in the energy modeling study (discussed in the Modeled Performance Comparisons of Energy, Emissions, and Cost section) to provide a site and source energy, emissions, and cost comparison to standard gas forced air (GFA) systems for a range of typical Minnesota homes. Furthermore, these results were fed into a detailed policy and life cycle analysis (discussed in the Economics and Policy section) that examined not only ongoing energy consumption, cost, and emission impacts, but also the embodied energy and environmental impacts of GSHP systems.

## Discussion of Results

### *Field Study*

The main goal of the field study was to measure the operational energy efficiency of residential ground source heat pump installations throughout Minnesota. This allowed for a careful analysis of the operational characteristics and calculation of in situ COPs for these systems.

There were considerable difficulties in data acquisition, not only for energy performance, but also basic system information such as installation cost, use of backup heat, and loop field descriptions (such as size and fluid mixes). Originally, the study intended to use modeled energy savings compared to conventional GFA systems to estimate payback periods. However, the installation cost information provided by GSHP system owners and installers was not adequate for this analysis and payback periods based on the actual system costs could not be calculated.

For the analysis, three GSHP installations had to be dropped entirely from the initial 37 due to data quality issues. Missing data, malfunctioning equipment, or homeowner behavior (such as vacations) meant that segments of data from the remaining 34 systems also had to be dropped in some cases. The data that remained were consistent and could be used for COP calculations and other performance analyses.

Compressor-only COPs do not include the energy required to pump the heat transfer fluid through the loop field, which is critical to overall system performance. Therefore, they are not an accurate estimate of total system performance in the field. To this end, a second set of COPs with compressor plus loop field pump energy was calculated (Table 49). These COP values were calculated for the entire season. As such, they are a much better indicator of long-term seasonal performance. Including the additional field loop pump energy tends to reduce the operational COP of the GSHP system. These values ranged from 1.51 to 7.19 on the heating side, and from 0.23 to 23.44 on the cooling side. The median heating and cooling COPs were 3.19 and 5.2 respectively, which roughly matches commonly used and generally accepted performance expectations. However, there was again wide variability in COP values. This is disconcerting because it suggests that homeowners purchasing GSHP systems may be "rolling the dice" in

terms of performance when it comes to their specific system. While some homeowners may receive GSHP systems that operate much more efficiently than expected, an equal number receive systems that perform worse – some substantially lower – than expected.

Table 49: Final Compressor + loop pump COP Values.

| | Heating COP | Cooling COP |
|---|---|---|
| Minimum Value | 1.51 | 0.23 |
| 25th Percentile | 2.88 | 3.91 |
| Median | 3.19 | 5.20 |
| 75th Percentile | 3.75 | 10.13 |
| Maximum Value | 7.19 | 23.44 |

In addition to wide variation in cooling performance, field data also showed a wide variability in the use of cooling. A large percentage of homeowners in the field study chose not to operate the GSHP during the summer, or severely curtailed its use. This has several important implications. First, GSHP systems have been shown to operate most efficiently in cooling mode. However this benefit could not be realized in this study because cooling loads and cooling use were small and inconsistent in this set of single family homes. Second, savings from the use of water-heating desuperheaters could not be realized as many GSHP systems were either turned off or used infrequently in the summer. A desuperheater can take waste heat from the house and efficiently move it into the domestic hot water when the GSHP is working in cooling mode. This results in "essentially free" hot water. Third, the ground loop fields were not "recharged" with waste heat from the house during the summer cooling season. Although this issue was not examined in depth due to inadequate sample size, thermal drift over time could feasibly lead to reduced efficiency in the winter because ground temperatures remain lower than expected. In this light, GSHP installations in warmer climates or commercial and multi-family residential buildings with larger and more consistent cooling loads are generally considered a better match for this technology.

To determine how the in situ COPs compared to the manufacturer's rated COP, the compressor-only COPs were measured at incoming water temperatures matching the fluid conditions used to establish the equipment COP rating. On the heating side, 32 houses had sufficient data at this condition. These units had a large range of COPs with a median of 3.5. In the heating mode, seven (22%) of the heat pumps performed within 10% of manufacturer-provided rated COPs and sixteen (50%) of the heat pumps performed at or above their rated COP. For cooling, only fifteen houses met the necessary parameters for compressor-only COPs. These systems had an even larger range with a median of 5.0. In the cooling mode, four heat pumps (27%) performed within 10% of the rated EER values, with eight heat pumps (53%) performing at or above their rated EER.

It should be noted that these compressor-only values represent performance during very specific and discreet periods where the incoming water temperatures were near the temperature used for the equipment rating, and should not be confused with seasonal performance values. It is just a snapshot to see if the equipment is operating at or near its rated

performance. There is clearly a large variation in compressor-only COPs, and some of this could be expected across different regions of Minnesota and house types, as well as manufacturers and equipment capacities. Certainly, the loop field installation also played a large role in this variability, with a variety of soils, loop field types, installation practices and attention to detail, such as appropriate sizing calculations. Despite a slight majority of compressors performing below rated performance, average compressor-only COPs for both heating and cooling were above the rated averages. This is because compressors that were performing better than their ratings tended to do so by a larger margin than those that were performing worse than their ratings.

Since we found a wide range in the COPs of both the systems and the compressors at rated conditions, it is difficult to discern whether the overall system performance was due to the heat pump equipment (compressor) or due to installation variables. However, it is clear that it would be hard for a poor performing heat pump to overcome a poor system installation. Whereas a poor system could significantly reduce the performance of a high performing heat pump. Unfortunately these system effects are hard to isolate with the limited system design and installation information that was available for these systems.

## *Energy Modeling*

The main goal of the energy modeling section was to systematically compare the performance of ground source heat pumps to more conventional GFA-based systems using a set of standardized model houses. By using energy modeling and standardizing the model houses, variables could be controlled to ensure as close to an "apples to apples" comparison as possible between GSHP equipment and other HVAC equipment. The modeling process used real COP data (compressor plus loop pump COPs shown in Table 49 above) from the field study as input for the energy models. The full range of COP values was used in the modeling - 1$^{st}$ quartile (25$^{th}$ percentile), 2$^{nd}$ quartile (median), and 3$^{rd}$ quartile (75$^{th}$ percentile) - to estimate energy, cost, and emissions savings across a wide spectrum of likely GSHP performance.

The modeling was also divided into 9 cases based on a matrix of options: 2000, 3000, and 4000 square feet houses (total conditioned area), each modeled at different efficiency levels – high, medium and low. The high efficiency cases represented homes with a 90 AFUE furnace that would meet the 2015 MN residential energy code. The medium efficiency cases represented homes with an 80 AFUE furnace that would have met 1980's MN residential energy code. Finally, the low efficiency cases represented homes with a 70 AFUE furnace that were built before energy codes were established but had undergone some level of insulation retrofit. GSHP equipment with low, medium, and high efficiency (1$^{st}$, 2$^{nd}$, and 3$^{rd}$ quartiles) were inserted into these cases, then compared with the same models operating with GFA equipment and conventional split AC units. This modeling was done for a Minneapolis/St. Paul climate using REM Rate version 14.5.1. The low efficiency 4000sf case was later dropped from the modeling because its design heat load was significantly larger than the capacity of the largest GSHP system in the field study.

There are some major differences between GSHP and GFA-based systems that had to be addressed in the energy modeling. One of these is the approach to providing additional heat. While GFA-systems are typically oversized by a significant fraction, GSHP systems normally rely on a backup heat source. There are several reasons for this including the additional expense

of installing a larger GSHP system, both heat pump and loop field, as well as utility incentives available for dual-fuel GSHP-based systems. For the modeling approach, GFA systems were oversized by 25% following standard industry practice, while GSHP systems were paired with backup electric resistance, which met 3% of the total heat load. This percentage was calculated from the average consumption of electric backup for systems monitored in the field study.

Another major difference between GSHP and GFA-based systems is the ability of GSHP systems to deliver hot water through the use of a desuperheater. In some scenarios, this can be an important benefit. In areas without access to natural gas, a desuperheater can provide cost and sometimes energy savings over propane-fired or electric resistance water heaters, especially in the summer. However, summer savings are largely dependent on the use of the GSHP in cooling mode. If the homeowner chooses not to operate the GSHP in cooling mode, the desuperheater will not provide hot water during the summer. Field study data showed that this was frequently the case, so the primary energy modeling results do not include the impacts of desuperheaters.

Energy modeling results clearly showed that GSHP systems save site energy. The vast majority of these savings come on the heating side. Very little savings were found on the cooling side simply because cooling energy use was so small. Depending on the efficiency and size of the house, total site energy savings of 40 – 60% were typical. As expected, GSHP systems in low efficiency houses compared to 70 AFUE furnaces showed greater energy savings than GSHP systems in high efficiency houses compared to 90 AFUE furnaces. However, GSHP cases typically used 2x more electricity than GFA-based cases. This had several important implications, discussed below.

To afford a fair comparison between different forms of energy used on site (electricity versus natural gas or propane), the authors also analyzed source energy consumption. Because of the inefficiency with which thermal energy is converted into electrical energy at the power plant, grid electricity has a high source energy factor compared to natural gas or propane burned on site for heat. Modeling results showed that GSHP systems in general do not save source energy compared to high efficiency (90 AFUE) furnaces installed in homes meeting current 2015 MN energy code. GSHP systems do exhibit significant source energy savings when compared to inefficient homes with low efficiency mechanical equipment. And in medium efficiency homes, GSHPs save significant source energy only when they achieve high levels of efficiency themselves (75th percentile of COPs in the field study). Since propane and natural gas have similar source energy factors, this analysis changes little when comparing GSHP systems to propane-fired GFA equipment.

Increased electrical use by GSHP systems also greatly impacted $CO_2$ emissions. Using current emissions factors provided by the state for grid electricity, natural gas, and propane, modeling results showed no $CO_2$ emissions savings for GSHP systems. This is primarily because current $CO_2$ emission rates for electricity on the MN grid are roughly 5x higher than natural gas per unit of energy. In virtually all cases $CO_2$ emissions were significantly increased compared to homes using propane or natural gas for water and space heat. Modeling results showed that total $CO_2$ emissions compared to natural gas increased by 5 – 30% per house even at high levels of GSHP efficiency (75th percentile of COPs in the field study). If the carbon intensity of grid electricity were reduced by approximately 45%, mid COP GSHP systems could break even with 90 AFUE GFA equipment installed in homes built to 2015 MN energy code.

Yearly energy costs were also analyzed using current rates for propane, natural gas, and electricity. Standard rates of 15 and 14 cents/kWh (including additional surcharges, fees, and taxes) were used for summer and winter electricity costs for GFA-based systems. A discounted electricity rate of 10 cents/kWh was used for GSHP systems during the heating season to account for dual fuel, off peak, or interruptible programs for which GSHPs can typically qualify. A propane price of $2.00/gallon and a natural gas price of $1.00/therm were based on the most recent 5 year MN averages.

In comparison to natural gas, GSHP systems achieved significant energy cost savings only compared to low efficiency (70 AFUE) GFA-based systems installed in low efficiency houses. Even with discounted electricity rates, energy costs increased when compared to 90 AFUE GFA equipment installed in homes built to 2015 MN energy code. However, this analysis is quite sensitive to the cost of electricity. If the discounted electricity rate used by GSHPs for the heating season is reduced to 6 - 7 cents/kWh, significant savings are available in nearly all cases.

In comparison to propane, GSHP energy cost savings change dramatically. Over the past 5 years (2010 – 2015) propane has averaged more than twice the cost of natural gas per unit of energy. GSHPs showed very significant cost savings ($700 or more per year) compared to propane-fired GFA-based systems at all levels of home efficiency and GSHP performance. Even greater energy cost savings would be possible compared to homes heated with electric resistance heat. Therefore, in outstate areas with limited natural gas service, GSHP systems typically offer substantial cost savings in nearly every case. Furthermore, they offer significantly improved energy cost stability compared to propane-fired systems, which have been subject to volatile fuel prices in the last several years.

