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Ground Source Heat Pumps vs. Conventional HVAC: A Comparison of Economic and Environmental Costs

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A COMPARISON OF ECONOMIC AND ENVIRONMENTAL COSTS

THESIS

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Abstract

The world is undergoing a dramatic transformation with regard to how it produces and consumes energy due to increasing demand from developing nations and diminishing new resource discoveries. In addition, there has been increased concern over the effect of carbon dioxide emissions on the environment. All of these issues have created a combined pressure to force the world to begin to redefine how energy is utilized. Geothermal or ground source heat pumps (GSHPs) may provide one potential solution to these problems. This research investigated vertical borehole closed-loop GSHP systems in direct comparison to natural gas furnaces combined with traditional air-conditioning (NGAC) for 51 locations in the United States. The study utilized Trane Trace 700, Geothermal Loop Design, and Building Life-Cycle Cost 5 software packages for analysis. Although the installation costs for GSHP systems were 257% higher than NGAC systems, the operating costs were 33% lower. The mean simple and discounted payback periods for the GSHP system were 10 and 15 years, respectively. Carbon dioxide emissions were found to be 2.2% higher for the GSHP systems due to their use of coal-fired electricity in most locations. The overall life-cycle cost was 19.0% lower when selecting the GSHP system over the NGAC system.

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Dedication

To my wife and daughter

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Dr. Alfred Thal Jr., for his guidance and support throughout the course of this thesis effort. The insight and experience he provided was greatly appreciated. I would also like to acknowledge my committee members, Dr. Charles Bleckmann and Capt Ryan Kristof, for their expertise and commitment to this research. Finally, I would like to recognize my wife and daughter. They have sacrificed in this effort as well, encountering countless hours when I was not able to share my time with them. Without their love and support, none of this would have been possible.

Paul W. Fredin

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I. Introduction

The world is undergoing a dramatic transformation with regard to how it produces and consumes energy. The world energy market is experiencing increasing demand from developing nations at the same time when new resource discoveries are diminishing. Energy prices have risen to record levels and caused a significant strain on people all over the globe. Readily exploitable sources of energy are increasingly under control of hostile regimes and represent a national security threat to the nations of the world. In addition, there has been increased concern over the effect of carbon dioxide emissions on the environment. The likelihood of increased costs from regulation of carbon dioxide emissions has dramatically increased in the last few years. The science behind global warming is still a contentious issue, but the prospect of increased legislation and taxation on fossil fuels has magnified the urgency of developing alternative methods of heating and cooling facilities. All of these issues have created a combined pressure to force the world to begin to redefine how energy is consumed. Ground source heat pumps (GSHPs) may provide one potential solution to this massive problem.

Background

There are many ways to attack this worldwide energy challenge, but this research effort specifically targets the use of energy in facilities for heating and cooling. Facilities consume 71% of the electricity, 39% of the total energy, and create 39% of the carbon dioxide emissions in the United States, making the built environment one of the largest impacts on the natural world (USGBC, 2008). Facility energy use has grown much faster than any other sector and this trend is expected to continue.

Although many areas have a significant impact on energy use, none have an impact of the same magnitude as that of buildings. There are many different technologies available to tackle world energy use, but this effort specifically focuses on low-temperature geothermal technologies for use in facility heating and cooling. Ground source heat pump (GSHP) is the preferred name for this type of system. Using GSHP terminology is officially sanctioned by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), and helps alleviate any confusion with high-temperature geothermal sources, such as those found in Iceland and the western United States.

GSHPs are not a new technology, but they are relatively unknown in America. The technology is proven, with an installed base in the United States exceeding 600,000 units (Hughes, 2008). This may seem like a large number, but it is virtually insignificant when compared to conventional systems. In order to get an idea of their market penetration, one example is residential construction. There are 58.2 million natural gas furnaces and 65.9 million split system central air conditioners out of 111.1 million residences in the United States as of 2005 (Department of Energy, 2005). This puts GSHP systems at far less than 1% of the total installed units in the United States. Thus, it seems as though inexpensive fossil fuels coupled with an extreme focus on low initial cost have relegated GSHPs to relative obscurity. Given the recent rise in energy prices and the resurgence of the environmental movement, GSHPs may become much more commonplace in the years to come.

Ground Source Heat Pump Overview

GSHPs are not a new technology, nor are they extremely complicated. They accomplish heating and cooling by taking advantage of the relatively stable temperature of the ground below the surface. There are many different types of GSHPs, but the basic technology at work is very much the same for all types. A more detailed description of the configurations is accomplished in the literature review, but a brief overview is conducted in this section.

GSHP Technology

The basic premise behind the GSHP system is that the ground provides a heat source in winter and a heat sink during the summer. The system consists of two separate loops that are connected through a heat exchanger. The first loop, or ground loop, consists of a polyethylene pipe that is filled with a heat transfer fluid. This fluid is pumped through the pipe in the ground where it either absorbs or discharges heat depending on the season. The second loop is a standard vapor compression refrigeration cycle used to move heat from an area of lower temperature to an area of higher temperature or vice versa. This is the same cycle utilized in air conditioning systems, but includes additional reversing valves to allow for heating and cooling operation. These loops are linked through the use of a heat exchanger inside the heat pump itself. The system works to move heat from the conditioned space to the ground in the summer and works in reverse to move heat from the ground to the space in the winter. The intricacies of these systems will be reviewed in detail in the literature review section of this work.

GSHP Advantages

GSHPs have numerous proven benefits. They are extremely energy efficient in that they have a coefficient of performance (COP) as high as 5.0 on some models. This is the equivalent of 500% efficiency using traditional standards. This feat is achieved by moving 5 units of "free" heat from the ground while only paying for 1 unit of energy to move it. This high level of efficiency could be further improved to a COP of 6 to 8 with existing technology and the theoretical limit could be as high as 14 (Hughes, 2008). Another major advantage is that GSHPs require only electricity for their operation, greatly simplifying utility requirements. All buildings have an electrical service and a GSHP eliminates the need for fuel deliveries or the construction of a natural gas service line. This is especially advantageous for rural customers lacking access to natural gas who have limited choices for energy supplies. Rural electric cooperatives have brought electricity to nearly all parts of the country, making GSHPs highly attractive for users that live outside major urban areas.

The electricity required for operation can also be produced by renewable sources on site or purchased from an offsite renewable energy producer. Since GSHP systems only require electricity, they have no localized emissions and do not require any special permits. This can be of great advantage to large, commercial users faced with hiring certified boiler operators and obtaining permits for air emissions with traditional systems. One final advantage is that there is no noisy external unit above ground that is subject to damage or disruption. The ground loop for a GSHP is safely buried outside the facility and will continue to operate as long as there is electricity available. In addition, the cost of the brick enclosures used to obscure external HVAC equipment can be totally discarded.

GSHP Disadvantages

Despite all of the advantages, GSHPs do have some shortfalls. One crucial limitation is the higher initial cost. They may also have higher peak electrical demand during the heating season compared to a traditional furnace. In addition, they may not be environmentally friendly if the source of electricity utilized comes from nonrenewable sources. GSHP systems also have a much larger footprint during construction of the borehole field that needs to be considered when planning the phasing of construction. Finally, some locations have low soil thermal conductivity and are not suitable for GSHP systems.

Problem Statement

Engineers currently do not have a reliable measure to compare traditional HVAC systems to GSHPs when designing and building new facilities. Studies have been completed in the past, but they did not consider the rapid price escalation of fossil fuels and the dramatic increase in environmental considerations that have occurred in the last several years. Case studies exist, but they only consider the direct economic impact of individual HVAC systems and neglect the potential cost of the emissions they produce. These case studies are often limited to one area and are not readily applicable to other areas of interest. Engineers and designers are at a disadvantage when it is time to design a new facility. GSHP technology is often viewed as a high-risk option and fails to get the exposure and focus that is required to make informed decisions.

Another major issue is that the effects of carbon dioxide emissions are often not fully considered in project planning. The Environmental Protection Agency tracks several types of emissions, but carbon dioxide emissions are not currently regulated and do not require permits. The main focus has traditionally been on particulates and compounds that contribute to acid rain, such as sulfur dioxide. Carbon dioxide emissions have generally been thought of as harmless, since their immediate impacts are not always clear. Carbon dioxide emissions have become a huge concern on a national and international level. Existing fossil fuel users will have a huge liability for carbon dioxide emissions if costly legislation is introduced. This work seeks to fully identify the direct economic costs related to HVAC systems in addition to the potential costs that could be generated by the increased legislation and taxation of carbon dioxide emissions. The final result is intended to provide a complete analysis of GSHPs that can be used by decision makers to make informed HVAC choices in the design phase of new and retrofitted facilities. Traditional economic analyses have focused on direct costs and fail to recognize the burden that emissions have on the world. This effort combines a traditional economic analysis with an environmental impact analysis utilizing the common terms of monetary value.

Research Objectives

The main objective of this research was to conduct a study of GSHPs compared to traditional HVAC systems. The system chosen for direct comparison was that of the natural gas furnace, split-system air-conditioning (NGAC) system. Many large commercial facilities have centralized four-pipe systems that rely on boilers for heating and air-cooled chillers or cooling towers for cooling. These are beyond the scope of this study as they require much more extensive designs and are more difficult to replicate for all of the locations in this study. This research was designed to study decentralized systems such as the GSHP and NGAC systems and was conducted with the intent of making a comparison from a combined economic and environmental perspective. This research focused on the following investigative questions:

1. How do the installed cost and operating costs of NGAC systems compare to those of GSHP systems?

2. What are the simple and discounted payback periods, savings to investment ratio, and internal rate of return when comparing conventional NGAC systems to GSHPs?

3. How does the energy use of conventional NGAC systems compare to that of GSHPs?

4. How does the quantity and potential cost of carbon dioxide emissions of conventional NGAC systems and GSHPs compare?

5. How does the total life-cycle cost of conventional NGAC systems compare to that of GSHPs?

6. How does the total life-cycle cost of conventional NGAC systems compare to that of GSHPs considering the combination of traditional costs and the costs of offsetting carbon dioxide emissions?

Methodology

This research effort was based upon the hypothetical design of an office building with standard construction materials and finishes applied. A hypothetical model was used due to the fact that actual data on identical structures throughout the United States containing traditional NGAC and GSHP systems is not available. This notional structure was assumed to be constructed with average thermal resistance and level of air infiltration. An HVAC design for a traditional NGAC and a GSHP system was completed utilizing climate data for each of the 50 states and the District of Columbia. The design incorporated the energy gains and losses for the hypothetical building for each location. Although the process could be done manually, this research effort utilized several different software packages for analysis. Trane Trace 700 was used to conduct the performance, load calculations, and equipment sizing for the hypothetical building utilized in this effort. The costs for all of the HVAC equipment were calculated using RSMeans Construction Cost Book 2007 Software. This software accounts for local cost factors and price variability among the different locations. Once these costs were obtained, Building Life-Cycle Cost 5 (BLCC5) was utilized to conduct the economic and emission analysis portion of this project. This program has the ability to compute the life-cycle cost of multiple designs to determine which is most advantageous. The main feature of this software focuses on evaluating designs that have a higher initial cost, but lower operating costs. BLCC5 also has the ability to calculate the carbon dioxide emissions that accompany different types of systems based on their type of electricity generation and fuel use. These emissions were then added into the overall system cost by utilizing market rates for offsetting carbon emissions. Finally, the costs from the equipment installation and operating costs were combined with the costs from emissions to give the total life-cycle cost of an HVAC system when considering all of the potential impacts. Once all of this data was created and analyzed, the true economic and environmental impacts of GSHP and conventional HVAC systems is clear.

Assumptions/Limitations

There were a number of technical assumptions required to complete this research effort. One primary assumption made was that of the ground heat exchanger loop itself. Thermal conductivity (*k*) of soils is highly variable throughout the country and is affected by the moisture level present. For the sake of this research, an average *k* value was assumed for all designs. The value chosen represents the midpoint between heavy, saturated soils and light, dry soils.

Another major assumption was that the drilling required for the ground source heat exchanger was located in average soils and that bedrock was not encountered. The cost for hard rock drilling is often much higher, although it provides excellent thermal conductivity. In most cases, boreholes can be drilled to the depth of bedrock and the number of boreholes can be increased to develop the required length.

Despite the numerous configurations of GSHPs, this study was limited to closed-loop ground coupled vertical borehole installations. This is the only configuration that is universally applicable and is not highly sensitive to site conditions. The large heating and cooling loads required by the average commercial facility make vertical borehole installations the method of choice. The land area required for a horizontal installation is not feasible at most project sites. In addition, only low-temperature GSHP installations were considered. There are substantial high-temperature geothermal resources available in the United States, but the low temperature application is the most universally applicable method and is not as sensitive to local ground temperature fluctuations.

GSHPs have the option of adding a desuperheater unit to produce hot water from the waste heat of the unit. They are extremely efficient and produce hot water at the efficiency of the unit in the winter and produce essentially free hot water from waste heat during the summer. Despite this advantage, domestic hot water needs are small enough in magnitude that they were not considered in this effort.

Finally, this effort only developed models for the 50 states and the District of Columbia. It did not include any overseas locations. Overseas locations bring in other levels of variability and were not included in this study.

Implications

This study should serve as a tool for use when determining heating and cooling systems for new facilities. This information will assist in the selection of the appropriate heating and cooling systems for each state. Although each site has slight variations, this effort will serve as a baseline data source for use in feasibility studies for years to come. In addition, this document will allow organizations to make initial baseline decisions without performing expensive feasibility studies.

Preview

This work consists of four additional chapters including the literature review, methodology, results and analysis, and discussion. The literature review explains the different types of GSHPs, how they work, and some of their advantages and limitations. It further explains vertical closed-loop GSHPs as they are the main focus of this work. The methodology chapter explains the finer points of how this study was conducted. It includes information on design, energy costs, maintenance costs, emissions estimates, and emissions costs. The next chapter covers the results from the study to include their sensitivity to changes in parameters such as electricity costs, natural gas costs, emission offset costs, and installation costs. Finally, the last chapter reviews the findings of this study and recommends areas for future research.

II. Literature Review

The intent of this chapter is to form the framework from which ground source heat pumps (GSHPs) may be understood. It covers the environmental and energy policies that shape their development as well as the sources of energy that are responsible for their economic and environmental impact on the world. The rest of the chapter is dedicated to an in-depth description of the GSHP and the natural gas furnace with split system air-conditioning (NGAC) systems and their operations. It reviews all types of GSHP systems, but primarily focuses on the major components of vertical closed-loop GSHP systems. Finally, the most pertinent research available in the literature is covered to build a strong foundation for this study.

Energy Policy

Energy policy has played an important role in world affairs since the first discoveries of fossil fuels. All modern presidents have had some form of energy policy, but it did not rise to the level of prominence that it currently has until the energy crisis of the 1970s. The current official policy of record is the National Energy Policy which was developed by the National Energy Policy Group in May of 2001 (Bush, 2001). Because the world has seen dramatic changes since this report was compiled, the National Energy Policy Status Report was created and released in January of 2005 (Bush, 2005). This status report detailed 106 measures that have been addressed and acted upon since 2001. They include expanded leasing opportunities for high temperature geothermal resources on public lands and additional funding for GSHP tax incentives along with many other more traditional energy initiatives.

In addition to the National Energy Policy, there are other governing documents to consider. The Energy Independence and Security Act of 2007 was developed in order to connect energy policy to the impacts that energy has on United States international policy (Bush, 2007). It specifically identifies the use of GSHPs in support of the high performance green building and net zero energy building initiatives.

Finally, there is Executive Order 13423, Strengthening Federal Environmental, Energy, and Transportation Management that was enacted in January of 2007 (Bush, 2007). This order requires that federal agencies reduce their energy intensity by 30% by the year 2015. All requirements were initiated prior to the record oil prices experienced in 2008; therefore, it is likely that even more stringent measures will be proposed in the coming years.

Environmental Policy

Environmental policy has risen in importance in the last several years. The general public gave little thought to global warming and appeared content with the apparent containment of the ozone hole that received enormous coverage in the late 1980s and early 1990s. The next major concern that developed was global climate change caused by anthropogenic carbon emissions. Scientific study and debate ensued until the Kyoto Protocol was adopted by a gathering of world leaders in 1997 (United Nations, 1997). This measure dealt with the control of greenhouse gas emissions and dictated how much each country was allowed to emit. As of 2008, 182 countries have ratified the measure, but the United States is one of a handful of nations resisting its implementation. The failure to implement the Kyoto Protocol has caused concern in the scientific community and has led to continued study and debate, but little further action was taken for years.

This was where the issue stood until 2005. In that year, the catastrophe of Hurricane Katrina received national attention. The severity of the storm was largely blamed on the effects of the increased energy available to hurricanes due to the warming of the atmosphere and the oceans. This event coincided with the production of the documentary film “An Inconvenient Truth” by former Vice President Al Gore. These two events elevated global warming to the highest levels of public discourse and helped initiate further action.

The effort to combat global climate change made it to the Supreme Court in 2007 in the case of Massachusetts v. Environmental Protection Agency (EPA) (Court, 2007). This landmark case established carbon dioxide as an air pollutant covered under the Clean Air Act and has paved the way for the regulation of carbon emissions. In this case, Massachusetts claimed their state suffered damages from global climate change in the form of land loss and other damages. The case sought to force the EPA to regulate carbon emissions from new cars produced in America. The Supreme Court directed the EPA to redefine the rationale on why carbon emissions are not currently regulated. If this new reasoning is determined to be insufficient, then carbon emissions would fall under immediate regulation. The full effects of this case are still developing and sweeping changes can be expected at the EPA.

The next major attempt at environmental policy change came in 2008. In that year, the increase of public support for global warming policy change prompted the U.S. Senate to debate legislation item S.3036, which is a bill to direct the administrator of the Environmental Protection Agency to establish a program to decrease emissions of greenhouse gases (Senate, 2008). This was otherwise known as the Lieberman-Warner Climate Security Act of 2008. This was essentially a bill that would have instituted a cap and trade system administered by the federal government. The legislation did not pass, but it is imperative that leaders consider the impact that the passing of this legislation could have on their operations when they consider their facilities and energy use. If a cap and trade system were put in place, fossil fuel users would experience huge increases in the total cost of heating and cooling for their facilities.

GSHP and NGAC Energy Sources

Now that the impacts of energy and environmental policies have been defined, a brief overview of electricity and natural gas supply and pricing is in order. These energy sources have the greatest variability and effect on the outcome of this research. The cost of electricity and natural gas are of paramount importance to this project. They are not independent entities and are subject to price fluctuations based on policy and regular market interactions.

Electricity

The price and supply of electricity directly impacts the long term feasibility of GSHP systems versus NGAC systems. It is important to have a basic understanding to ensure that the future years' pricing model is unbiased and accurate. Long term forecasting is extremely difficult, but the intent is to project values into the future for this effort. The Building Life-Cycle Cost 5 software package has rate increase projections built into the system, but it is important to know how they were derived. Figure 1 identifies all of the sources of energy used to generate electricity.

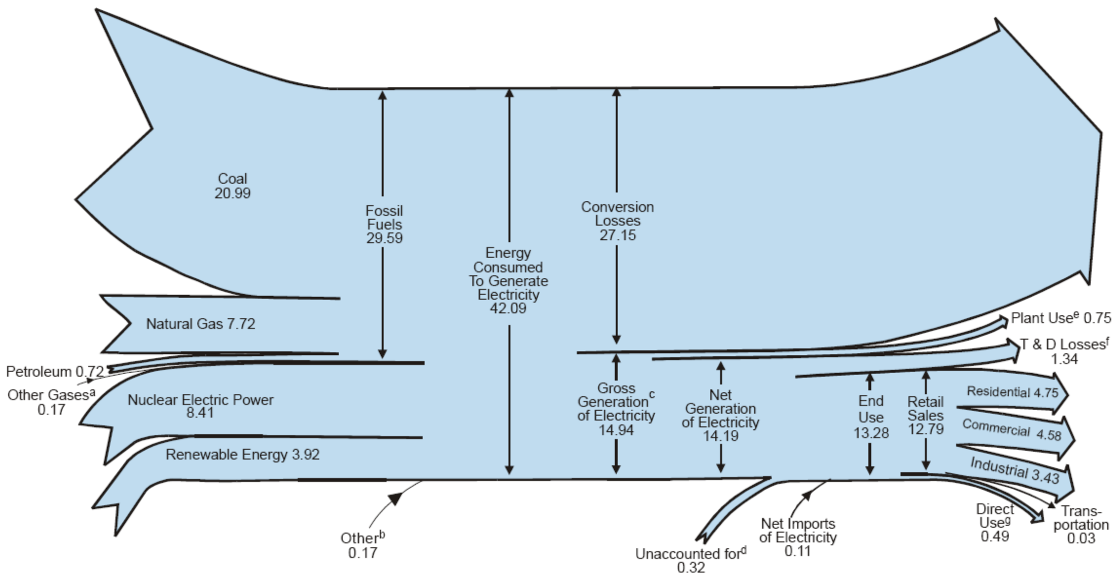

Figure 1. Electricity Flow, Quadrillion BTUs (EIA, 2007)

There are a few major features to note of from Figure 1. Renewable energy makes up only 3.92 Quadrillion BTUs of the total power generated in the U.S., making it the smallest contributor at 9.31%. Hydroelectric power has little growth potential due to environmental concerns, but wind power has seen huge increases in recent years. Although wind power has a low percentage of generating capacity, it offers consumers the choice to purchase clean energy.

Another important point is that a staggering amount of energy is lost in traditional power generation. This loss is unavoidable, as generating electricity is only 35%

efficient on average (EIA, 2007). Many people falsely believe that transmission creates these huge losses, but the truth is that these losses are minor compared to the inefficiency of generation. Every year, 27.15 Quadrillion BTUs are lost in the generation of electricity. All of these factors are key components of the carbon emission calculations for this project. It is important to understand the inefficiency of electricity generation and how much fuel must be consumed to deliver power to the nation's electric grid. GSHP systems may show tremendous promise, but their overall environmental impact is inherently tied to the source of electricity available. There may be no emissions on site for GSHP systems, but it is imperative to consider the impact from the electricity they consume. They are highly efficient, but may potentially create more carbon dioxide emissions than competing systems if their electricity source is not clean.

The interaction of electricity with the price of natural gas is a major issue. Figure 1 shows 7.72 Quadrillion BTUs, or 18.3% of electricity generation, is derived from natural gas. This inherently links the two prices as many utility companies are unable to switch their fuel use away from natural gas due to emission concerns. The price of electricity and natural gas will affect each other as the markets fluctuate.

The environment may be of concern for consumers, but it is fair to say that price is more important to most consumers. The price of electricity has one of the biggest impacts on consumption. While electricity is commonly sold with a pricing structure that includes a separate charge for production and distribution, this effort focuses on the combined average price. Demand charges are not considered as they add an unnecessary level of complexity. Despite this fact, it is important to note that GSHP systems can decrease the peak load and can help to reduce electricity demand charges. The table of values used for calculations is located in Appendix B.

Natural Gas

Now that the flow and use of electricity has been explained, it is time to investigate natural gas. Natural gas is not used directly in a GSHP system, but it is relevant because this research is comparing the environmental and economic elements of the GSHP to that of a natural gas furnace. Natural gas flows from gas-only wells and as a byproduct of oil wells. In contrast to electricity production, natural gas has far fewer losses between the point of origin and the point of use. However, large amounts of energy are expended in the exploration, extraction, and transmission of natural gas, but these losses were not considered here. This study focuses on natural gas from the point of use perspective. Most of the major energy losses occur during combustion after the gas has reached the consumer. Figure 2 shows that commercial use of natural gas accounts for 3.01 of 23.05 trillion cubic feet consumed, or 13.5% of total consumption. It is unlikely that a major shift away from natural gas in favor of GSHP systems will affect pricing in the near future, but external price pressure on natural gas could facilitate a faster transition to GSHP systems. The shift toward GSHP systems could result in an increase in electricity consumption during the winter heating season, but as previously stated, a large portion of natural gas is used for electricity production. The net change in use may be relatively minor in many markets.

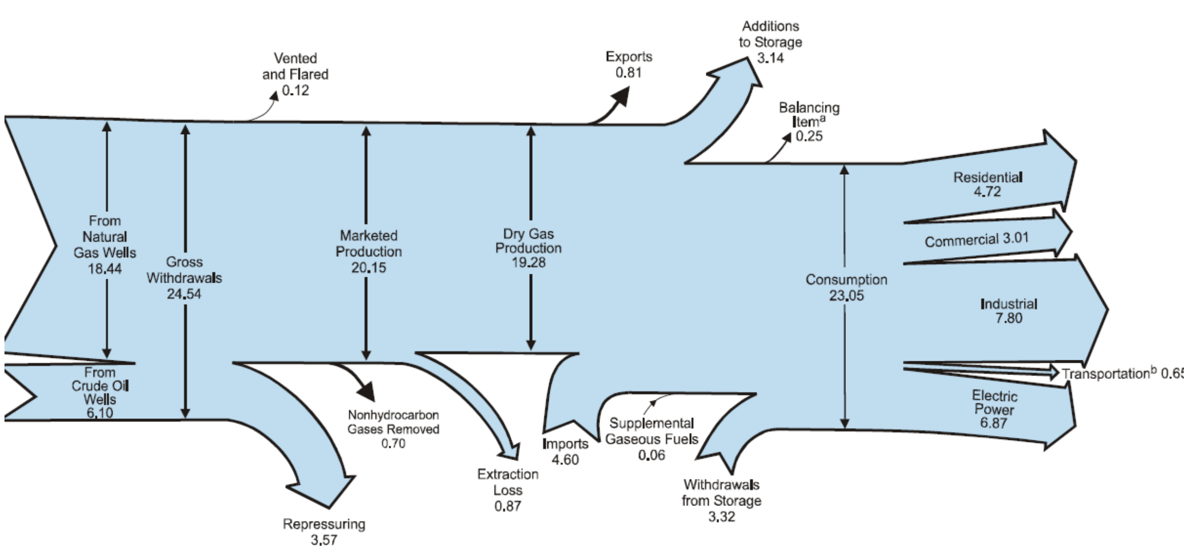

Figure 2. Natural Gas Flow, Trillion Cubic Feet (EIA, 2007)

A major consideration with natural gas is the potential for increased use in transportation. Natural gas use for transportation currently accounts for 0.85 Quadrillion BTUs, or less than 3% of the total use as shown in Figure 2. There is pressure to greatly increase this amount in order to lessen the dependence on foreign oil. Interest has been renewed in natural gas vehicles due to unstable gasoline prices which could have a significant impact on the price of natural gas for heating use. The “Pickens Plan” is the most noteworthy plan being debated for dramatically shifting the energy economy of the United States. This plan intends to replace the 22% of natural gas used for power generation with wind power (Pickens, 2008). This could be beneficial for the country, but it could also destabilize the natural gas market.

This effort will proceed with accurate price information as of 2007 and will only model limited uncertainty, not a massive shift in use. Natural gas is sold with a pricing structure that includes a price at the wellhead and a delivered price; this effort will focus on the combined average price. The commercial retail prices used in this work are located in Appendix C.

A large variation exists in the cost of electricity and natural gas throughout the country. This is an incredibly important factor in the selection of a GSHP compared to a NGAC system. All factors are important, but operational efficiency with a high installed cost may not displace an operationally inefficient system with a low installation cost. These factors were critical during the data analysis portion of this work.

HVAC System Descriptions

Now that the energy and environmental issues have been examined, it is time to review the HVAC systems being studied. The main focus of this effort is to compare GSHP systems to traditional NGAC systems. NGAC systems are the primary choice for new and retrofit installations in the light commercial sector and are the most competitive with GSHP systems. Many large, commercial locations utilize a natural gas boiler and a chiller that circulates chilled water to variable air volume units, but these are beyond the scope of this research. The level of design required would not be feasible for the scale of this research. This effort seeks to use the NGAC system as a representative sample of the efficiency available from larger commercial systems. GSHP systems are highly scalable along with commercial systems that utilize smaller modular equipment instead of large chiller and boiler plants. Utilizing this small building size allows accurate calculations to be computed that can be scaled up to represent much larger facilities of varying sizes. This research effort seeks to make comparisons between decentralized HVAC systems that can be applied to much larger scale buildings. While large boiler and chiller plants still dominate, there are many organizations that are using smaller, modular, decentralized systems in new construction. There are several reasons for this, but the two most common are maintenance and redundancy. As systems are decentralized, they can be repaired in smaller units where the individual capital cost is much lower than the repair of one larger unit. Additionally, since the building is served by many smaller units, the loss of one will not cripple the facility, it will only inconvenience the occupants of the room serviced by the unit.

Other methods of heating include electric resistance heaters, fuel oil furnaces, and LP furnaces, but these are much less common than natural gas. Other methods of cooling include window air conditioning units, swamp coolers, and absorption chillers, but again, these are much less popular and are not as universally applicable. For these reasons, the NGAC system was the baseline comparison system studied in this effort.

The following section covers some heating and cooling fundamentals and describes the various characteristics of the NGAC system under study. Then, GSHP systems will be explained in detail. The explanation includes all types, but focuses primarily on closed-loop vertical borehole GSHPs. Finally, industry development and the development of standards are discussed.

Natural Gas Furnace and Split-System Air Conditioning Overview

NGAC systems are by far the most widely used systems for residential and light commercial buildings in the United States. They are relatively easy to install and they require very limited maintenance. Adding to their popularity is their relative ease of use. There are no fuel deliveries as with fuel oil or propane; they simply have the natural gas piped in through a supply line. Obtaining adequate electricity to supply the equipment is not a problem as the building will generally have a robust electrical system. As previously stated, commercial buildings often have a boiler and chiller operation with a four-pipe distribution system that services variable air volume units that are fed by centralized air handling units. These systems are much more complex to analyze and are not considered in this effort. In addition, many new commercial facilities utilize decentralized heating and cooling units, which allow for greater modularity and ease of repair. This further supports the study of the NGAC system in this comparison.

Natural Gas Furnace

It is important to understand the basic principles of how NGAC systems operate. Natural gas furnaces are generally of the induced draft, fan-assisted, or premixed type (Haines & Wilson, 2003). Of these, the induced draft type is most commonly found in residential applications and light commercial systems. Figure 3 shows an example of the induced draft gas furnace. These types of units are not tremendously complicated and are well understood by most users. They rely on the inlet gas pressure and the stack effect to provide combustion air and mixing (Haines & Wilson, 2003). Typical residential and commercial furnaces operate with approximately 80% efficiency (Lekov, Franco, & Meyers, 2006).

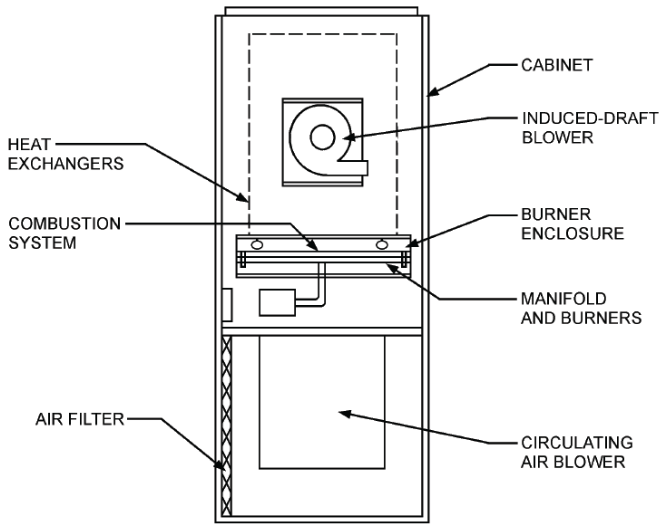

Figure 3. Induced Draft Gas Furnace (ASHRAE, 2008)

An alternative option is the full condensing furnace. These are generally a variation of the fan-assisted units previously mentioned. These units cool the combustion gasses through secondary heat exchangers before they are released to extract even more energy. Some models can reach efficiencies of 96% (Lekov, Franco, & Meyers, 2006). Condensing furnaces are remarkably efficient and have the added advantage of low exhaust temperatures so that plastic pipe can be used for the exhaust. Regardless of the type of furnace being used, the heated air is distributed throughout the structure through a series of supply and return ducts.

Split System Air Conditioning

Split system air conditioners are the traditional central air conditioners that are familiar to most people. They are used extensively in residential construction and in commercial structures with decentralized cooling systems. They are basically air-to-air heat pumps that have much in common with the ground source heat pumps discussed in the next section. The main difference is that these systems only function in a cooling capacity. They are based on the standard mechanical two-phase closed vapor compression refrigeration cycle as shown in Figure 4.

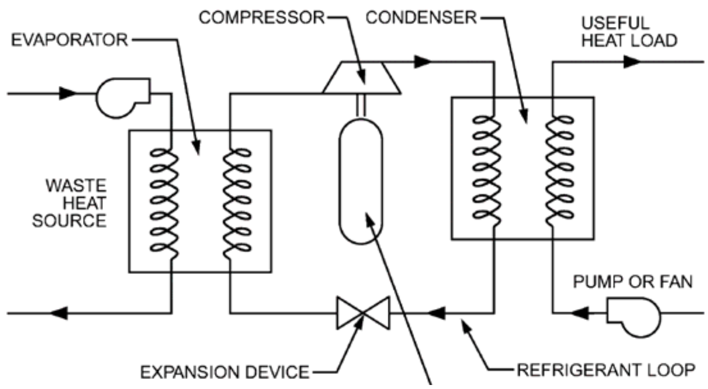

Figure 4. Closed Vapor Compression Refrigeration Cycle (ASHRAE, 2008)

In this refrigeration cycle, a compressor is used to increase the pressure of the refrigerant gas with the use of an electric motor. This compression process raises the temperature of the refrigerant gas which then flows through piping to a condenser where heat is removed. The refrigerant has now changed from gas to liquid and passes through an expansion valve, reducing the pressure. At this point, it passes through the evaporator where it picks up additional heat from the conditioned space. Finally the cold, low pressure vapor returns to the compressor to repeat the cycle (Haines & Wilson, 2003). This is the standard mechanical two-phase closed vapor compression refrigeration cycle used extensively in cooling applications.

Basic Heat Pump Fundamentals

Before considering ground source heat pumps, it is imperative to have a solid understanding of the basic principles behind the heat pump itself. Heat pumps have a lot in common with the split system air conditioning systems mentioned in the last section. They operate in exactly the same manner in cooling mode; however they are much different in heating mode. A heat pump is simply a machine that takes advantage of the well understood principles of the mechanical two-phase closed vapor compression refrigeration cycle previously detailed. The main difference between a heat pump and the split system air conditioner is the addition of expansion valves, bypass valves, and reversing valves. These valves allow the process to run in reverse to satisfy heating and cooling requirements. This means the evaporator coil and condensing coil must change roles depending on the season. This is shown in Figure 5.