An important factor to consider in the comparison of GSHP and GFA systems is the ability of GSHPs to supplement the domestic hot water heater with the use of a desuperheater. To determine whether desuperheaters provide energy, emissions, and cost savings within the larger framework of GSHP systems, we performed a side study of the technology using energy modeling. In Minnesota climates, most residential GSHP systems operate in cooling mode relatively infrequently, limiting the energy and cost savings available from the use of a desuperheater. However, there is still a benefit, and 62% of GSHP systems in the field study incorporated a desuperheater. The exact savings available from a desuperheater are often difficult to estimate because they strongly depend on operation of the GSHP in cooling mode. As seen in the field study, many Minnesotans choose not to use the cooling mode on their GSHP or do so infrequently. This means that desuperheater savings vary greatly depending on individual preferences and choices and may not match their potential or predicted savings.

Based on energy modeling results, cooling season desuperheater use accounts for between 80 - 90% of the total energy savings offered by the desuperheater. This confirms the necessity of GSHP operation in the cooling season, if significant energy savings are expected from the desuperheater. Model results show that desuperheaters do increase site energy savings compared to propane and natural gas-fired GFA-based systems. However, the savings is relatively small, amounting to 2-4% of the total site energy savings offered by the GSHP system. Source energy savings over natural gas and propane-fired GFA systems are smaller and in some cases negative compared to site energy savings. The source energy savings that can be attributed to the desuperheater alone are larger, because the desuperheater reduces the GSHP systems' reliance on electric resistance hot water tanks. Modeled energy cost savings over

natural gas-fired GFA systems increase slightly and more so for propane-fired GFA with the addition of the desuperheater. $CO_2$ emissions savings over natural gas and propane-fired GFA systems are negative in almost all comparison cases and remain negative despite the addition of a desuperheater.

## Economics and Policy

Currently under MN law, GSHPs do not quality as a renewable energy technology. However, they do qualify as an efficiency or conservation improvement. Under the mandated conservation improvement program (CIP), nearly all electric utilities in the state of Minnesota offer incentives for installing and/or operating GSHP systems to replace electric resistance heat. Installation incentives are generally in the range of several hundred dollars per ton of capacity, commonly less than 10% of the installation cost. Operational incentives are also typically available - primarily inclusion in special rate programs such as dual fuel, off peak, or interruptible service. Participation in these programs normally requires installation of additional equipment, such as back-up fuel-fired furnaces or other heating devices that can store heat for use when electric power is curtailed. When paired with this equipment, discounted electric rates can be applied to the electricity used by the GSHP. These programs have been justified under the assumption that GSHP systems save energy, similar to other conservation improvements.

From a site energy perspective, there is no doubt that GSHP systems save energy. However, the comparison of electrical energy obtained from the grid to fossil fuels burned on site for heat is an important one. Currently in the northern MISO region, the largest share of electricity is still generated using coal. While the use of renewables and especially wind power has been increasing rapidly in recent years, grid electricity in this region still has $CO_2$ emissions per unit of energy 5x higher than that of natural gas burned on site. Losses inherent in the conversion of thermal energy to electricity as well as power transmission, combined with the heavy use of coal, are largely responsible for the large $CO_2$ emission factor. While GSHP systems can eliminate the use of on-site combustion of natural gas or propane, the increase in electrical consumption makes it difficult for these systems to achieve operational $CO_2$ savings. Combining the use of GSHP systems with onsite renewables, such as photovoltaics, would be one way to circumvent this issue. Currently, costs are quite high for this approach, however.

In an effort to achieve a more complete picture of the emissions comparison between GFA-based systems and GSHP systems, a detailed life cycle analysis (LCA) was performed using GaBi 5 software. The functional unit of this analysis was defined as the equipment and operational energy necessary to provide space heating and cooling as well as water heating to single family houses in a Minneapolis/St. Paul climate over the course of 20 years. This lifespan was chosen to match the expected lifespan of the heat pump itself. $CO_2$ emissions of all the material components of both GFA and GSHP equipment were included using the GaBi database. $CO_2$ emissions involved in transportation and installation of the GFA and GSHP equipment (including the loop field for the GSHPs) were also included. These emissions were added to the yearly operating emissions from the energy modeling analysis.

LCA model results showed that the vast majority of $CO_2$ emissions over a 20 year life span are due to operational emissions (heating and cooling energy consumption). Typically 5% or less of the total life cycle emissions were embodied in the equipment, transportation, and installation

of the systems. As expected, GSHP systems had greater embodied impacts than GFA-based systems due to installation of the loop fields. Since operating emissions were also generally higher, GSHP systems showed negative emissions savings over their life cycle in nearly all cases.

# Conclusions

This study brings new information and insights into a broader statewide conversation of GSHP systems. It will provide utilities and regulators with an improved technical baseline and performance information for treating GSHP systems as measures within utility conservation program portfolios, help guide statewide policies regarding GSHP systems, and provide more detailed performance information to assist consumers interested in purchasing GSHP systems.

On average, the field study confirmed that GSHP systems are operating near or above rated COPs. Even when the additional energy from loop field pumps is included, the operational COPs remain close to expectations. However, items of concern include a wide variation in performance, which means that some homeowners receive systems that perform significantly worse than expected. Also, cooling use is infrequent in this set of single family homes. This limited the potential savings provided by desuperheaters and likely leads to lower ground temperatures since the loop field is not being "recharged" with waste heat from the house during the summer. There were twenty one GSHP installing contractors for the thirty seven systems. The contractor with the largest number of installations had eight systems in the study. Sixteen contractors installed only one system each. When checking the COPs against the installers we looked for one installer to have multiple high or multiple low COPs. However, we found that the COPs were mixed and did not correlate to particular contractors. No single contractor seemed to out-perform any other contractor.

Seasonal system COPs from the field study were used directly in the energy modeling analysis. In all cases, modeled GSHP systems reduced site energy consumption compared to GFA-based systems w/AC by 40–60%. However, with the current electricity grid carbon profile and common utility rate structures, GSHPs did not compare as favorably in terms of source energy, $CO_2$ emissions, or yearly operating costs.

Energy cost results suggested that yearly savings are possible compared to low efficiency natural gas-fired GFA-systems installed in houses with high heating and cooling loads. However, these houses could likely see similar cost (and emissions) benefits with a lower cost of implementation by tackling insulation, air sealing, and conventional mechanical system upgrades. Yearly energy costs were higher for GSHP in all cases compared to high efficiency (90AFUE) natural gas-fired GFA-systems installed in well-insulated homes meeting 2015 MN energy code. However, in outstate areas without access to natural gas, modeled energy cost savings were very significant compared to propane-fired GFA-based systems. With these savings, a reasonable payback for GSHP installations may be possible depending on the cost of installation.

$CO_2$ emissions typically increased by 5-30% even with highly efficient GSHP systems (operating at or above 75th percentile in the field study). Conclusions from a 20 year life cycle analysis were similar. Future improvements to reduce the source energy and carbon intensity of the electrical grid could change the current impacts of residential GSHP systems in Minnesota, but would require a reduction in the current $CO_2$ emission rate of 40–45%.

Based on the findings of this comprehensive study, the overall story for GSHP systems in Minnesota is mixed. For the higher performing GSHP systems, the operational energy costs were lower than conventional gas-fired systems, especially for propane. However, the wide

range of system performance, higher life-cycle costs, and current fuel mix of the electricity grid could be barriers to wider adoption of these systems. In terms of energy consumption, energy cost, and emissions, there are three things that could help GSHP systems be more competitive with conventional gas-fired systems in Minnesota houses. First, significant improvements in GSHP system COPs will increase source energy savings, lower operational energy cost, and reduce $CO_2$ emissions. Reducing installation costs and improving GSHP performance will improve overall life-cycle costs for the GSHP systems compared to more traditional gas-fired, forced-air systems. Last, as the electricity fuel mix moves away from fossil fuels, the operational $CO_2$ emissions of the GSHP systems will be reduced.

# Recommendations and Future Study

While this study is a large advancement for our knowledge-base on the performance of residential ground source heat pump systems in Minnesota, there remain some unanswered questions and research opportunities.

It is clear that there are significant differences in the actual COPs of the installed systems that we monitored. Further research might be able to identify key design and installation practices that would ensure a higher operational COP. Clearly the GSHP systems with very high COPs will show greater energy savings, lower emissions, and lower operational costs.

Despite our best efforts to use only those GSHP systems with no or electric-only auxiliary (or back-up) heating, this wasn't possible. Many GSHP systems were being added to existing gas forced-air systems and others were choosing to install fossil-fueled supplemental heating to take advantage of off-peak and dual-fuel rate incentives. There was a wide variety of back-up heating options used in the systems studied ranging from no back-up at all to electric resistance only, to fossil-fueled furnaces and fireplaces. On average, for those systems with electric auxiliary heating, it was used only 3% of the heating run time. This and other corrective measures ensured that this change had a small impact on the overall in situ COP measurements. It would have been useful to determine how system sizing and control strategies might impact back-up heating needs, as well as, general GSHP operation, emissions, efficiency, and cost; but unfortunately this was beyond the scope of this study.

One surprising observation was the limited cooling hours for many of the GSHP systems in this study. When cooling is required, GSHP will usually outperform standard air-source air-conditioning system. While increased cooling use does raise the absolute energy used and utility costs, it would show better saving for the GSHP systems. A second consideration is that during cooling, waste heat is placed back into the loop field. This can provide a warmer incoming water temperature in the fall and early winter to further increase the heating COP. Also summer cooling using a GSHP with a desuperheater can provide very inexpensive water heating. Again many systems did not use this technology and many systems had limited summer use. Nevertheless, for systems which have a larger cooling load, such as commercial buildings, these operational changes would likely increase the potential savings for the GSHP systems.

Lastly, this study did not attempt to track time of day electrical usage, which may have been of interest to the utilities and provided some changes to the emissions and cost profiles of these systems. This type of information would have required a much more in-depth analysis and was outside the scope of this study.

# References


Bishop, M. (2014, September 1) Geothermal industry striving for inclusion. Retrieved from: Air Conditioning, Heating and Refrigeration News.com. (http://www.achrnews.com/articles/127506-geothermal-industry-striving-for-inclusion) Date Accessed: November 14, 2015

DSIRE. 2016. "Residential Renewable Energy Tax Credit . http://programs.dsireusa.org/system/program/detail/1235 . Date Accessed: November 14, 2015.

Brand, L., Yee, S., & Baker, J. (2015*). Improving gas furnace performance: A field study and laboratory study at end of life* (DOE/GO-102015-4624). Golden, CO: National Renewal Energy Laboratory.

Global Energy Options & Oak Ridge National Laboratories. (2000). *Emissions and Economic Analysis of Ground Source Heat Pumps in Wisconsin* (Research Report 201-1). Madison, WI: Energy Center of Wisconsin. Retrieved from Seventhwave (formerly Energy Center of Wisconsin) website. (http://www.seventhwave.org/publications/emissions-and-economic-analysis-ground-source-heat-pumps-wisconsin )

McKay, S., & Wilson, M. (2008, July). *An analysis of a monitored ground source heat pump installed at the National Energy Foundation's Phase II Building*. Paper presented at Windsor Conference: Air Conditioning and the Low Carbon Cooling Challenge, Windsor, UK, London, U.K: Network for Comfort and Energy Use in Buildings (NCEUB), Retrieved from: NCEUB website. (http://www.nceub.org.uk/dokuwiki/lib/exe/fetch.php?media=nceub:uploads:members:w2008:short_presentation_posters:w2008_74mc-kay_wilson.pdf)

Michaels Engineering. (2008) *Performance, Emissions, Economic Analysis of Minnesota Geothermal Heat Pumps, Final Report*.(Michaels No. MJ807AAN). La Crosse, WI: Author. Retrieved from Michaels Engineering website

Minnesota Public Utilities Commission. 2014. Minnesota Public Utilities Commission Staff Briefing Papers in the Matter of Establishing a Distributed Solar Value Methodology. tahttps://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showPoup&documentId=%7B293918FF-F783-4150-85B7-95E8C1C2F680%7D&documentTitle=20143-97076-01 Published Date: March 12, 2014. Date Accessed: November 14, 2015.