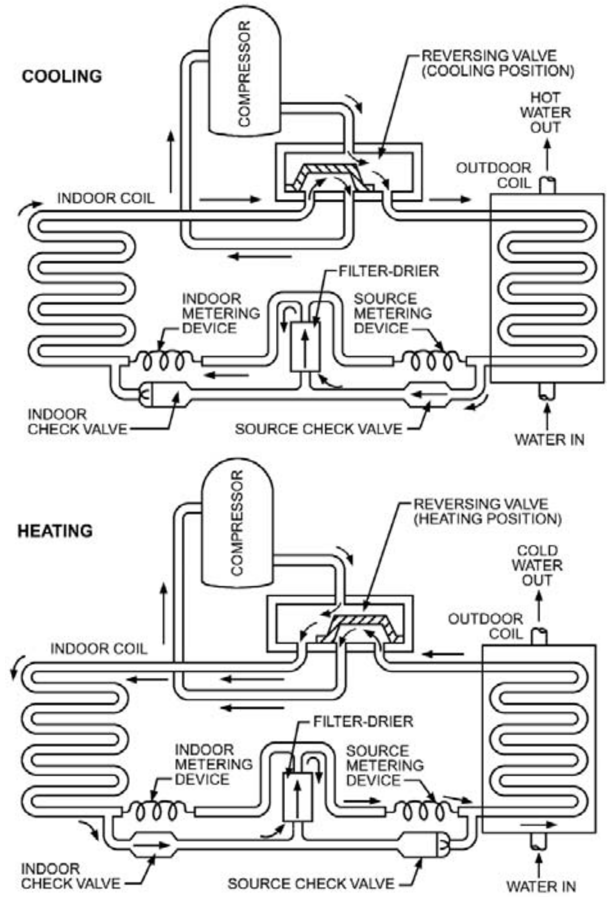

Figure 5. Water Source Heat Pump-Cooling and Heating Mode (ASHRAE, 2008)

Air source heat pumps have been used in both heating and cooling modes for years, but they are extremely inefficient at temperatures below 0°F (Haines & Wilson, 2003). The only way these heat pumps could meet the heating load in cold climates was the addition of auxiliary heating. This generally took the form of electric resistance heat strips, which are 100% efficient, but not cost effective due to the expense of electricity. This led to the development of ground source heat pumps. Once the ground was used as the heat source and sink, a greater range of operating temperatures was possible, allowing for more efficient heating and cooling throughout the year. Despite this benefit, low fossil fuel prices and high installation costs have limited the market penetration of GSHPs. If fossil fuel price volatility continues, GSHPs may become a much more prominent feature in heating and cooling system discussions.

Ground Source Heat Pump Overview

GSHP is the general term used to describe systems that use groundwater, surface water, or the ground itself to conduct the heat exchange required to heat and cool facilities. The basic premise is to use the relatively constant temperature of the ground, groundwater, or open water as a heat source in winter and a heat sink in summer. This is possible due to the relatively stable temperatures found underground at depths greater than six to eight feet. The ground temperature helps moderate the temperature differential faced by heating and cooling equipment. The approximate groundwater temperatures for the United States are shown in Figure 6. These temperatures are a good indication of the deep earth ground temperature at these locations.

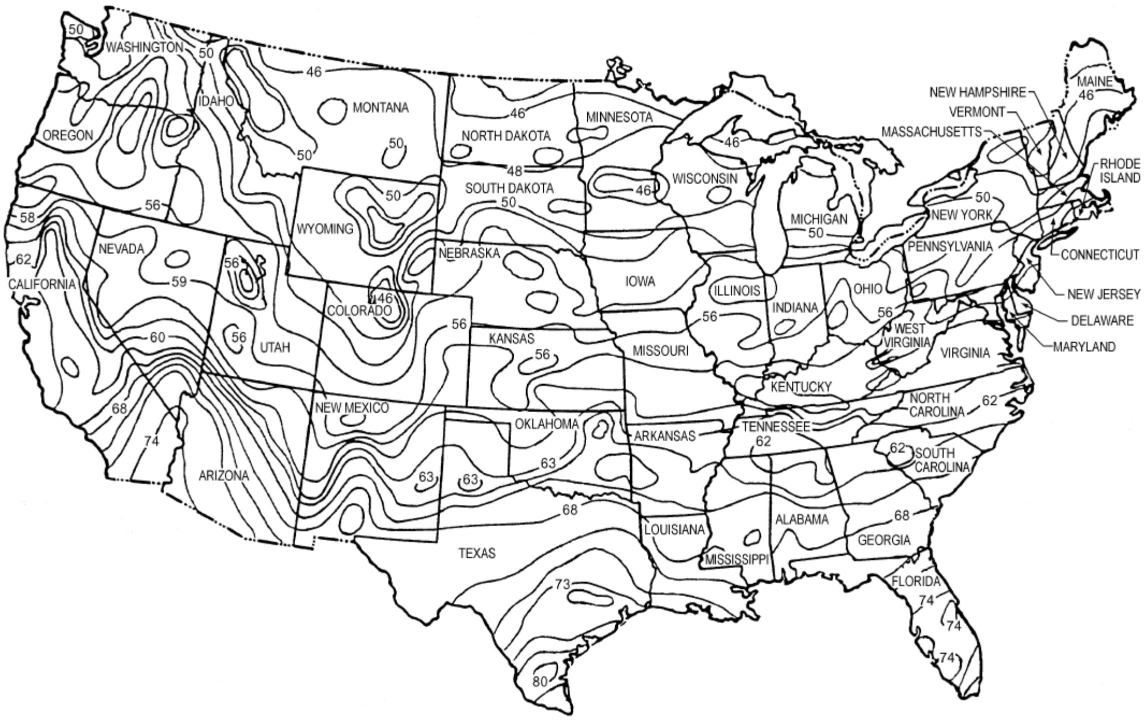

Figure 6. United States Groundwater Temperatures (°F) (ASHRAE, 2007)

Ground temperature varies greatly throughout the United States, which directly affects the design and selection of GSHP systems. Although every type of GSHP utilizes similar heat sources and sinks, there is not one type of system that is superior in all situations. The issues of lot size, easements, availability of surface water or well water, and soil thermal conductivity must be considered with each specific case.

Several varieties of GHSPs exist, but all share similar characteristics. The mechanical unit inside the facility is generally the same in all systems; the difference is the type of heat source and heat sink employed. The three main families of systems are surface water heat pumps (SWHPs), ground water heat pumps (GWHPs), and ground coupled heat pumps (GCHPs) (Kavanaugh & Rafferty, 1997). Examples of each system can be seen in Figure 7. Each of these systems can be further subdivided within each category according to their particular characteristics as explained in the upcoming sections.

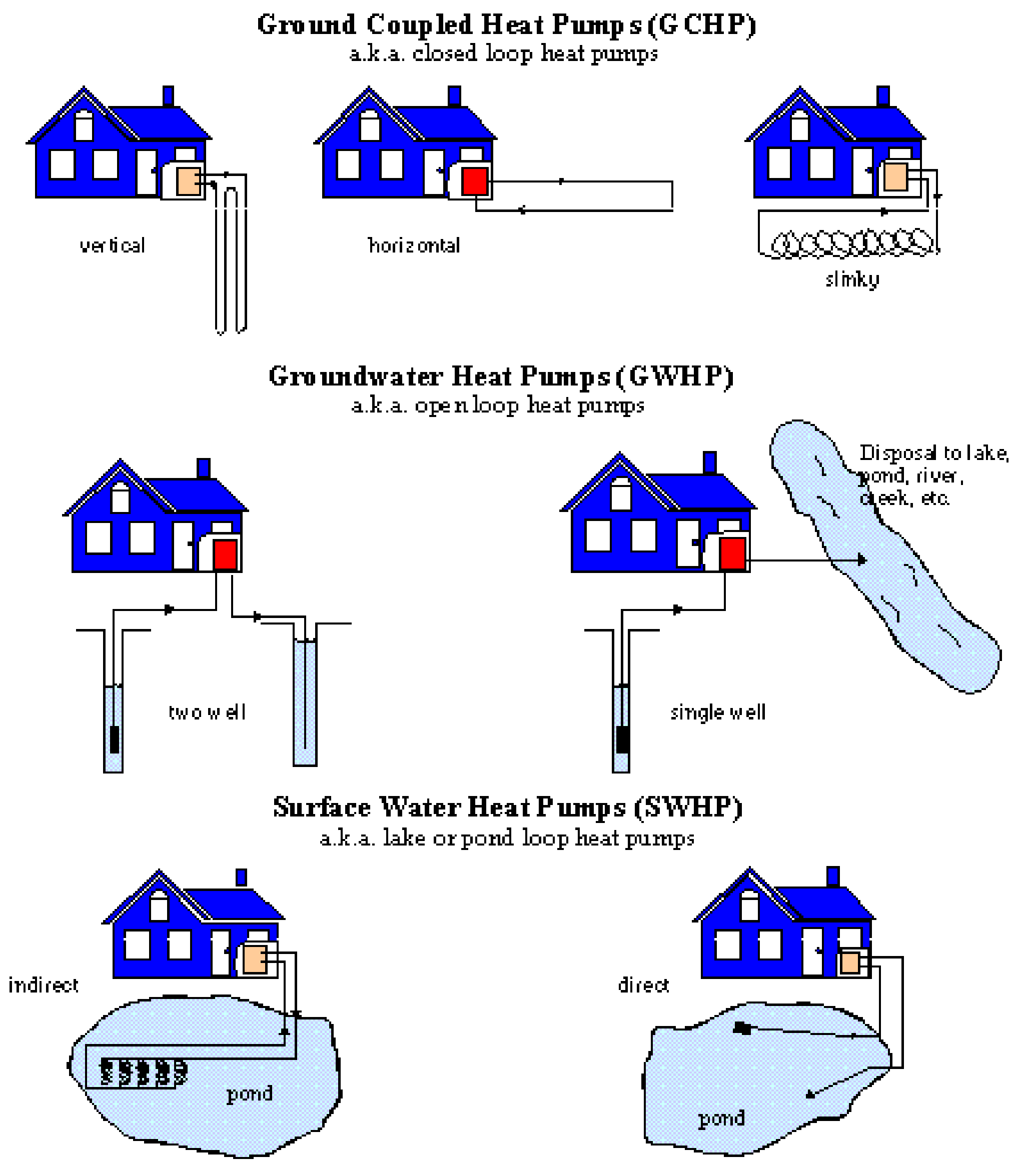

Figure 7. Ground Source Heat Pump Types (Geo Heat Center, 2008)

Surface Water Heat Pumps

SWHP systems consist of either open-loop or closed-loop systems. Open-loop SWHPs use surface water directly, with no intermediary fluid serving as the heat exchanging medium. These systems can utilize open bodies of water to include ponds, rivers, lakes, and the ocean. The use of surface water has the disadvantage of potential high levels of sediment and dissolved solids. Corrosion must be considered when using saltwater, hence it is often not an economical choice. Open-loop SWHP systems are very simple in their installation as they only need a supply and return line from the body of water being used. Caution must be used if it is to be installed in a flowing body of water as the supply and return lines may be exposed to debris and other dangers.

Closed-loop SWHP systems solve the problems of corrosion, sediment, and dissolved solids by utilizing a heat exchanger made of polyethylene pipe. This potentially creates a problem by putting large amounts of pipe in a body of water. There is the possibility of discharging antifreeze into the body of water if the pipe is damaged. This type of installation is not permitted in many public bodies of water, but is highly effective in a privately constructed pond that is at least 8-10 feet deep (Oklahoma State University, 1988).

Ground Water Heat Pumps

GWHPs utilize well water directly, with no separate heat exchanger. These were some of the first systems to be developed due to their relative simplicity and the availability of existing water wells. The well water is pumped through the system and then either injected into the ground through a second well, or discharged into a surface body of water. This system is very efficient; however, long term use can lead to scaling of the heat exchanger if a high mineral content exists in the water. This scaling greatly reduces the overall efficiency of the unit. The advantages of GWHP systems include lower initial cost, compact size, and availability of well drilling contractors. The potential disadvantages consist of limited groundwater and groundwater regulations prohibiting its use for heating and cooling or injection back into the ground (Kavanaugh & Rafferty, 1997).

Ground Coupled Heat Pumps (Closed-Loop Ground Source Heat Pumps)

GCHPs, otherwise known as closed-loop GSHPs, are the most common type of system installed today and their popularity has led them to be known simply as closed-loop GSHPs (Kavanaugh & Rafferty, 1997). Significant confusion has arisen through the use of GCHP and closed-loop GSHP terminology. Closed-loop GSHP is the preferred nomenclature for this type of system and is used throughout this work. These systems can be broken down further into the two main categories consisting of horizontal and vertical installations. Both types of systems are popular and their closed-loop designs solve many of the problems encountered in open-loop systems.

<u>Horizontal Closed-Loop Ground Source Heat Pump</u>

Horizontal closed-loop GSHP systems are very popular for smaller heating and cooling loads and are particularly attractive for residential and light commercial projects with large lot sizes available for development. The advantage of a horizontal installation is that the equipment used to dig the foundation for the building can also be used for digging the trenches for the loop installation. This greatly reduces the installation cost since professional borehole drilling is not required. The large lot size is necessary due to the fact that several loops are required to obtain enough contact area for heat exchange. The pipe can be placed under grassed areas or parking lots. Horizontal closed-loop GSHPs can be further categorized as single pipe, multiple pipe, or slinky™ installations (Kavanaugh & Rafferty, 1997). Single pipe installations involve one pipe, installed in a horizontal loop, buried in a trench. Multiple pipe systems consist of up to six pipes placed in the same trench with adequate separation. Slinky™ systems resemble the child's spring-like toy due to their spiral appearance. The slinky™ system has the advantage of more contact area per linear foot of trench than the traditional single and multiple pipe systems. Horizontal closed-loop GSHPs are very popular and effective where ample land is available and the heating and cooling loads are moderate.

Vertical Closed-Loop Ground Source Heat Pump

The most common installation for a closed-loop system is that of a vertical borehole GSHP. The only major difference is that it utilizes vertical boreholes for its heat exchanger. A ground source heat pump with a vertical U-tube ground heat exchanger is shown in Figure 8. This type of installation is more expensive and requires borehole drilling, but has the advantages of a smaller construction footprint and the ability to support much higher heating and cooling loads. In general, the closed-loop vertical borehole installation is the least variable, low risk option for most locations. The great depth of installation allows for a much larger heat exchange capacity and also serves to shield the well field from the seasonal temperature swings occurring in the upper layers of soil. Vertical boreholes typically range from 50 feet to 600 feet

(Kavanaugh & Rafferty, 1997). The only depth limitation is the pumping power required and the capability of the drilling contractor.

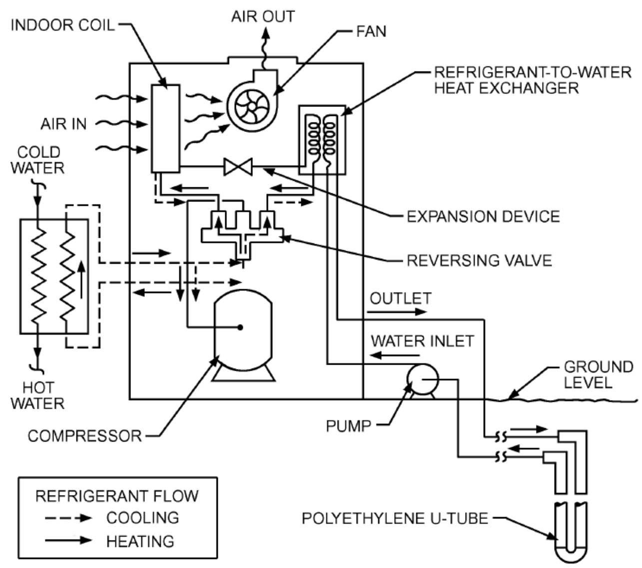

Figure 8. Vertical Closed-Loop GSHP System (Kavanaugh, 1985)

The primary disadvantage in vertical loop installation is cost. Vertical boreholes can be very expensive, especially if extensive rock formations are encountered. Modern sonic drilling rigs have lowered the cost of hard rock drilling, but it can still be quite high. Even if the drilling is relatively straightforward, additional permits are often required and the boreholes must be professionally grouted to ensure that groundwater is protected. Vertical boreholes are the method of choice for large installations, but cost control during design can be a critical factor. In order to understand why these systems have such a high upfront cost, it is essential to understand the drilling and installation process.

Vertical Closed-Loop GSHP Installation Details

Vertical closed-loop GSHP systems are the main focus of this entire research effort. It is important to define those aspects that set these systems apart from other GSHP systems. Vertical closed-loop GSHP systems are often much more expensive than similar GSHP systems, but they are the most universally applicable and popular systems available. There are three main areas that set these systems apart from other GSHP systems and they all deal with the construction of the ground source heat exchanger itself. They include borehole drilling, borehole grouting, and the physical properties of the grout material itself.

Vertical Closed-Loop GSHP Borehole Drilling

Drilling the vertical boreholes for ground source heat exchangers (GSHE) is by far the most expensive component of the GSHP installation. The drilling can be relatively trouble-free when passing through layers of loam or clay, but it can become much more difficult when rock formations are encountered. Several types of drills are available for the installation of vertical boreholes. Many drilling rigs were developed for use in other industries, but have been adapted for GSHE installations. Drills from the water well, oil and gas, and rock quarry industries are suitable for GSHE installations. The expense of drilling is often related to the economic cycles of these competing industries. When demand is low, ample drilling rigs and crews are available. Conversely, when these industries experience increased activity, as in the oil and gas industry, the number of available drilling rigs and crews diminish. This effect has been moderated somewhat by the increase in drillers specializing in GSHE installations.

While these systems are still in the minority, the industry is rapidly developing and drillers can operate on GSHE work alone.

Several types of drills are employed in borehole drilling to include the hollow-stem auger drill, wet rotary drill, down-hole and top-hole hammer, and sonic rock drill. As its name implies, the hollow-stem auger has a cutting head with a hollow drill pipe stem. This design allows the cuttings to flow up through the drill pipe to be discharged on the surface. This drill is very common for moderate depth holes penetrating soils containing few cobbles or boulders (Oklahoma State University, 1988).

A wet rotary drill may be used if a substantial amount of rock is expected. This drill utilizes a roller cone bit surfaced with tungsten carbide or industrial diamonds that cuts through rock layers and is well suited for highly variable conditions. An inner pipe forces drilling mud down the shaft and over the cutting head, cooling the head and providing a medium for the cuttings to flow to the surface. The existence of extensive hard rock layers is not cause for halting a project in most cases, but does provide significant challenges and increases the expense of GSHE installation. However, hard rock layers generally have higher levels of thermal conductivity and the additional effort of drilling in hard, igneous rock may be advantageous due to the enhanced efficiency it provides. Wet rotary drills can penetrate hard rock layers, but the production rate and life expectancy of the cutting heads will be greatly reduced (Oklahoma State University, 1988).

Down-hole hammers or top-hole hammers, such as those used in quarry operations, are more effective methods of drilling through hard rock layers. As the name implies, a hammer drill is utilized in order to increase the production rate. While they are more expensive to operate, they are often the only option in very hard rock (Oklahoma State University, 1988).

A better option, although not very common, is the sonic rock drill, which has been developed to combat expense and relatively slow production rate. This drill is similar to the wet rotary drill mentioned earlier, but has the important addition of out-of-balance weights creating sinusoidal vibrations. These drills act much like a dentist's drill by simultaneously rotating, vibrating, and applying downward pressure. Sonic drills greatly improve drilling speeds and can drive down the project cost, despite the increased cost of the equipment (Oklahoma State University, 1988).

Vertical Closed-Loop GSHP Borehole Grouting Procedures

Grouting of vertical borehole ground heat exchangers is of pivotal importance to the success of a GSHP system. Early in the development of the GSHP industry, grouting was not commonplace, but this has changed dramatically and is now required in most parts of the country. Grouting is performed primarily for environmental protection and efficient heat exchange. Environmental reasons for grouting are to provide protection for the water supply by preventing surface contaminants from entering the borehole, to prevent water migration between aquifers, and to seal off known contaminated formations. Environmental considerations are critically important to the acceptance of GSHPs. They are promoted to be environmentally friendly, but if blamed for damaging aquifers, their public approval will be greatly diminished. Some parts of the country do not require grouting as part of a GSHP installation and run the risk of depleting and fouling groundwater. A major environmental concern also exists in coastal communities where GSHP systems have not been grouted. In these areas, the potential exists to have brackish or saltwater intrude on fresh water aquifers when the confining pressure is diminished (Oklahoma State University, 1991).

Even if the environmental concerns are not enough to encourage grouting, the heat transfer benefits alone should ensure that vertical boreholes are grouted. Technical reasons for grouting include providing a high thermal conductivity medium of transfer, eliminating voids in the annular space of the borehole between the ground and the heat exchanger, and preventing shrinkage and material settling around the ground heat exchanger. Air voids provide one of the most efficient insulators available and can greatly diminish the performance of the ground heat exchanger. Grouting ensures sufficient contact between the ground heat exchanger and the surrounding soil (Oklahoma State University, 1991).

In the early years of GSHP installations, several problems arose from improper grouting procedures. Drillers would force the cuttings down the borehole to fill the space, resulting in poor heat transfer and potentially increased permeability. The cuttings placed in the hole were not returned in the same order they were removed, so the fill material did not match that of the surrounding soil. This meant unmatched material permeability leading to improper water migration between aquifers. Using cuttings as fill also causes bridging near the top of the hole, leaving voids along the lower portion of the borehole.

A second problem early on was using drilling mud as a substitute for grout. Because drilling mud and grout are both bentonite-based, drillers believed one could be substituted for the other. This is not the case, as grout consists primarily of bentonite, while drilling mud consists mostly of water. Drilling mud has low solids content and was developed to cool and lubricate the drill bit, and serve as a medium to transfer cuttings to the surface. Properly mixed drilling mud consists of 50 pounds of bentonite mixed with 100 gallons of water, resulting in a solution of 6% solids by weight (Oklahoma State University, 1991). This solution contains very little bentonite causing it to shrink greatly when the water dissipates. This results in large air voids and is detrimental to proper heat transfer.

Proper grouting of boreholes is critical to the effectiveness of a GSHP system. This cannot be done by simply mixing the grout and pouring it down the borehole. The borehole may contain water and other impediments to proper grouting. In order to ensure a borehole is professionally grouted, a tremie pipe must be inserted with the ground heat exchanger loop. The tremie pipe is a flexible tube sent down the borehole to facilitate the placement of grout. It allows the grout to be pumped from the bottom of the borehole to the top, ensuring all unwanted material is displaced from the hole. Once the ground heat exchanger and the tremie pipe reach the bottom of the borehole, the grout can be mixed and pumped. The pumping proceeds until all the water, drilling cuttings, and debris have been displaced and pure grout flows from the borehole. Once the grouting is complete, the borehole will have excellent heat transfer properties and will be environmentally secure.

Vertical Closed-Loop GSHP Borehole Grout Physical Properties

Proper grouting materials have a high solids content and very low permeability. The high solids content ensures the material will not shrink after placement and will provide sufficient heat transfer capability. Early in the development of GSHP systems, grout mixtures had relatively low thermal conductivity. Mixtures attaining 0.85 BTU/(hr·ft·°F) were considered to be thermally enhanced grouting materials. At the time, this was a definite advantage over existing materials such as an unmodified 30% solids bentonite grout which exhibited 0.43 BTU/hr ft ˚F, but much has improved since then (Kavanaugh & Rafferty, 1997).

Huge advances have been made in modern grouting thermal conductivity with the use of silica sand admixtures and other advanced materials. Many advances have come directly from the GSHP industry while others have come from the oil, gas, and water well drilling industries. The most common type of thermally enhanced grout is a high-solids bentonite-based mixture containing silica sand. This grout is typically composed of a 30% solids bentonite mixture with up to 250 pounds of silica sand per 50 pounds of bentonite raising the solids content to 66% and attaining a thermal conductivity of 1.00 BTU/(hr·ft·°F) (Geo Pro Incorporated, 2008). Recent advances in bentonite-based thermally enhanced grouts are allowing the dramatic increases in the use of silica sand due in large measure to better grout pumps. Thermal conductivity of grouts today may reach 1.20 BTU/(hr·ft·°F) by adding 400 pounds of silica sand per 50 pounds of bentonite, which raises the solids content to 71.4% (Geo Pro Incorporated, 2008). The limiting factor of high solids content material is the capability of the pump injecting the grout into deep boreholes of the ground heat exchanger.

The modern advances in thermally enhanced grouts involve materials that do not require the addition of silica sand to achieve high thermal conductivity. One such product is IDP-357, produced by the Baroid company, a division of Halliburton. This is a one-sack grout achieving a thermal conductivity of 1.1 to 1.6 BTU/(hr·ft·°F) with a low solids content of 35-40% (Baroid Industrial Drilling Products, 2008). This relatively new product requires more scientific testing to ensure its long term reliability. However, if it can maintain a 1.6 BTU/(hr·ft·°F) rating, GSHP system performance will improve dramatically. This product has the potential to greatly reduce the borehole depth requirement, substantially decreasing the cost of GSHP systems.

A required feature for grouting materials is low permeability. A material with zero permeability would be ideal; however, such a material is not economically feasible. The purpose of a nearly impermeable grout is to ensure the material has a much lower permeability than the surrounding soil. Table 1 shows the relative permeability of various materials in comparison to bentonite grout. Bentonite grout has a very low permeability, but it is not always lower than the materials surrounding the borehole. If the surrounding material has a lower permeability rate than bentonite, then groundwater flow will be insignificant, not causing a problem. Bentonite grout prevents environmental problems within the water table and serves as a highly workable material providing adequate heat transfer.

Table 1. Permeability of Geological Materials (Oklahoma State University, 1991)

Material	Permeability (K) in cm/sec
Gravel	10^{-2} to 10^{2}
Clean Sand	10^{-4} to 10^{-2}
Silty Sand	10^{-5} to 10^{-1}
Glacial Till	10^{-10} to 10^{-7}
Unweathered Marine Clay	10^{-11} to 10^{-8}
Shale	10^{-12} to 10^{-8}
Igneous Rock (Ungractured)	10^{-8} to 10^{-4}
Sandstone	10^{-7} to 10^{-4}
Limestone or Dolomite	10^{-4} to 10^{-7}
Bentonite Grout	10^{-8}

Industry Standards and Development

A major hurdle in the development of GSHPs has been the relatively recent development of policy, standards, certification, and accreditation. The lack of governing standards in the past often limited GSHP use in the public and private sector. The HVAC community is very cautious when adopting new technology to ensure continued delivery of quality designs to their customers. Deviating from existing standards often presents significant risk to professional engineers. The development of professional and industry groups such as the International Ground Source Heat Pump Association, Geothermal Heat Pump Consortium, and the Association of Energy Engineers has helped to overcome this problem. These groups have developed training, curriculum, and certification tests for the industry ensuring consistent, professional, and reliable designs. The professional development and endorsement of GSHPs by the EPA and ASHRAE has enabled GSHPs to become an HVAC option for mainstream use. GSHPs present a promising, proven technology that will likely become a prominent part of the U.S. energy portfolio.

GSHP Research Initiatives

GSHPs are not a new technology, but several areas require additional study. Numerous studies have been completed to conduct feasibility studies for construction, but few have attempted to quantify the environmental impacts along with economic interests. Studies that focused on environmental issues were limited to actual quantities of emissions. This advanced the level of understanding of the technology, but did not provide suitable values for comparison. It is imperative to equate carbon dioxide emissions to dollars for a simplified and fair comparison. Everything has a price and the actual cost of the system coupled with emissions must be considered.

The values assumed in the research of these studies are also a limiting factor. Since these studies were conducted, the GSHP industry has changed dramatically compared to traditional HVAC systems. Once a natural gas furnace reaches the 95% efficiency range, additional study only leads to marginal improvement. Exceeding 100% efficiency is impossible, and the gains become incrementally smaller approaching the theoretical limit. On the other hand, recent increases in the efficiency of GSHPs will make for very interesting comparisons in this study and in future endeavors. One study that advanced the knowledge of GSHP applications was conducted by Vanderburg (2002). It approached GSHPs from a strict economic and energy perspective, mentioning some background environmental legislation, but failing to incorporate environmental impacts into the model. The results obtained in the study are largely outdated due to dramatic changes in energy prices. Despite omitting environmental considerations, this effort significantly advanced GSHP knowledge.

This work was also subject to the limits in technology in place during the study effort. The thermally enhanced grout available at the time had much lower thermal conductivity values than what is available today. As previously mentioned, modern installations routinely achieve 1.2 BTU/(hr·ft·°F) and 1.6 BTU/(hr·ft·°F) grouts have been developed. This improvement in technology has completely changed the design of the ground heat exchanger. Also, the coefficient of performance (COP) has changed dramatically. It is difficult to find a manufacturer today that produces a unit operating with a COP under 3.0. Today's units typically operate with a COP of 4.0. Vanderburg's thesis utilized a mean value of 3.3 for COP, but this research used updated values to match that of currently available heat pump models (Vanderburg, 2002).

Many studies providing a good basis of comparison have been completed in the last few years. A study was prepared in July 2008 for the Minnesota Department of Commerce (Minnesota Department of Commerce, 2008). The report was compiled using DOE2 software, available through the Department of Energy, and provides a useful comparison on energy and emissions of GSHPs. Of greatest concern with this study was an energy efficiency ratio (EER) value of 14.1, which is the minimum required by code, used in the calculations. Many factors affect the EER and demonstrating this level of performance using full simulated conditions is unlikely. This study also gave GSHPs a lifespan of 19 years, which may prove to be unrealistic (Minnesota Department of Commerce, 2008).

The most stunning conclusion developed in Minnesota's study was the fact that some GSHP systems actually increased the carbon dioxide emissions compared to traditional HVAC systems. This was due to the fact that much of the power generation in Minnesota comes from coal-fired power plants with very low efficiency when analyzed from the source of generation to the point of use. This current work intends to explore this critical finding.

Another interesting conclusion was that GSHP systems often lower the peak electrical demand in summer and increase the peak demand in winter. GSHPs displace the burning of natural gas, but natural gas is very competitive from a carbon dioxide emission and economic perspective. It is a relatively clean fuel with few emissions. The challenge is to ensure that GSHP systems do no harm and actually improve the overall environmental impact to the world.

Also used for comparison in this effort is the study performed by Mathias and Bolling (2008) in which they provided an in depth look at four different types of systems in addition to GSHPs. The systems in question included a high efficiency furnace and electric air conditioner, a GSHP, an absorption air conditioner and direct heating system, and a thermally-driven heat pump. Their study was limited to five major cities, but provided a large variety of climate conditions. The primary conclusion from the study was that the GSHP was superior to the other systems in terms of payback in every scenario. The payback periods ranged from 4-15 years for the test locations of Louisville, KY; Houston, TX; Minneapolis, MN; Sacramento, CA; and Phoenix, AZ (Mathias & Bolling, 2008). Although, the study only covered five locations, it provides a foundation on which to build.

With an understanding of GSHP systems, it is clear that additional studies are necessary to advance the knowledge within the discipline. The next section covers the methodology used in this effort. It builds on previous research and attempts to combine the full effects of economics, energy, and environmental issues into one coherent, measureable process.

III. Methodology

This chapter reviews the methods employed in this study, defining the calculations that were applied and identifying the tools and software that were utilized. It begins with a brief explanation of heating and cooling load design determination; it then outlines the ground source heat pump (GSHP) and natural gas furnace with split-system air-conditioning (NGAC) design and installation cost calculations. Next, the operating cost and energy use calculations are explained. The basic financial measures of simple payback period (SPP), discounted payback period (DPP), savings to investment ratio (SIR), and internal rate of return (IRR) are also reviewed. The carbon dioxide emission quantity and offset credit cost calculations are then defined for both systems. Finally, the life-cycle cost calculations are identified in the closing section of this chapter.

Building Heating and Cooling Load Calculations

One of the greatest factors considered in this analysis was that the heating and cooling loads for each location of this study are unique and depend on several input parameters. These values provide the basis for design of the competing systems. Therefore, this section will provide a brief explanation of the primary factors that were used.

Building Construction Details

Since much of the built world consists of office space, the hypothetical building being modeled in this study consisted of general office space with standard office equipment and occupancy loads. The design was based on a conventionally constructed commercial office building of 2,000 square feet with assumed occupancy during normal business hours, five days per week. The size was meant to represent a typical space for heating and cooling that could be either a single zone in a large facility or the entire space for a smaller facility. Once the comparison was completed for one zone, the type of system used could be scaled up to cover all zones. While size is extremely important, the physical characteristics of the building being studied are equally important.

The hypothetical building was modeled as a general purpose office building without any special construction details. A complete list of assumed building characteristics, including materials and thermal resistance values, is contained in Appendix D. All the information was loaded into Trane Trace 700 software to fully develop the model. The hypothetical building consisted of a basic concrete block wall with a brick facing and three inches of insulation. The roof was a standard commercial steel roof with eight inches of insulation. The building was considered to be single story, resting on a four-inch concrete slab. The windows were double-pane and filled with argon. Minimal air infiltration into the facility was assumed as it was well sealed for energy efficiency. In addition to building materials, the basic load information was included according to the template provided in the Trane Trace 700 software. This included loads from lighting, equipment, people, and sunlight infiltration. The model represented Trane Trace 700 default settings with only minor changes.

Weather Information

While building construction and internal loads are tremendously important to developing heating and cooling design loads, the weather for each location was the dominant factor. Weather can be modeled several ways, but the two most common are the heating degree day (HDD) method and hourly bin method. The HDD method is simple to use, but it does not provide the accuracy required for commercial designs. The hourly bin method provides weather information on an hourly basis for the location in question. Trane Trace 700 provides the ability to model heating and cooling loads on an hourly basis for the entire design life of the project, so the hourly bin method was the best choice.

For the purpose of this study, this investigation was limited to the locations listed in Appendix A, which includes major cities and military installations serving as a proxy for the entire state. This research is not a combination of factors from a state; it represents the actual characteristics of the locations listed. The purpose was to provide real examples of locations where GSHP systems could be employed, with the intent that engineers at these locations could utilize this document in support of their facility heating and cooling decisions.

The heating and cooling load design parameters developed in this section include the peak heating and cooling load and the equivalent full-load heating and cooling hours for each location included in the study. Trane Trace 700 has additional features to facilitate analysis, but this study utilized Building Life-Cycle Cost 5 software for the additional analysis required. From this information, the sizing and selection of equipment along with the calculation of the system installation cost were computed.

GSHP Design and Installation Cost Calculations

Once the design heating and cooling loads were determined, the next major step was the design of the GSHP system itself. The first consideration was the type of heat pump utilized. Many levels of efficiency are available and not all heat pumps have the same performance. The following subsections focus on the borehole loop length design and all of the parameters affecting it.

GSHP System Efficiency

GSHP units are manufactured throughout the world and operate under highly varied conditions. In order to ensure a valid method of comparison, the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) conducts testing and certification for all GSHP units. They conduct tests measuring the energy efficiency ratio (EER), coefficient of performance (COP), heating capacity, cooling capacity, and required flow rates for the equipment. In order to ensure that these tests are valid, they maintain strict adherence to the standards adopted by the Air-Conditioning and Refrigeration Institute (ARI), International Organization for Standardization (ISO), and the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) 13256-1. These standards ensure that the units are tested at the common entering water temperatures of 77°F for cooling and 32°F for heating. However, these temperatures do not represent common operating ranges and fail to give a realistic measure of performance, as the temperatures experienced by heat pumps vary throughout the season. It is imperative to use fixed values for testing, but doing so does not give an accurate design parameter.