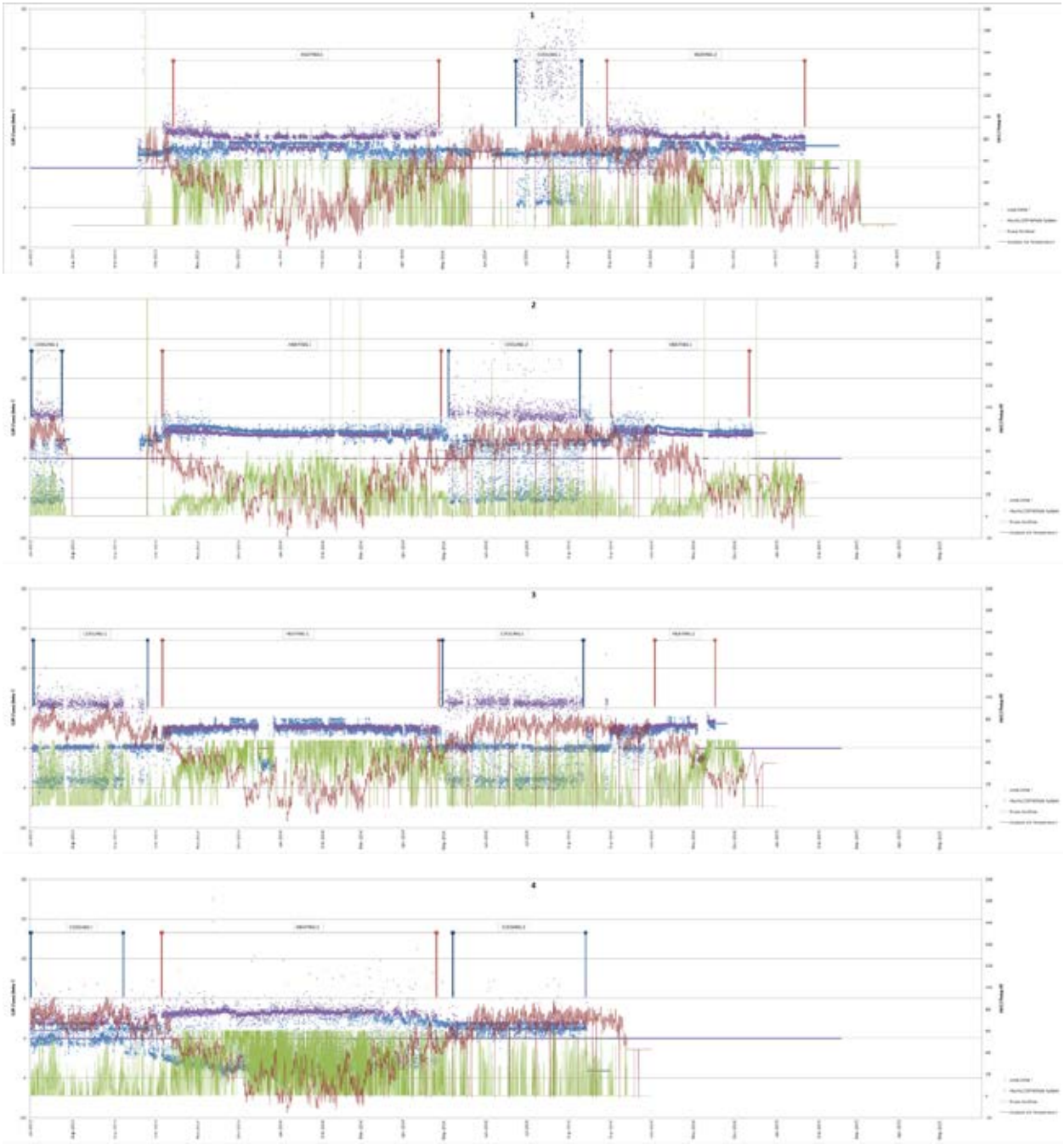
Olszewski, M. & Fontana, E.C. (1983). *Heat Pump Desuperheaters for Supplying Domestic Hot Water.* Oak Ridge, TN: Oak Ridge National Laboratory, Oak Ridge TN.

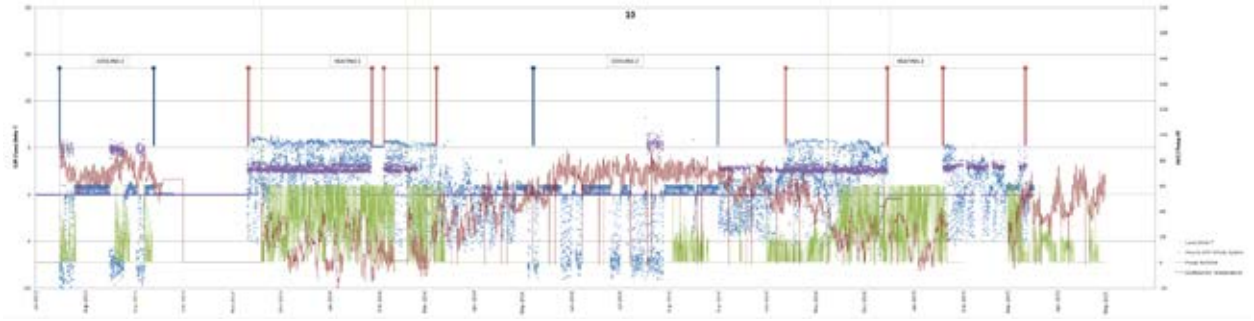
Puttagunta, S., Aldrich, R. A., Owens, D., & Mantha, P. (2010). Residential Ground-Source Heat Pumps: In-field System Performance and Energy Modeling. *GRC Transactions*, *34*, 941-948, retrieved from Consortium for Advanced Residential Buildings (CARB) website.

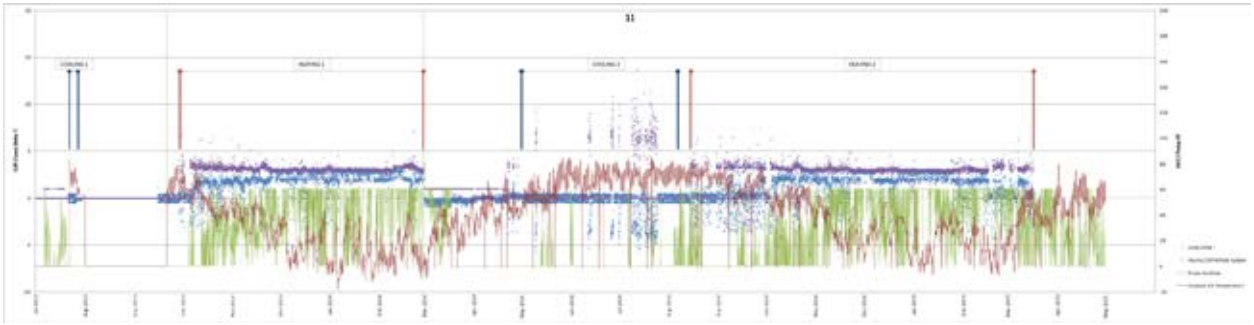
Williams, C. (2012, October 12). "State-by-state comparison of geothermal heat pump legislation." Heat Spring Magazine, 2012. (https://blog.heatspring.com/state-by-state-comparison-of-geothermal-heat-pump-legislation. Published Date: October 12, 2012.) Date Accessed: November 14, 2015Appendix A

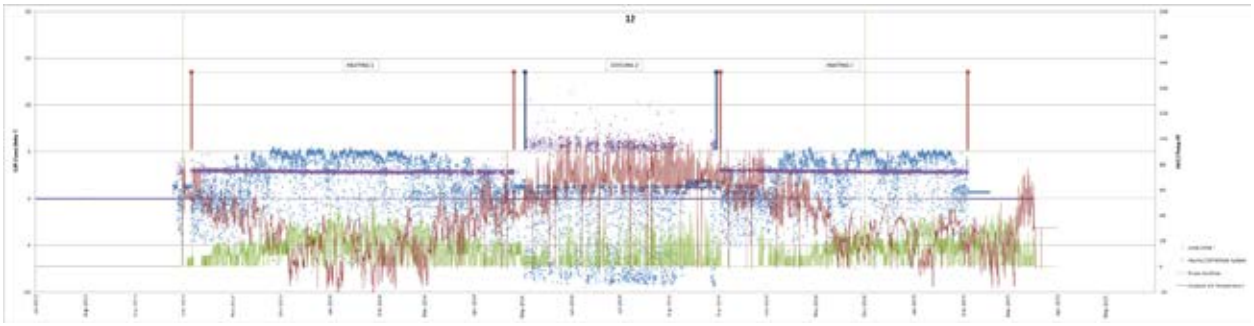
# Appendix A

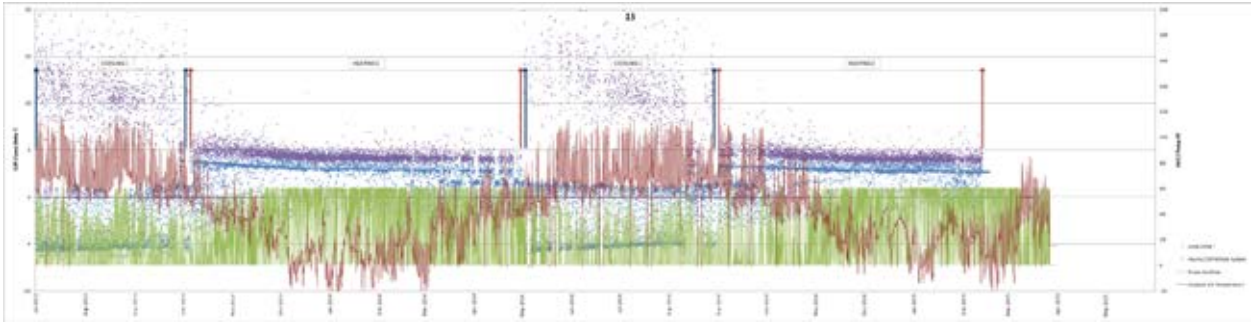
Following graphs are site-specific four-variable graphs used to determine heating and cooling seasons using color shifting. (Site numbers are 1-37 shown at the top center of each graph)

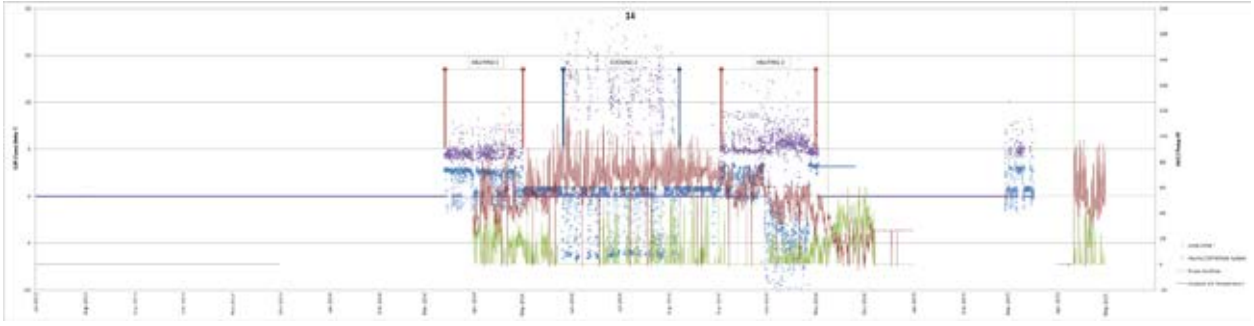


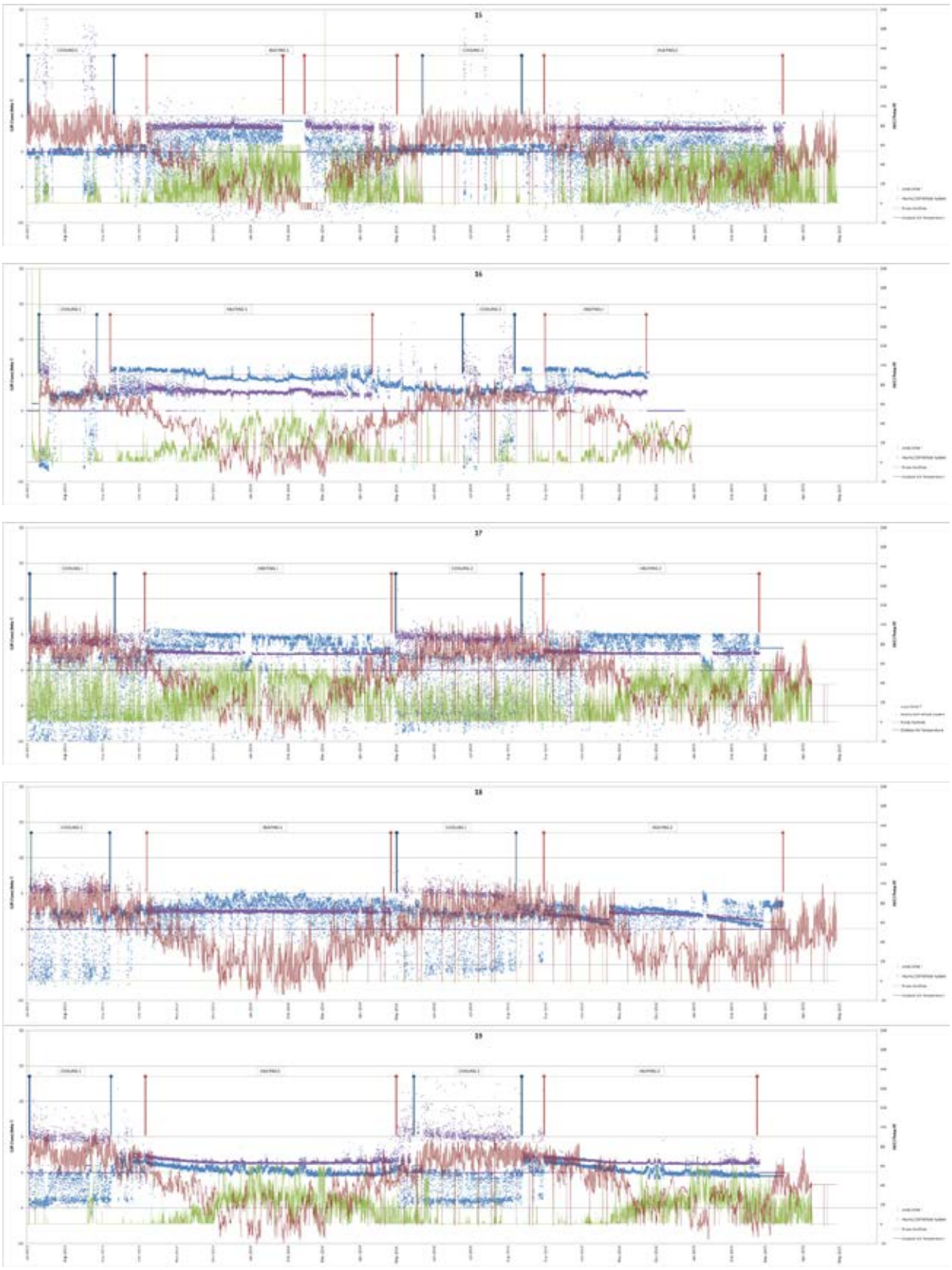


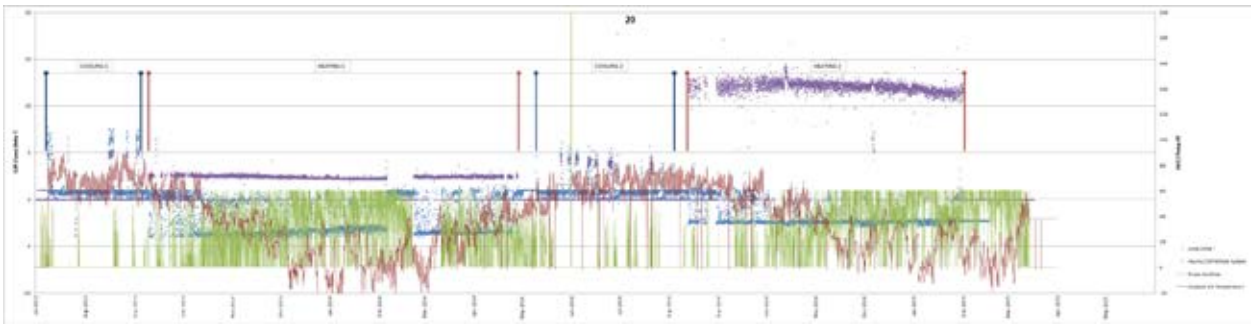


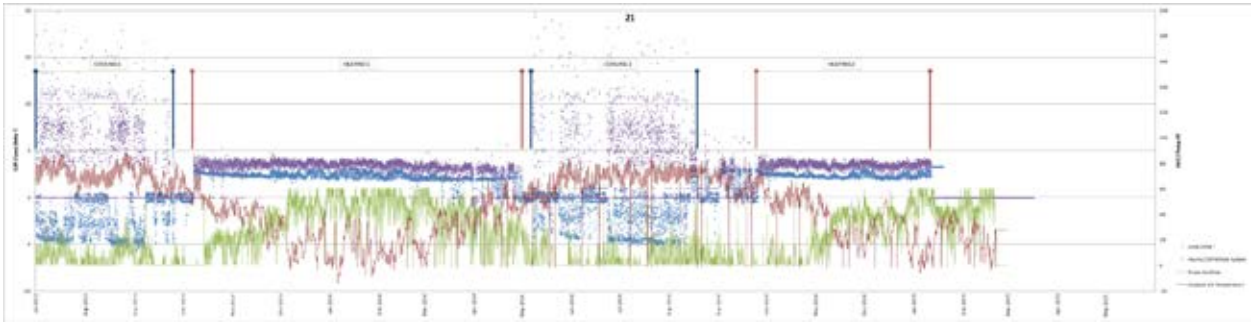


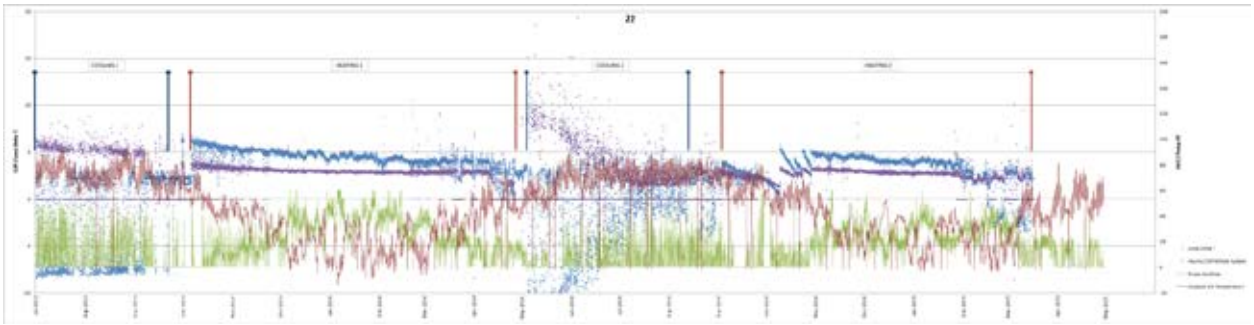


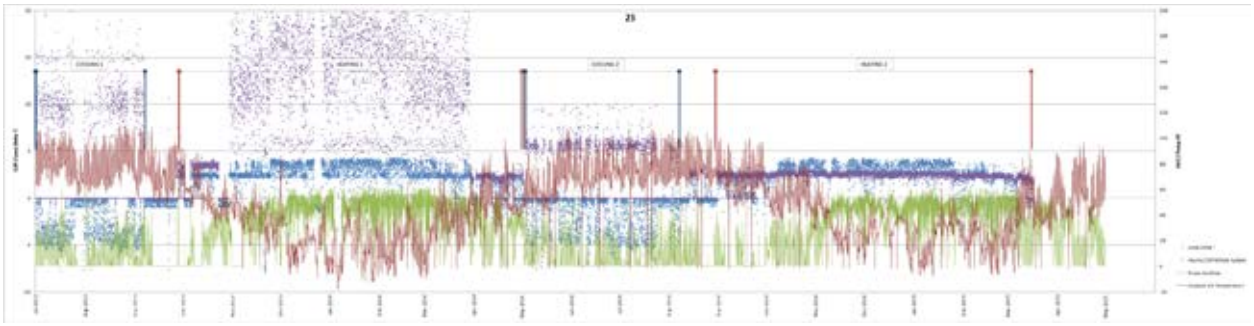


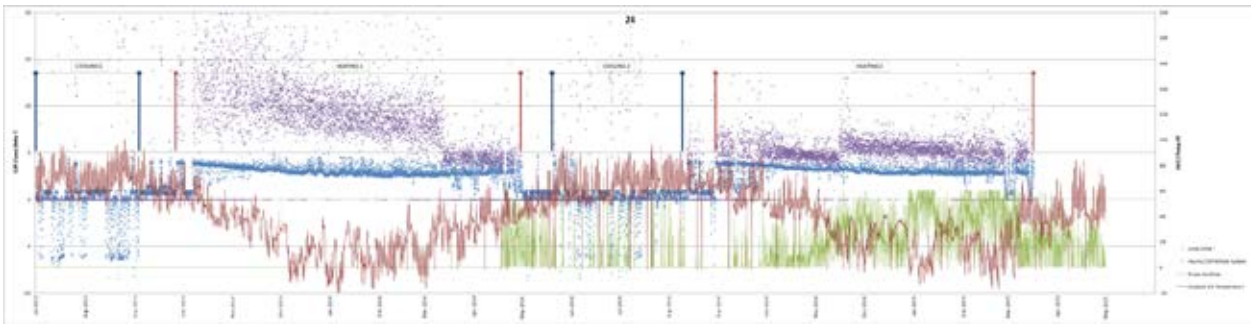


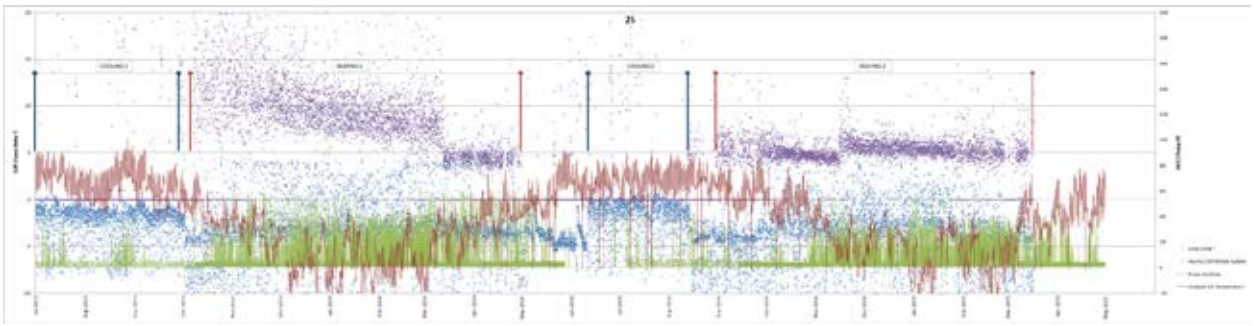


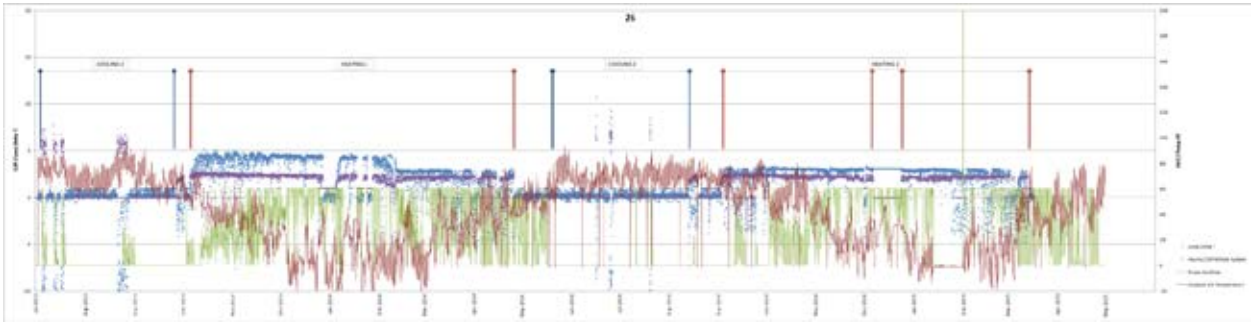


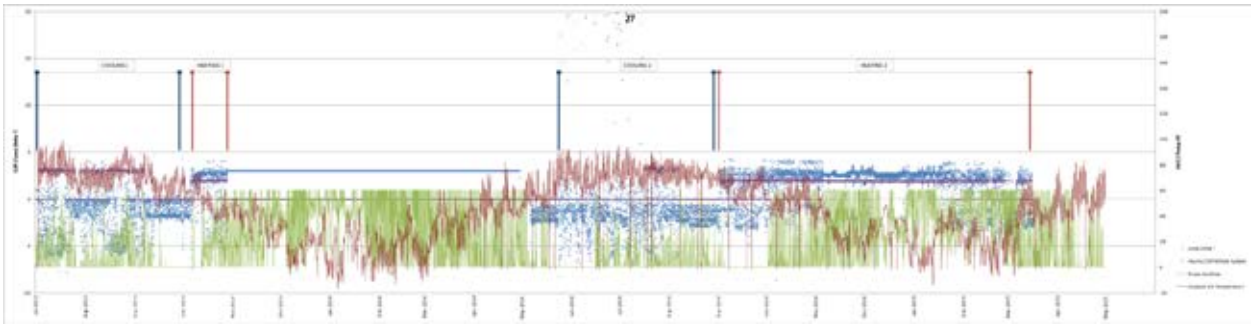


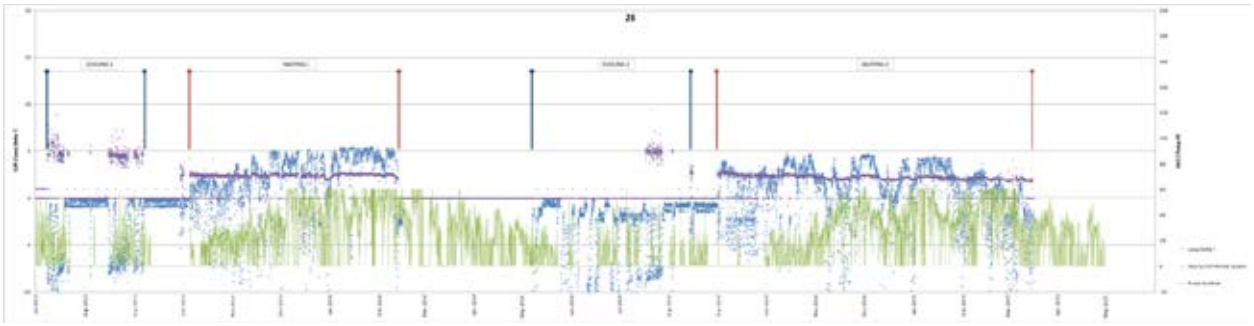


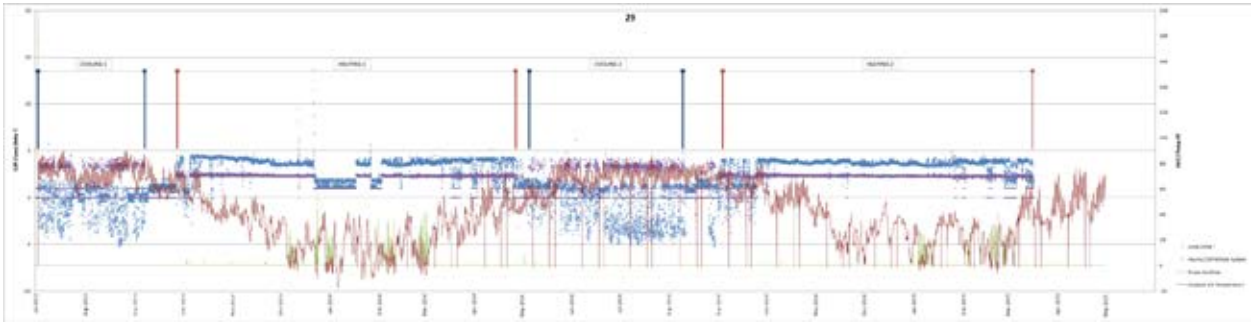


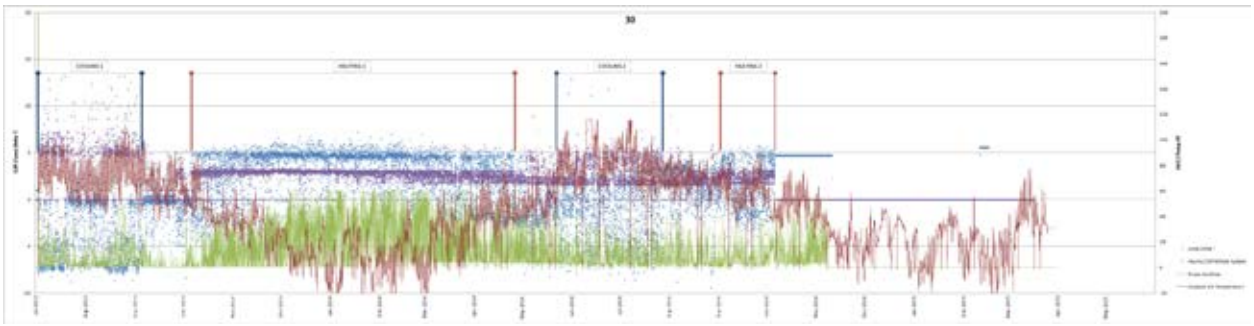


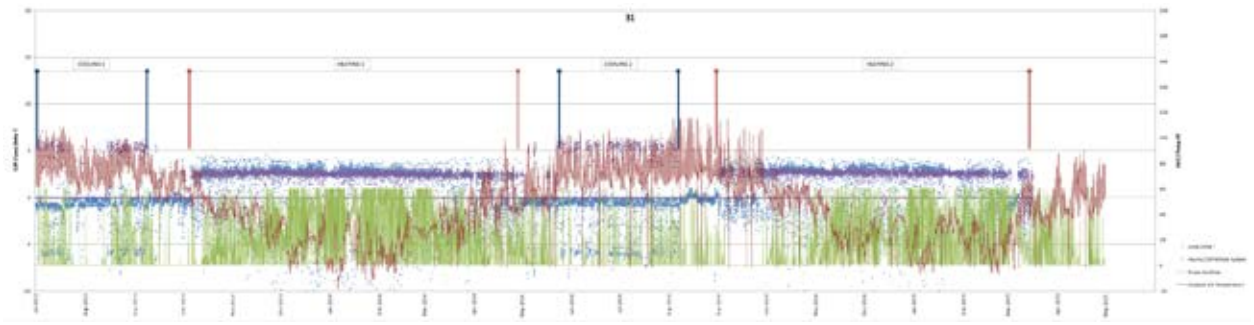


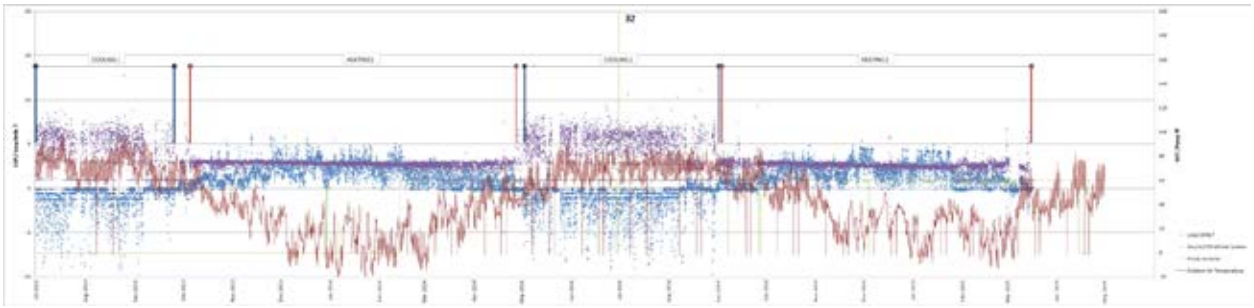


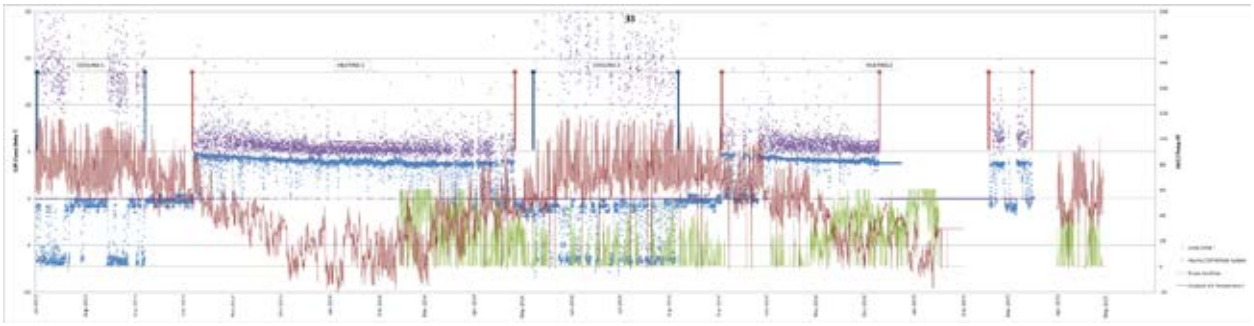


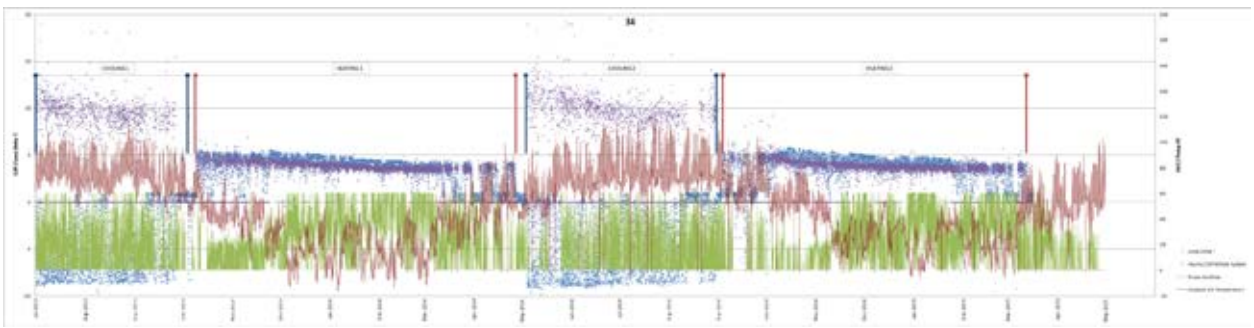


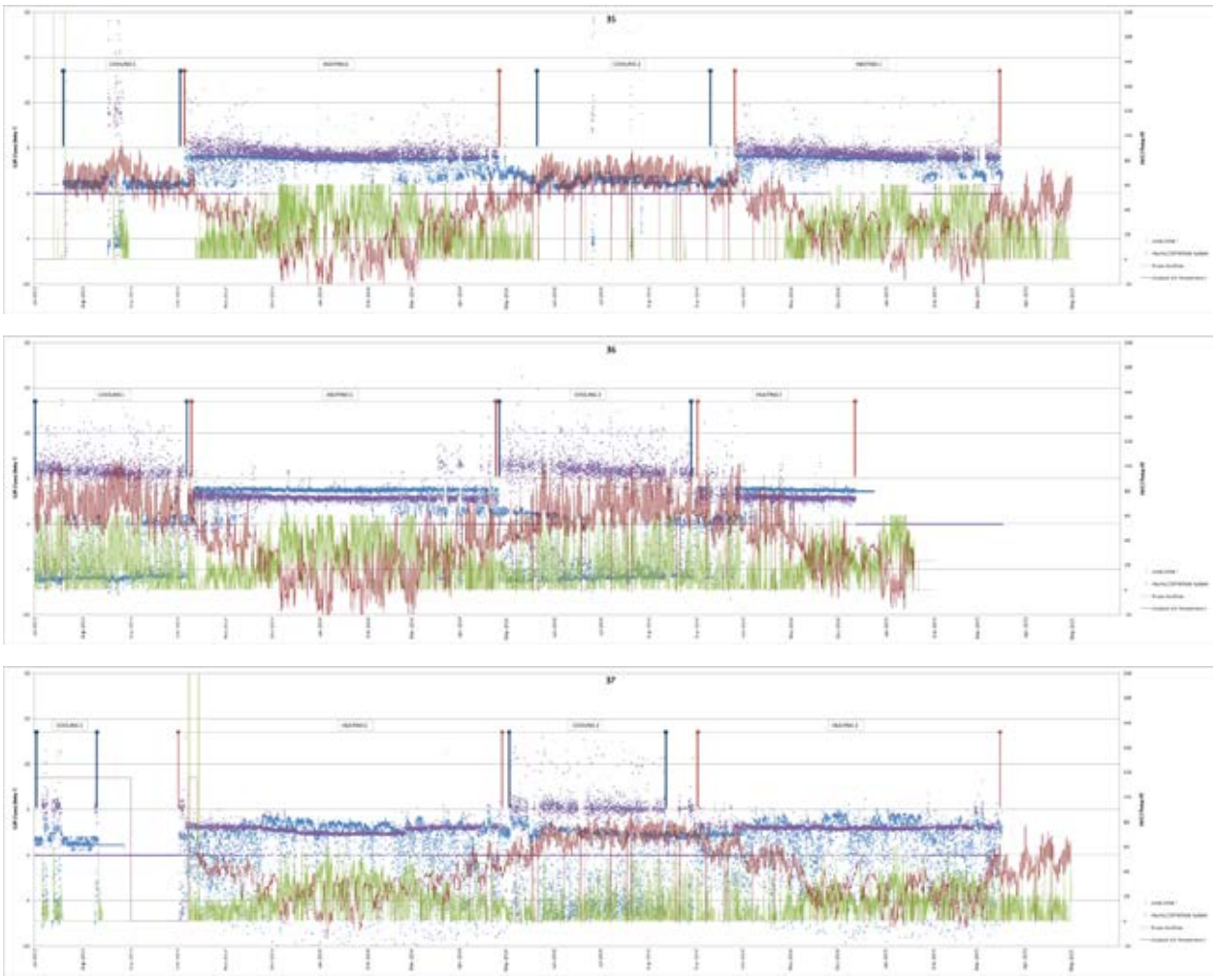












# Appendix B

Following are user input cost charts that can be used to calculate energy cost savings for GSHP systems. Readers can input their own assumptions for natural gas, propane, and electric rates and generate their own energy cost comparisons for heating, cooling, and domestic hot water.

How to use these tables:

1) Determine your expected utility rates for electricity, natural gas and/or propane. Enter them in the first table below - "Cost inputs"- noting their corresponding letter. The cost rates must match the units specified ($/therm, $/gallon, etc.).
2) The calculation tables which follow are arranged by house size and efficiency level (2000sf, 3000sf, 4000sf, and low, mid, high efficiency). Select the table with the house that most closely matches your desired test scenario. For a description of the house size, equipment, and efficiency assumptions for each case, see Figure 13: Characteristics and house size--small, medium and large and Table 9: Energy performance characteristics of high efficiency house of the Energy Modeling Approach.
3) Using the selected calculation table, enter a dollar cost in each shaded box by multiplying the listed number by your assumed utility rates (letters A – G). Column 1 calculates heating costs. Column 2 calculates fan energy costs. Column 3 calculates cooling costs. Column 4 calculates domestic hot water heating costs.
4) Add costs across each row to enter a total energy cost in the rightmost column. Total energy cost for each system (natural gas-fired GFA, propane-fired GFA, GSHP) can be compared to determine possible cost savings.

Note that GSHP efficiency level is a "system level" efficiency that includes the impacts of the loop field. It does not necessarily correspond to the efficiency of the heat pump unit itself and is therefore difficult to determine prior to installation and testing.

**Table B-1: Cost Inputs**

| Cost inputs | | | |
|---|---|---|---|
| Base case GFA with natural gas | A = | average natural gas charge, $/therm | |
| | B = | winter electric charge, $/kWh | |
| | C = | summer electric charge, $/kWh | |
| Base case GFA with propane | D = | average propane charge, $/gallon | |
| | B = | winter electric charge, $/kWh | |
| | C = | summer electric charge, $/kWh | |
| GSHP case | E = | DHW average electric charge | |