AHRI maintains a database of all current and historical heat pumps that have been produced. For this study, the list was filtered to include only those which are currently being manufactured. The AHRI data was also sorted to include only systems supplying less than ten tons of cooling. The intention was to focus on small, efficient, decentralized units that are employed in a typical building. This sorting of data produced a list of 560 heat pumps with ground loop installation capability. From this list, the mean COP was determined to be 3.46. This number was somewhat lower than expected, due to the fact that the volume of low performance units outstrips that of the high performance units that are available. A high level of performance is available, but many manufacturers produce a large volume of units with a COP of 3.0 which results in a lower mean value. For example, Climatemaster, the leading GSHP manufacturer, lists units that operate in the 3.2-3.5 COP range for their standard, single-stage units. This can be compared to their two-stage line of products operating in the 3.6-4.0 COP range. The equipment exists for extremely efficient GSHP operations, but less expensive options are available. Based on the mean value of 3.46 for the COP under test conditions, the heat pumps for this research were selected to best mirror this value. Additional calculations were conducted to determine actual field performance under conditions expected for each location. This provided more accurate performance data than strictly applying the values obtained from ARI lab test data. Once the average performance capability for a heat pump was determined, the borehole loop length was the next parameter defined. This required an iterative process where the heat pump and the ground loop interact and affect the performance of one other.

Borehole Loop Length Design

The largest expense in most GSHP installations is that of the ground heat exchanger itself. Due to this fact, it is imperative to ensure that great care goes into this phase of the design. The length of borehole is of pivotal importance to the efficient operation of a GSHP system. If the loop length is under designed in a cooling dominated location, the ground temperature may rise to unacceptable levels during the cooling season and render the system useless. An opposite situation occurs when a loop is under designed in a heating dominant location. In this case, the heat available from the ground will not meet requirements and the system will cool the ground to a level where the heat pump can no longer function. For these reasons, the design of the borehole loop length is the most critical step in a GSHP design. The loop length design is governed by two equations, one for cooling capacity and one for heating capacity. The loop lengths required for cooling and heating are shown in Equation 1 and Equation 2 (Kavanaugh & Rafferty, 1997).

$$L_c = (q_aR_{ga}+(q_{lc}-3.41W_c)(R_b+PLF_mR_{gm}+R_{gd}F_{sc}))/t_g-((t_{wi}+t_{wo})/2)-t_p) \quad (1)$$

$$L_h = (q_aR_{ga}+(q_{lh}-3.41W_h)(R_b+PLF_mR_{gm}+R_{gd}F_{sc}))/t_g-((t_{wi}+t_{wo})/2)-t_p) \quad (2)$$

where the equation variables are defined as:

L_c = ground heat exchanger loop length required for cooling (ft)
L_h = ground heat exchanger loop length required for heating (ft)
F_{sc} = short-circuit heat loss factor
PLF_m = part-load factor during design month
q_a = net annual average heat transfer to the ground (BTU/h)
q_{lc} = building design cooling block load (BTU/h)
q_{lh} = building design heating block load (BTU/h)
R_{ga} = effective thermal resistance of the ground, annual pulse (h·ft·^{0}F/BTU)
R_{gd} = effective thermal resistance of the ground, daily pulse (h·ft·^{0}F/BTU)

R_{gm} = effective thermal resistance of the ground, monthly pulse (h·ft·^{0}F/BTU)
R_b = thermal resistance of bore (h·ft·^{0}F/BTU)
t_g = undisturbed ground temperature (^{0}F)
t_p = temperature penalty for interference of adjacent bores (^{0}F)
t_{wi} = liquid temperature at heat pump inlet (^{0}F)
t_{wo} = liquid temperature at heat pump outlet (^{0}F)
W_c = power input at design cooling load (W)
W_h = power input at design heating load (W)

In these equations, note that the sign convention dictates positive for heating and negative for cooling heat transfer rates.

The equations appear to be quite unwieldy, but the values required for the calculations are relatively easy to acquire. To make this process even more straightforward and to reduce errors associated with it, commercial software has been developed to assist with the calculations. Several software packages are available, but Ground Loop Design (GLD) produced by Thermal Dynamics Incorporated was utilized in this effort.

Once the calculations are accomplished for each equation, it can be determined if the system is heating or cooling dominated. This would seem to be an easy determination, but the loads are very close in some instances and further calculations are required. Despite the use of the GLD software, several inputs must be researched to ensure that the appropriate inputs are used. The factors that have the greatest impact on the loop length design are detailed in the upcoming sections.

Ground Temperature

One of the major factors in GSHP design is that of the existing ground temperature. This affects the amount of heat that can be rejected into or extracted from the ground. The ground temperature varies throughout the year to varying depths, but remains nearly constant once surface effects are attenuated. The temperatures utilized in this study come from the Closed-Loop Ground Source Heat Pump Installation Guide produced by the International Ground Source Heat Pump Association. These represent the deep earth temperatures for selected cities and have been tested and verified. Temperatures vary from site to site and should be tested prior to installing a large commercial GSHP system, but these values provide sufficient detail for this study. One point of interest is that the ground temperature closely mirrors the average air temperature in most locations. Due to the long term interaction of the ground with solar radiation and the air, they eventually reach an equilibrium temperature. One question that often arises when discussing ground temperature is that of the slight temperature increase that occurs with increasing depth. It is important to note that even commercial GSHP boreholes do not exceed 600 feet and generally are about 300 feet in depth. At these relatively shallow depths, the temperature increase is negligible, absent some active high-temperature geothermal heat source. Studies of oil and gas drilling logs reveal that this temperature change is only one to three degrees for every 100 feet of additional depth (Oklahoma State University, 1988).

Soil Thermal Conductivity

In addition to ground temperature, soil thermal conductivity is extremely important to GSHP systems. There are limitless combinations of strata of material and levels of moisture in the subsurface affecting the thermal conductivity. Therefore, it is well beyond the scope of this study to obtain soil content and moisture information for every location. For the purpose of this research, an average thermal conductivity of 1.3

BTU/(hr·ft·°F) was used, representing the average obtained from soil that is between moist and saturated (Kavanaugh & Rafferty, 1997). Boreholes saturated with standing groundwater provide the best thermal conductivity; however, this is not the case at many sites. Many boreholes are fairly dry depending on the season causing the thermal conductivity to drop off until additional rainfall raises the groundwater level.

Grout Thermal Conductivity

The next major consideration impacting thermal conductivity is that of the grout utilized in the borehole installation. For the purposes of this research, a value of 1.2 BTU/(hr·ft·°F) was used (Geo Pro Incorporated, 2008). This value represents the thermal conductivity that can be obtained using traditional bentonite-based grout materials in conjunction with high levels of silica sand for solids content.

Pipe Thermal Conductivity

The pipe used for this research is 1.25-inch SDR-11 polyethylene pipe. This is the largest diameter that can be placed in a four-inch borehole. The pipe has an outer diameter of 1.66 inches and the two-pipe loop combined with the U-bend fitting have a 3.75-inch width when coupled for insertion into the borehole. The tremie pipe must also fit inside the borehole until the grout has been pumped, taking up additional space. This pipe was selected because it minimizes the head loss associated with long loop lengths and provides enhanced heat transfer over smaller sizes of pipe. The heat transfer through the pipe wall is an important factor, affecting the overall performance of the GSHP. The pipe used in this study has a thermal conductivity of 0.104 BTU/(hr·ft·°F) (ASHRAE, 2007).

One additional consideration is the placement of the pipe within the borehole itself. Devices have been designed to force the pipe toward the outside of the borehole, thereby maximizing contact with the soil and minimizing the thermal interaction between the pipes. Spring loaded clips that deploy after the pipe is placed in the borehole force the pipes outward increasing contact with virgin soil. These devices prove to be minimally effective and greatly complicate the insertion of the pipe; therefore, they were not considered in this study. The pipe placement was considered as average throughout the borehole meaning they are placed at varying distances from the borehole wall.

Heat Transfer Fluid

Another major consideration in design is that of the heat transfer fluid. This is incredibly important from two major aspects. The first is freeze protection, as the system must obviously be protected from freezing. In colder climates, a GSHP system may operate in below-freezing temperatures when in heating mode. This requires that an antifreeze mixture be utilized. Even locations that rarely have freezing conditions must be protected. If a pump failure occurs during operation and the outside temperature is below freezing, the pipes in the system may freeze and cause severe damage.

Viscosity is another major factor for the heat transfer fluid. A pure water system works well, but is not freeze protected. Once the antifreeze compound is added though, the viscosity increases at low temperatures. This increases the work required by the circulating pump and lowers the overall system efficiency. Therefore, the risk of freezing must be balanced with the optimum viscosity for operation. Antifreeze concentration values used in this model vary from 0% in warm climates to 23.5% for installations in regions with extremely low temperatures. The GLD software takes this into account when computing the loop pump work required.

Entering Water Temperature

One final major design consideration was that of the entering water temperature (EWT). This is simply the maximum and minimum allowable temperatures for the fluid entering the heat pump unit. The heat pump units themselves have a large range of allowable temperatures. Most units can run in the range of 10˚F to 110˚F. The issue here is one of efficiency versus loop length. If a high EWT for cooling and low EWT for heating is allowed, then the loop length required is greatly reduced. However, a problem arises when the loop length is reduced because the system efficiency decreases as well. It is a constant balance between low installation cost and long-term efficiency. For the purposes of this study, the designs are based on heating EWTs of ground temperature minus 12.5˚F and cooling EWTs of ground temperature plus 25˚F. This methodology is in agreement with the recommendations of ASHRAE and provides a balance between loop length and long-term efficiency.

GSHP Installation Cost

Many different components must be considered when determining the cost of a GSHP system. The major expense of installation is drilling the vertical boreholes for the ground heat exchanger. The costs are highly variable, depending on the local market and the availability of drill rigs and skilled crews, and can range from $3.00/ft to $16.00/ft (ASHRAE, 2007). Another major consideration is the number of boreholes required for the project. Large projects are much more economical per borehole because only one mobilization is required. Costs will be much higher for small projects with only a few boreholes. For the purposes of this research, this project was considered to be a small-scaled portion of a large commercial project. Based on the size and scale of this project, the borehole price is substantially lower. Prices have dropped significantly in recent years, bringing the large, commercial drilling price down to $5.00 to $6.00 per foot (Hughes, 2008). The value of $5.50 per foot was used in this research and was adjusted by the location cost factors found in RS Means Building Construction Cost Data 2007 Book.

Now that the major expense of the borehole has been explained, the rest of the components must be considered. First, the heat pump was selected based on the maximum required heating and cooling output. In some locations, multiple units were required to meet the heating and cooling demand. Another expense is the circulation pump for the ground loop. This consists of a small pump or series of pumps that circulate the heat transfer fluid. They vary in size and depend on the pumping work demanded by the ground loop. The pump size was calculated using the GLD software. The next item considered was the length of pipe utilized in the borehole. This is a simple calculation, doubling the borehole length to find the required length of pipe. The length of supply headers was omitted for the GSHP system just as the air conditioning refrigerant piping and natural gas supply line piping were omitted for the NGAC system.

The next major expense was that of the grout and silica sand required for the borehole. This is a simple volumetric calculation dependent on the length and diameter of the hole. Hypothetically, the borehole is perfectly straight and smooth on the sides, which is not the case in the real world. The amount of grout required should be increased to include a safety factor for an irregularly drilled borehole. One convenient way to allow for this is by omitting the subtraction of the volume of the polyethylene pipe. This provides ample safety in the volume of grout required.

The final cost to consider is the antifreeze mixture used in the loop itself. This is a calculation of the volume of the pipes multiplied by the antifreeze concentration. The water used in the mixture is assumed to be drinking water obtained from a source on site at no cost. All of the installation components were assigned a cost and a local cost factor obtained from the RS Means Building Construction Cost Data 2007 Book as shown in Appendix H. It is important to note that the cost of some items consists of labor and materials, while others are materials only with the labor embedded in the cost.

NGAC Design and Installation Cost Calculations

The design and installation of a traditional NGAC system is much more straightforward than that of the GSHP system. This is due to the fact that there are fewer parameters to consider and they have a greater familiarity throughout the engineering community. The basic design utilized the same load information as for the GSHP system. It employed the same peak design loads and the same equivalent full load hours as developed by Trane Trace 700. The major difference with the NGAC systems is that they are divided into three major components: natural gas furnace, air conditioning condensing unit, and air handling unit.

Natural Gas Furnace

Natural gas furnaces are manufactured to operate at several different levels of efficiency. Like the GSHPs, an average value for efficiency was used in the calculations.

Despite the availability of residential condensing furnaces functioning at up to 96% efficiency, the vast majority of commercial units produced are only about 80% efficient. It would be incorrect to select an extremely efficient condensing furnace when many currently manufactured models lack this high efficiency level. The models selected for this effort exceed the maximum design heating load to ensure they meet design criteria. The selected efficiency was calculated from the Air Conditioning Heating and Refrigeration Institute's 2008 report entitled "Consumer's Directory of Certified Efficiency Ratings." This report tested and certified 1,843 commercial natural gas-fired furnaces. The efficiency ratings ranged from 78% to 82% with a mean of 80.3% and a standard deviation of 0.62. Therefore, an 80.3% efficiency rating was used for all energy consumption calculations. The pricing for the furnaces used in this research was obtained from RS Means Building Construction Cost Data 2007 Book as shown in Appendix I. Cost factors were applied to the study locations to account for variability in labor and material costs.

Air Conditioning Condensing Unit

The next major consideration is that of the air conditioning condensing unit. This component of the air conditioning system is located outside the facility and rejects the heat into the atmosphere with the use of a condensing coil and refrigerant. The performance of these units can be measured with the seasonal energy efficiency ratio (SEER) or the energy efficiency ratio (EER). The SEER is the most commonly used and is the type of efficiency ratio dictated by the federal government. This measurement uses the load conditions expected throughout the cooling season to measure the efficiency of the unit. This is defined by Air Conditioning Heating and Refrigeration Institute's ARI 210-240 Standard (AHRI, 2008). The problem with this standard is that the calculations are based on one fixed location which does not adequately reflect the conditions for all locations considered in this research.

The EER measurement is closely related to SEER, but differs in that it is based on a set temperature of 95°F outside air temperature according to AHRI specifications. This temperature could be set at any level for testing, but 95°F is the standard. This provides an unbiased and accurate measurement of the efficiency of the unit throughout the study locations. This also allows a direct comparison with the GSHP systems in this study, since AHRI uses the EER as their standard measure of performance. Although EERs are often used for water-source equipment, they can be used for air-source equipment as well. The SEER methodology is useful for selecting equipment, but the EER is a better overall measure of performance. The use of the EER allows for the most accurate comparison with the GSHP systems developed in this research.

Based on an analysis of 2,500 air-cooled air conditioning units obtained from the AHRI listing for split-system units, a mean EER of 11.44 with a standard deviation of 0.71 was obtained. This is the value used for all air conditioning and energy use calculations. All costs for equipment were obtained from RS Means Building Construction Cost Data 2007 Book.

Air Handling Unit

The final component of the system that must be considered was the air handling unit. While GSHP systems do not require moving large amounts of air, traditional heating and cooling systems do. The air handling unit was selected to provide up to 2,000 cubic feet per minute of airflow to the conditioned space. This unit was powered by a 1/3 horsepower electric motor operating at 85% efficiency. The cost for this piece of equipment was again obtained from RS Means Building Construction Cost Data 2007 Book.

Energy Use Calculations

Installation costs are important in this study, but another tremendously important aspect is that of energy use. Pressure is mounting to become more efficient and curtail energy use throughout the world. It is important to have an accurate account of actual energy use to make informed choices on what type of system to install.

Ground Source Heat Pump Energy Use

As mentioned previously, GSHP systems only require electricity for their operation. This greatly simplifies the calculations on their actual energy use. The only consideration for the energy use of a GSHP system includes the electricity consumed by the heat pump and the circulating pump for the borehole field. These can be further subdivided into heating and cooling for each section to ensure there is an accurate understanding of the impact of each component during each season of the year. The calculations for energy use are defined by Equations 3 through 6,

$$\text{GSHP Cooling Energy} = \frac{(\text{Cooling Load} \cdot \text{Cooling Hours})}{(\text{Energy Efficiency Ratio})} \qquad (3)$$

$$\text{GSHP Circulating Pump Cooling Energy} = \frac{(\text{Pump Power} \cdot \text{Cooling Hours})}{(\text{Motor Efficiency})} \tag{4}$$

$$\text{GSHP Heating Energy} = \frac{(\text{Heating Load} \cdot \text{Heating Hours})}{(3.415(\text{BTU/WHr}) \cdot \text{COP})} \tag{5}$$

$$\text{GSHP Circulating Pump Heating Energy} = \frac{(\text{Pump Power} \cdot \text{Heating Hours})}{(\text{Motor Efficiency})} \tag{6}$$

where all variables have previously been defined. The sum of the products of these four equations gives the total energy consumption of a GSHP system for the entire heating and cooling season. The result is given in watt-hours which converts easily into the more familiar form of kilowatt-hours.

It is important to note that the values for EER and COP vary for each location in the study. While many locations have the same hypothetical heat pump unit, their performance varies due to the specific conditions of the site. Previous studies have used the full EER value obtained under specific lab conditions. This produces an impractical value that is not useful in the real world. Therefore, this study utilizes the values for EER and COP as calculated by the GLD software under simulated conditions for each study location.

Natural Gas Split-System Air Conditioning Energy Use

Although the calculations for a NGAC system are not as straightforward as those for the GSHP system, they are not too unwieldy. For the air conditioning condensing unit, the calculation is similar to that of the GSHP when operating in cooling mode and is represented by Equation 7.

$$\text{NGAC Cooling Energy} = \frac{(\text{Cooling Load} \cdot \text{Cooling Hours})}{(\text{Energy Efficiency Ratio})} \quad (7)$$

The next consideration was the energy use of a natural gas furnace during the heating season. This calculation consists of the energy used during actual combustion coupled with the energy used by the air handler to distribute the heat. This calculation is represented by Equation 8, where HL = heating load, HH = heating hours, AFUE = annual fuel utilization efficiency, FP = fan power and η = motor efficiency.

$$\text{NGAC Heating Energy} = \frac{(\text{HL} \cdot \text{HH})}{(3.415\ \text{BTU/WHr} \cdot \text{AFUE})} + \frac{(\text{FP} \cdot \text{HH})}{(\eta)} \quad (8)$$

This completes the calculation of energy use by the two competing systems. The output values are in kilowatt-hours, thereby ensuring accurate comparison of the systems. Additional manipulation will be required in the upcoming sections to calculate utility costs.

Operating and Maintenance Cost Calculations

There are two major areas that contribute to the operating costs of the systems in this study. The first is the cost of the electricity and/or natural gas required for operation, computed from the energy use calculated in the previous section. The second is the maintenance required for the units. This value was estimated from RS Means Facility Maintenance Cost Data 2007 Book and adjusted for the local cost factor.

GSHP Operating Cost

Since the GSHP system is operated solely on electricity, this calculation is simple. The operating cost is obtained by multiplying the total energy use calculated in the previous section by the applicable state utility rate as shown in Equation 9 where GSHP EUC = GSHP energy use cooling, CPEUC = circulating pump energy use cooling, GSHP EUH = GSHP energy use heating, CPEUH = circulating pump energy use heating and ER = electricity rate.

$$\text{GSHP Total Energy Cost} = (\text{GSHP EUC}+\text{CPEUC}+\text{GSHP EUH}+\text{CPEUH})\cdot\text{ER} \quad (9)$$

GSHP Maintenance Cost

In addition to utility costs is the issue of maintenance. According to the RS Means Facility Maintenance Cost Data 2007 Book, it costs $0.12/ square foot annually to maintain a GSHP in a large office. The maintenance cost has limited impact on the project due to the fact that it is only slightly lower than the cost of maintaining a traditional system. Despite this, calculating the maintenance cost is important because it is a key component of the annual operations. This calculation is straightforward and the cost is adjusted according to the location cost factor (LCF) for each location, as shown in Equation 10.

$$\text{GSHP Maintenance Cost} = (\text{Maintenance Rate/SF})\cdot(\text{Building SF})\cdot(\text{LCF}) \quad (10)$$

NGAC Operating Cost

The NGAC system calculations consist of two separate elements. The electricity required for the operation of the air conditioner and the furnace fan are determined. Then, the amount of natural gas consumed to support heating requirements is determined. These calculations are represented by Equations 11 through 13.

$$\text{AC Energy Cost Cooling} = (\text{Cooling Electricity Use})\cdot(\text{Electricity Rate}) \quad (11)$$

$$\text{Furnace Fan Energy Cost Heating} = (\text{Fan Electricity Use})\cdot(\text{Electricity Rate}) \quad (12)$$

$$\text{Natural Gas Cost Heating} = (\text{Natural Gas Use})\cdot(\text{Natural Gas Rate}) \quad (13)$$

NGAC Maintenance Cost

The maintenance cost associated with the NGAC system is \$0.15/ square foot annually for a large office, according to RS Means Facility Maintenance Cost Data. This value was then adjusted for the location cost factors. This is a significant factor in the overall operations budget, but it is so similar to that of the GSHP system that it does not change the overall economics of the systems appreciably. The calculation is shown in Equation 14.

$$\text{NGAC Maintenance Cost} = (\text{Maintenance Rate/ SF})\cdot(\text{Building SF})\cdot(\text{LCF}) \quad (14)$$

With the installation and operating costs determined, the next step was to determine the study design life in preparation for the financial calculations. Design life is a critical component of the financial formulas used in this work.

Design Life Calculations

Determining the design life ensured that this study was an accurate representation of the real world. The design life is composed of the equipment service life, GSHP underground piping life, and the design itself. This information is important to the Building Life-Cycle Cost 5 software used to compute the basic financial parameters.

Comprehensive Design Life

An economic analysis is often performed when organizations must decide what type of system to install in new construction and retrofit applications. Previous analyses have been conducted utilizing study periods of up to 50 years. This is a good timeframe from the perspective of the useful life of a building, but is generally too long when energy use is a factor. The last 50 years have demonstrated the tremendous transformations in energy use that can occur during the useful life of a facility. This is shown in Figure 9.

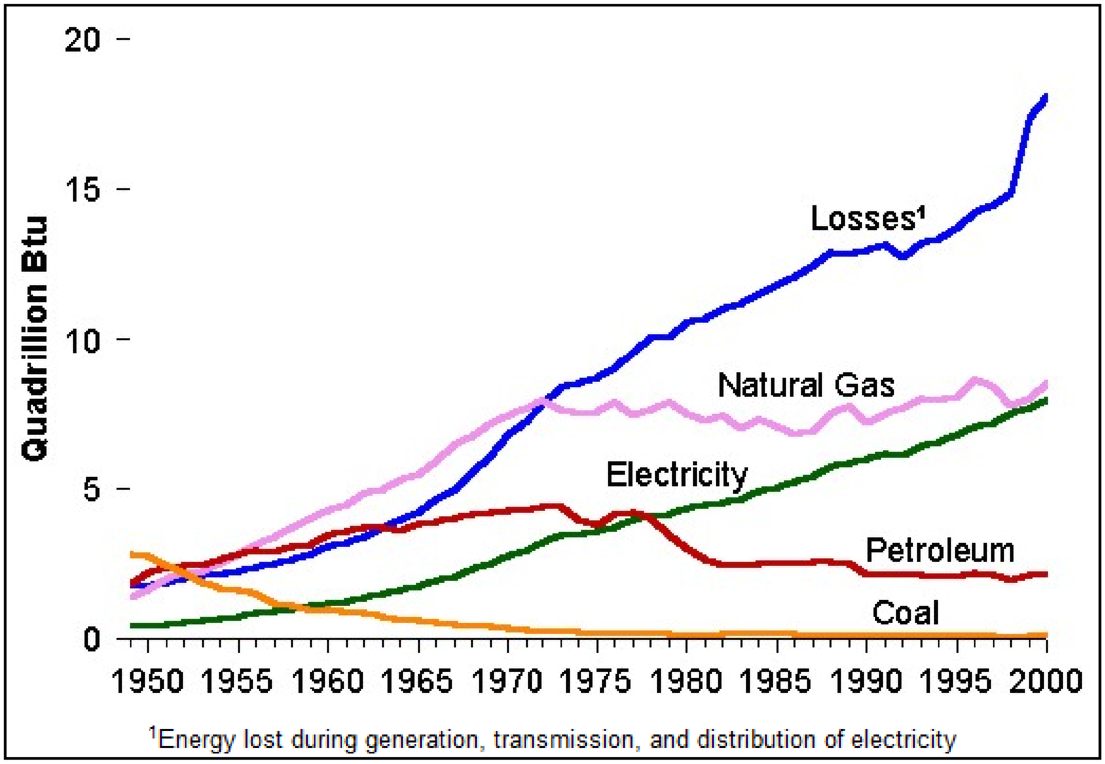

Figure 9. United States Historical Energy Use (EIA, 2000)

It is clear from Figure 9 that the amount and type of energy used in the United States has changed tremendously over the past five decades. When the increased consumption and instability that developing nations add to an increasingly complex energy system is considered, it becomes even more apparent that a 50-year study horizon is not tenable. In addition, this does not consider the possibility that a breakthrough technology could be developed within the next 50 years, disrupting the current order of energy markets and defining an entirely new paradigm. Based on all of these considerations, the Federal Energy Management Program of the Department of Energy has mandated through Executive Order 13123 that a 25-year study period be utilized (Fuller, 2005). For these reasons, this effort only considered a 25-year time horizon.

Equipment Design Life

One of the largest considerations when conducting economic analysis calculations is the expected design life of the components of the system in the study. This has become a major consideration as the cost of components and skilled labor have increased in price. The expected service life has an enormous impact on all economic calculations. The five major components considered with regard to life-cycle cost include the air conditioning condenser, air handler, natural gas furnace, heat pump, and ground heat exchanger piping. The first four have accurate data available from the 2007 ASHRAE Handbook, HVAC Applications, as shown in Table 2.

Table 2. Equipment Service Life (ASHRAE, 2007)

Equipment Type	Service Life (years)
AC Unit	20.0
NGAC Air Handler	20.0
NG Furnace	18.0
GSHP Heat Pump	25.0

It is important to note that the value for commercial water-to-air heat pumps was given as greater than 24 years in the ASHRAE Handbook. However, this value was rounded up to 25 years after consulting the ASHRAE online database of equipment service life. It is constantly updated and contains over 38,000 entries on various types of equipment (ASHRAE, 2008). The database indicated that the service life was well beyond 24 years and could safely be rounded up to the 25-year design life utilized in this study. The only remaining major component to consider is that of the GSHP polyethylene pipe that makes up the ground heat exchanger.

GSHP Polyethylene Pipe Design Life

The final service life consideration was that of the ground heat exchanger piping. The pipe in question is SDR-11 polyethylene pipe. This pipe has been tested and found to have a mean projected failure time of 165 years (Plastics Pipe Institute, 2008). In addition, the minimum design life is projected to be greater than 65 years with 95% confidence. This proves that the pipe will remain in service long after the other components of the GSHP system have been replaced.

Financial Calculations

Many financial measurements are available, but this effort focuses on those mandated by the Department of Energy's Federal Energy Management Program. These key measures include the savings to investment ratio (SIR), adjusted internal rate of return (AIRR), simple payback period (SPP), and the discounted payback period (DPP).

Savings to Investment Ratio

The first financial metric considered was that of the SIR. It is a measure of the economic performance of a project that expresses the relationship between its savings and its increased investment cost (in present value terms) as a ratio (Fuller & Peterson, 1996). This is very similar to the traditional cost-benefit ratio and is primarily used on projects where an alternative option has lower operations costs compared to the traditional system. The SIR is shown by Equation 15 (Fuller & Peterson, 1996).

$$SIR_{A:BC} = \frac{\Delta E + \Delta W + \Delta OM\&R}{\Delta I_o + \Delta Repl - \Delta Res} \tag{15}$$

where

$SIR_{A:BC}$	=	Ratio of operational savings to investment-related additional costs, computed for the alternative relative to the base case,	
ΔE	=	$(E_{BC} - E_A)$	Savings in energy costs attributable to the alternative,
ΔW	=	$(W_{BC} - W_A)$	Savings in water costs attributable to the alternative,
$\Delta OM\&R$	=	$(OM\&R_{BC} - OM\&R_A)$	Difference in OM&R costs,
ΔI_0	=	$(I_A - I_{BC})$	Additional initial investment cost required for the alternative relative to the base case,
$\Delta Repl$	=	$(Repl_A - Repl_{BC})$	Difference in capital replacement costs,
ΔRes	=	$(Res_A - Res_{BC})$	Difference in residual value, and

where **all amounts are in present values**.

Internal Rate of Return

The next major financial measure determined was the IRR. It is simply the annual percentage yield over the study period. It is a measure that must generally exceed the investor's minimum acceptable rate of return (MARR) in order for a project to be feasible. The MARR is generally equal to the discount rate, or cost of capital. The IRR requires extensive calculations when solved individually, but is easily determined once the SIR has been determined. This is shown in Equation 16, where AIRR = adjusted internal rate of return, r = reinvestment percentage rate, SIR = savings to investment ratio and N = number of years in the study period (Fuller & Peterson, 1996).

$$AIRR = (1 + r)\,(SIR)^{\frac{1}{N}} - 1 \tag{16}$$

Simple Payback Period

The next financial measure that was considered was the SPP. It does not consider the time value of money; essentially the discount rate is zero for this calculation. It is simply the number of periods for a project's net revenues to equal or pay back its upfront cost (Eschenbach, 2003). The formula for the SPP is shown in Equation17 (Fuller & Peterson, 1996).

$$\sum_{t=1}^{y} \frac{[\Delta E_t + \Delta W_t + \Delta OM\&R_t - \Delta Repl_t + \Delta Res_t]}{(1 + d)^t} \geq \Delta I_0 \tag{17}$$

where

ΔE_t	=	$(E_{BC} - E_A)_t$	Savings in energy costs in year t,
ΔW_t	=	$(W_{BC} - W_A)_t$	Savings in water costs in year t,
$\Delta OM\&R_t$	=	$(OM\&R_{BC} - OM\&R_A)_t$	Difference in OM&R costs in year t,
$\Delta Repl_t$	=	$(Repl_A - Repl_{BC})_t$	Difference in capital replacement cost in year t,
ΔRes_t	=	$(Res_A - Res_{BC})_t$	Difference in residual value in year t (usually zero in all but the last year of the study period),
d	=		Discount rate, and
ΔI_0	=	$(I_A - I_{BC})_o$	Additional initial investment cost.

This basic equation was applied through the Building Life-Cycle Cost 5 software to generate the output for this parameter. The value obtained through this calculation is critical to obtain funding. Many private companies target a 2.5 year simple payback, but the minimum payback required for funding a government project is 10 years (AFCESA, 1999).

Discounted Payback Period

The final financial measure considered was that of the DPP. It is similar to the SPP calculation; however, it includes the time value of money in the form of the discount rate. The DPP is the number of periods until the compounded sum of net revenues equals the compounded value of the first cost (Eschenbach, 2003). It has the same formula as the SPP, but the discount rate is not zero. The formula is shown in Equation 18 (Fuller & Peterson, 1996).

$$\sum_{t=1}^{y} \frac{[\Delta E_t + \Delta W_t + \Delta OM\&R_t - \Delta Repl_t + \Delta Res_t]}{(1 + d)^t} \geq \Delta I_0 \quad (18)$$

where

ΔE_t	=	$(E_{BC} - E_A)_t$	Savings in energy costs in year t,
ΔW_t	=	$(W_{BC} - W_A)_t$	Savings in water costs in year t,
$\Delta OM\&R_t$	=	$(OM\&R_{BC} - OM\&R_A)_t$	Difference in OM&R costs in year t,
$\Delta Repl_t$	=	$(Repl_A - Repl_{BC})_t$	Difference in capital replacement cost in year t,
ΔRes_t	=	$(Res_A - Res_{BC})_t$	Difference in residual value in year t (usually zero in all but the last year of the study period),
d	=		Discount rate, and
ΔI_0	=	$(I_A - I_{BC})_o$	Additional initial investment cost.

The cost of capital can be significant and may have a major impact on the overall feasibility of a project. This was especially critical in this study given that GSHP systems often have high initial costs accompanied by very low operating costs. The DPP is calculated using market interest rates, U.S. Treasury bond rates, or whatever rate is available to the organization under study. The standard rate for government projects is 7.00% according to the Office of Management and Budget (OMB, 1992). This represents a good starting point for most analyses as this nearly equates to the 10-year Treasury Bill rate combined with the current inflation rate. Once the rates have been established, the DPP is relatively easy to calculate. In the case of this research, this value was computed through the use of BLCC5 software. It gives a good indication about the feasibility of a project and should be considered before investment is made. It shows the value of the project while taking into account the true time value of money.

Carbon Dioxide Emission Calculations

As mentioned in the introduction of this work, carbon dioxide emission analysis was one of the major focus areas of this project. The intent of this project was to quantify the emissions that result from the use of GSHP and NGAC systems. Even though GSHP systems have no emissions on site, it is critical that the impact of the electricity required be considered. The carbon dioxide emissions were evaluated two ways. First, the actual quantity of emissions was calculated. Second, the cost of these emissions was calculated using current emission offset costs.

Carbon Dioxide Emission Quantity

Calculating the quantity of carbon dioxide emissions is a relatively easy task given the wealth of information that is available. The Environmental Protection Agency (EPA) has developed specific emission factors for many different types of combustion in addition to electricity generation. These emission factors include values for CO_2, SO_2, NO_X, N_2O, Hg, and particulate matter. These values are all derived from EPA AP-42 Chapter 1 emissions factors for the combustion of natural gas and the production of electricity (EPA, 1998). These values are shown in Table 3.

Table 3. EPA Emission Factors

	CO_2	SO_2	NO_X	N_2O	Hg	PM
	lbs/MMBtu	lbs/MMBtu	lbs/MMBtu	lbs/MMBtu	lbs/MMBtu	lbs/MMBtu
Natural Gas	117.6	5.88E-04	9.80E-02	2.16E-03	2.55E-07	7.45E-03
	CO_2	SO_2	NO_X	N_2O	Hg	PM
	lbs/MWh	lbs/MWh	lbs/MWh	lbs/MWh	lbs/MWh	lbs/MWh
Electricity	1,662	4.4470	3.6720	0.0170	0.000044	0.7710

The values for the combustion of natural gas hold true throughout the United States, but significant variation exists in the type of electricity generation available. The values for electricity generation represent the averages for the nation. This fails to account for the different types of electricity generation available at each site. The use of BLCC5 software alleviates potential problems by utilizing emission factors that are computed for the type of power generation available at each location. This software simplifies the process of multiplying the electrical and natural gas use for each system by the associated emission factor, giving the total emissions for the given system. While all of these emissions are important, this work only considers the quantity of carbon dioxide produced. As demonstrated in Table 3, it is the largest source of emissions by several orders of magnitude. This is the leading perceived cause of global warming and that was why carbon dioxide was the focus of this effort.

Carbon Dioxide Emission Offset Credit Cost

Once the quantity of carbon dioxide emissions was established, it was relatively easy to determine the value of those emissions. Currently, carbon emissions are tracked but have no liability associated with them. As mentioned in Chapter II, there is a high probability that this will change within the lifetime of the systems installed today. For this reason, it is imperative to calculate the monetary value of those emissions and determine their impact on the economics of HVAC system selection. The two most prominent organizations currently involved in carbon emissions trading are the Chicago Climate Exchange and the New York Mercantile Exchange. Their most recent emissions auction was conducted under the Regional Greenhouse Gas Initiative, which is a consortium of utility companies located in the Northeastern United States. As of December 2008, one ton of carbon emissions have been trading at a minimum of $2.00

with the most recent auction price reaching $3.07 (Esch, 2008). The price of $2.00 per ton was then assessed to the emissions and applied to the cost of each system. Once emissions quantities and monetary values were established, the comprehensive life-cycle cost values were calculated.

Life-Cycle Cost Calculations

A key measure for project feasibility is life-cycle cost, which is simply the summation of the present value of all inputs and expenses of a system throughout its projected service life. This is a critical measure because it ensures that the time value of money is considered, which is especially important for projects with great differences in installation and operating costs. The formula for life-cycle cost is shown in Equation 19 (Fuller & Peterson, 1996).

$$LCC = I_0 + Repl - Res + E + OM\&R \tag{19}$$

LCC = Total LCC in present value dollars of a given alternative,
I_0 = Initial investment costs,
Repl = Present-value capital replacement costs,
Res = Present-value residual (resale value, scrap value, salvage value) less disposal costs,
E = Present-value energy costs, and
OM&R = Present-value non-fuel operating, maintenance, and repair costs.

For this project, two separate life-cycle costs were calculated. First, the traditional life-cycle cost was calculated considering only the costs of installation, operation, and maintenance. Second, these costs were combined with the carbon emission offset costs incurred by each system to define the comprehensive life-cycle cost of the system.

Summary

This section has detailed the methodology used in this study. It included the formulas and calculations required to determine the installed cost, operating cost, SIR, AIRR, SPP, DPP, carbon dioxide emission quantity, carbon dioxide emission offset cost, LCC, and LCC considering carbon dioxide emission offset costs. The next section details the results of this study.

IV. Results and Analysis

This chapter details the results of this study comparing ground source heat pump (GSHP) systems to traditional natural gas furnace and split-system air-conditioning (NGAC) systems. First, it covers the installation and operating costs of each of the systems. Next, the basic financial metrics and overall energy use of each system is compared. In addition, the carbon dioxide emissions and offset costs are evaluated for both systems. The life-cycle cost is then calculated for each of the systems. Finally, the effect of electricity prices, natural gas prices, GSHP installation costs, and carbon dioxide emission offset credit expenses on the overall competitiveness of each system was evaluated through a detailed sensitivity analysis. This analysis was based on 51 independent locations covering all 50 states and the District of Columbia. Appendix A lists these locations by city and state; however, they are shortened to their state name or abbreviation for brevity in this document.

Installation and Operating Cost Results

Installation Cost Results

The installed cost of the NGAC and GSHP systems was investigated, and as expected, the costs of GSHP systems were substantially higher. This is demonstrated in Table 4 and Figure 10. There was a wide range of price differentials, ranging from 176% higher in California to 560% in Alaska. The mean cost increase for the GSHP system was 257% over the traditional NGAC system. This finding was not shocking, given the relative complexity of the GSHP system.

Table 4. NGAC vs. GSHP Installed Cost

	NGAC	GSHP	GSHP-NGAC	% Increase		NGAC	GSHP	GSHP-NGAC	% Increase
AL	$3,315	$9,102	$5,787	275%	MT	$3,861	$12,657	$8,796	328%
AK	$3,475	$19,476	$16,001	560%	NE	$3,770	$9,805	$6,035	260%
AZ	$3,384	$10,998	$7,614	325%	NV	$4,288	$10,371	$6,083	242%
AR	$3,622	$9,096	$5,474	251%	NH	$3,896	$9,732	$5,836	250%
CA	$5,130	$9,051	$3,921	176%	NJ	$4,562	$9,790	$5,228	215%
CO	$3,921	$9,176	$5,255	234%	NM	$3,551	$6,785	$3,234	191%
CT	$4,519	$11,049	$6,530	244%	NY	$5,514	$11,199	$5,685	203%
DE	$4,258	$8,899	$4,641	209%	NC	$3,365	$7,930	$4,565	236%
DC	$4,132	$9,817	$5,685	238%	ND	$3,719	$12,461	$8,743	335%
FL	$3,016	$8,004	$4,988	265%	OH	$3,816	$8,921	$5,105	234%
GA	$3,260	$8,869	$5,609	272%	OK	$3,471	$7,503	$4,032	216%
HI	$4,560	$20,276	$15,715	445%	OR	$4,296	$9,557	$5,260	222%
ID	$3,471	$7,363	$3,892	212%	PA	$4,166	$10,206	$6,040	245%
IL	$4,257	$10,522	$6,265	247%	RI	$4,380	$10,492	$6,111	240%
IN	$3,715	$9,701	$5,986	261%	SC	$3,218	$7,911	$4,693	246%
IA	$3,762	$10,088	$6,326	268%	SD	$3,298	$9,013	$5,715	273%
KS	$3,559	$7,541	$3,982	212%	TN	$3,698	$7,729	$4,030	209%
KY	$3,841	$8,035	$4,194	209%	TX	$3,496	$10,000	$6,504	286%
LA	$3,357	$10,859	$7,502	323%	UT	$3,711	$8,149	$4,438	220%
ME	$3,774	$10,698	$6,924	283%	VT	$3,450	$8,586	$5,137	249%
MD	$3,909	$9,069	$5,160	232%	VA	$3,753	$9,195	$5,442	245%
MA	$4,861	$11,151	$6,290	229%	WA	$4,317	$8,235	$3,918	191%
MI	$4,423	$10,946	$6,524	248%	WV	$4,014	$8,225	$4,211	205%
MN	$4,839	$15,770	$10,931	326%	WI	$4,313	$12,007	$7,694	278%
MS	$2,965	$7,838	$4,872	264%	WY	$3,627	$9,187	$5,561	253%
MO	$3,968	$9,502	$5,534	239%	**mean**	**$3,899**	**$9,971**	**$6,073**	**257%**

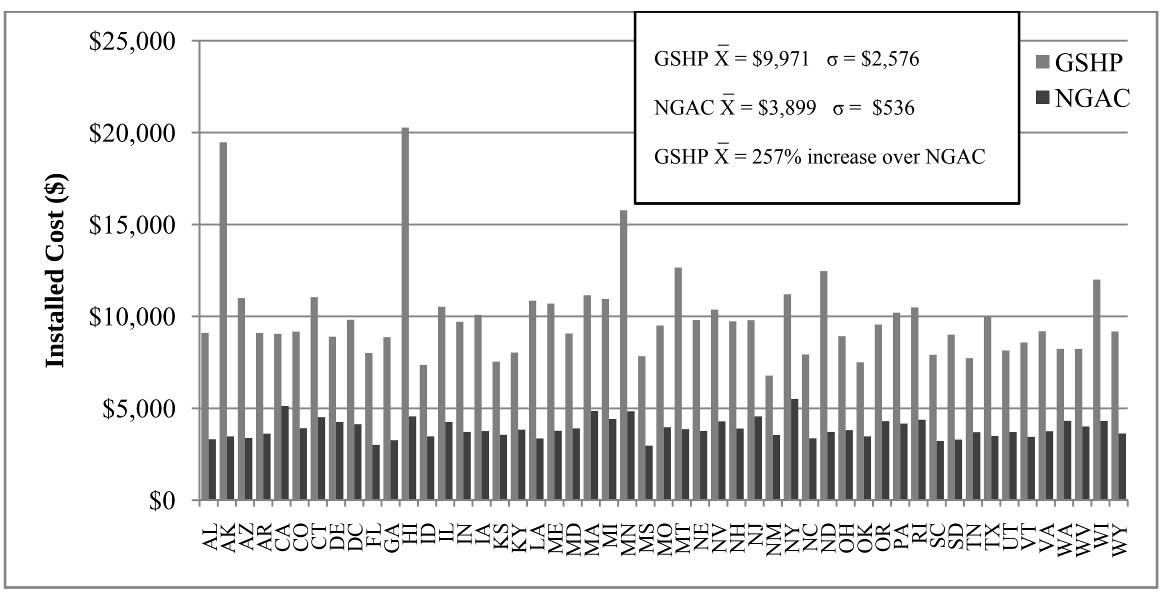

Figure 10. NGAC vs. GSHP Installed Cost ($)

Operating Cost Results

The operating costs, including energy related expenses and maintenance, of the NGAC system were compared to the GSHP system. The results are shown in Table 5 and Figure 11. As expected, the operating costs were lower for the GSHP system compared to the NGAC system in nearly all locations. Alaska was the sole location with higher operating costs, as a consequence of extreme conditions, low ground temperature, and lack of balanced heating and cooling seasons. The largest decrease in operating costs, at 60%, occurred in West Virginia. The mean overall operations and maintenance cost savings was 33% when comparing the GSHP system to the traditional NGAC system.

Table 5. NGAC vs. GSHP Annual Operating Cost

	NGAC	GSHP	NGAC-GSHP	% Decrease		NGAC	GSHP	NGAC-GSHP	% Decrease
AL	$1,907	$1,367	$539	28%	MT	$1,912	$1,160	$752	39%
AK	$2,230	$2,427	-$197	-9%	NE	$1,864	$1,090	$774	42%
AZ	$1,573	$1,358	$215	14%	NV	$1,725	$1,418	$306	18%
AR	$1,500	$1,068	$432	29%	NH	$2,667	$1,842	$825	31%
CA	$1,576	$1,268	$309	20%	NJ	$2,490	$1,933	$557	22%
CO	$1,389	$865	$524	38%	NM	$1,429	$881	$548	38%
CT	$2,505	$2,052	$453	18%	NY	$2,400	$1,983	$417	17%
DE	$2,412	$1,414	$997	41%	NC	$1,675	$995	$681	41%
DC	$2,382	$1,793	$589	25%	ND	$1,982	$1,172	$810	41%
FL	$1,634	$1,462	$172	11%	OH	$2,062	$1,147	$915	44%
GA	$1,664	$1,301	$363	22%	OK	$1,682	$1,012	$670	40%
HI	$5,000	$4,532	$468	9%	OR	$1,969	$878	$1,091	55%
ID	$1,628	$695	$934	57%	PA	$2,211	$1,290	$921	42%
IL	$2,117	$1,393	$724	34%	RI	$2,590	$1,616	$974	38%
IN	$1,927	$1,117	$810	42%	SC	$1,596	$1,080	$516	32%
IA	$2,032	$1,225	$808	40%	SD	$1,701	$1,011	$690	41%
KS	$1,883	$963	$920	49%	TN	$1,763	$995	$767	44%
KY	$1,709	$904	$806	47%	TX	$1,669	$1,582	$87	5%
LA	$1,736	$1,452	$284	16%	UT	$1,398	$854	$545	39%
ME	$2,931	$1,925	$1,006	34%	VT	$2,323	$1,635	$688	30%
MD	$2,271	$1,605	$666	29%	VA	$1,702	$961	$741	44%
MA	$2,648	$1,869	$779	29%	WA	$1,642	$732	$910	55%
MI	$2,121	$1,377	$743	35%	WV	$2,001	$805	$1,196	60%
MN	$2,303	$1,412	$891	39%	WI	$2,176	$1,370	$807	37%
MS	$1,676	$1,320	$356	21%	WY	$1,785	$888	$897	50%
MO	$1,995	$1,106	$889	45%	**mean**	**$2,023**	**$1,365**	**$658**	**33%**

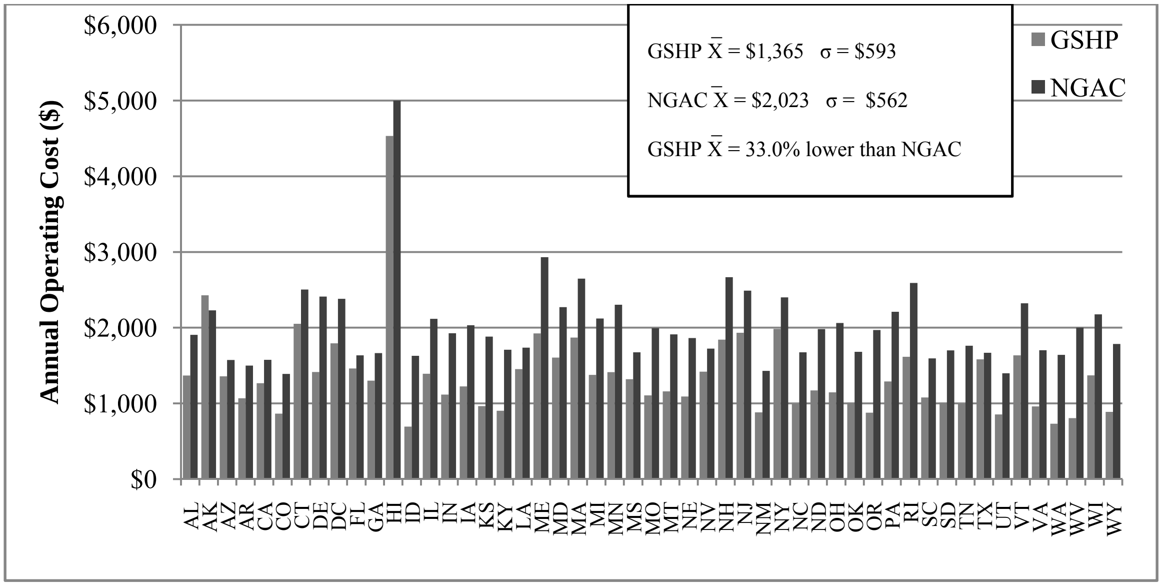

Figure 11. NGAC vs. GSHP Annual Operating Cost ($)

Financial Results

The economic values associated with each system, to include the savings to investment ratio (SIR), internal rate of return (IRR), simple payback period (SPP), and discounted payback period (DPP), were calculated and compared. These values were computed without considering tax incentives or emissions expenses, since those inputs can change over time. The intention of this analysis was to determine the financial feasibility of each system on its own merits under existing conditions. Tax incentives and emissions expenses are encompassed in an upcoming section. These SIR, IRR, SPP, and DPP values are referenced in the next four subsections and are summarized in Table 6.

Table 6. SIR, IRR, SPP, DPP

	SIR	IRR	SPP	DPP		SIR	IRR	SPP	DPP
AL	3.43	12.41%	11	17	MT	1.97	9.95%	13	21
AK	N/A	N/A	N/A	N/A	NE	3.78	12.84%	9	13
AZ	1.01	7.06%	21	25	NV	1.57	8.96%	19	25
AR	2.86	11.59%	12	20	NH	4.63	13.77%	8	10
CA	6.79	15.52%	13	19	NJ	4.14	13.26%	10	15
CO	3.86	12.94%	10	16	NM	17.36	19.94%	6	8
CT	2.31	10.65%	13	21	NY	2.69	11.33%	14	21
DE	9.15	16.91%	5	7	NC	6.22	15.12%	7	10
DC	3.51	12.52%	10	16	ND	2.15	10.32%	12	19
FL	1.78	9.50%	19	25	OH	6.59	15.38%	6	8
GA	2.31	10.65%	15	22	OK	8.85	16.75%	7	9
HI	1.36	8.33%	19	25	OR	8.06	16.32%	5	7
ID	6.82	15.54%	10	15	PA	4.78	13.91%	7	10
IL	3.33	12.28%	10	15	RI	4.93	14.05%	7	9
IN	4.06	13.17%	8	12	SC	4.60	13.73%	10	14
IA	3.30	12.23%	10	16	SD	3.85	12.93%	9	14
KS	11.81	18.11%	5	6	TN	10.41	17.52%	6	8
KY	9.44	17.06%	6	7	TX	0.45	3.67%	21	N/A
LA	1.00	7.02%	20	25	UT	5.63	14.66%	9	12
ME	4.28	13.41%	7	10	VT	5.03	14.15%	8	11
MD	4.54	13.68%	9	12	VA	4.74	13.88%	8	11
MA	3.94	13.03%	9	13	WA	14.40	19.05%	5	6
MI	3.19	12.09%	10	15	WV	14.38	19.04%	4	5
MN	1.67	9.21%	13	21	WI	2.61	11.19%	11	18
MS	3.13	12.00%	13	21	WY	3.54	12.55%	10	16
MO	5.09	14.19%	7	10	**mean**	**5.03**	**13.11%**	**10**	**15**

Note: N/A indicates the financial ratio could not be calculated due to negative input values

Savings to Investment Ratio Results

Table 6 shows the significant variability among the study locations. The SIR may be a simple ratio, but is dependent on the competing system saving money during operation. The GSHP system in Alaska actually costs more to operate than the NGAC system, resulting in a negative value, and thus indicating that it is a poor location for a GSHP system. Other locations fared much better, reaching a high of 17.36 in New Mexico, indicating superior project feasibility. This location is well suited for a GSHP system and will provide a substantial benefit. A value of 1.00, as in the case of Louisiana, indicates the two alternatives are evenly matched and there is no advantage in utilizing the GSHP system. The mean SIR value was 5.03, indicating that the GSHP is generally a favorable investment in most locations.

Internal Rate of Return Results

The internal rate of return, which is the overall rate of return on the investment including all installation, operations and maintenance, salvage and disposal costs, was computed. This value must exceed 7% in order to cover the cost of capital for this study. This is the discount rate for government institutions set by the Office of Management and Budget (OMB, 1992). Other organizations, such as individuals and companies in the private sector, may require other discount rates depending on the funding source. Table 6 shows the varying IRR values with extremes of a negative rate of return in Alaska and a positive 19.94% in New Mexico. The mean IRR value was 13.11%, exceeding the cost of capital and indicating most locations would benefit from a GSHP system.

Simple Payback Period Results

The simple payback period is a commonly used measure of financial feasibility in the business and government sector. As previously explained, it represents the number of years of operating cost savings required to offset the large upfront cost of the GSHP system. The SPP neglects the time value of money and is not a perfect representation of reality. Table 6, Figure 12, and Figure 13 show these results.

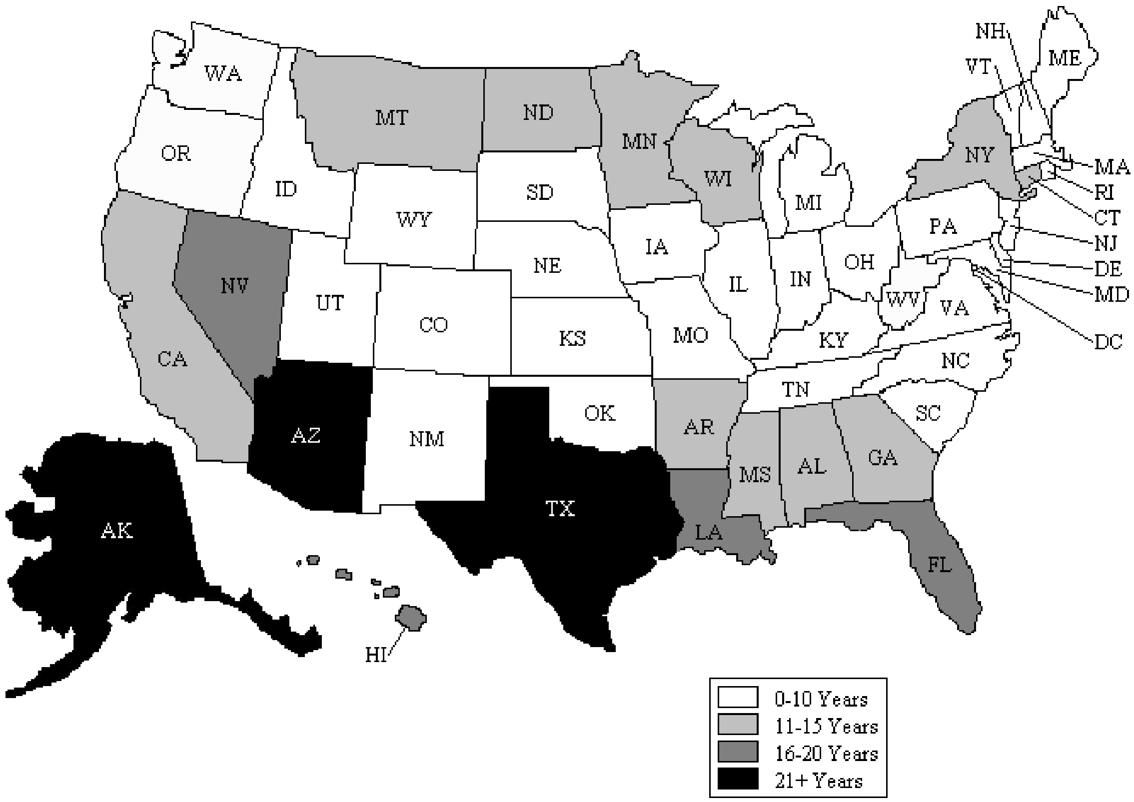

Figure 12. NGAC vs. GSHP Simple Payback Period Map (years)

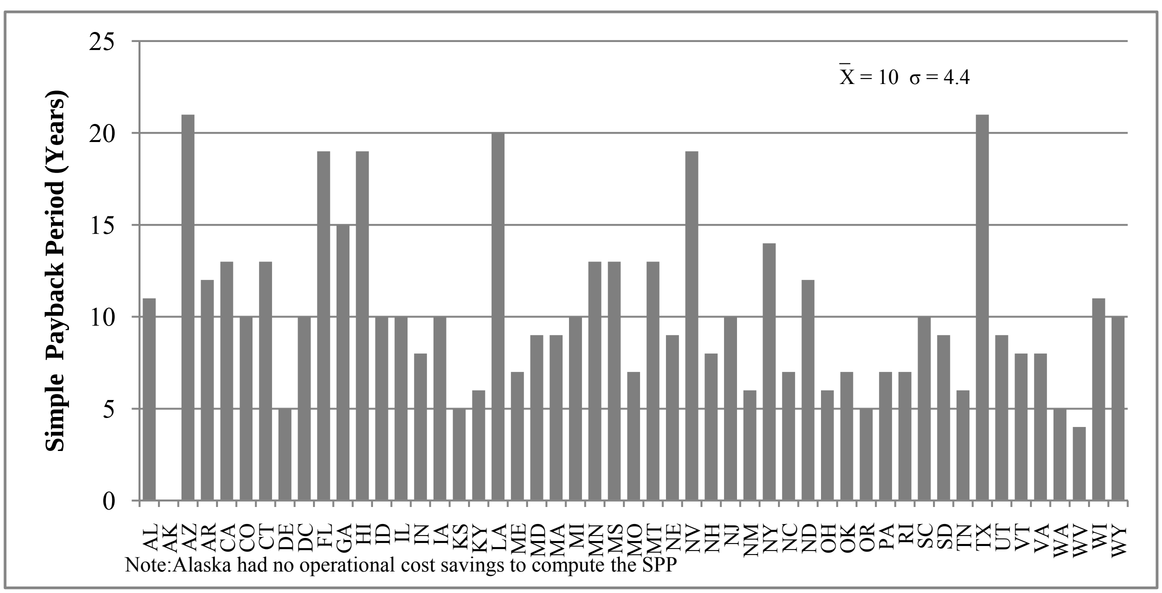

Figure 13. NGAC vs. GSHP Simple Payback Period (years)

Alaska, with a negative operational savings and lacking a positive payback period, was the worst performing location. Other low performing areas include Arizona, Texas, Louisiana, Florida, Hawaii, and Nevada as a result of high cooling demand and relatively high ground temperatures. West Virginia was the best performing location, with a 4-year simple payback period. The values vary by location and are highly dependent on local factors such as ground temperature, utility prices, and seasonal heating and cooling demand. The mean SPP value was 10 years, indicating that GSHP technology has potential, but is not cost effective in all locations. The SPP is an important measure, but the DPP often gives a better measure of actual profitability as shown in the next section.

Discounted Payback Period Results

The DPP is similar to the SPP, but includes the time value of money, which is especially important when making comparisons with a large initial cost followed by years of lower operating costs. The initial outlay of capital can be very difficult to overcome and must be a key consideration. Alaska, as the worst performing location, and did not have a positive cash flow to compute the DPP. Texas had operational savings; however, not enough to generate a positive monetary value so the DPP could not be calculated. West Virginia performed best with a 5-year DPP. The mean DPP was 15 years, clearly indicating this technology is not suitable in every location. These results are summarized in Figure 14 and Figure 15.

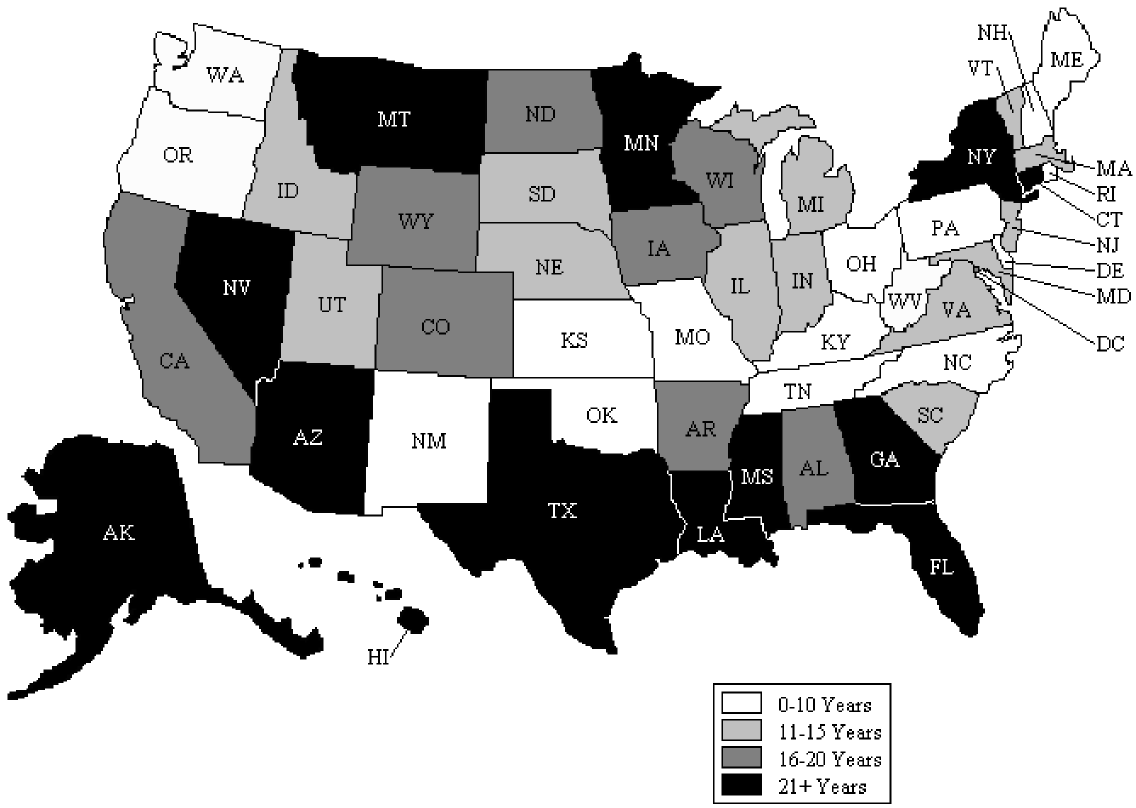

Figure 14. NGAC vs. GSHP Discounted Payback Period Map (years)

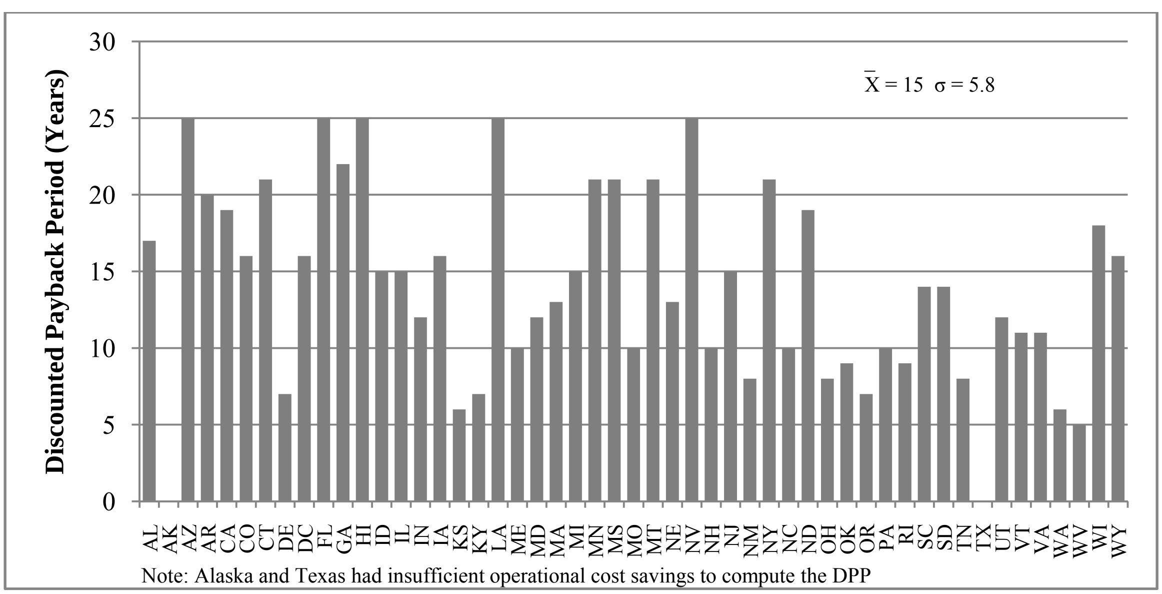

Figure 15. NGAC vs. GSHP Discounted Payback Period (years)

Energy Use Results

The level of energy use between the conventional NGAC system and the GSHP system was investigated to determine which had a higher level of energy use, regardless of cost. This data was generated for all 51 locations included in the study. The GSHP energy use was quantified strictly by the amount of electricity required in kWhr because these systems require no direct use of fossil fuel for their operation. Conversely, the NGAC system consumes natural gas and electricity. This required the energy use to be calculated and converted into common units to allow for reasonable comparison.
The requirement of electricity for the split-system air conditioner and natural gas for the furnace of the NGAC system was calculated. These values were then converted into either kWhr or MBTU for ease of comparison. The GSHP energy consumption calculations were much more straightforward as the energy use was simply computed in kWhr and converted to MBTU for direct comparison. Table 7, Table 8, and Figure 16 show substantial energy savings through the use of the GSHP system.

Table 7. NGAC vs. GSHP Energy Analysis (kWhr)

	Electricity Calculations				Natural Gas Calculations				Combined Savings	
			Annual	25-Year			Annual	25-Year	Annual	25-Year
	NGAC	GSHP	Savings	Savings	NGAC	GSHP	Savings	Savings	Savings	Savings
AL	9,367	12,672	-3,304	-82,607	14,795	0	14,795	369,863	11,490	287,256
AK	915	17,890	-16,975	-424,386	67,642	0	67,642	1,691,045	50,666	1,266,659
AZ	10,208	13,072	-2,864	-71,606	9,401	0	9,401	235,023	6,537	163,417
AR	7,632	11,985	-4,354	-108,842	20,229	0	20,229	505,726	15,875	396,884
CA	1,614	6,846	-5,232	-130,791	28,166	0	28,166	704,146	22,934	573,354
CO	2,133	9,133	-7,000	-174,996	35,094	0	35,094	877,350	28,094	702,354
CT	3,299	11,993	-8,694	-217,350	39,225	0	39,225	980,634	30,531	763,284
DE	4,838	10,315	-5,477	-136,926	31,311	0	31,311	782,786	25,834	645,860
DC	6,418	11,810	-5,392	-134,809	26,455	0	26,455	661,385	21,063	526,576
FL	10,426	13,410	-2,984	-74,610	9,240	0	9,240	230,991	6,255	156,382
GA	9,568	12,388	-2,820	-70,505	12,712	0	12,712	317,792	9,891	247,287
HI	20,113	18,397	1,716	42,908	0	0	0	0	1,716	42,908
ID	2,673	9,085	-6,413	-160,321	33,517	0	33,517	837,923	27,104	677,602
IL	6,068	13,131	-7,063	-176,570	36,118	0	36,118	902,944	29,055	726,374
IN	3,661	12,180	-8,519	-212,979	40,274	0	40,274	1,006,858	31,755	793,879
IA	4,010	12,902	-8,892	-222,302	42,735	0	42,735	1,068,373	33,843	846,071
KS	5,462	10,551	-5,088	-127,209	29,691	0	29,691	742,267	24,602	615,057
KY	5,161	10,012	-4,851	-121,272	28,664	0	28,664	716,612	23,814	595,339
LA	9,924	13,809	-3,885	-97,129	14,691	0	14,691	367,268	10,806	270,140
ME	1,909	12,119	-10,210	-255,246	47,253	0	47,253	1,181,331	37,043	926,085
MD	5,151	11,285	-6,135	-153,363	30,019	0	30,019	750,469	23,884	597,106
MA	3,454	10,173	-6,719	-167,974	35,576	0	35,576	889,398	28,857	721,424
MI	3,272	12,390	-9,118	-227,948	41,088	0	41,088	1,027,206	31,970	799,258
MN	3,369	14,742	-11,374	-284,343	49,242	0	49,242	1,231,050	37,868	946,706
MS	9,067	12,751	-3,684	-92,112	17,245	0	17,245	431,116	13,560	339,004
MO	5,335	11,814	-6,479	-161,978	32,189	0	32,189	804,713	25,709	642,735
MT	1,794	12,067	-10,272	-256,811	44,863	0	44,863	1,121,563	34,590	864,752
NE	4,601	12,991	-8,389	-209,735	40,647	0	40,647	1,016,168	32,257	806,433
NV	7,733	11,786	-4,053	-101,324	15,808	0	15,808	395,194	11,755	293,870
NH	2,226	11,520	-9,293	-232,337	40,449	0	40,449	1,011,233	31,156	778,897
NJ	4,909	10,791	-5,882	-147,049	33,535	0	33,535	838,382	27,653	691,334
NM	4,443	8,638	-4,195	-104,866	24,441	0	24,441	611,014	20,246	506,148
NY	4,567	10,321	-5,753	-143,835	31,191	0	31,191	779,783	25,438	635,947
NC	5,879	10,522	-4,642	-116,060	22,385	0	22,385	559,631	17,743	443,571
ND	2,102	14,168	-12,065	-301,637	55,206	0	55,206	1,380,140	43,140	1,078,503
OH	4,131	10,488	-6,357	-158,923	35,338	0	35,338	883,450	28,981	724,526
OK	6,379	9,976	-3,598	-89,941	22,004	0	22,004	550,097	18,406	460,156
OR	1,778	8,966	-7,188	-179,697	36,369	0	36,369	909,229	29,181	729,533
PA	3,247	11,267	-8,020	-200,504	36,799	0	36,799	919,976	28,779	719,472
RI	3,080	11,446	-8,366	-209,157	37,487	0	37,487	937,181	29,121	728,024
SC	7,443	11,244	-3,801	-95,026	16,612	0	16,612	415,302	12,811	320,276
SD	2,702	12,048	-9,346	-233,641	42,693	0	42,693	1,067,332	33,348	833,690
TN	5,998	9,917	-3,919	-97,978	23,855	0	23,855	596,373	19,936	498,394
TX	10,647	13,744	-3,098	-77,441	10,359	0	10,359	258,965	7,261	181,524
UT	3,185	9,714	-6,530	-163,240	33,675	0	33,675	841,878	27,146	678,638
VT	2,493	11,801	-9,308	-232,688	40,602	0	40,602	1,015,062	31,295	782,374
VA	6,062	11,238	-5,176	-129,394	25,416	0	25,416	635,392	20,240	505,998
WA	1,761	7,721	-5,960	-149,006	28,971	0	28,971	724,284	23,011	575,279
WV	4,567	9,668	-5,102	-127,544	29,391	0	29,391	734,770	24,289	607,226
WI	2,682	12,570	-9,888	-247,204	45,436	0	45,436	1,135,905	35,548	888,701
WY	1,740	10,920	-9,180	-229,494	40,322	0	40,322	1,008,050	31,142	778,556
mean	**5,122**	**11,615**	**-6,494**	**-162,349**	**31,106**	**0**	**31,106**	**777,659**	**24,612**	**615,310**