| | F = | GSHP winter electric charge, $/kWh | |
| | G = | GSHP summer electric charge, $/kWh | |

## Table B-2: 2000sf house size:

| | 2000sf, low efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 1439 x A = | | 733 x B = | | 1934 x C = | | 227 x A = | | |
| Base case GFA (propane) | 1576 x D = | | 733 x B = | | 1934 x C = | | 249 x D = | | |
| GSHP low efficiency | 10756 x F = | | 1594 x F = | | 909 x G = | | 4074 x E = | | |
| GSHP mid efficiency | 9847 x F = | | 1594 x F = | | 791 x G = | | 4074 x E = | | |
| GSHP high efficiency | 8411 x F = | | 1594 x F = | | 615 x G = | | 4074 x E = | | |

| | 2000sf, mid efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 768 x A = | | 615 x B = | | 1758 x C = | | 221 x A = | | |
| Base case GFA (propane) | 841 x D = | | 615 x B = | | 1758 x C = | | 242 x D = | | |
| GSHP low efficiency | 6565 x F = | | 1169 x F = | | 821 x G = | | 4074 x E = | | |
| GSHP mid efficiency | 6008 x F = | | 1169 x F = | | 703 x G = | | 4074 x E = | | |
| GSHP high efficiency | 5129 x F = | | 1169 x F = | | 528 x G = | | 4074 x E = | | |

| | 2000sf, high efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 547 x A = | | 674 x B = | | 879 x C = | | 201 x A = | | |
| Base case GFA (propane) | 599 x D = | | 674 x B = | | 879 x C = | | 220 x D = | | |
| GSHP low efficiency | 5275 x F = | | 978 x F = | | 586 x G = | | 3956 x E = | | |
| GSHP mid efficiency | 4806 x F = | | 978 x F = | | 498 x G = | | 3956 x E = | | |
| GSHP high efficiency | 4132 x F = | | 978 x F = | | 381 x G = | | 3956 x E = | | |

## Table B-3: 3000sf house size

| | 3000sf, low efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 1892 x A = | | 909 x B = | | 2784 x C = | | 261 x A = | | |
| Base case GFA (propane) | 2072 x D = | | 909 x B = | | 2784 x C = | | 286 x D = | | |
| GSHP low efficiency | 14155 x F = | | 2041 x F = | | 1260 x G = | | 4806 x E = | | |
| GSHP mid efficiency | 12924 x F = | | 2041 x F = | | 1084 x G = | | 4806 x E = | | |
| GSHP high efficiency | 11078 x F = | | 2041 x F = | | 850 x G = | | 4806 x E = | | |

| | 3000sf, mid efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 987 x A = | | 762 x B = | | 2520 x C = | | 252 x A = | | |
| Base case GFA (propane) | 1081 x D = | | 762 x B = | | 2520 x C = | | 276 x D = | | |
| GSHP low efficiency | 8440 x F = | | 1451 x F = | | 1143 x G = | | 4806 x E = | | |
| GSHP mid efficiency | 7708 x F = | | 1451 x F = | | 967 x G = | | 4806 x E = | | |
| GSHP high efficiency | 6594 x F = | | 1451 x F = | | 733 x G = | | 4806 x E = | | |

| | 3000sf, high efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 766 x A = | | 850 x B = | | 1202 x C = | | 231 x A = | | |
| Base case GFA (propane) | 839 x D = | | 850 x B = | | 1202 x C = | | 253 x D = | | |
| GSHP low efficiency | 7356 x F = | | 1263 x F = | | 762 x G = | | 4689 x E = | | |
| GSHP mid efficiency | 6741 x F = | | 1263 x F = | | 645 x G = | | 4689 x E = | | |
| GSHP high efficiency | 5774 x F = | | 1263 x F = | | 528 x G = | | 4689 x E = | | |

## Table B-4: 4000sf house size

| | 4000sf, high efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 950 x A = | | 1055 x B = | | 1553 x C = | | 261 x A = | | |