Table 8. NGAC vs. GSHP Energy Analysis (MBTU)

	Electricity Calculations				Natural Gas Calculations				Combined Savings	
			Annual	25-Year			Annual	25-Year	Annual	25-Year
	NGAC	GSHP	Savings	Savings	NGAC	GSHP	Savings	Savings	Savings	Savings
AL	32	43	-11	-282	53	0	53	1,314	41	1,033
AK	3	61	-58	-1,447	238	0	238	5,951	180	4,505
AZ	35	45	-10	-244	33	0	33	824	23	580
AR	26	41	-15	-371	71	0	71	1,778	56	1,405
CA	6	23	-18	-446	99	0	99	2,473	81	2,025
CO	7	31	-24	-597	124	0	124	3,092	100	2,495
CT	11	41	-30	-742	138	0	138	3,452	108	2,710
DE	17	35	-19	-467	110	0	110	2,757	92	2,290
DC	22	40	-18	-460	93	0	93	2,319	74	1,860
FL	36	46	-10	-255	33	0	33	824	23	570
GA	33	42	-10	-241	44	0	44	1,108	35	868
HI	69	63	6	146	0	0	0	0	6	148
ID	9	63	-54	-1,341	118	0	118	2,937	64	1,595
IL	21	45	-24	-602	127	0	127	3,169	103	2,568
IN	13	42	-29	-727	142	0	142	3,555	113	2,828
IA	10	44	-34	-858	151	0	151	3,761	116	2,905
KS	19	36	-17	-434	104	0	104	2,602	87	2,168
KY	18	34	-17	-414	101	0	101	2,525	84	2,110
LA	34	47	-13	-331	52	0	52	1,288	38	955
ME	7	41	-35	-871	166	0	166	4,148	131	3,278
MD	18	39	-21	-523	106	0	106	2,654	85	2,133
MA	12	35	-23	-573	125	0	125	3,117	102	2,545
MI	11	42	-31	-778	144	0	144	3,607	113	2,830
MN	13	50	-38	-945	173	0	173	4,328	135	3,383
MS	31	44	-13	-314	61	0	61	1,520	48	1,205
MO	18	40	-22	-553	113	0	113	2,834	91	2,283
MT	6	41	-35	-876	158	0	158	3,942	123	3,065
NE	16	44	-29	-716	143	0	143	3,581	115	2,868
NV	26	40	-14	-346	56	0	56	1,391	42	1,048
NH	8	39	-32	-793	142	0	142	3,555	111	2,763
NJ	17	37	-20	-502	119	0	119	2,963	98	2,460
NM	15	30	-14	-358	86	0	86	2,138	71	1,780
NY	16	35	-20	-491	110	0	110	2,757	91	2,268
NC	20	36	-16	-396	78	0	78	1,958	63	1,563
ND	7	48	-41	-1,029	195	0	195	4,869	154	3,840
OH	14	36	-22	-542	125	0	125	3,117	103	2,575
OK	22	34	-12	-307	77	0	77	1,932	65	1,625
OR	6	31	-25	-613	128	0	128	3,195	103	2,583
PA	11	38	-27	-684	130	0	130	3,246	103	2,563
RI	11	39	-29	-714	132	0	132	3,298	103	2,585
SC	25	38	-13	-324	59	0	59	1,468	46	1,143
SD	9	41	-32	-797	151	0	151	3,761	119	2,965
TN	21	34	-13	-334	84	0	84	2,087	70	1,753
TX	36	47	-11	-264	36	0	36	902	26	638
UT	11	33	-22	-557	119	0	119	2,963	96	2,405
VT	9	40	-32	-794	143	0	143	3,581	112	2,788
VA	21	38	-18	-442	90	0	90	2,241	72	1,800
WA	6	26	-20	-508	102	0	102	2,550	82	2,043
WV	16	33	-17	-435	103	0	103	2,576	86	2,143
WI	9	43	-34	-843	160	0	160	3,993	126	3,150
WY	6	37	-31	-783	142	0	142	3,555	111	2,773
mean	**17**	**40**	**-23**	**-571**	**109**	**0**	**109**	**2,736**	**87**	**2,166**

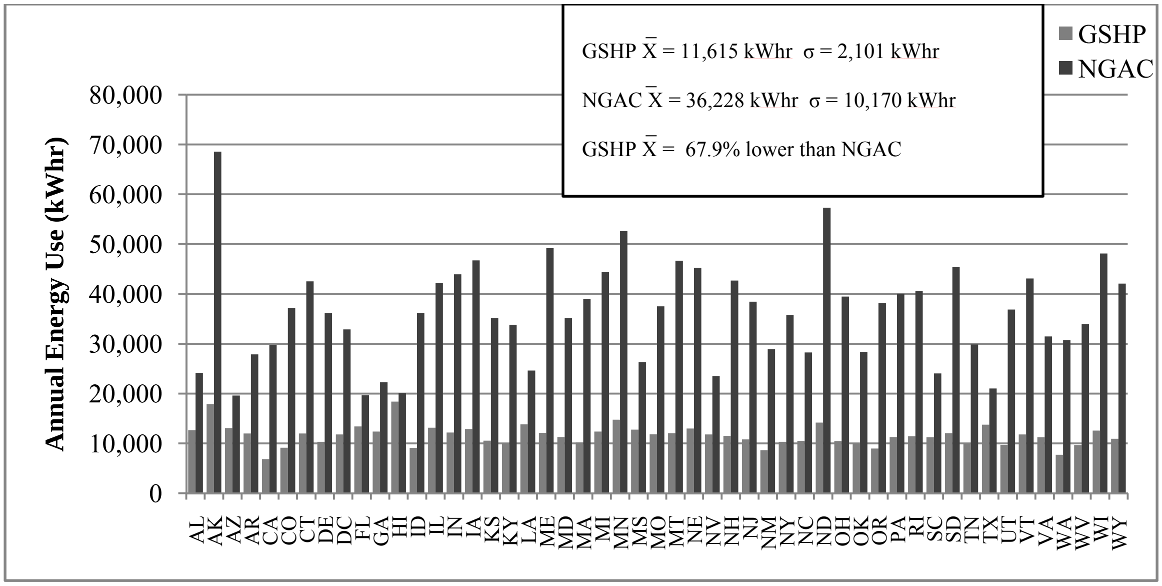

Figure 16. NGAC vs. GSHP Energy Analysis (kWhr)

The energy use for the GSHP system is lower than the NGAC system for every location calculated in this study. The minimum 25-year combined savings is that of Hawaii at 42,908 kWhr (3,660 MBTU) and the maximum savings is 1,266,659 kWhr (112,603 MBTU) in Alaska. The mean energy savings of the GSHP versus NGAC system over the 25-year life-cycle was 615,310 kWhr (54,136 MBTU). The annual energy savings of the GSHP versus the NGAC system was 67.9%, indicating a substantial advantage to the GSHP system. Despite the savings in energy consumption, the initial costs and type of energy being used must be considered. It is important to note that not all BTUs are created equal when it comes to energy consumption. The tables show large improvements in overall energy use, but there is a noticeable difference in the price of electricity and natural gas among the study locations. Although the energy use can be accurately compared, the price and availability of energy has tremendous variability depending on its source. For example, electricity ranges from $0.0547/kWhr in Idaho to $0.2305/kWhr in Hawaii for commercial customers. In addition, natural gas prices vary from $7.57/1,000 CF in Alaska to $28.31/1,000 CF in Hawaii. Energy use is a stable factor, but the economics vary tremendously. Next, carbon dioxide emissions and their effect on each system was studied to ensure that decisions are made considering economic and environmental costs.

Carbon Dioxide Emission Results

Carbon dioxide emissions were critical to this research. These emissions were considered two ways. First, the actual quantity of emissions was calculated and the value between the systems was compared. Second, market rates for emission offset credits were applied to establish a monetary value for these emissions.

Carbon Dioxide Emission Quantity Results

Carbon dioxide emissions between conventional NGAC systems and GSHP systems were compared. Other emissions are worthy of study, but this effort focused solely on carbon emissions because they have been linked to global warming and are not currently regulated. In addition, carbon dioxide emissions are far greater in magnitude than any of the other compounds produced from natural gas combustion or electricity generation. The emissions were calculated in kilograms and converted to metric tons since this is the unit of exchange for carbon dioxide emission trading.

The GSHP system requires electricity for its operation, but it is only as environmentally friendly as its source. This study utilized a systems approach considering the entire atmosphere as the frame of reference. It is inappropriate to claim that GSHP systems have no emissions simply because they do not occur at the point of use. This is often conveniently omitted from sales literature promoting GSHP systems. It is true that zero emissions occur on site, but it is essential to consider the system providing the electricity. Many locations in this study receive over 90% of their electricity from coal-fired power plants. The use of BLCC5 software allowed the calculation of emissions from each system to be adjusted for each location in this study. In most instances, the difference in emissions generated during the cooling season was negligible, as the NGAC and GSHP systems deliver similar levels of efficiency. In areas with long heating seasons, the electricity required for the GSHP system can often generate more emissions than the natural gas system it seeks to replace. The carbon dioxide emissions data is represented in Table 9, Figure 17, and Figure 18.

Table 9. NGAC vs. GSHP Emissions Analysis (metric tons)

	Elctricity		Annual	25-Year	Natural Gas		Annual	25-Year	Combineed		Annual	25-Year
	NGAC	GSHP	Savings	Savings	NGAC	GSHP	Savings	Savings	NGAC	GSHP	Savings	Savings
AL	9.28	12.55	-3.27	-81.81	2.78	0.00	2.78	69.40	12.05	12.55	-0.50	-12.41
AK	0.64	12.51	-11.87	-296.68	12.58	0.00	12.58	314.35	13.22	12.51	0.71	17.68
AZ	9.69	12.41	-2.72	-67.99	1.74	0.00	1.74	43.55	11.44	12.41	-0.98	-24.44
AR	7.97	12.51	-4.55	-113.62	3.76	0.00	3.76	93.90	11.73	12.51	-0.79	-19.72
CA	0.87	3.68	-2.81	-70.29	5.23	0.00	5.23	130.64	6.09	3.68	2.41	60.35
CO	2.02	8.64	-6.62	-165.54	6.53	0.00	6.53	163.30	8.55	8.64	-0.09	-2.24
CT	3.13	11.36	-8.24	-205.88	7.30	0.00	7.30	182.35	10.42	11.36	-0.94	-23.53
DE	4.53	9.67	-5.13	-128.31	5.83	0.00	5.83	145.61	10.36	9.67	0.69	17.30
DC	7.74	14.24	-6.50	-162.46	4.90	0.00	4.90	122.48	12.64	14.24	-1.60	-39.98
FL	7.57	9.73	-2.17	-54.14	1.74	0.00	1.74	43.55	9.31	9.73	-0.42	-10.59
GA	8.93	11.56	-2.63	-65.80	2.34	0.00	2.34	58.52	11.27	11.56	-0.29	-7.28
HI	17.14	15.68	1.46	36.55	0.00	0.00	0.00	0.00	17.14	15.68	1.46	36.55
ID	1.37	9.45	-8.07	-201.82	6.21	0.00	6.21	155.14	7.58	9.45	-1.87	-46.68
IL	6.23	13.49	-7.26	-181.37	6.70	0.00	6.70	167.38	12.93	13.49	-0.56	-13.99
IN	3.62	12.03	-8.42	-210.36	7.51	0.00	7.51	187.80	11.13	12.03	-0.90	-22.56
IA	2.97	13.46	-10.49	-262.27	7.95	0.00	7.95	198.68	10.92	13.46	-2.54	-63.59
KS	5.81	11.22	-5.41	-135.22	5.50	0.00	5.50	137.44	11.30	11.22	0.09	2.22
KY	5.35	10.38	-5.03	-125.76	5.34	0.00	5.34	133.36	10.69	10.38	0.30	7.60
LA	7.97	11.09	-3.12	-78.00	2.72	0.00	2.72	68.04	10.69	11.09	-0.40	-9.96
ME	1.10	6.96	-5.86	-146.54	8.77	0.00	8.77	219.10	9.86	6.96	2.90	72.56
MD	4.67	10.24	-5.57	-139.15	5.61	0.00	5.61	140.17	10.28	10.24	0.04	1.02
MA	2.62	7.73	-5.11	-127.61	6.59	0.00	6.59	164.66	9.21	7.73	1.48	37.05
MI	2.49	9.41	-6.93	-173.17	7.62	0.00	7.62	190.52	10.11	9.41	0.69	17.34
MN	4.03	16.23	-12.20	-304.97	9.15	0.00	9.15	228.62	13.18	16.23	-3.05	-76.35
MS	8.14	11.45	-3.31	-82.71	3.21	0.00	3.21	80.29	11.36	11.45	-0.10	-2.42
MO	5.55	12.29	-6.74	-168.42	5.99	0.00	5.99	149.69	11.54	12.29	-0.75	-18.73
MT	1.87	12.61	-10.74	-268.36	8.33	0.00	8.33	208.21	10.20	12.61	-2.41	-60.15
NE	4.82	13.60	-8.78	-219.52	7.57	0.00	7.57	189.16	12.38	13.60	-1.21	-30.37
NV	6.08	9.27	-3.19	-79.65	2.94	0.00	2.94	73.49	9.02	9.27	-0.25	-6.16
NH	2.32	12.02	-9.70	-242.41	7.51	0.00	7.51	187.80	9.84	12.02	-2.18	-54.62
NJ	3.38	7.44	-4.06	-101.37	6.26	0.00	6.26	156.50	9.65	7.44	2.21	55.12
NM	4.34	8.43	-4.09	-102.32	4.52	0.00	4.52	112.95	8.85	8.43	0.43	10.63
NY	3.47	7.84	-4.37	-109.22	5.83	0.00	5.83	145.61	9.29	7.84	1.46	36.39
NC	5.79	10.37	-4.58	-114.39	4.14	0.00	4.14	103.42	9.93	10.37	-0.44	-10.96
ND	2.45	16.53	-14.07	-351.81	10.29	0.00	10.29	257.20	12.74	16.53	-3.79	-94.61
OH	3.94	9.99	-6.06	-151.38	6.59	0.00	6.59	164.66	10.52	9.99	0.53	13.28
OK	5.55	8.68	-3.13	-78.21	4.08	0.00	4.08	102.06	9.63	8.68	0.95	23.85
OR	1.06	5.34	-4.28	-106.99	6.75	0.00	6.75	168.74	7.81	5.34	2.47	61.76
PA	2.98	10.34	-7.36	-183.97	6.86	0.00	6.86	171.47	9.84	10.34	-0.50	-12.50
RI	1.43	5.31	-3.88	-96.95	6.97	0.00	6.97	174.19	8.40	5.31	3.09	77.24
SC	6.87	10.37	-3.51	-87.64	3.10	0.00	3.10	77.57	9.97	10.37	-0.40	-10.07
SD	2.70	12.03	-9.33	-233.20	7.95	0.00	7.95	198.68	10.65	12.03	-1.38	-34.51
TN	5.64	9.33	-3.69	-92.14	4.41	0.00	4.41	110.23	10.05	9.33	0.72	18.09
TX	7.94	10.25	-2.31	-57.74	1.91	0.00	1.91	47.63	9.85	10.25	-0.40	-10.11
UT	3.10	9.47	-6.36	-159.07	6.26	0.00	6.26	156.50	9.37	9.47	-0.10	-2.58
VT	2.64	12.48	-9.84	-246.03	7.57	0.00	7.57	189.16	10.20	12.48	-2.28	-56.87
VA	5.56	10.31	-4.75	-118.68	4.74	0.00	4.74	118.39	10.30	10.31	-0.01	-0.29
WA	1.45	6.36	-4.91	-122.71	5.39	0.00	5.39	134.72	6.84	6.36	0.48	12.01
WV	4.25	9.00	-4.75	-118.74	5.44	0.00	5.44	136.08	9.70	9.00	0.69	17.34
WI	2.81	13.18	-10.37	-259.25	8.44	0.00	8.44	210.93	11.25	13.18	-1.93	-48.32
WY	1.87	11.45	-9.58	-239.49	7.51	0.00	7.51	187.80	9.39	11.45	-2.07	-51.70
mean	**4.62**	**10.63**	**-6.00**	**-150.09**	**5.78**	**0.00**	**5.78**	**144.54**	**10.40**	**10.63**	**-0.22**	**-5.55**

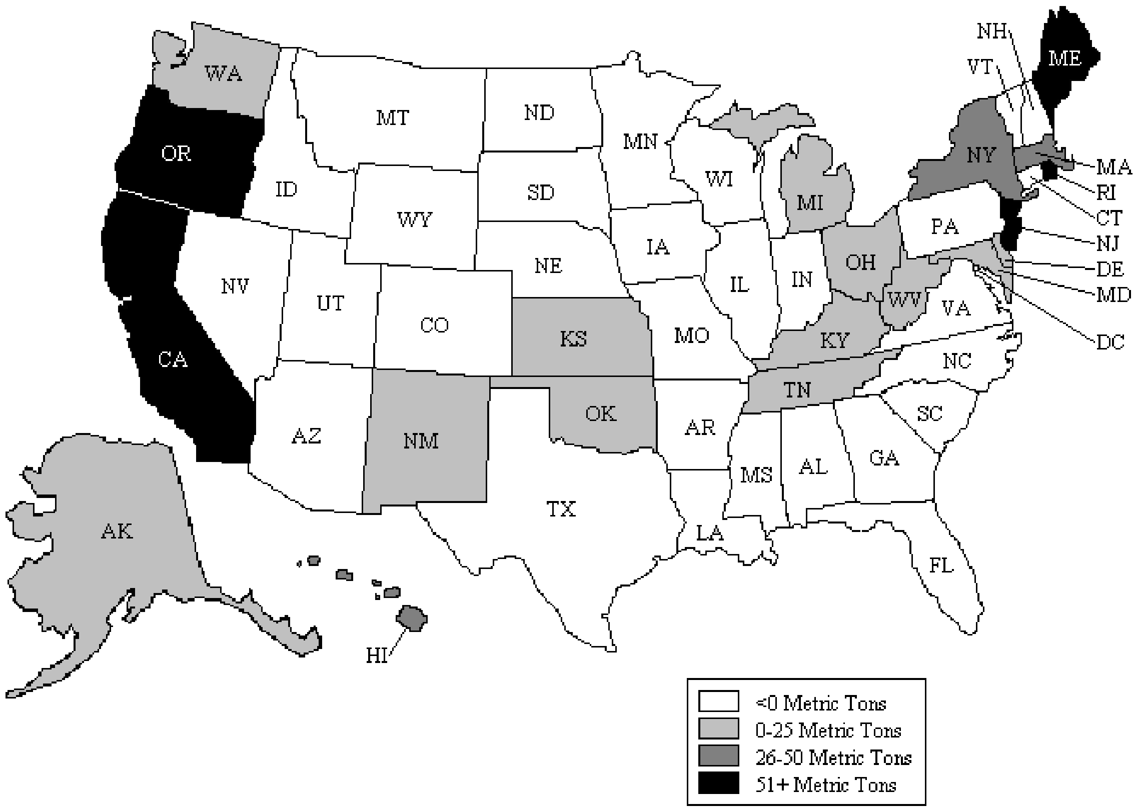

Figure 17. GSHP Emission 25-Year Life-Cycle Savings by State (metric tons)

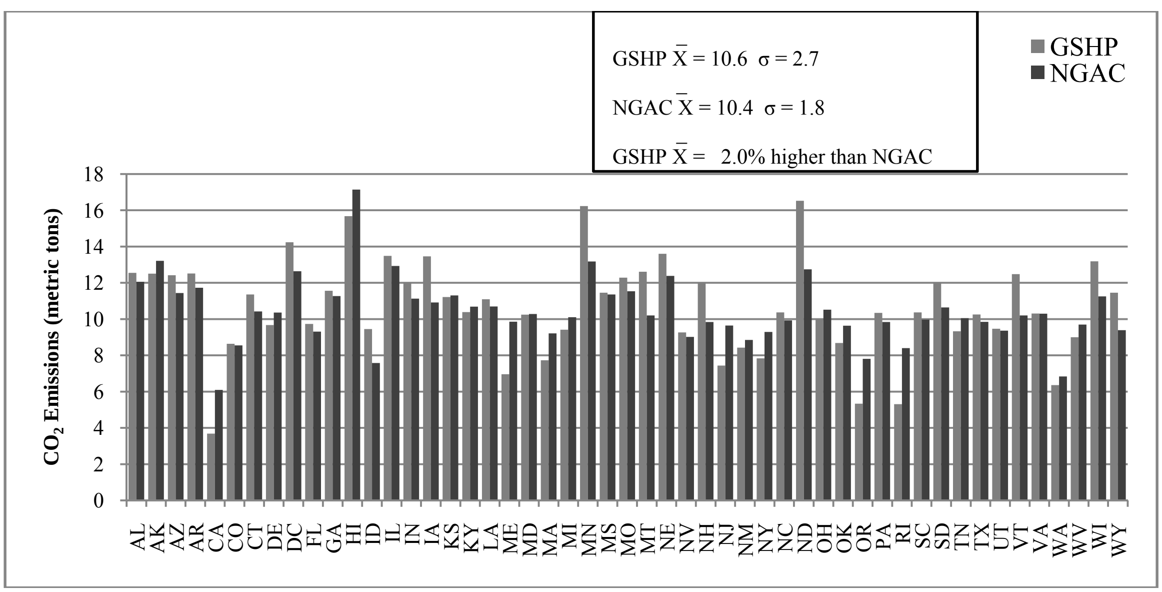

Figure 18. NGAC and GSHP Annual Carbon Dioxide Emissions (metric tons)

Table 9 and Figure 18 demonstrate that the emissions results are highly varied and depend on the type of power generation used at each location. There is no overriding trend with respect to heating or cooling dominant zones. The values range from saving 77.24 tons of emissions through the entire 25-year life-cycle of GSHP usage in Rhode Island to increasing emissions by 94.61 metric tons in North Dakota over the 25-year life-cycle. The mean value for all locations considered is a net increase of 5.55 metric tons of carbon dioxide emissions when using a GSHP system in place of an NGAC system over the life of the study. This value has a large standard deviation of 37.39, attesting to its variability, and can be attributed to the source of electricity, climate conditions, and system performance.

Carbon dioxide Emission Offset Cost Results

Emissions vary widely from location to location. Even if the facility in question is located in a region dominated by coal-fired electricity generation, procuring power from a renewable source is possible. Deregulation has separated the production and distribution of electricity into two transactions. If the building owner does not wish to seek a source of renewable electricity or install renewable electricity generation on site, carbon emission credits can be purchased to cover utility use. Many organizations are active in carbon trading; however, the most reputable and stable market is that of the Chicago Climate Exchange. The most current rates available for carbon dioxide emissions stand at $2.00 per metric ton which is the value used for comparison in this analysis. Table 10 shows the value of these emissions.

Table 10. Combined Emission Offset Analysis ($)

	NGAC	25-Year NGAC	GSHP	25-Year GSHP	Annual Savings	25-Year Savings
AL	$24.11	$602.64	$25.10	$627.47	-$0.99	-$24.82
AK	$26.43	$660.80	$25.02	$625.45	$1.41	$35.35
AZ	$22.87	$571.84	$24.83	$620.74	-$1.96	-$48.89
AR	$23.45	$586.29	$25.03	$625.74	-$1.58	-$39.44
CA	$12.19	$304.69	$7.36	$183.97	$4.83	$120.70
CO	$17.10	$427.54	$17.28	$432.01	-$0.18	-$4.47
CT	$20.84	$521.02	$22.72	$568.08	-$1.88	-$47.05
DE	$20.72	$517.96	$19.33	$483.35	$1.38	$34.61
DC	$25.27	$631.78	$28.47	$711.76	-$3.20	-$79.97
FL	$18.62	$465.46	$19.47	$486.64	-$0.85	-$21.18
GA	$22.54	$563.62	$23.13	$578.19	-$0.58	-$14.57
HI	$34.28	$857.00	$31.36	$783.88	$2.92	$73.11
ID	$15.16	$378.94	$18.89	$472.32	-$3.74	-$93.36
IL	$25.86	$646.50	$26.98	$674.48	-$1.12	-$27.98
IN	$22.26	$556.47	$24.06	$601.60	-$1.81	-$45.13
IA	$21.84	$545.90	$26.92	$673.10	-$5.09	-$127.18
KS	$22.61	$565.24	$22.43	$560.79	$0.18	$4.44
KY	$21.38	$534.40	$20.77	$519.20	$0.61	$15.20
LA	$21.39	$534.66	$22.18	$554.59	-$0.80	-$19.92
ME	$19.72	$493.06	$13.92	$347.93	$5.81	$145.11
MD	$20.56	$514.11	$20.48	$512.08	$0.08	$2.03
MA	$18.42	$460.59	$15.46	$386.47	$2.96	$74.10
MI	$20.22	$505.39	$18.83	$470.70	$1.39	$34.69
MN	$26.35	$658.85	$32.46	$811.56	-$6.11	-$152.70
MS	$22.71	$567.78	$22.90	$572.62	-$0.19	-$4.84
MO	$23.07	$576.83	$24.57	$614.29	-$1.50	-$37.45
MT	$20.41	$510.21	$25.22	$630.53	-$4.81	-$120.30
NE	$24.77	$619.17	$27.20	$679.91	-$2.43	-$60.73
NV	$18.04	$450.96	$18.53	$463.28	-$0.49	-$12.32
NH	$19.67	$491.78	$24.04	$601.02	-$4.37	-$109.23
NJ	$19.29	$482.27	$14.88	$372.01	$4.41	$110.24
NM	$17.71	$442.71	$16.86	$421.45	$0.85	$21.25
NY	$18.59	$464.66	$15.67	$391.87	$2.91	$72.78
NC	$19.86	$496.59	$20.74	$518.51	-$0.88	-$21.92
ND	$25.48	$637.06	$33.05	$826.31	-$7.57	-$189.22
OH	$21.05	$526.14	$19.98	$499.58	$1.06	$26.56
OK	$19.26	$481.60	$17.36	$433.90	$1.91	$47.70
OR	$15.62	$390.47	$10.68	$266.93	$4.94	$123.52
PA	$19.68	$491.96	$20.68	$516.96	-$1.00	-$25.00
RI	$16.79	$419.81	$10.61	$265.31	$6.18	$154.48
SC	$19.94	$498.43	$20.74	$518.58	-$0.81	-$20.14
SD	$21.29	$532.28	$24.05	$601.31	-$2.76	-$69.03
TN	$20.10	$502.56	$18.66	$466.38	$1.45	$36.18
TX	$19.69	$492.30	$20.50	$512.51	-$0.81	-$20.21
UT	$18.73	$468.26	$18.94	$473.41	-$0.21	-$5.15
VT	$20.41	$510.17	$24.96	$623.93	-$4.55	-$113.74
VA	$20.59	$514.85	$20.62	$515.43	-$0.02	-$0.58
WA	$13.68	$342.01	$12.72	$317.99	$0.96	$24.02
WV	$19.39	$484.86	$18.01	$450.17	$1.39	$34.68
WI	$22.50	$562.57	$26.37	$659.23	-$3.87	-$96.64
WY	$18.77	$469.28	$22.91	$572.70	-$4.14	-$103.40
mean	**$20.81**	**$520.24**	**$21.25**	**$531.34**	**-$0.44**	**-$11.09**

The costs associated with the current carbon emission offsets appear to be minor; however, these values represent the emission offset credits required for the 2,000 square foot hypothetical office building utilized in this study and are calculated at the current low rate of $2.00 per metric ton. If these values are increased for a facility over 100,000 square feet and the price goes up, the carbon emission offsets will not seem as inconsequential. The traditional NGAC system requires annual offsets ranging from $12.19 to $34.98 with a mean of $20.81. The GSHP system requires annual offsets that range from $7.36 to $33.05 with a mean of $21.25. Although these values are very similar and the average offset required for the GSHP system is higher than that of the NGAC system, the savings between the two had a wide range of values. The lowest value was -$189.22 in North Dakota, indicating the cost to operate the GSHP was high. The greatest savings was $154.98 in Rhode Island, indicating the GSHP system saved money over the life of the project. These values are relatively small compared to other operations and maintenance costs, but again, when increased for a larger facility, they could affect the overall organizational budget. The carbon emission offset program is currently voluntary and emission trading prices could rise dramatically if their use becomes mandatory.

Life-Cycle Cost Results

The study of the total LCC of conventional NGAC and GSHP systems involved calculating the costs incurred by installing, operating, and maintaining each system for the 25-year service period. These calculations were conducted using the net present value of each of the parameters to give an accurate portrayal of the true cost of the system to include the time value of money. This detail is important when studying systems: one with a very high installation cost accompanied by low operating costs and the other with a low installation costs accompanied by higher operating costs. The net present value life-cycle cost method is preferred as recommended by the Federal Energy Management Program (Fuller & Peterson, 1996). Table 11, Figure 19, and Figure 20 show the life-cycle cost values.

Table 11. Net Present Value 25-Year Life-cycle Cost ($)

	NGAC LCC	GSHP LCC	Savings		NGAC LCC	GSHP LCC	Savings
AL	$31,072	$25,648	$5,424	MT	$30,854	$26,092	$4,762
AK	$33,274	$46,667	($13,393)	NE	$29,888	$22,730	$7,158
AZ	$26,284	$26,228	$56	NV	$28,069	$26,602	$1,467
AR	$25,642	$21,764	$3,878	NH	$40,530	$31,702	$8,828
CA	$27,139	$23,365	$3,774	NJ	$38,483	$32,702	$5,781
CO	$24,150	$18,728	$5,422	NM	$24,209	$17,224	$6,985
CT	$39,161	$35,289	$3,872	NY	$37,744	$34,211	$3,533
DE	$37,839	$26,074	$11,765	NC	$27,517	$19,990	$7,527
DC	$37,469	$31,792	$5,677	ND	$31,385	$25,983	$5,402
FL	$27,429	$26,134	$1,295	OH	$32,486	$22,682	$9,804
GA	$27,372	$24,612	$2,760	OK	$27,441	$19,810	$7,631
HI	$32,490	$31,726	$764	OR	$31,708	$19,039	$12,669
ID	$26,852	$21,697	$5,155	PA	$34,804	$25,028	$9,776
IL	$33,477	$27,223	$6,254	RI	$39,751	$29,371	$10,380
IN	$30,684	$22,982	$7,702	SC	$26,553	$21,089	$5,464
IA	$30,884	$24,692	$6,192	SD	$27,525	$21,066	$6,459
KS	$29,995	$19,326	$10,669	TN	$28,809	$19,727	$9,082
KY	$28,254	$18,772	$9,482	TX	$27,597	$29,090	($1,493)
LA	$28,404	$28,386	$18	UT	$23,995	$17,876	$6,119
ME	$43,889	$33,437	$10,452	VT	$35,941	$28,262	$7,679
MD	$35,707	$28,854	$6,853	VA	$28,147	$20,415	$7,732
MA	$40,585	$32,874	$7,711	WA	$27,503	$16,257	$11,246
MI	$33,812	$27,320	$6,492	WV	$32,047	$17,543	$14,504
MN	$36,319	$31,861	$4,458	WI	$34,040	$27,891	$6,149
MS	$27,481	$24,144	$3,337	WY	$29,089	$23,420	$5,669
MO	$31,682	$22,687	$8,995	**mean**	**$31,440**	**$25,453**	**$5,988**

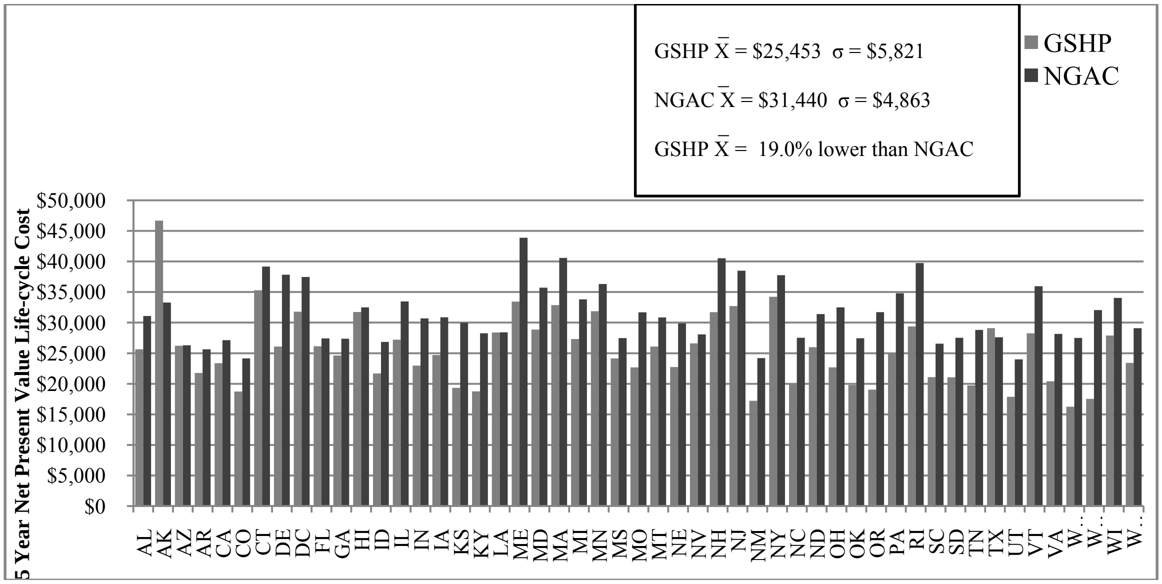

Figure 19. Net Present Value 25-Year Life-cycle Cost ($)

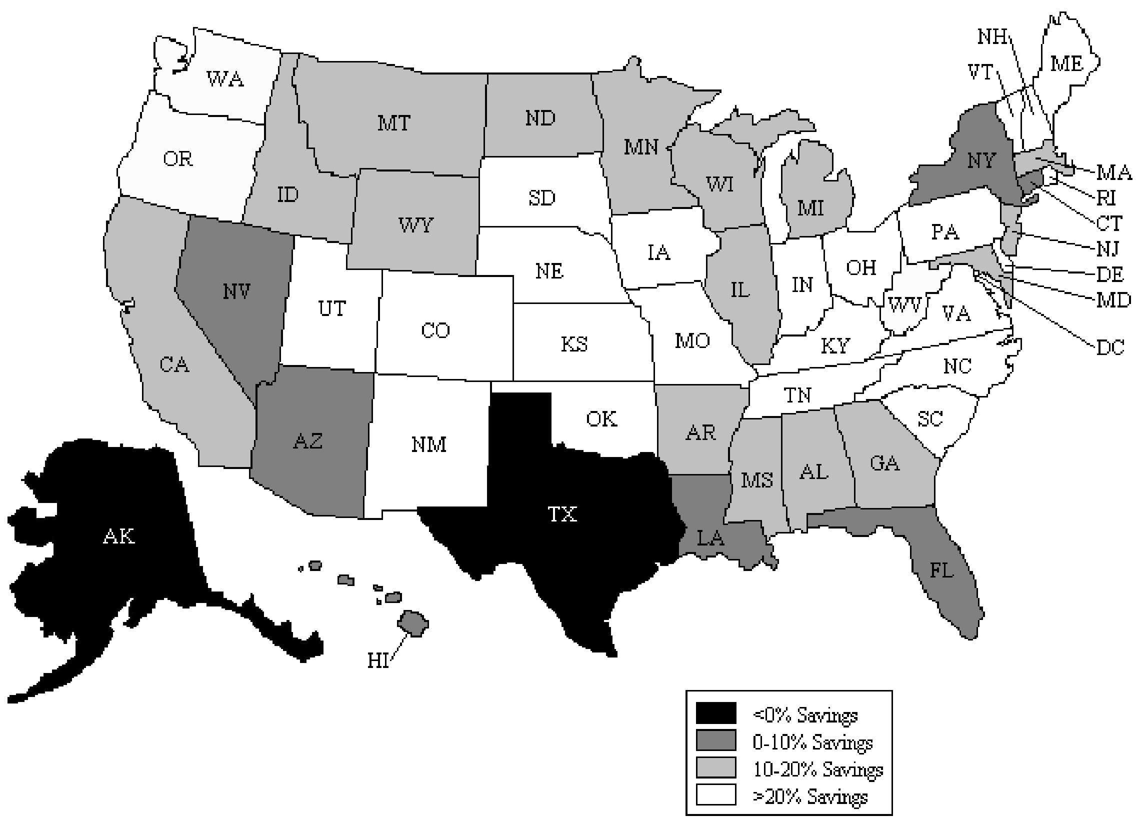

Figure 20. GSHP vs. NGAC 25-Year Life-Cycle Savings (% Savings)

Table 11 and Figure 19 show that the GSHP system saved money in nearly every location. The only two locations with negative savings were that of Alaska and Texas. Alaska's negative LCC savings can be attributed to the low ground temperature coupled with a high heating demand and almost non-existent cooling demand. The negative savings in Texas is due to its relatively high ground temperature, high cooling demand, low natural gas prices, and relatively high electricity costs. The mean savings for all locations considered was $5,988 with the highest savings of $14,505 occurring in West Virginia. This demonstrates that the GSHP system is not well suited to every location, but can have substantial benefits if the conditions are appropriate.

Life-Cycle Cost Sensitivity Analysis Results

Life-cycle cost is one of the best measures of project feasibility and is impacted by several factors. It is important to investigate factors such as electricity supply price, natural gas supply price, GSHP installed cost, and carbon dioxide emission cost to determine their impact on the type of system selected. Each was studied separately and the results are discussed in the following sections.

All 51 locations in this study were analyzed, but five locations were chosen for additional discussion. The locations were selected based on their geographic separation and climate zone in order to demonstrate the performance of GSHP systems in different conditions. The United States climate zones are shown in Figure 21.

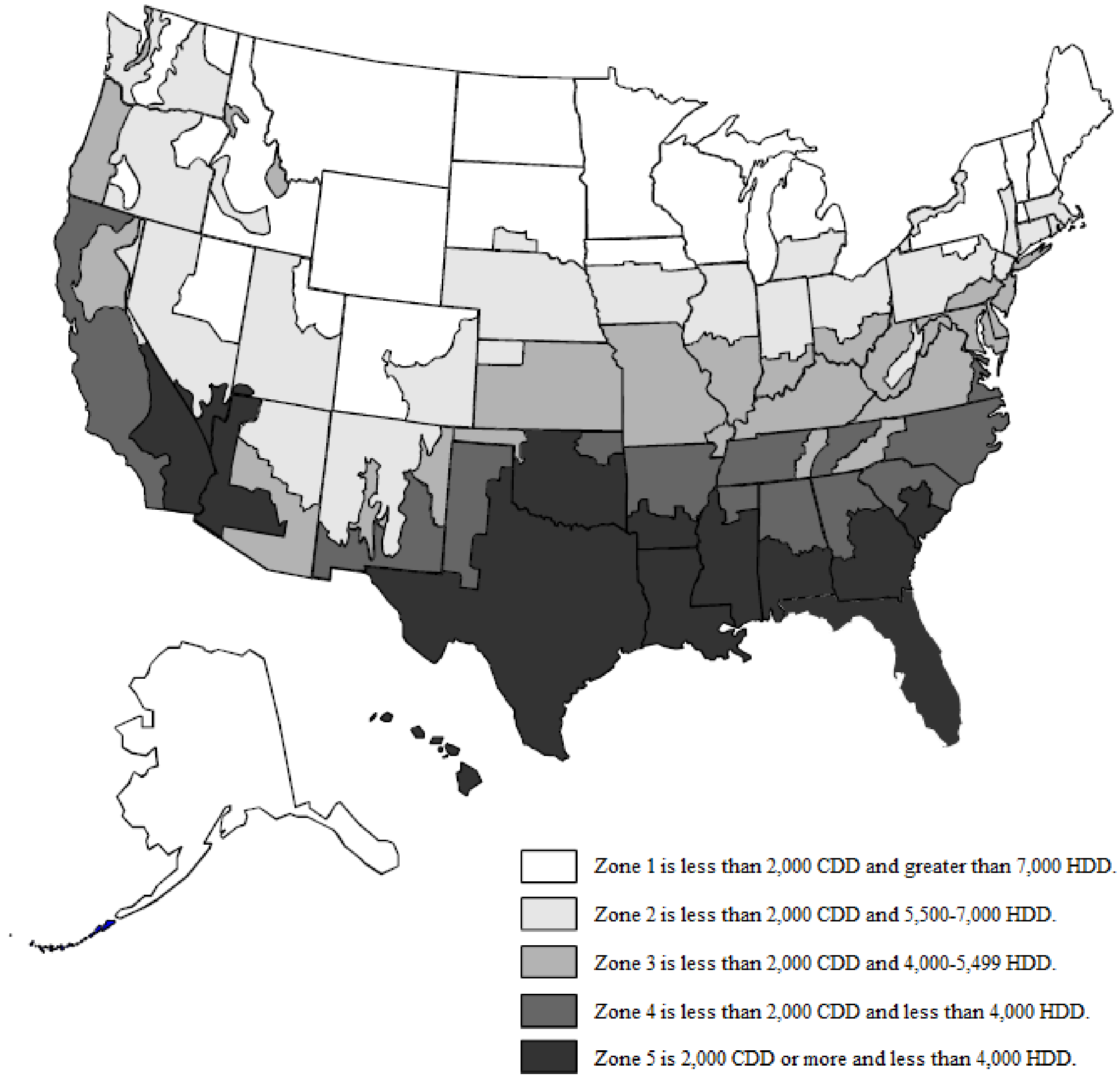

Figure 21. United States Climate Zones

Ellsworth Air Force Base (AFB), South Dakota, is located in climate zone 1 and represents those bases with very large heating requirements. Boston, Massachusetts, which coincides with Hanscom AFB, was chosen because it demonstrates the conditions of the Northeast and it is solidly located in climate zone 2. Dayton, Ohio, and Wright-

Patterson AFB, located in climate zone 3, represent the Midwest. Travis AFB, California, was selected to demonstrate the feasibility of the West Coast and is located in climate zone 4. Finally, Maxwell AFB, Alabama, was chosen to demonstrate the effects of the Deep South, as it is located in climate zone 5. For the remainder of this effort, these locations will be referenced by their state name for brevity. Despite the use of the abbreviation, it must be remembered that these sites represent one actual location within the state and are not a state-wide average. Several states have multiple climate zones that can dramatically change parameters in this study. Although five specific sites were chosen for thorough investigation, each has different aspects affecting the competitive balance between NGAC and GSHP systems.

One final note of caution must be made regarding this analysis. It is imperative to understand that the LCC values calculated in earlier sections utilized the Department of Energy official utility price escalation values for calculation that were built into the Building Life-Cycle Cost 5 software. These values adjusted the prices according to government projections and accounted for increases above and beyond inflation. This sensitivity analysis discards these annual values of escalation and simply considers a one-time shift in price at the beginning of the study that is adjusted for inflation and interest for the rest of the study period. Due to this method of calculation, some LCC values at the 0% level for electricity and natural gas may not reflect the exact same value as that calculated in previous sections. The GSHP installed cost and carbon dioxide offset cost sensitivity sections are unaffected by this change as they use the standard escalation rates used in earlier sections.

Electricity Price Sensitivity Results

When investigating the sensitivity of life-cycle cost, the price of electricity is a primary factor to consider. Both NGAC and GSHP systems use electricity, but do so in varying amounts. The price of electricity relative to other parameters can have a huge impact on system selection. To conduct this analysis, the life-cycle costs of each system were calculated while varying today's price of electricity between a 50% reduction and a 200% increase from current values. While a 50% reduction or 200% increase in electricity prices may seem unlikely, it is important to note that the current price differential for electricity is \$0.054 in Idaho compared to \$0.23 in Hawaii, so this is definitely within the realm of possibility. Electricity prices have historically had lower volatility than natural gas prices, but the prospect of increased legislation due to environmental issues could cause dramatic price increases.

The GSHP system is fully exposed to changes in electricity prices while the NGAC system has some margin of safety, since its heating requirement is delivered through natural gas. Therefore, it stands to reason that the GSHP system has much more sensitivity to electricity than the NGAC system. This has been demonstrated by the results of this section. The GSHP system exhibited an advantage in LCC at current conditions that is eventually eroded due to escalating electricity prices. The only exception to this is California, which had a slight disadvantage at current prices. This is demonstrated in Figure 22 through Figure 26. It is clear that greatly increased electricity prices are significantly detrimental to the adoption of GSHP systems while also increasing the LCC for the competing NGAC system. As the price of electricity rises, the point of LCC equivalence is reached between the NGAC and GSHP systems. These points are 43.0% for South Dakota, 26.3% for Massachusetts, 92.0% for Ohio, -0.70% for California, and 31.5% for Alabama. Beyond these points, the GSHP system is at a distinct LCC disadvantage due to the high price of electricity. These locations are just a representative sample; the complete results for all 51 study locations are located in Appendix J and Appendix K.

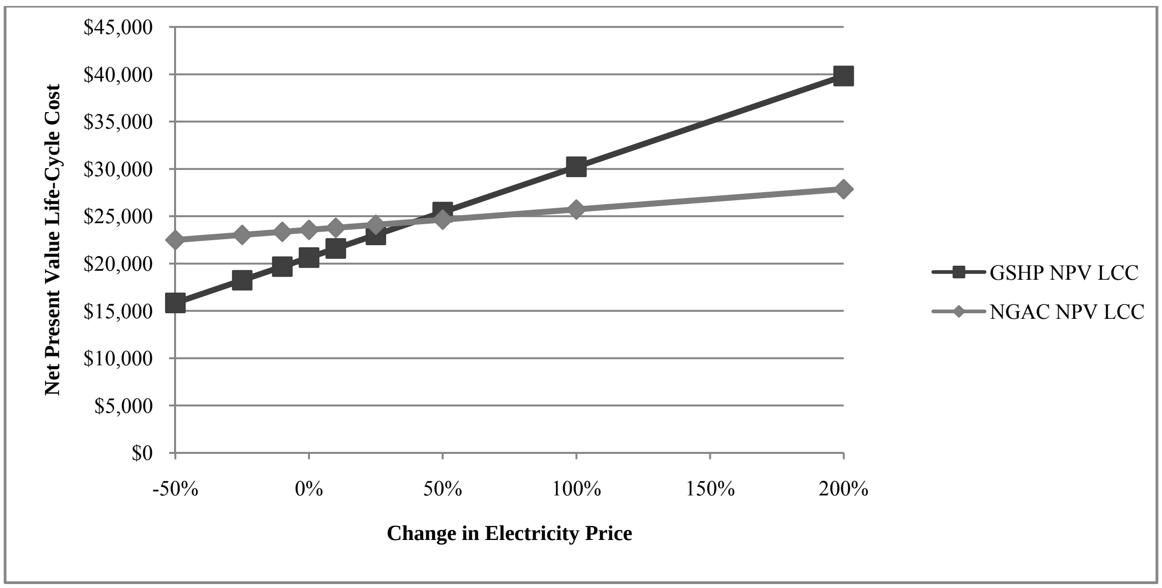

Figure 22. South Dakota GSHP and NGAC NPV LCC Electricity Price Sensitivity

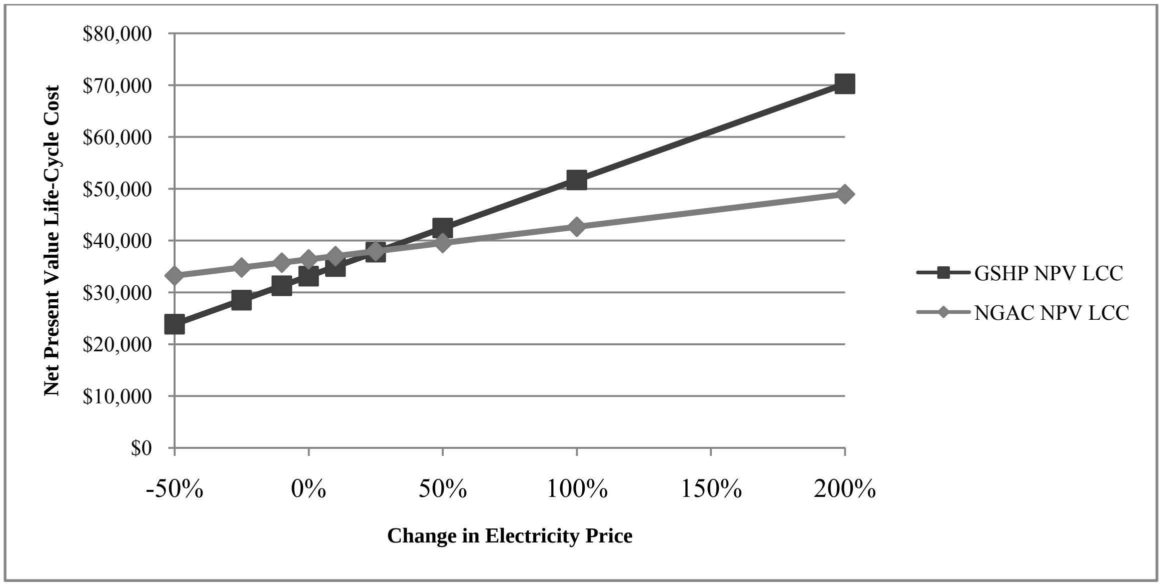

Figure 23. Massachusetts GSHP and NGAC NPV LCC Electricity Price Sensitivity

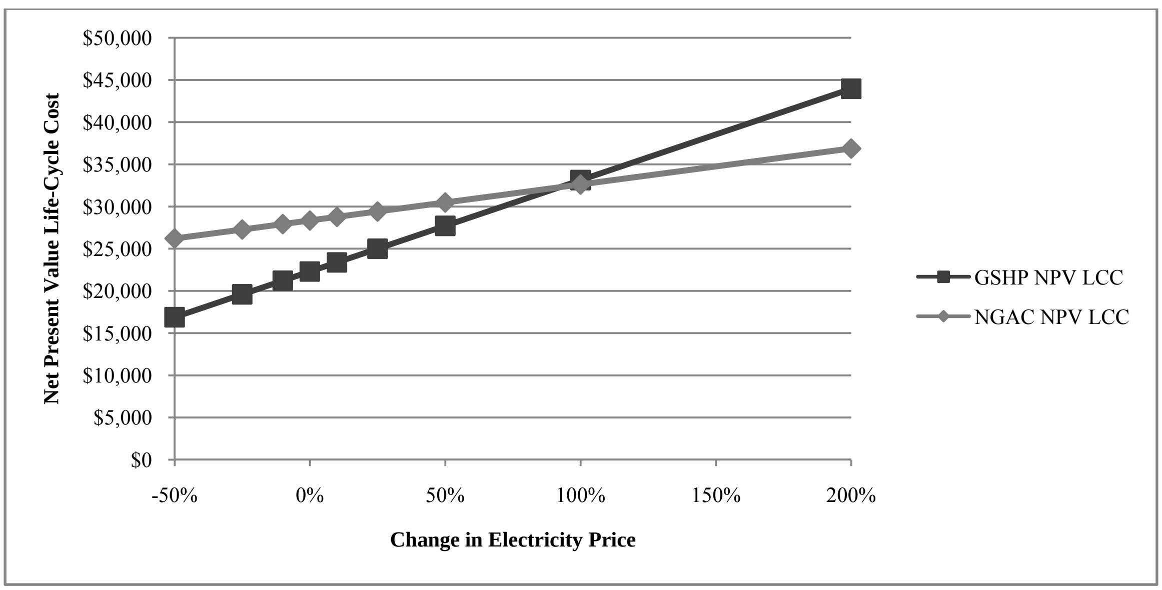

Figure 24. Ohio GSHP and NGAC NPV LCC Electricity Price Sensitivity

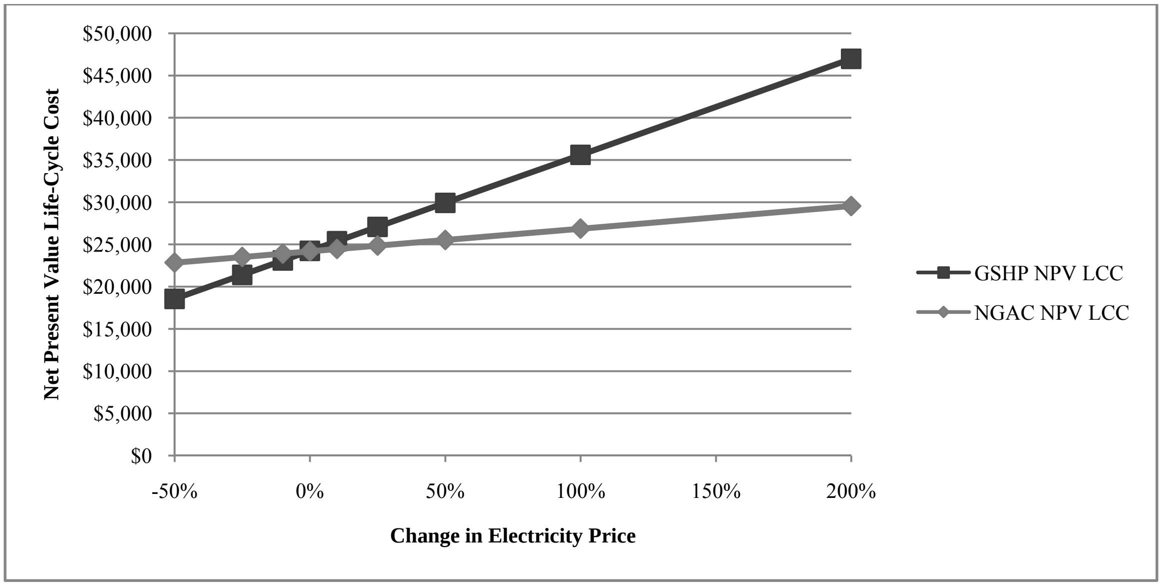

Figure 25. California GSHP and NGAC NPV LCC Electricity Price Sensitivity

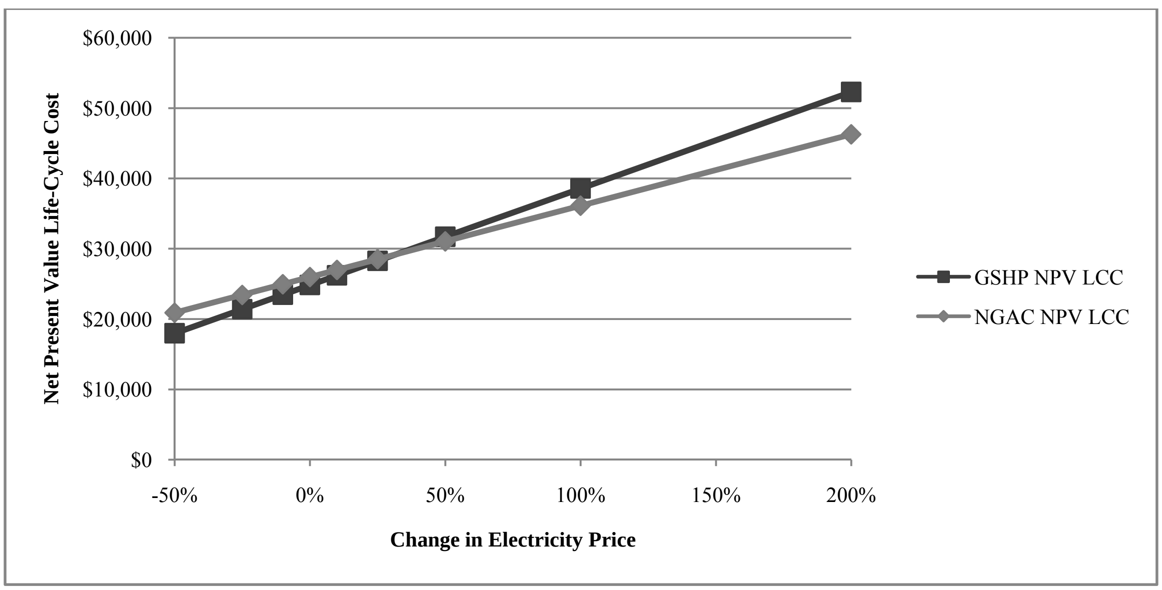

Figure 26 Alabama GSHP and NGAC NPV LCC Electricity Price Sensitivity

Natural Gas Price Sensitivity

The next major consideration with regard to life-cycle cost was natural gas price sensitivity. Although some interaction exists between the price of electricity and natural gas, for this analysis the price of electricity are assumed to remain static throughout the varying price levels of natural gas. The price of natural gas was modeled from a 50% decrease to a 200% increase of current prices. Using such a wide range in price fluctuation in the model may seem extreme, but natural gas prices have nearly doubled in most locations over the last ten years.

The same five locations were selected for further analysis and are featured in this section; however, these locations are just a representative sample of the locations studied. The full data table is available in Appendix L. A similar pattern of sensitivity developed, proving to be beneficial to the GSHP system. In this case, the GSHP system has a LCC advantage that is magnified through increasing natural gas prices. The GSHP is unaffected by rising natural gas prices, while the NGAC system has massive increases in LCC. Each location has a point of LCC equivalence, occurring at various changes from the current price. This percentage of change value is -19.8% for South Dakota, -15.7% for Massachusetts, -38.5% for Ohio, 0.5% for California, and -12.1% for Alabama. These values may seem to provide substantial protection for the GSHP system in most locations, but the volatility of natural gas prices could easily remove this competitive advantage. California is especially susceptible to changes in price, as it is near the point of equivalence at current prices. This puts substantial risk on design engineers when selecting the type of heating and cooling system for a building. Unless a long-term natural gas contract is in place, this uncertainty could cause significant increase in cost throughout the life of the system. The GSHP system removes this natural gas price risk, but increases the sensitivity to changes in electricity prices. These results are shown in Figures 27 through 31.

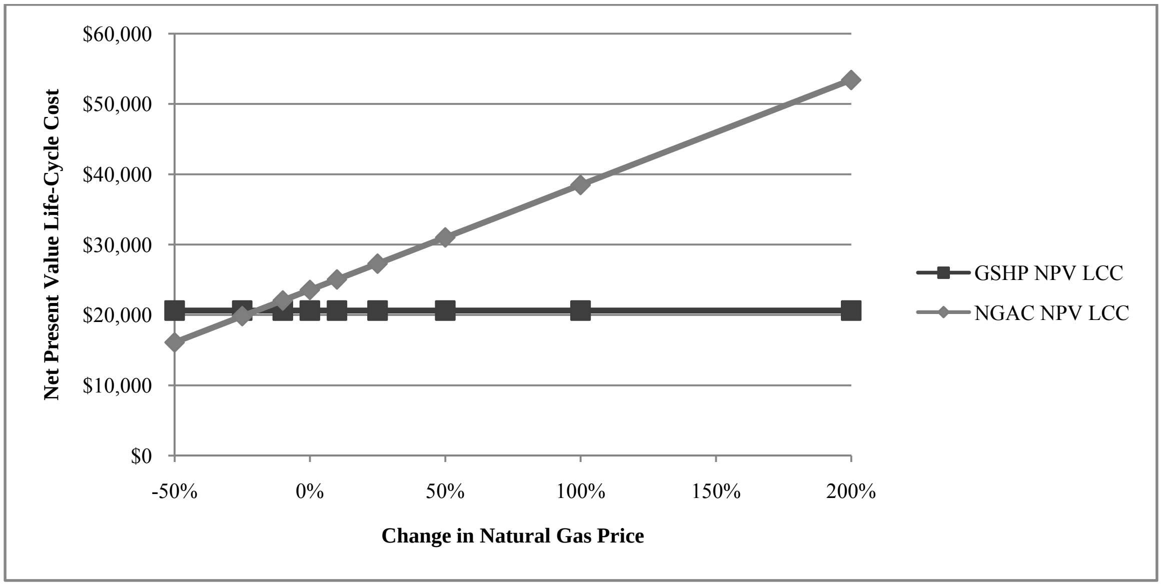

Figure 27. South Dakota GSHP and NGAC NPV LCC Natural Gas Price Sensitivity

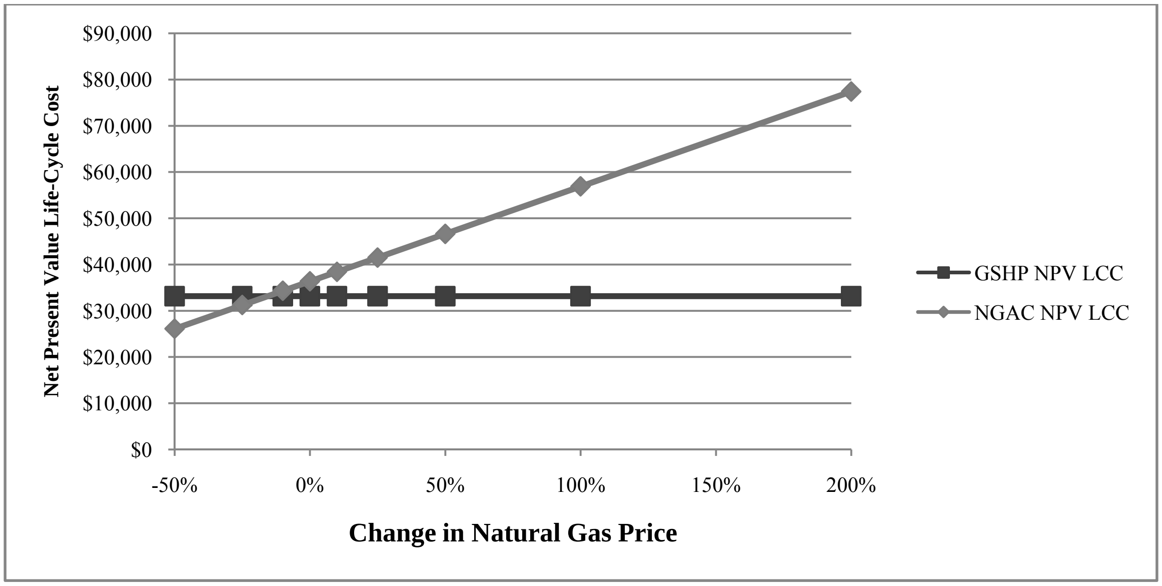

Figure 28. Massachusetts GSHP and NGAC NPV LCC Natural Gas Price Sensitivity

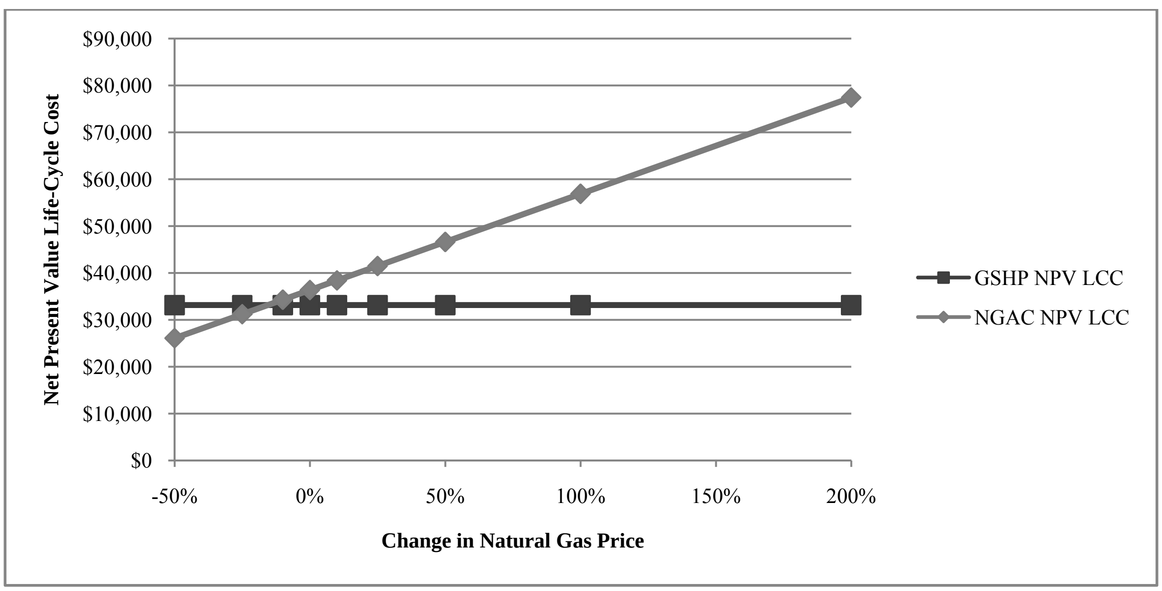

Figure 29. Ohio GSHP and NGAC NPV LCC Natural Gas Price Sensitivity

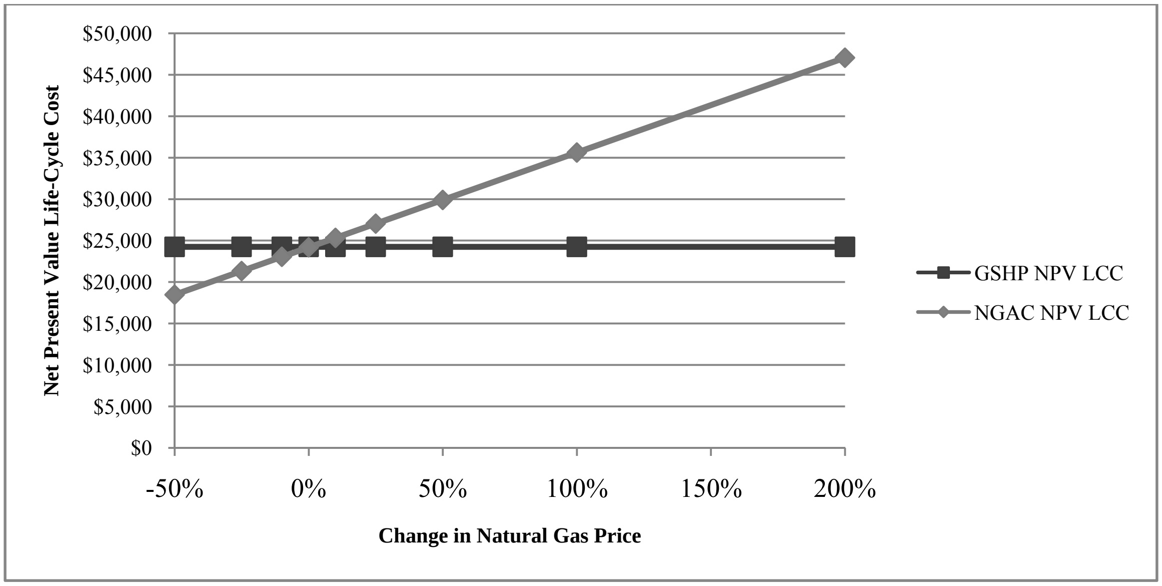

Figure 30. California GSHP and NGAC NPV LCC Natural Gas Price Sensitivity

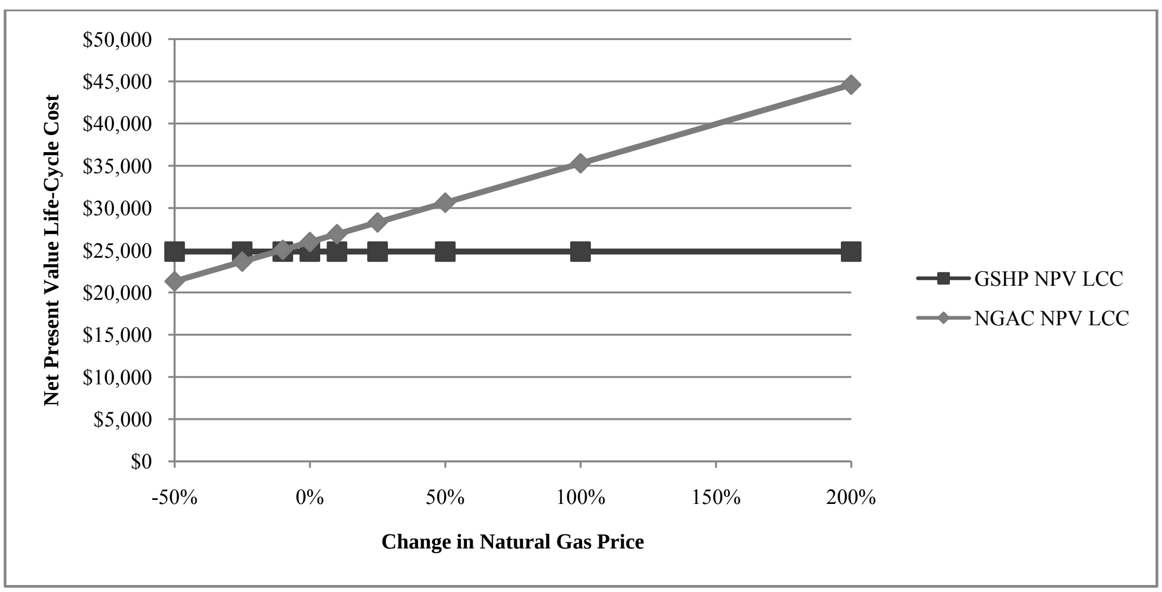

Figure 31. Alabama GSHP and NGAC NPV LCC Natural Gas Price Sensitivity

This section has shown that the NGAC system has substantially higher sensitivity to changes in natural gas prices. This may seem intuitively obvious; however, this level of sensitivity in locations with high cooling requirements was unexpected.

Ground Source Heat Pump Installation Cost Reduction Sensitivity Results

GSHP systems can be competitive with NGAC systems and their overall life-cycle cost consists largely of upfront costs. Based on this issue, it is appropriate to analyze how a generalized reduction in installation costs for GSHP systems would affect their competitiveness. The installation cost of GSHP systems could be greatly reduced in many ways. Currently, the most common cost reduction measure is in the form of the tax credits available for GSHP installation. Commercial GSHP systems qualify for a 10% Federal Tax Credit with no limit on the dollar amount. This is the largest source of installation cost reduction in the market right now, but advances could be made in drilling and materials technology, or the tax credit could be increased to further enhance this value.

Without taking specific cost reduction methods into account, general cost reductions were modeled for the life-cycle cost. These cost reductions were modeled at 10%, 25%, 50% and 75%. The installation cost reduction may seem high, but it is important to remember the relatively low market penetration of GSHP systems at this time. As they have become more popular, their manufacturing and installation costs have dropped dramatically. A 75% reduction is not expected in the near future, but lesser reductions are plausible.

The analysis was conducted on all 51 study locations, but the same five mentioned previously are detailed here. The full data table for all locations is located in Appendix M. The LCC for the NGAC system is held constant while varying levels of cost reduction are applied to the GSHP system. This is shown in Figure 32 through Figure 36. It is clear that the life-cycle cost advantage can be greatly increased as the installed cost of the GSHP system is reduced. These reductions are conceivable as GSHP systems gain in market share and increase in production. The high installed cost is one of the greatest challenges for GSHP systems to overcome, but it is not insurmountable. This section has shown that the life-cycle cost advantage that GSHP systems currently enjoy can be substantially expanded through the use of tax credits and generalized installation cost reduction.