| Base case GFA (propane) | 1040 x D = | | 1055 x B = | | 1553 x C = | | 286 x D = | | |
| GSHP low efficiency | 9144 x F = | | 1499 x F = | | 938 x G = | | 5422 x E = | | |
| GSHP mid efficiency | 8353 x F = | | 1499 x F = | | 821 x G = | | 5422 x E = | | |
| GSHP high efficiency | 7151 x F = | | 1499 x F = | | 645 x G = | | 5422 x E = | | |

| | 4000sf, mid efficiency house | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case for comparison | furnace/GSHP heating energy (therms or kWh) | Column 1 (dollars) | furnace/GSHP fan energy (kWh) | Column 2 (dollars) | air conditioner/ GSHP cooling energy (kWh) | Column 3 (dollars) | DHW fuel consumption (therms or kWh) | Column 4 (dollars) | Total cost: Column 1 + 2 + 3 + 4 |
| Base case GFA (nat. gas) | 1139 x A = | | 850 x B = | | 3341 x C = | | 282 x A = | | |
| Base case GFA (propane) | 1247 x D = | | 850 x B = | | 3341 x C = | | 309 x D = | | |
| GSHP low efficiency | 9730 x F = | | 1665 x F = | | 1465 x G = | | 5510 x E = | | |
| GSHP mid efficiency | 8880 x F = | | 1665 x F = | | 1231 x G = | | 5510 x E = | | |
| GSHP high efficiency | 7620 x F = | | 1665 x F = | | 909 x G = | | 5510 x E = | | |

# Appendix C

**Table C- 1: Survey of GSHP Rebates Offered by Minnesota Utilities**

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| Agralite Electric Cooperative | Co-op | Residential rebate of $400 per ton. | No efficiency minimums. |
| Alexandria Light and Power | Muni | Residential and commercial rebate of $200 per ton. | Minimum EER and COP depend on type of pump (closed-loop vs. open-loop, water-to-air vs. water-to-water vs. direct exchange). |
| Arrowhead Electric Cooperative | Co-op | Residential rebate of $400 per ton. | No efficiency minimums. |
| Austin Utility | Muni | Residential and commercial rebate of $200 per ton plus additional bonus for systems that are more efficient than minimum ratings. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Beltrami Electric Cooperative | Co-op | Residential rebate of $20 per kW or $200 per ton installed, with a limit of $600. | |
| BENCO Electric Cooperative | Co-op | Residential and commercial rebate of $400 per ton for GSHPs controlled by the utility for load management and $200 per ton for those that are uncontrolled. | No minimum efficiency requirement. |
| Blooming Prairie | Muni | Residential rebate of $200 per ton plus an additional $25 per ton for each 1 EER above minimum efficiency. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Brown County Electric Cooperative | Co-op | Flat residential rebate of $1,000 plus a reduced rate on the kilowatt hours used for heating and cooling with the heat pump. | |
| Clearwater – Polk Electric Cooperative | Co-op | Flat residential rebate of $3000. | |
| Connexus Energy | Co-op | $400 per ton residential rebate with no efficiency requirement; $400 per ton commercial rebate with efficiency requirement and maximum rebate of $100,000 or 50% of project cost. | Commercial minimum EER of 11.7 and COP of 3.0 for closed-loop, minimum EER of 14.5 and COP of 3.3 for open-loop. |

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| Cooperative Light and Power | Co-op | Residential rebate form posted on their website does not indicate what the rebate amount or terms are. | |
| Crow Wing Light and Power | Co-op | Residential rebate of $100 per ton. | Closed-loop minimum EER of 14.1, open-loop minimum EER of 16.2 |
| Dakota Electric Association | Co-op | Residential rebate of $400 per ton, commercial rebate of $400 per ton with a maximum rebate of $100,000 or 50% of project cost. | No efficiency minimums. |
| East Central Energy | Co-op | Residential and commercial rebate of $400 per ton with minimum EER of 11.7 and COP of 3.0 for closed-loop and minimum EER of 13.5 and COP of 3.3 for open-loop. | |
| Fairmont | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Federated Rural Electric Association | Co-op | Residential rebate of $300 per ton. | No minimum efficiency ratings. |
| Freeborn-Mower Cooperative Services | Co-op | Residential rebate of $300 per ton. | No minimum efficiency ratings. |
| Goodhue County Co-op Electric Association | Co-op | Rebate of $200 per ton. | No minimum efficiency ratings. Unclear if the rebate is only available to residential customers or if it is available to commercial customers as well. |
| Grand Marais | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Great River Energy | Co-op | Great River Energy's incentives are listed under the incentives offered by its 28 member cooperatives. | |

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| Iowa Lakes Electric Cooperative | Co-op | Residential and commercial rebates of $300 per ton for a new GSHP and $150 per ton for GSHPs replacing older GSHPs. | No minimum efficiency ratings. |
| Itasca-Mantrap Electric Cooperative | Co-op | Residential rebate of $400 per ton, with a 5-ton maximum. | No minimum efficiency ratings. |
| Kandiyohi Power Cooperative | Co-op | Residential rebate of $200 per ton. | No minimum efficiency ratings. |
| Lake City | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Lake Country Power | Co-op | Residential rebate of $400 per ton. | No minimum efficiency ratings. |
| Lake Region Electric Cooperative | Co-op | Residential rebate of $400 per ton for closed loop system with manual J load calculation and system providing at least 90% of total block heating requirement; $200 per ton for HDD system with manual J load calculation with system providing at least 90% of total block heating requirement or other closed loop system; $100 per ton for open loop system. | No stated minimum efficiency ratings. |
| Litchfield | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Lyon-Lincoln Electric Cooperative | Co-op | $400 residential rebate for installation of any GSHP, additional rebate of $400 if the GSHP is Energy Star certified. | |
| McLeod Co-op Power Association | Co-op | Residential and commercial rebate of $400 per ton. | No minimum efficiency ratings. |

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| Meeker Co-op Light and Power | Co-op | Rebate of $200 per ton for demand-controlled GSHPs and $100 per ton for uncontrolled, with a 5-lb max. | No minimum efficiency ratings. Unclear whether rebates are only residential or also available to commercial customers. |
| Mille Lacs Energy Co-op | Co-op | Residential rebate of $400 per ton. | No minimum efficiency ratings. |
| Minnesota Valley Co-op L&P | Co-op | Rebate of $12 per 1,000 BTUs, must have COP of 3.3 or higher. | Unclear whether rebates are only residential or also available to commercial customers. |
| Minnesota Valley Electric Cooperative | Co-op | Loan with 4% interest rate for up to $5000 for the cost of GSHP installation | |
| Moorhead Public Service | Muni | Residential and commercial rebate of $200 per ton. | Energy Star certification required; minimum EER and COP ratings depend on type of pump (open-loop vs. closed-loop, water-to-air vs. water-to-water vs. direct exchange). |
| Mora | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| New Prague | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Nobles Co-op Electric | Co-op | Residential rebate of $200 per ton. | Minimum EER of 11.7 EER and 3.0 COP for closed-loop; 13.5 EER and 3.3 COP for open-loop. |
| North Branch | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| North Itasca Electric Co-op | Co-op | None | |
| North Star Electric Co-op | Co-op | Residential and commercial rebate of $200 per ton for open-loop GSHP systems (maximum residential rebate of $2,500 and commercial rebate of $7,500), and $400 per ton for closed-loop GSHP systems (maximum residential rebate of $5,000 and commercial rebate of $15,000). | Minimum EER of 16.2 and COP of 3.6 for open-loop systems; minimum EER of 14.1 and COP of 3.3 for closed-loop systems. |
| Northwestern Wisconsin Electric | IOU | None | |
| Ottertail Power | IOU | Offers up to $20,000 in loans for residential customers seeking to install GSHPs, up to $15,000 for customers for combination electric systems, and up to $100,000 for business customers for GSHPs under CIP. Alternatively, customers can receive a rebate of $240 per ton for split systems with 12.0 or greater EER, package-terminal GSHPs with 11.0 or great EER, or a $600 per ton rebate on Energy Star-labeled GSHPs or those proved to have a qualified minimum COP rating. | 1.9% interest on DollarSmart Financing program. COP rating for rebate depends on type of pump (open-loop vs. closed-loop, water-to-air vs. water-to-water vs. direct exchange). |
| Owatonna | Muni | Rebate for residential customers of $200 per ton plus $150 per 1.0 EER over minimum efficiency requirement plus $250 per desuperheater. Rebate for commercial customers of $200 per ton plus $50 per 1.0 EER over minimum efficiency requirement. | Minimum EER and COP rating for rebate depends on type of pump (open-loop vs. closed-loop, water-to-air vs. water-to-water vs. direct exchange |
| PKM Electric Cooperative | Co-op | Residential rebate of $200 per ton with a maximum incentive of $2,500 per ton for an open-loop GSHP system and of $400 per ton with a maximum incentive of $400 per ton with a maximum incentive of $5,000 per ton for a closed-loop GSHP system. | Minimum EER of 16.2 and COP of 2.6 for an open-loop system; and minimum EER of 14.1 and COP of 3.3 for a closed-loop system. |
| People's Cooperative Services | Co-op | Residential rebate of $300 per ton. Must be configured for load control. | No minimum efficiency requirements. |

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| Preston | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Princeton | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Red Lake Electric Cooperative | Co-op | Residential and commercial rebate of $200 per ton for open-loop GSHP systems (maximum residential rebate of $2,500 and commercial rebate of $7,500), and $400 per ton for closed-loop GSHP systems (maximum residential rebate of $5,000 and commercial rebate of $15,000). | Minimum EER of 16.2 and COP of 3.6 for open-loop systems; minimum EER of 14.1 and COP of 3.3 for closed-loop systems. |
| Red River Valley Co-op Power Association | Co-op | Residential and commercial rebate of $200 per ton for open-loop GSHP systems (maximum residential rebate of $2,500 and commercial rebate of $7,500), and $400 per ton for closed-loop GSHP systems (maximum residential rebate of $5,000 and commercial rebate of $15,000). | Minimum EER of 16.2 and COP of 3.6 for open-loop systems; minimum EER of 14.1 and COP of 3.3 for closed-loop systems. |
| Redwood Electric Cooperative | Co-op | Residential rebate of $1,000 per GSHP with at least 16.0 EER. | Must be under controlled cooling program. |
| Redwood Falls | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Renville-Sibley Cooperative Power Association | Co-op | Residential rebate of $400 for non-Energy-Star-rated GSHPs and of $800 for Energy-Star-rated GSHPs. | |

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| Rochester | Muni | Commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies; residential rebate of $200 per ton plus $150 per ton for each 1 EER above minimum qualifying efficiencies plus $250 per desuperheater. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Roseau Electric Cooperative | Co-op | Residential and commercial rebate of $200 per ton for open-loop GSHP systems (maximum residential rebate of $2,500 and commercial rebate of $7,500), and $400 per ton for closed-loop GSHP systems (maximum residential rebate of $5,000 and commercial rebate of $15,000). | Minimum EER of 16.2 and COP of 3.6 for open-loop systems; minimum EER of 14.1 and COP of 3.3 for closed-loop systems. |
| Runestone Electric Association | Co-op | Residential rebate of $200 per ton with a $1,000 maximum. | No minimum efficiency requirements. |
| Saint Peter | Muni | None | |
| Shakopee Public Utilities | Muni | Residential rebate of $100 per ton. | Complicated scheme for additional rebate based on EER. |
| Sioux Valley Energy | Co-op | Residential and commercial rebate of $600 per GSHP. | No minimum efficiency requirements. |
| South Central Electric Association | Co-op | Residential and commercial rebate of $400 per ton. | No minimum efficiency requirements. |
| Spring Valley | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Staples | Muni | Residential and commercial rebate of $200 per ton plus $250 for a desuperheater. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Stearns Co-op Electric Association | Co-op | Residential rebate of $150 per ton, with a maximum rebate of 5 tons. | No minimum efficiency requirements. |

| Utility | Utility Type | Incentive offered | Details |
|---|---|---|---|
| Steele-Waseca Electric Cooperative | Co-op | Residential rebate of $400 per ton. | No minimum efficiency requirements. |
| Todd-Wadena Electric Cooperative | Co-op | Residential and commercial rebate of $600 per ton for Energy-Star-rated GSHPs. | |
| Traverse Electric Cooperative | Co-op | Residential and commercial rebate of $600 per Energy-Star-rated GSHP system for systems that are two tons or larger. | |
| Tri-County Electric Cooperative | Co-op | Residential and commercial rebate of $300 per ton. | No minimum efficiency requirements. |
| Waseca | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Wells | Muni | Residential and commercial rebate of $200 per ton plus $25 per ton for each 1 EER above minimum qualifying efficiencies. | Minimum EER and COP requirements depend on GSHP type (closed-loop vs. open-loop, water-to-water vs. water-to-air vs. direct exchange). |
| Wild Rice Electric Cooperative | Co-op | Residential and commercial rebate of $200 per ton for open-loop GSHP systems (maximum residential rebate of $2,500 and commercial rebate of $7,500), and $400 per ton for closed-loop GSHP systems (maximum residential rebate of $5,000 and commercial rebate of $15,000). | Minimum EER of 16.2 and COP of 3.6 for open-loop systems; minimum EER of 14.1 and COP of 3.3 for closed-loop systems. |
| Wright-Hennepin Co-op Electric Association | Co-op | Residential rebate of $150 per ton. | No minimum efficiency requirement. |
| Xcel Energy | IOU | Residential rebate for GSHP $150 per ton, up to 5 tons. | Offered only for Energy Star-certified closed-loop systems with a minimum EER rating of 14.1. |

# Appendix D

With the purpose to inform potential GSHP consumers about the cost-effectiveness of the GSHP technology compared to the more conventional GFA technology, we propose a "GSHP vs. GFA" comparison from a different angle: use GFA model's capital cost and GSHP model's 20-year maintenance and operational (M+O) savings over GFA model to project a GSHP model's capital cost that makes the two technologies equally cost-effective.

The baseline is a GFA model costs $5,634 and contains an 80 AFUE, 70,000Btu furnace and a 13 SEER, 2-ton AC.

In the high price scenario:

- Furnace: an 80 to 90 AFUE increase will cost 25% more; a 70,000 to 135,000 Btu increase will cost 38%.
- AC: a 13 to 17 SEER increase will cost 150% more; a 2 to 5 ton increase will cost 100% more.