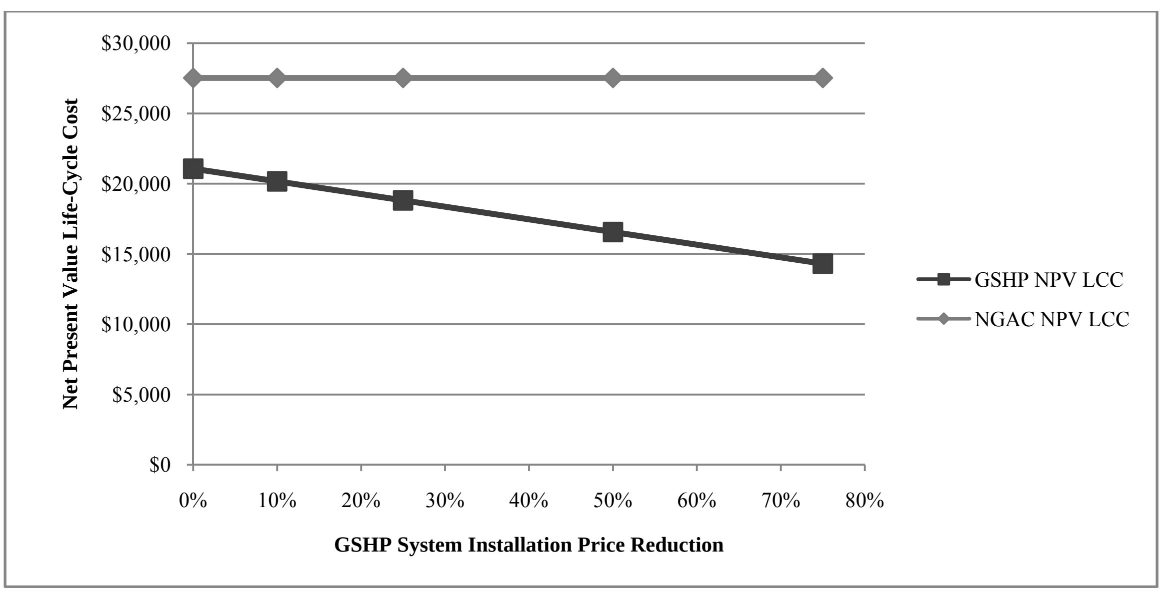

Figure 32. South Dakota GSHP and NGAC NPV LCC Installed Cost Sensitivity

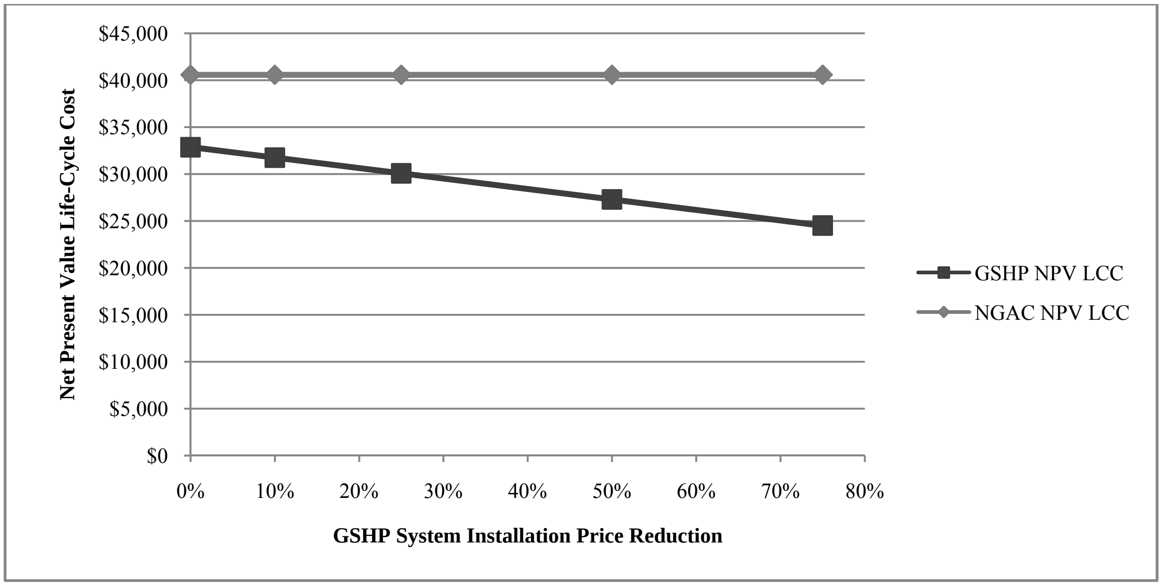

Figure 33. Massachusetts GSHP and NGAC NPV LCC Installed Cost Sensitivity

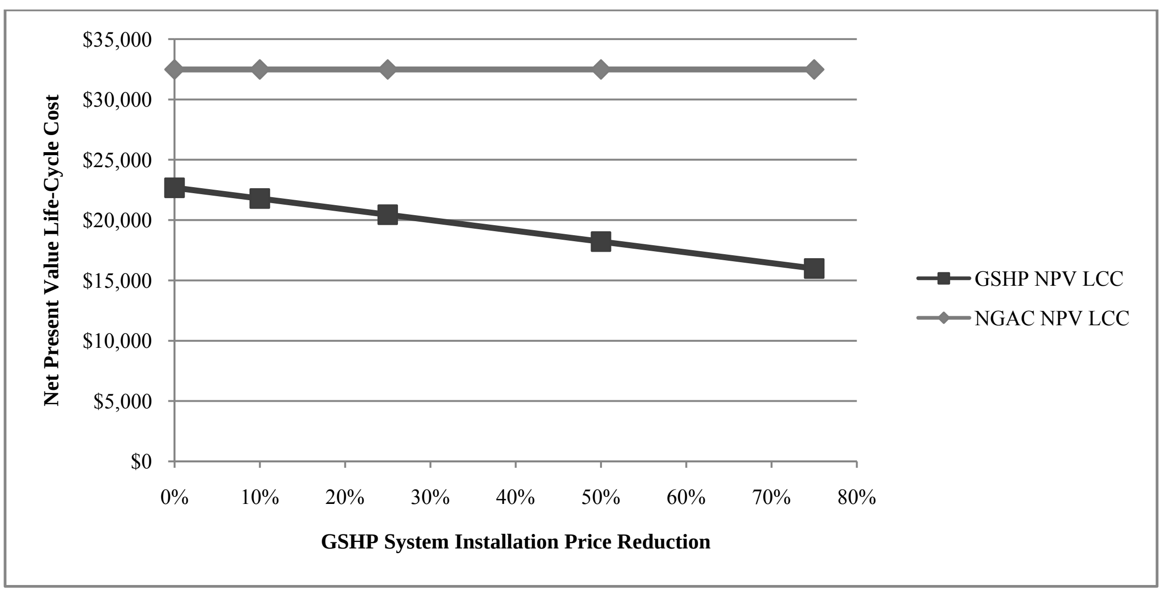

Figure 34. Ohio GSHP and NGAC NPV LCC Installed Cost Sensitivity

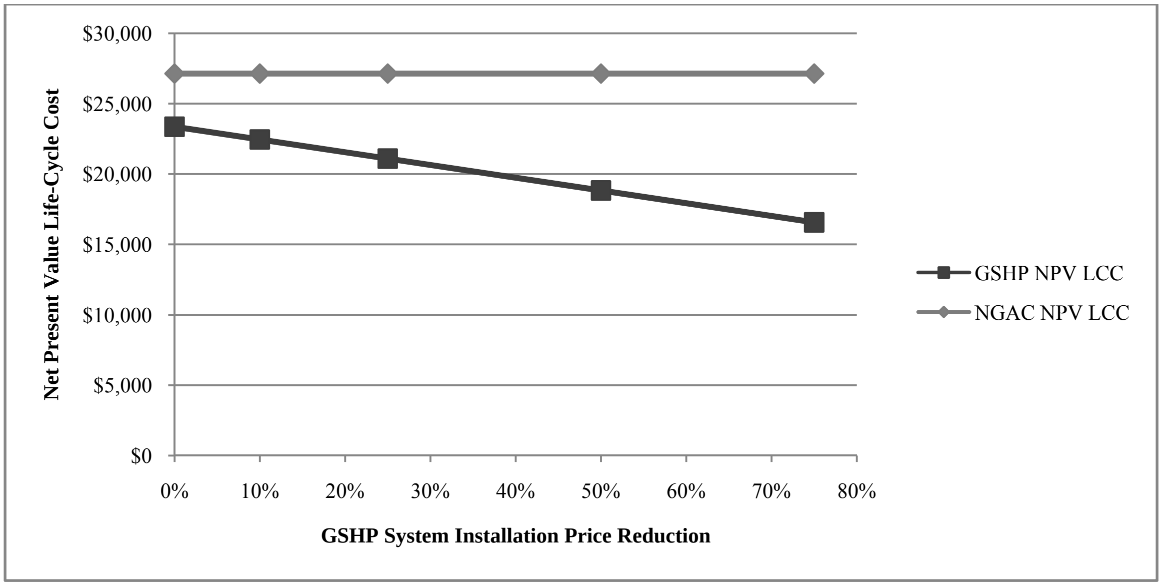

Figure 35. California GSHP and NGAC NPV LCC Installed Cost Sensitivity

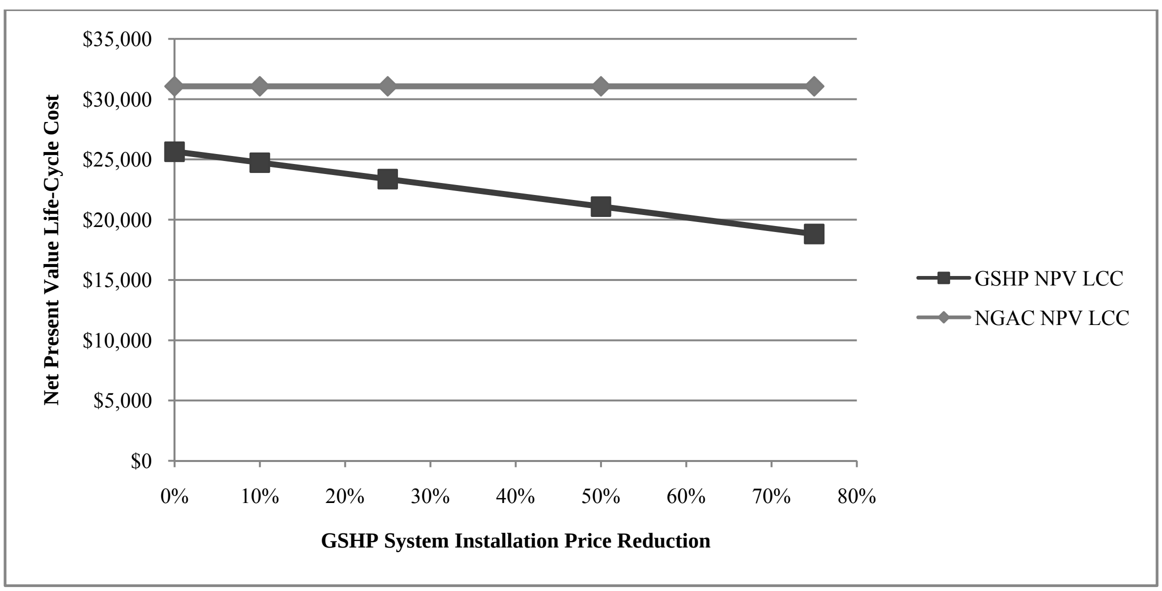

Figure 36. Alabama GSHP and NGAC NPV LCC Installed Cost Sensitivity

Carbon Dioxide Emission Offset Cost Results

Previous sections of this work have shown that GSHP systems do not always have lower overall emissions and the complete life-cycle cost analysis does not necessarily favor the GSHP system. In many cases, the GSHP system has been penalized by its poor environmental performance by creating carbon dioxide emission offset costs greater than those of the NGAC system. Table 12 shows the total life-cycle cost for each system when considering the cost of carbon dioxide emissions at the current market rate of $2.00/metric ton.

Table 12. NGAC and GSHP PV LCC CO_2 Emission Offset Costs ($2/ton)

	NGAC PV LCC	GSHP PV LCC	GSHP LCC Savings		NGAC PV LCC	GSHP PV LCC	GSHP LCC Savings
AL	$31,353	$25,940	$5,412	MT	$31,092	$26,386	$4,706
AK	$33,582	$46,959	-$13,377	NE	$30,177	$23,047	$7,130
AZ	$26,551	$26,517	$33	NV	$28,279	$26,818	$1,461
AR	$25,915	$22,056	$3,860	NH	$40,759	$31,982	$8,777
CA	$27,281	$23,451	$3,830	NJ	$38,708	$32,875	$5,832
CO	$24,349	$18,929	$5,420	NM	$24,415	$17,420	$6,995
CT	$39,404	$35,554	$3,850	NY	$37,961	$34,394	$3,567
DE	$38,080	$26,299	$11,781	NC	$27,748	$20,232	$7,517
DC	$37,764	$32,124	$5,640	ND	$31,682	$26,368	$5,314
FL	$27,646	$26,361	$1,285	OH	$32,731	$22,915	$9,816
GA	$27,635	$24,882	$2,753	OK	$27,665	$20,012	$7,653
HI	$32,889	$32,091	$798	OR	$31,890	$19,163	$12,727
ID	$27,029	$21,917	$5,111	PA	$35,033	$25,269	$9,764
IL	$33,778	$27,537	$6,241	RI	$39,947	$29,495	$10,452
IN	$30,943	$23,262	$7,681	SC	$26,785	$21,331	$5,455
IA	$31,138	$25,006	$6,133	SD	$27,773	$21,346	$6,427
KS	$30,258	$19,587	$10,671	TN	$29,043	$19,944	$9,099
KY	$28,503	$19,014	$9,489	TX	$27,826	$29,329	-$1,502
LA	$28,653	$28,645	$9	UT	$24,213	$18,097	$6,117
ME	$44,119	$33,599	$10,520	VT	$36,179	$28,553	$7,626
MD	$35,947	$29,093	$6,854	VA	$28,387	$20,655	$7,732
MA	$40,800	$33,054	$7,746	WA	$27,662	$16,405	$11,257
MI	$34,048	$27,539	$6,508	WV	$32,273	$17,753	$14,520
MN	$36,626	$32,239	$4,387	WI	$34,302	$28,198	$6,104
MS	$27,746	$24,411	$3,335	WY	$29,308	$23,687	$5,621
MO	$31,951	$22,973	$8,978	**mean**	**$31,683**	**$25,700**	**$5,983**

The addition of carbon dioxide emission offset credit costs has shifted the life-cycle cost advantage for some study locations, but has not shifted the overall advantage from one system to another in most cases. Alaska and Texas remain the only locations with higher life-cycle costs for the GSHP systems over the NGAC system, even when considering emission offset credit costs at current market rates. This analysis reveals that 20 locations have become less attractive for the GSHP system. Table 13 shows that the losses in LCC range from $1 to $72 when considering the impact of emission offset credits. The remaining 31 locations improved their position in LCC competitiveness, ranging from $2 to$88, due to carbon emission offset costs. The mean value for improvement in LCC competitiveness between the NGAC and GSHP systems was $7, a trivial amount when compared to the mean LCC value of the systems considered. To put this into perspective, the mean LCC without considering carbon dioxide emission offset costs was $31,440 for the NGAC and $25,453 for the GSHP. When the emission costs were added, the mean LCC only rose to $31,683 for the NGAC and $25,700 for the GSHP, making the money required for carbon offset costs at current market rates insignificant at this time.

Table 13. GSHP PV 25-Year LCC Savings Over NGAC ($)

	GSHP Savings No Offset	GSHP Savings $2/ton	GSHP LCC Difference		GSHP Savings No Offset	GSHP Savings $2/ton	GSHP LCC Difference
AL	$5,424	$5,412	$12	MT	4,762	$4,706	$56
AK	-$13,393	-$13,377	-$16	NE	7,158	$7,130	$28
AZ	$56	$33	$23	NV	1,467	$1,461	$6
AR	$3,878	$3,860	$18	NH	8,828	$8,777	$51
CA	$3,830	$3,774	$56	NJ	5,781	$5,832	-$51
CO	$5,422	$5,420	$2	NM	6,985	$6,995	-$10
CT	$3,872	$3,850	$22	NY	3,533	$3,567	-$34
DE	$11,765	$11,781	-$16	NC	7,527	$7,517	$10
DC	$5,677	$5,640	$37	ND	5,402	$5,314	$88
FL	$1,295	$1,285	$10	OH	9,804	$9,816	-$12
GA	$2,760	$2,753	$7	OK	7,631	$7,653	-$22
HI	$764	$798	-$34	OR	12,669	$12,727	-$58
ID	$5,155	$5,111	$44	PA	9,776	$9,764	$12
IL	$6,254	$6,241	$13	RI	10,380	$10,452	-$72
IN	$7,702	$7,681	$21	SC	5,464	$5,455	$9
IA	$6,192	$6,133	$59	SD	6,459	$6,427	$32
KS	$10,669	$10,671	-$2	TN	9,082	$9,099	-$17
KY	$9,482	$9,489	-$7	TX	-1,493	-$1,502	$9
LA	$18	$9	$9	UT	6,119	$6,117	$2
ME	$10,452	$10,520	-$68	VT	7,679	$7,626	$53
MD	$6,853	$6,854	-$1	VA	7,732	$7,732	$0
MA	$7,711	$7,746	-$35	WA	11,246	$11,257	-$11
MI	$6,492	$6,508	-$16	WV	14,504	$14,520	-$16
MN	$4,458	$4,387	$71	WI	6,149	$6,104	$45
MS	$3,337	$3,335	$2	WY	5,669	$5,621	$48
MO	$8,995	$8,978	$17	**mean**	**5,989**	**5,982**	**$7**

Carbon dioxide emission offset credits do not play an important role in the financial feasibility of a project at this time, but this could potentially change in the future. The current market rates for carbon dioxide emission offset credits represent a fraction of the actual emissions and are artificially low. Once carbon emission credit markets move from voluntary to mandatory, a tremendous increase in price for those emission credits can be expected. It is imperative to investigate the effect this would have on the feasibility of a GSHP system compared to a NGAC system. This analysis was conducted utilizing a range of values up to $2,000 per metric ton. The tables show the relative growth in life-cycle cost as the emissions credits increase in price. The results are shown in Appendix N and Appendix O. The tables in the appendix may be overwhelming at first glance and are more thoroughly explained by graphical representation of specific locations. The same five locations were selected in order to demonstrate the effect of emission offset cost increases, and are shown in Figure 37 through Figure 41.

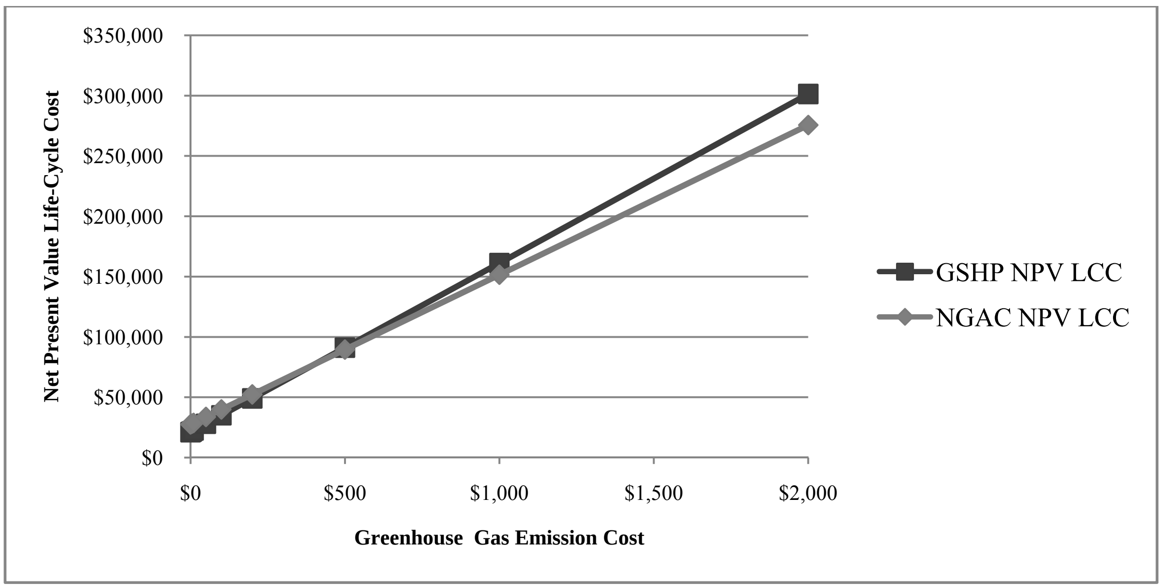

Figure 37. South Dakota GSHP/NGAC NPV LCC CO_2 Emission Sensitivity

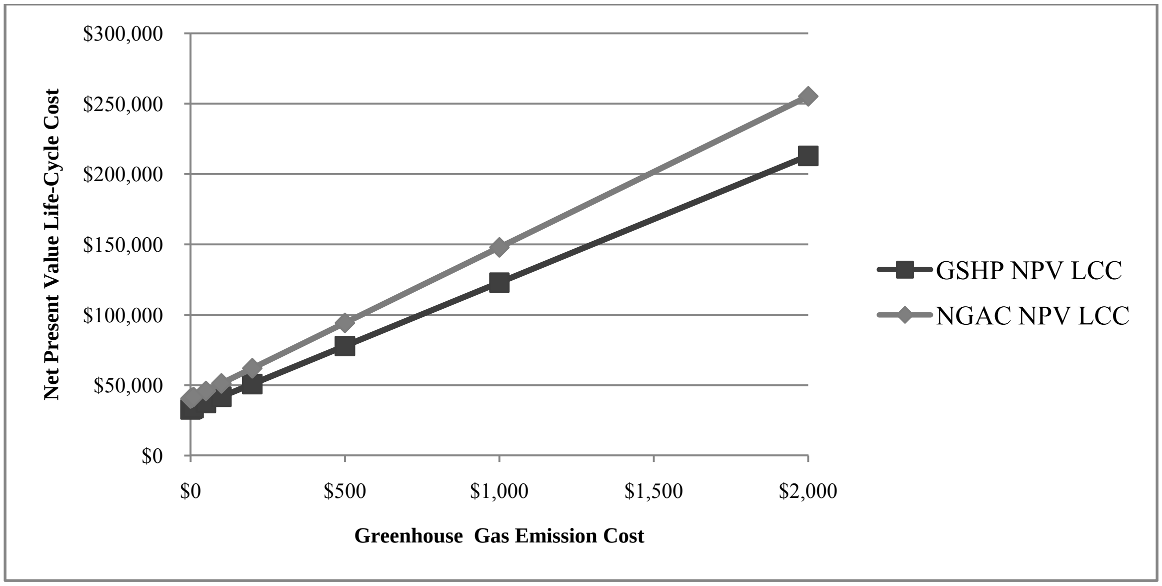

Figure 38. Massachusetts GSHP/NGAC NPV LCC CO_2 Emission Sensitivity

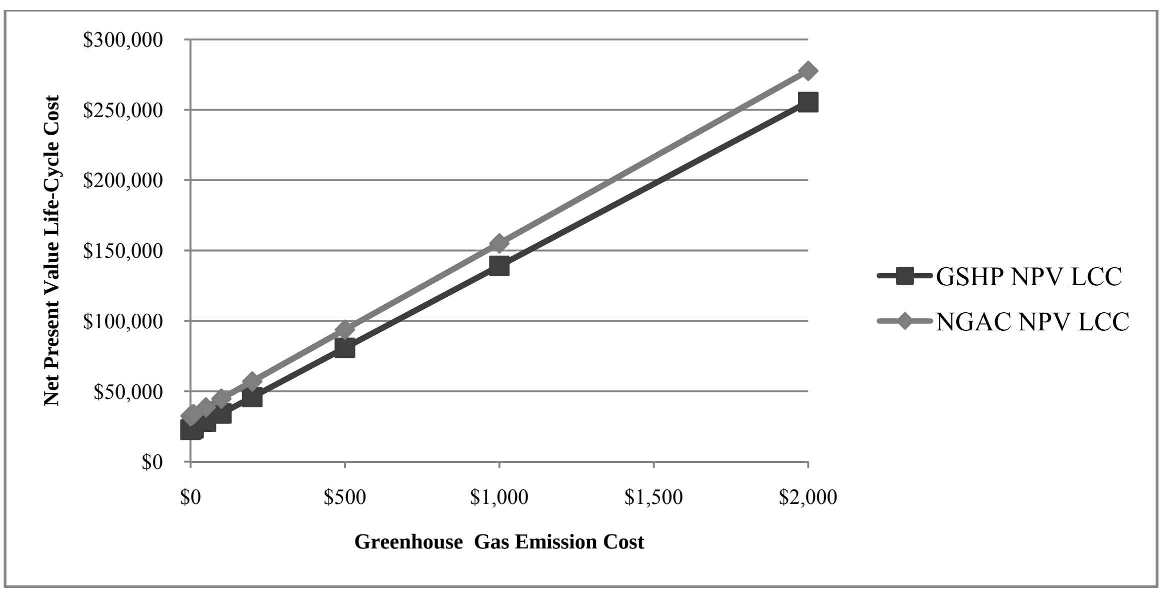

Figure 39. Ohio GSHP/NGAC NPV LCC CO_2 Emission Sensitivity

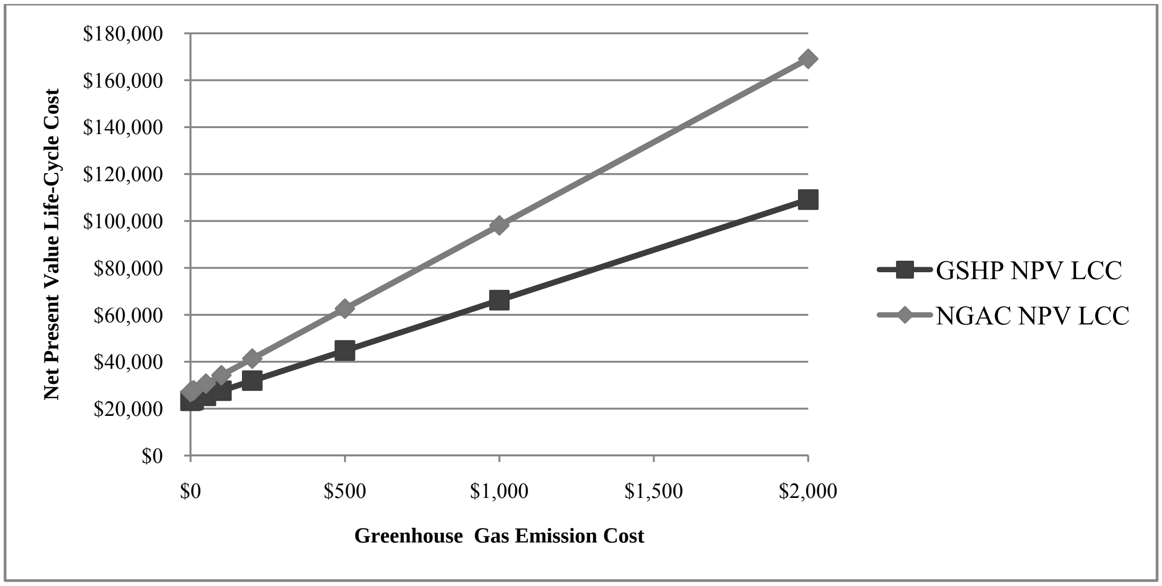

Figure 40. California GSHP/NGAC NPV LCC CO_2 Emission Sensitivity

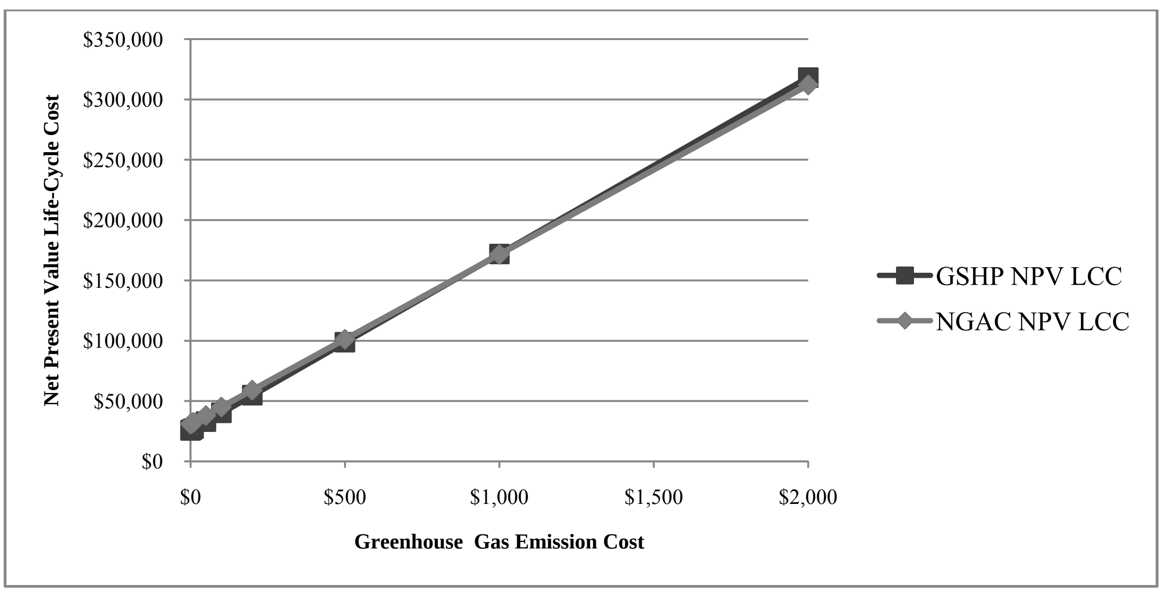

Figure 41. Alabama GSHP/NGAC NPV LCC CO_2Emission Sensitivity

These examples fall into two categories: those maintaining and those losing their LCC advantages. In the two extreme climate locations of South Dakota and Alabama, the GSHP systems have a LCC advantage at current conditions that is eventually overcome by the cost escalation of carbon dioxide emission costs. The price of carbon dioxide emissions must rise to $401.43 before the GSHP system in South Dakota loses its advantage in LCC, while the price must increase to $938.41 before Alabama loses its advantage. This result is an interesting example of a cost-effective GSHP with poor environmental performance relative to the NGAC system which can decrease its long-term financial performance if carbon dioxide emission rates increase. The locations of Massachusetts and Ohio maintained their LCC advantage with slight increases for the NGAC versus the GSHP system. California broadened the LCC advantage of the GSHP substantially as the cost of carbon emissions was increased. This has demonstrated that GSHP systems do not always have superior environmental performance and those locations with extreme climates are the most taxing.

At the beginning of this research effort, it was assumed there might be a major difference in emissions from the two competing systems. Lower emissions were promoted by commercial interests in the GSHP marketplace; however, many other studies called this claim into question. This emission reduction would have been a significant advantage in the final life-cycle cost analysis. This research has shown that the emissions from the GSHP and NGAC systems are often very similar and are actually better for NGAC systems in some locations. Despite this fact, current carbon emission offset credit rates are not substantial enough to shift the LCC advantage from one system to another.

V. Conclusions

This research effort sought to find answers to several questions with regard to installation cost, operating cost, energy use, financial attractiveness, carbon dioxide emissions, and life-cycle cost of ground source heat pump (GSHP) systems. The literature review established a substantial body of knowledge on which to proceed, but it indicated there was much more research to be conducted. The methodology explained how Trane Trace 700, Building Life-Cycle Cost 5, and Geothermal Loop Design software were applied to complete this project. In addition, RS Means Construction Cost 2007 Book data was used in conjunction with Microsoft Excel to calculate and model the values studied in this research. The results section detailed all of the findings of this study and modeled significant levels of variability in the quantities affecting GSHP systems and natural gas furnaces with split-system air-conditioning (NGAC) systems.

Summary

This project provided an in-depth analysis on 51 locations within the United States with regard to the economic and environmental impacts of GSHP and NGAC systems. The locations were selected based on proximity to population centers and military installations within each state. Tremendous variability exists throughout each state and these results should not necessarily be considered applicable to other locations within that state.

The GSHP system had an average installed cost that was 257% higher than that of the NGAC system. This presents a significant barrier to acceptance in the public and private sector. Despite the savings occurring during a building's useful life, first cost is often a key concern for project designers. Whether a small commercial project or a multimillion dollar office building is being constructed, the bottom line often comes down to installed cost.

The GSHP system had lower operating costs in nearly all locations. The average savings was 33% over the traditional NGAC system. This offers a substantial savings for the customer throughout the life of the system, but a challenge arises because construction funds and operation funds are not often linked. The implementation of GSHP systems relies upon focused long-term thinking by decision makers.

This research utilized several financial measures to assess the value of GSHP systems. The average simple payback period found in this study was 10 years. A general trend of longer payback periods developed in locations with climate extremes. Locations with relatively balanced heating and cooling loads proved more advantageous, since the alternating seasons make use of the ground heat loss or gain from the previous season.

This study also considered the discounted payback period (DPP) as a method of comparison. The mean value for the DPP was found to be 15 years. This demonstrates that while the GSHP system may save money during its operation, it takes time to overcome the high initial cost. The compounding affect of the DPP lengthened the payback periods for most locations by several years, proving the high initial cost can be very damaging to the overall financial feasibility of a GSHP system.

Substantial effort was placed on the study of energy use by each system. The GSHP saved energy in every location considered in this study, with an average savings of 67.9%. Despite this advantage, saving energy does not necessarily translate into saving money as was indicated by the financial analysis section. The critical point of saving energy is based on the actual type of fuel being saved. One solution provided by GSHP systems is that natural gas previously used for heating could be redirected into the transportation system. GSHP systems rely solely on electricity, which is the top commodity produced through renewable methods. The ability to generate electricity through solar, photovoltaic, and hydroelectric methods to power GSHP systems helps alleviate many of the challenges presented by non-renewable sources of energy.

Carbon dioxide emissions were examined in this effort, and the results were somewhat surprising. The emissions, on average, were 2.2% higher for the GSHP system when considering all locations. The electricity source in most parts of the country relies heavily on coal-fired production and the efficiency of the electricity supply system is relatively low, resulting in elevated emissions in most cases. This critical area must be addressed if organizations choose to proceed with GSHP systems.

The fact that emissions were often higher for the GSHP system negated one of the benefits hypothesized at the beginning of this work. It was originally assumed that the relative efficiency of the GSHP system would provide lower emissions levels, regardless of the source of electricity. Since emissions were not always lower for the GSHP systems, no additional benefit arose from the carbon emission offset credits. This perceived advantage was not realized and failed to change the financial competition between GSHP and NGAC systems.

The final point of this research engaged in the net present value life-cycle cost (LCC) calculations. Other measures are commonly used, but net present value LCC methodology is often the best way to ensure that the full cost of each system is considered. The GSHP system provided an average of $5,988 in LCC savings over the NGAC system for the design life of the system, with a higher LCC in only two locations. This value is substantial when the average 25-year LCC of the NGAC system was $31,440 and compared to the GSHP system at $25,453. This resulted in a 19.0% reduction in LCC just by choosing the GSHP system, a testament to their overall attractiveness.