In the low price scenario:

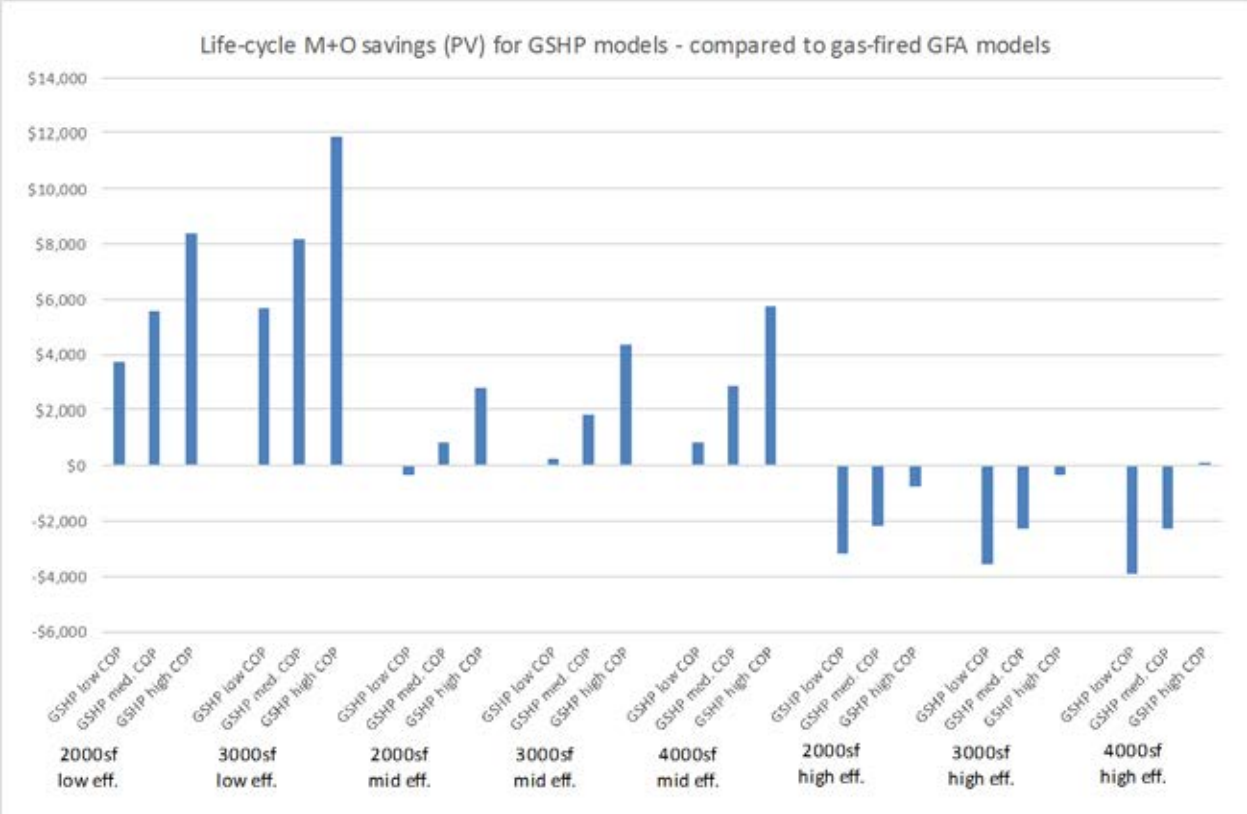
- Every increase is cut by half.

**Table D-1. Estimated capital cost of GFA w/AC models for each house in high price scenario and low price scenario**

| House | High price scenario | Low price scenario |
|---|---|---|
| 2000sf low eff. | $ 5,634 | $ 5,634 |
| 3000sf low eff. | $ 7,746 | $ 6,690 |
| 2000sf mid eff. | $ 8,102 | $ 6,868 |
| 3000sf mid eff. | $ 11,140 | $ 8,155 |
| 4000sf mid eff. | $ 14,178 | $ 9,443 |
| 2000sf high eff. | $ 10,570 | $ 8,102 |
| 3000sf high eff. | $ 14,534 | $ 9,621 |
| 4000sf high eff. | $ 18,497 | $ 11,140 |

Life-cycle (20 years) M+O savings of each GSHP model compared to its corresponding gas-fired GFA model are illustrated in Figure D-1. All GSHP models can achieve positive life-cycle M+O savings in low- and mid-efficiency houses except for low-COP GSHP model in 2000sf mid-efficiency house. All GSHP models have negative life-cycle M+O savings in high-efficiency houses. Such results imply that improvement in technology efficiency may not be as cost-effective as improvement in house efficiency.

**Figure D-1: Life-cycle maintenance and operational (M+O) savings for GSHP models, compared to gas-fired GFA models.**

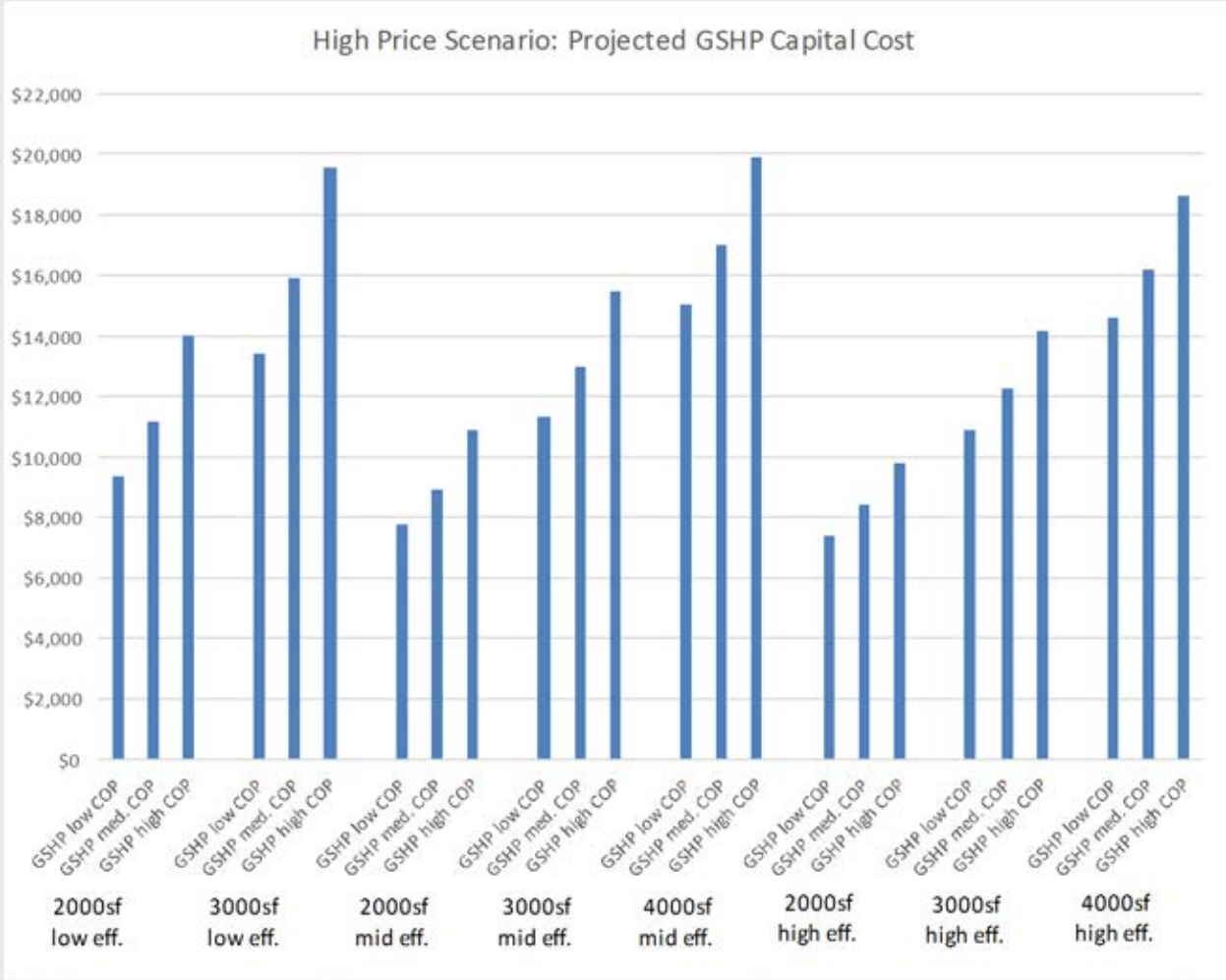



The projected GSHP model's capital cost would be "cap price" for any GSHP model to achieve positive life-cycle savings over GFA model. In other words, a GSHP model costs less than the "cap price" will lead to positive life-cycle savings over GFA model, whereas a GSHP model costs more than the "cap price" will end up costing more than GFA model across lifetime.

The projected GSHP model's capital cost may include GSHP tag price, installation of loop field and all other necessary costs.

In the high price scenario, the projected GSHP model's capital cost ranges from $7,402 to $19,926 (Figure D-2). The projected costs can be further reduced by incentives and rebates for qualified GSHP models.

**Figure D-2: Projected GSHP capital cost in high price scenario**



In the low price scenario, the projected GSHP model's capital cost ranges from $4,934 to $15,191 (Figure D-3). The projected costs can be further reduced by incentives and rebates for qualified GSHP models.

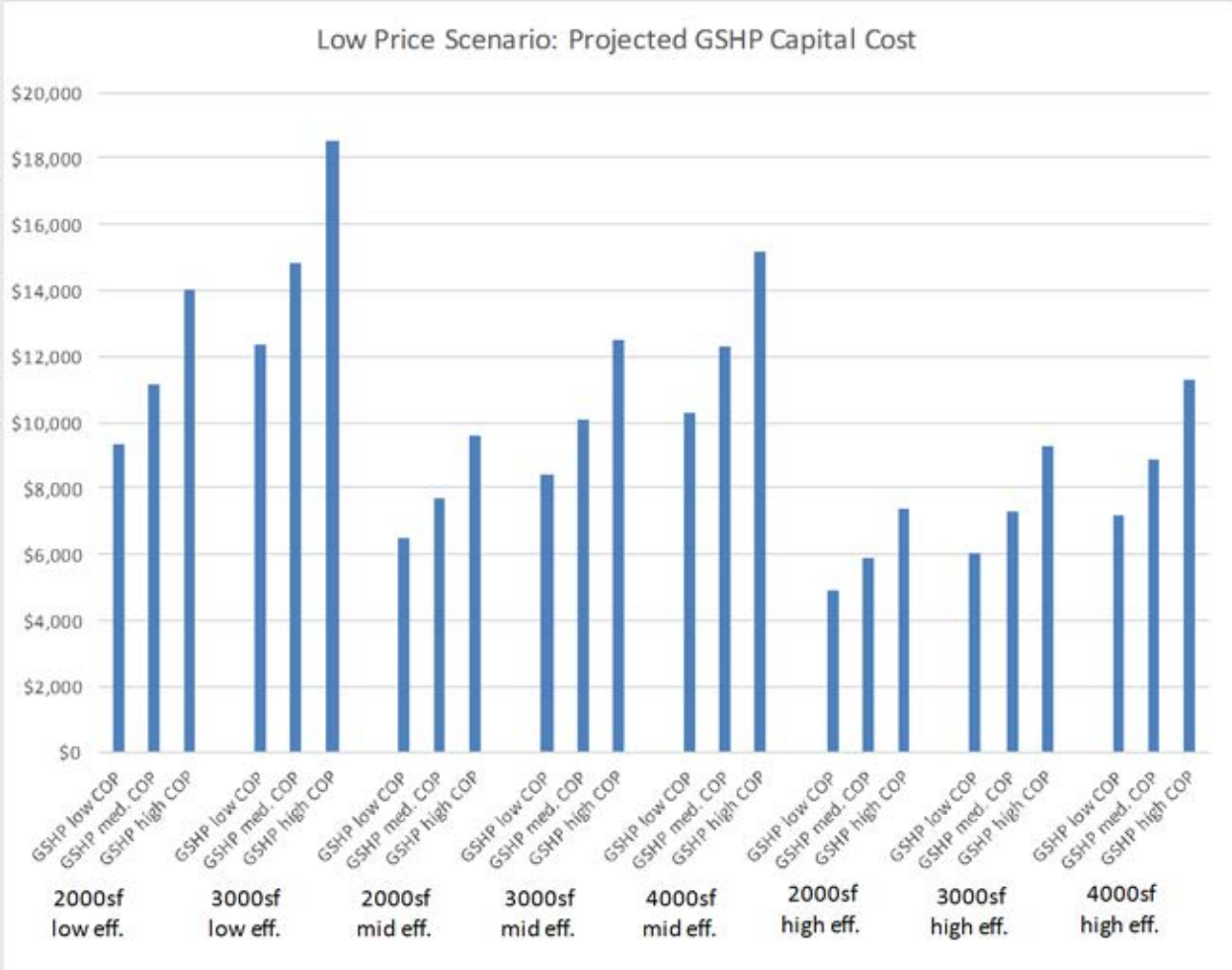



**Figure D-3: Projected GSHP capital cost in low price scenario**