Despite the data, it is important to note that GSHP systems will not always be more attractive in every location, as tremendous variability exists throughout the country. A test borehole should be constructed to confirm the thermal conductivity of a site before designing a large commercial project. Even with extensive site data, numerous factors must be considered and a thorough investigation should be completed by an experienced engineer before deciding on which system is most advantageous for an organization. GSHP systems show promise; however, they are not always the preferred option for every location.

Limitations and Future Research

Correcting shortcomings of previous works was a key objective to this research effort, but more research can always be performed. Six major topics could be further developed to refine the results obtained by this study.

1. Domestic hot water desuperheaters were not included in this effort and could greatly impact the results. These devices utilize heat that is otherwise rejected into the ground for functions such as domestic hot water heating. This method salvages excess energy and typically employs it for heating water. Desuperheater

use could greatly increase the value of GSHP systems, especially in cooling dominated locations with excess heat. They are responsible for much of the energy demand that would otherwise be provided by the GSHP, allowing it to be sized much smaller.

2. The thermal conductivity and diffusivity of the ground were based on average values throughout the country. Future research could specifically study each location and conduct tests to determine the actual values for each site.

3. The design of the GSHP borehole fields in this project was strictly carried out according to ASHRAE recommended design standards. The design recommendation on entering water temperatures could be tested in an iterative process to obtain better values for the efficiency of GSHPs. Varying the maximum allowable temperatures for cooling and minimum allowable temperatures for heating would help determine whether a more expensive, more efficient system or a less expensive, less efficient system would be most economical.

4. The use of backup electric heating coils in conjunction with GSHP units would dramatically reduce the required size of the borehole field and the cost associated with it. These heating coils allow the GSHP unit to be sized well below the maximum heating design level. This provides considerable installation cost savings at the expense of higher operating costs during those few extremely cold days when the electric coils are used. This causes problems in calculations because the exact number of operating hours requiring auxiliary heat must be

determined in order to estimate the cost. This cost could obscure the true financial feasibility of the system.

5. An analysis utilizing the most efficient GSHP and NGAC systems on the market could be conducted. This study used average efficiency values for each class of equipment instead of values from the most efficient units on the market. Performing a study of full condensing furnaces and two-stage GSHP systems with much higher efficiencies, along with higher first costs, could change the results.
6. The use of hybrid GSHP systems was not considered in this effort. Many large, commercial GSHP systems incorporate chillers and cooling towers in order to reduce the borehole length requirement. They use electricity at off-peak times to dissipate heat and reduce the burden on the GSHP system. Hybrid systems involve much more detailed calculations and were not included in the scope of this work. The combination of a GSHP along with traditional heating and cooling can produce a highly efficient system at a lower overall cost.

Appendix A. Heating and Cooling Load Calculation Selected Locations

State	Location	State	Location
Alabama	Maxwell AFB	Montana	Great Falls
Alaska	Anchorage	Nebraska	Omaha
Arizona	Luke AFB	Nevada	Las Vegas
Arkansas	Little Rock	New Hampshire	Concord
California	Travis AFB	NewJersey	McGuire AFB
Colorado	Colorado Springs	New Mexico	Holloman AFB
Connecticut	Hartford	New York	New York
Delaware	Dover AFB	North Carolina	Seymour Johnson AFB
Washington, D.C.	Washington DC	North Dakota	Minot AFB
Florida	Tyndall AFB	Ohio	Dayton
Georgia	Moody AFB	Oklahoma	Altus AFB
Hawaii	Honolulu	Oregon	Kingsley Field ANGB
Idaho	Mountain Home AFB	Pennsylvania	Pittsburg
Illinois	Scott AFB	Rhode Island	Providence
Indiana	Grissom JARB	SouthCarolina	Shaw AFB
Iowa	Sioux City	South Dakota	Ellsworth AFB
Kansas	Wichita	Tennessee	Nashville
Kentucky	Louisville	Texas	San Antonio
Louisiana	Shreveport	Utah	Salt Lake City
Maine	Portland	Vermont	Montpellier
Maryland	Baltimore	Virginia	Richmond
Massachusetts	Boston	Washington	McChord AFB
Michigan	Detroit	West Virginia	Charleston
Minnesota	Minneapolis/St Paul	Wisconsin	Milwaukee
Mississippi	Columbus AFB	Wyoming	F.E. Warren AFB
Missouri	Whiteman AFB		

Appendix B. Commercial Electricity Prices (¢/kWhr)

Alabama	9.30	Montana	7.83
Alaska	11.90	Nebraska	6.74
Arizona	8.75	Nevada	9.96
Arkansas	7.19	New Hampshire	14.06
California	14.25	NewJersey	15.50
Colorado	7.02	New Mexico	7.86
Connecticut	14.96	New York	16.17
Delaware	11.36	North Carolina	7.63
Washington, D.C.	13.19	North Dakota	6.81
Florida	9.62	Ohio	8.86
Georgia	9.00	Oklahoma	8.16
Hawaii	23.05	Oregon	7.06
Idaho	5.47	Pennsylvania	9.34
Illinois	8.80	Rhode Island	11.94
Indiana	7.43	SouthCarolina	7.97
Iowa	7.87	South Dakota	6.83
Kansas	7.21	Tennessee	7.91
Kentucky	6.84	Texas	10.06
Louisiana	9.13	Utah	6.61
Maine	14.11	Vermont	12.19
Maryland	12.25	Virginia	6.65
Massachusetts	15.65	Washington	6.29
Michigan	9.08	West Virginia	5.96
Minnesota	7.75	Wisconsin	8.94
Mississippi	9.03	Wyoming	6.24
Missouri	7.45		

(EIA, 2007)

Appendix C. Commercial Natural Gas Prices ($/1,000 cubic feet)

Alabama*	15.82	Montana	9.81
Alaska	7.57	Nebraska	9.26
Arizona	12.84	Nevada	12.02
Arkansas	10.04	New Hampshire*	15.03
California	10.20	NewJersey	12.26
Colorado	8.01	New Mexico	9.91
Connecticut	12.61	New York*	11.91
Delaware	14.58	North Carolina	12.91
Washington, D.C.	13.74	North Dakota	8.38
Florida	13.19	Ohio	11.80
Georgia	13.14	Oklahoma*	12.17
Hawaii	28.31	Oregon	12.38
Idaho	10.79	Pennsylvania	12.82
Illinois	10.43	Rhode Island	14.92
Indiana	10.11	SouthCarolina	13.63
Iowa	9.97	South Dakota	8.79
Kansas	12.19	Tennessee	12.58
Kentucky	11.06	Texas	9.87
Louisiana	11.77	Utah	8.03
Maine	14.83	Vermont	12.79
Maryland*	13.28	Virginia	11.89
Massachusetts	14.50	Washington	12.37
Michigan*	10.75	West Virginia*	14.38
Minnesota	10.14	Wisconsin	10.50
Mississippi	10.97	Wyoming*	10.30
Missouri	11.96		

* Price data obtained from 2006 EIA report

(EIA, 2007)

Appendix D. Building Load Calculation Physical Characteristics

Internal Load			
People			
Type	General Office Space		
Density	143 sq ft/person		
Sensible	250 Btu/h		
Latent	200 Btu/h		
Lighting			
Type	Recessed Florescent, not vented, 80% load to space		
Heat Gain	0.3 W/sq ft		
Misc.			
Type	Standard Office Equipment		
Energy	0.5 W/sq ft		
Thermostat Settings			
Cooling dry bulb	75 °F		
Heating dry bulb	68 °F		
Relative humidity	50 %		
Cooling driftpoint	90 °F		
Heating driftpoint	55 °F		
Latent Capacity	Medium		
Air Flow			
Ventilation			
Type	General Office Space		
Cooling	20 cfm/person		
Heating	20 cfm/person		
Infiltration			
Type	Neutral Pressure, Average Construction		
Cooling	0.3 air changes/hr		
Heating	0.3 air changes/hr		
Construction			
Floor	4" LW Concrete	0.21261	Btu/h*ft2*°F
Roof	Steel sheet, 8" Ins	0.21353	Btu/h*ft2*°F
Wall	Face Brick, 6" Conc blk, 3" Ins	0.06011	Btu/h*ft2*°F
Partition	0.75" Gyp Frame	0.38795	Btu/h*ft2*°F
Glass Type			
Window	6mm Dbl Low-E (e2=.04) Clr 13mm Argon	0.233	Btu/h*ft2*°F
Skylight	6mm Dbl Low-E (e2=.04) Clr 13mm Argon	0.233	Btu/h*ft2*°F
Shading Coefficient		0.48	
Height			
Wall	10 ft		
Flr to flr	12 ft		
Plenum	2 ft		

Appendix E. Trane Trace 700 Heating and Cooling Load Design Output

			Cooling tons	Cooling kBtu/hr	Full Load Cooling hrs	Heating kBtu/hr	Full Load Heating hrs
AL	Alabama	Maxwell AFB	4.70	56.40	1819	29.70	1366
AK	Alaska	Anchorage	1.50	18.00	0	59.30	3128
AZ	Arizona	Luke AFB	4.40	52.80	2141	23.10	1116
AR	Arkansas	Little Rock	4.30	51.60	1583	33.00	1681
CA	California	Travis AFB	3.20	38.40	224	26.20	2948
CO	Colorado	Colorado Springs	2.60	31.20	523	39.80	2418
CT	Connecticut	Hartford	3.50	42.00	695	42.10	2555
DE	Delaware	Dover AFB	3.90	46.80	1015	36.60	2346
DC	Washington, D.C.	Washington DC	4.20	50.40	1320	35.20	2061
FL	Florida	Tyndall AFB	4.20	50.40	2297	24.20	1047
GA	Georgia	Moody AFB	4.60	55.20	1900	25.50	1367
HI	Hawaii	Honolulu	3.80	45.60	5046	3.50	0
ID	Idaho	Mountain Home AFB	3.00	36.00	614	36.30	2532
IL	Illinois	Scott AFB	4.30	51.60	1215	49.30	2009
IN	Indiana	Grissom JARB	3.60	43.20	786	46.60	2370
IA	Iowa	Sioux City	3.80	45.60	836	50.60	2316
KS	Kansas	Wichita	3.80	45.60	1225	41.10	1981
KY	Kentucky	Louisville	3.80	45.60	1150	39.80	1975
LA	Louisiana	Shreveport	4.80	57.60	1892	29.60	1361
ME	Maine	Portland	3.30	39.60	321	47.50	2728
MD	Maryland	Baltimore	4.10	49.20	1050	37.90	2172
MA	Massachusetts	Boston	3.60	43.20	729	40.70	2397
MI	Michigan	Detroit	3.70	44.40	642	42.20	2670
MN	Minnesota	Minneapolis/St Paul	3.80	45.60	662	54.10	2496
MS	Mississippi	Columbus AFB	4.50	54.00	1832	33.00	1433
MO	Missouri	Whiteman AFB	4.30	51.60	1050	43.10	2048
MT	Montana	Great Falls	2.60	31.20	408	52.80	2330
NE	Nebraska	Omaha	4.20	50.40	890	47.90	2327
NV	Nevada	Las Vegas	3.90	46.80	1773	26.40	1642
NH	New Hampshire	Concord	3.60	43.20	385	42.00	2641
NJ	NewJersey	McGuire AFB	4.00	48.00	1007	39.30	2340
NM	New Mexico	Holloman AFB	3.50	42.00	1038	31.00	2162
NY	New York	New York	3.40	40.80	1089	36.60	2337
NC	North Carolina	Seymour Johnson AFB	4.10	49.20	1239	32.60	1883
ND	North Dakota	Minot AFB	2.80	33.60	459	58.70	2579
OH	Ohio	Dayton	3.50	42.00	947	43.30	2238
OK	Oklahoma	Altus AFB	3.90	46.80	1436	35.00	1724
OR	Oregon	Kingsley Field ANGB	2.50	30.00	379	37.20	2681
PA	Pennsylvania	Pittsburg	3.30	39.60	737	42.40	2380
RI	Rhode Island	Providence	3.40	40.80	656	40.60	2532
SC	SouthCarolina	Shaw AFB	4.10	49.20	1626	29.60	1539
SD	South Dakota	Ellsworth AFB	3.20	38.40	593	48.10	2434
TN	Tennessee	Nashville	3.80	45.60	1375	37.00	1768
TX	Texas	San Antonio	4.40	52.80	2237	25.80	1101
UT	Utah	Salt Lake City	3.00	36.00	785	37.80	2443
VT	Vermont	Montpellier	3.60	43.20	455	42.00	2651
VA	Virginia	Richmond	4.40	52.80	1188	35.20	1980
WA	Washington	McChord AFB	2.40	28.80	395	30.30	2622
WV	West Virginia	Charleston	3.90	46.80	967	38.60	2088
WI	Wisconsin	Milwaukee	3.60	43.20	513	48.90	2548
WY	Wyoming	F.E. Warren AFB	2.60	31.20	353	41.60	2658

Appendix F. Ground Source Heat Pump Design Output

	Load Design Parameters			Borehole Length and Heat Pump Selection							
	Ground	EWT	EWT	Borehole	Heat Pump	Unit Size	Units	Glycol	H or C	EER	COP
	°F	°F Cool	°F Heat	ft		tons		%			
AL	67	92.0	54.5	1112.2	GSH 060	5.0	1	5.9	C	11.7	4.0
AK	36	61.0	23.5	1425.7	GSH 042	3.5	2	23.5	H	17.7	3.2
AZ	73	95.0	60.5	1214.9	GSH 060	5.0	1	5.9	C	11.0	4.1
AR	64	89.0	51.5	977.1	GSH 060	5.0	1	5.9	C	11.9	3.9
CA	64	89.0	51.5	646.0	GSH 042	3.5	1	5.9	H	13.1	4.3
CO	51	76.0	38.5	905.8	GSH 048	4.0	1	23.5	H	15.6	3.9
CT	49	74.0	36.5	900.1	GSH 060	5.0	1	23.5	H	14.3	3.5
DE	55	80.0	42.5	767.6	GSH 048	4.0	1	23.5	C	15.6	4.0
DC	57	82.0	44.5	899.1	GSH 060	5.0	1	5.9	C	13.1	3.7
FL	70	95.0	57.5	1059.4	GSH 060	5.0	1	5.9	C	10.9	4.1
GA	65	90.0	52.5	1097.7	GSH 060	5.0	1	5.9	C	11.9	3.9
HI	77	95.0	64.5	1910.5	GSH 048	4.0	1	0	C	13.6	4.4
ID	53	78.0	40.5	816.5	GSH 042	3.5	1	23.5	H	15.4	4.0
IL	57	82.0	44.5	946.3	GSH 060	5.0	1	23.5	H	13.2	3.9
IN	53	78.0	40.5	992.1	GSH 060	5.0	1	23.5	H	13.5	3.7
IA	51	76.0	38.5	1065.0	GSH 060	5.0	1	23.5	H	14.1	3.7
KS	56	81.0	43.5	793.3	GSH 048	4.0	1	18.3	H	15.3	4.0
KY	60	85.0	47.5	778.2	GSH 048	4.0	1	18.3	H	14.5	4.2
LA	66	91.0	53.5	1158.6	GSH 070	6.0	1	5.9	C	11.0	4.0
ME	54	79.0	41.5	1115.4	GSH 060	5.0	1	23.5	H	13.1	3.7
MD	55	80.0	42.5	841.5	GSH 060	5.0	1	18.3	C	13.5	3.7
MA	51	76.0	38.5	880.4	GSH 048	4.0	1	23.5	H	16.3	3.9
MI	50	75.0	37.5	916.8	GSH 060	5.0	1	23.5	H	14.3	3.5
MN	47	72.0	34.5	1165.6	GSH 070	6.0	1	23.5	H	13.8	3.4
MS	64	89.0	51.5	1053.1	GSH 060	5.0	1	5.9	C	12.0	3.9
MO	57	82.0	44.5	883.2	GSH 060	5.0	1	18.3	C	13.2	3.8
MT	48	73.0	35.5	1176.5	GSH 070	6.0	1	23.5	H	13.1	3.5
NE	53	78.0	40.5	986.3	GSH 060	5.0	1	23.5	H	13.9	3.7
NV	69	94.0	56.5	923.8	GSH 060	5.0	1	5.9	C	10.9	4.0
NH	45	70.0	32.5	929.4	GSH 060	5.0	1	23.5	H	15.4	3.4
NJ	55	80.0	42.5	798.7	GSH 048	4.0	1	23.5	H	15.7	4.0
NM	59	84.0	46.5	708.9	GSH 042	3.5	1	18.3	C	14.4	4.2
NY	50	75.0	37.5	735.2	GSH 048	4.0	1	23.5	H	16.3	3.8
NC	60	85.0	47.5	887.9	GSH 060	5.0	1	5.9	C	12.5	3.8
ND	45	70.0	32.5	1262.9	GSH 042	3.5	2	23.5	H	16.0	3.6
OH	56	81.0	43.5	915.7	GSH 048	4.0	1	18.3	H	15.1	4.1
OK	65	90.0	52.5	842.1	GSH 048	4.0	1	5.9	C	13.6	4.3
OR	54	79.0	41.5	884.2	GSH 042	3.5	1	18.3	H	14.8	4.0
PA	52	77.0	39.5	902.9	GSH 060	5.0	1	23.5	H	13.6	3.6
RI	50	75.0	37.5	872.6	GSH 060	5.0	1	23.5	H	14.0	3.5
SC	65	90.0	52.5	946.6	GSH 060	5.0	1	5.9	C	11.6	3.9
SD	50	75.0	37.5	1059.2	GSH 060	5.0	1	23.5	H	13.9	3.6
TN	60	85.0	47.5	800.7	GSH 048	4.0	1	5.9	C	14.5	4.1
TX	72	95.0	59.5	1178.3	GSH 060	5.0	1	5.9	C	11.0	4.1
UT	53	78.0	40.5	826.3	GSH 048	4.0	1	23.5	H	15.4	3.9
VT	46	71.0	33.5	924.5	GSH 060	5.0	1	23.5	H	15.1	3.4
VA	60	85.0	47.5	941.9	GSH 060	5.0	1	5.9	C	12.7	3.8
WA	49	74.0	36.5	698.4	GSH 042	3.5	1	23.5	H	15.9	3.8
WV	58	83.0	45.5	777.2	GSH 048	4.0	1	5.9	H	15.0	4.1
WI	49	74.0	36.5	1087.3	GSH 060	5.0	1	23.5	H	14.4	3.6
WY	48	73.0	35.5	949.0	GSH 060	5.0	1	23.5	H	14.0	3.5

Appendix G. RS Means Building Construction Cost 2007 Book Cost Factors

State	Location	Factor	State	Location	Factor
Alabama	Maxwell AFB	78.7	Montana	Great Falls	89.6
Alaska	Anchorage	124.2	Nebraska	Omaha	89.5
Arizona	Luke AFB	89.3	Nevada	Las Vegas	101.8
Arkansas	Little Rock	86.0	New Hampshire	Concord	92.5
California	Travis AFB	121.8	NewJersey	McGuire AFB	108.3
Colorado	Colorado Springs	93.1	New Mexico	Holloman AFB	84.3
Connecticut	Hartford	107.3	New York	New York	130.9
Delaware	Dover AFB	101.1	North Carolina	Seymour Johnson AFB	79.9
Washington, D.C.	Washington DC	98.1	North Dakota	Minot AFB	86.3
Florida	Tyndall AFB	71.6	Ohio	Dayton	90.6
Georgia	Moody AFB	77.4	Oklahoma	Altus AFB	82.4
Hawaii	Honolulu	121.3	Oregon	Kingsley Field ANGB	102.0
Idaho	Mountain Home AFB	82.4	Pennsylvania	Pittsburg	98.9
Illinois	Scott AFB	98.8	Rhode Island	Providence	104.0
Indiana	Grissom JARB	88.2	SouthCarolina	Shaw AFB	76.4
Iowa	Sioux City	87.3	South Dakota	Ellsworth AFB	78.3
Kansas	Wichita	84.5	Tennessee	Nashville	87.8
Kentucky	Louisville	91.2	Texas	San Antonio	83.0
Louisiana	Shreveport	79.7	Utah	Salt Lake City	88.1
Maine	Portland	89.6	Vermont	Montpellier	81.9
Maryland	Baltimore	92.8	Virginia	Richmond	89.1
Massachusetts	Boston	115.4	Washington	McChord AFB	102.5
Michigan	Detroit	105.0	West Virginia	Charleston	95.3
Minnesota	Minneapolis/St Paul	112.3	Wisconsin	Milwaukee	102.4
Mississippi	Columbus AFB	70.4	Wyoming	F.E. Warren AFB	86.1
Missouri	Whiteman AFB	94.2			

Appendix H: Ground Source Heat Pump Cost Data

Water Source Heat Pump Unit		Material	Labor	Total
Cooling (Tons)	Heating (Mbtu/hr)	Cost	Cost	Cost
1	13	$1,200	$325	$1,525
1.5	17	$1,325	$360	$1,685
2	19	$1,375	$385	$1,760
2.5	25	$1,450	$405	$1,855
3	27	$1,550	$465	$2,015
3.5	29	$1,600	$500	$2,100
4	31	$1,800	$540	$2,340
5	29	$2,100	$725	$2,825
7.5	35	$6,050	$1,075	$7,125
8.5	40	$6,275	$1,125	$7,400
10	50	$6,600	$1,225	$7,825
15	64	$10,900	$2,150	$13,050
20	100	$11,800	$2,475	$14,275
25	100	$16,100	$3,175	$19,275

Well Drilling, 4"-6"	Total Cost ($/ft)
	$5.50

High Density Polyethylene Pipe Size (inches)	Material Cost
1	$0.48
1.25	$0.55
1.5	$0.60
2	$1.00

Bentonite Grout (50 lb bag)	Material Cost
Thermally enhanced k = 1.2 when mixed with 400 lb silica sand	$20.58

Silica Sand (50 lb bag)	Material Cost
	$4.90

Ground Heat Exchanger Loop Pump	Material Cost	Labor Cost	Total Cost
(Cast Iron Flange Connection 3/4" to 1.5")			
1/12 hp	$269	$108	$377
1/8 hp	$450	$108	$558
1/3 hp	$500	$108	$608

Appendix I Natural Gas Furnace/Split System Air Conditioning Cost Data

Natural Gas Furnace Heating Size (Mbtu/hr)	Material Cost	Labor Cost	Total Cost
7.7	$410	$90	$500
14	$410	$97	$507
24	$405	$125	$530
49	$795	$157	$952
65	$875	$174	$1,049
75	$560	$174	$734
100	$600	$196	$796
Split System AC Condensing Unit Cooling Size (tons)	**Material Cost**	**Labor Cost**	**Total Cost**
1	$585	$171	$756
1.5	$700	$181	$881
2	$770	$203	$973
5	$1,575	$325	$1,900
10	$2,425	$465	$2,890
Air Handler, Modular Cooling Coil Size (tons)	**Material Cost**	**Labor Cost**	**Total Cost**
1.5	$560	$171	$731
2	590	186	$776
2.5	645	197	$842
3	710	210	$920
3.5	865	224	$1,089
4	980	260	$1,240
5	1050	310	$1,360

Appendix J. NGAC NPV LCC Electricity Price Sensitivity Analysis

	Electricity Price Variation								
	-50%	-25%	-10%	0%	10%	25%	50%	100%	200%
AL	$20,903	$23,441	$24,963	$25,979	$26,994	$28,517	$31,055	$36,131	$46,283
AK	$29,329	$29,647	$29,837	$29,964	$30,091	$30,281	$30,598	$31,232	$32,501
AZ	$16,951	$19,554	$21,115	$22,156	$23,197	$24,758	$27,360	$32,565	$42,974
AR	$18,396	$19,995	$20,954	$21,593	$22,233	$23,192	$24,791	$27,988	$34,382
CA	$22,852	$23,522	$23,924	$24,192	$24,460	$24,862	$25,532	$26,872	$29,552
CO	$19,763	$20,200	$20,461	$20,636	$20,811	$21,072	$21,509	$22,381	$24,127
CT	$31,439	$32,877	$33,739	$34,314	$34,889	$35,752	$37,190	$40,065	$45,816
DE	$29,736	$31,338	$32,298	$32,939	$33,579	$34,540	$36,141	$39,344	$45,749
DC	$27,516	$29,982	$31,462	$32,449	$33,435	$34,915	$37,381	$42,314	$52,179
FL	$16,619	$19,541	$21,294	$22,463	$23,632	$25,385	$28,307	$34,151	$45,839
GA	$18,069	$20,578	$22,083	$23,087	$24,090	$25,595	$28,104	$33,121	$43,156
HI	$36,401	$49,908	$58,012	$63,415	$68,818	$76,922	$90,429	$117,443	$171,471
ID	$22,063	$22,488	$22,744	$22,914	$23,085	$23,340	$23,766	$24,618	$26,322
IL	$26,392	$27,947	$28,881	$29,503	$30,125	$31,059	$32,614	$35,726	$41,948
IN	$25,087	$25,880	$26,355	$26,672	$26,989	$27,465	$28,257	$29,843	$33,013
IA	$26,119	$27,038	$27,590	$27,957	$28,325	$28,877	$29,796	$31,635	$35,312
KS	$23,690	$24,838	$25,526	$25,985	$26,444	$27,132	$28,280	$30,575	$35,164
KY	$22,220	$23,249	$23,866	$24,277	$24,689	$25,306	$26,335	$28,392	$32,506
LA	$18,756	$21,395	$22,979	$24,035	$25,091	$26,675	$29,315	$34,594	$45,153
ME	$36,872	$37,656	$38,127	$38,441	$38,755	$39,226	$40,011	$41,580	$44,719
MD	$27,220	$29,059	$30,162	$30,897	$31,632	$32,735	$34,574	$38,250	$45,603
MA	$33,228	$34,802	$35,747	$36,377	$37,007	$37,952	$39,527	$42,676	$48,975
MI	$27,998	$28,864	$29,383	$29,729	$30,076	$30,595	$31,461	$33,192	$36,655
MN	$30,814	$31,574	$32,031	$32,335	$32,639	$33,095	$33,856	$35,377	$38,420
MS	$18,124	$20,510	$21,941	$22,895	$23,849	$25,280	$27,665	$32,436	$41,977
MO	$25,431	$26,589	$27,284	$27,747	$28,210	$28,905	$30,063	$32,379	$37,011
MT	$25,850	$26,259	$26,505	$26,669	$26,832	$27,078	$27,487	$28,306	$29,943
NE	$24,192	$25,096	$25,638	$25,999	$26,360	$26,903	$27,806	$29,613	$33,228
NV	$20,473	$22,717	$24,064	$24,961	$25,859	$27,205	$29,449	$33,937	$42,914
NH	$33,672	$34,584	$35,131	$35,496	$35,861	$36,408	$37,320	$39,144	$42,791
NJ	$29,758	$31,975	$33,305	$34,192	$35,078	$36,409	$38,626	$43,060	$51,928
NM	$18,649	$19,667	$20,277	$20,684	$21,091	$21,702	$22,719	$24,754	$28,824
NY	$29,919	$32,070	$33,361	$34,222	$35,083	$36,374	$38,525	$42,828	$51,435
NC	$20,726	$22,033	$22,817	$23,340	$23,863	$24,647	$25,954	$28,568	$33,795
ND	$26,485	$26,902	$27,153	$27,319	$27,486	$27,736	$28,154	$28,988	$30,656
OH	$26,224	$27,291	$27,931	$28,357	$28,784	$29,423	$30,490	$32,623	$36,888
OK	$20,508	$22,025	$22,934	$23,541	$24,148	$25,057	$26,574	$29,607	$35,672
OR	$27,090	$27,456	$27,675	$27,821	$27,968	$28,187	$28,553	$29,284	$30,747
PA	$28,725	$29,609	$30,139	$30,493	$30,846	$31,376	$32,260	$34,027	$37,561
RI	$33,007	$34,079	$34,721	$35,150	$35,579	$36,221	$37,293	$39,436	$43,721
SC	$18,789	$20,517	$21,554	$22,246	$22,937	$23,974	$25,702	$29,159	$36,072
SD	$22,489	$23,027	$23,349	$23,565	$23,780	$24,102	$24,640	$25,715	$27,866
TN	$21,972	$23,354	$24,184	$24,737	$25,290	$26,119	$27,501	$30,265	$35,794
TX	$17,177	$20,298	$22,170	$23,418	$24,666	$26,539	$29,659	$35,900	$48,381
UT	$19,278	$19,891	$20,259	$20,505	$20,750	$21,118	$21,731	$22,958	$25,411
VT	$29,215	$30,100	$30,632	$30,986	$31,340	$31,871	$32,757	$34,528	$38,070
VA	$21,748	$22,922	$23,627	$24,097	$24,567	$25,271	$26,446	$28,795	$33,493
WA	$23,389	$23,712	$23,906	$24,035	$24,164	$24,357	$24,680	$25,326	$26,617
WV	$26,291	$27,084	$27,560	$27,877	$28,194	$28,670	$29,463	$31,049	$34,220
WI	$28,857	$29,555	$29,975	$30,254	$30,533	$30,953	$31,651	$33,049	$35,843
WY	$24,285	$24,602	$24,791	$24,918	$25,045	$25,234	$25,551	$26,183	$27,449

Appendix K. GSHP NPV LCC Electricity Price Sensitivity Analysis

	Electricity Price Variation								
	-50%	-25%	-10%	0%	10%	25%	50%	100%	200%
AL	$17,981	$21,415	$23,475	$24,848	$26,221	$28,281	$31,715	$38,581	$52,314
AK	$35,277	$41,479	$45,201	$47,682	$50,163	$53,884	$60,086	$72,491	$97,301
AZ	$19,978	$23,311	$25,310	$26,643	$27,976	$29,976	$33,308	$39,973	$53,302
AR	$16,476	$18,986	$20,493	$21,497	$22,501	$24,007	$26,518	$31,539	$41,582
CA	$18,565	$21,407	$23,112	$24,249	$25,386	$27,091	$29,933	$35,617	$46,985
CO	$15,566	$17,434	$18,554	$19,301	$20,049	$21,169	$23,037	$26,773	$34,245
CT	$24,657	$29,884	$33,020	$35,111	$37,202	$40,338	$45,565	$56,019	$76,927
DE	$18,752	$22,166	$24,214	$25,580	$26,946	$28,994	$32,408	$39,236	$52,892
DC	$21,727	$26,265	$28,988	$30,804	$32,619	$35,342	$39,881	$48,957	$67,111
FL	$17,321	$21,079	$23,335	$24,838	$26,341	$28,596	$32,355	$39,872	$54,906
GA	$17,343	$20,591	$22,540	$23,839	$25,138	$27,087	$30,335	$36,832	$49,824
HI	$47,957	$60,311	$67,724	$72,666	$77,607	$85,020	$97,374	$122,083	$171,501
ID	$12,597	$14,045	$14,914	$15,493	$16,072	$16,941	$18,389	$21,284	$27,076
IL	$20,081	$23,447	$25,467	$26,814	$28,160	$30,180	$33,547	$40,279	$53,745
IN	$17,400	$20,036	$21,618	$22,673	$23,728	$25,309	$27,946	$33,219	$43,766
IA	$18,349	$21,307	$23,082	$24,265	$25,449	$27,224	$30,182	$36,098	$47,931
KS	$14,401	$16,617	$17,947	$18,833	$19,720	$21,050	$23,266	$27,698	$36,563
KY	$14,698	$16,693	$17,890	$18,688	$19,486	$20,683	$22,678	$26,669	$34,650
LA	$20,222	$23,895	$26,099	$27,569	$29,038	$31,242	$34,915	$42,261	$56,954
ME	$23,054	$28,035	$31,024	$33,017	$35,010	$37,999	$42,981	$52,944	$72,871
MD	$19,810	$23,838	$26,254	$27,865	$29,476	$31,893	$35,921	$43,976	$60,087
MA	$23,877	$28,515	$31,298	$33,154	$35,009	$37,792	$42,430	$51,707	$70,260
MI	$20,564	$23,842	$25,808	$27,119	$28,431	$30,397	$33,675	$40,230	$53,341
MN	$25,579	$28,908	$30,905	$32,237	$33,568	$35,565	$38,894	$45,551	$58,866
MS	$16,309	$19,663	$21,676	$23,018	$24,360	$26,372	$29,727	$36,436	$49,854
MO	$17,337	$19,901	$21,440	$22,465	$23,491	$25,030	$27,594	$32,722	$42,979
MT	$20,513	$23,266	$24,918	$26,019	$27,120	$28,771	$31,524	$37,029	$48,039
NE	$17,381	$19,932	$21,462	$22,483	$23,503	$25,034	$27,585	$32,687	$42,890
NV	$20,157	$23,577	$25,629	$26,997	$28,365	$30,417	$33,837	$40,677	$54,358
NH	$21,786	$26,505	$29,336	$31,224	$33,111	$35,943	$40,661	$50,099	$68,973
NJ	$22,792	$27,665	$30,589	$32,538	$34,488	$37,411	$42,285	$52,031	$71,523
NM	$13,217	$15,195	$16,382	$17,173	$17,965	$19,151	$21,129	$25,085	$32,997
NY	$25,011	$29,873	$32,790	$34,735	$36,680	$39,597	$44,459	$54,183	$73,631
NC	$14,812	$17,151	$18,554	$19,490	$20,425	$21,828	$24,167	$28,845	$38,201
ND	$20,262	$23,073	$24,759	$25,884	$27,008	$28,695	$31,506	$37,128	$48,371
OH	$16,895	$19,602	$21,227	$22,310	$23,392	$25,017	$27,724	$33,139	$43,968
OK	$14,568	$16,940	$18,363	$19,311	$20,260	$21,683	$24,055	$28,798	$38,285
OR	$16,224	$18,068	$19,174	$19,912	$20,650	$21,756	$23,600	$27,289	$34,665
PA	$19,196	$22,262	$24,101	$25,328	$26,554	$28,394	$31,460	$37,591	$49,855
RI	$21,512	$25,493	$27,882	$29,475	$31,068	$33,457	$37,438	$45,402	$61,329
SC	$15,175	$17,786	$19,352	$20,397	$21,441	$23,007	$25,618	$30,840	$41,283
SD	$15,842	$18,240	$19,678	$20,637	$21,596	$23,034	$25,432	$30,226	$39,816
TN	$14,837	$17,123	$18,494	$19,408	$20,322	$21,693	$23,979	$28,549	$37,691
TX	$20,176	$24,204	$26,621	$28,233	$29,844	$32,261	$36,289	$44,346	$60,459
UT	$14,422	$16,293	$17,415	$18,164	$18,912	$20,034	$21,905	$25,647	$33,129
VT	$19,218	$23,409	$25,923	$27,600	$29,276	$31,791	$35,982	$44,364	$61,128
VA	$16,039	$18,216	$19,523	$20,394	$21,265	$22,571	$24,748	$29,103	$37,812
WA	$14,185	$15,600	$16,449	$17,015	$17,581	$18,430	$19,845	$22,675	$28,335
WV	$14,398	$16,077	$17,084	$17,756	$18,427	$19,435	$21,114	$24,471	$31,186
WI	$21,413	$24,687	$26,652	$27,961	$29,271	$31,235	$34,510	$41,058	$54,154
WY	$15,538	$17,523	$18,714	$19,508	$20,302	$21,493	$23,479	$27,449	$35,390

Appendix L. NGAC and GSHP NPV LCC Natural Gas Price Sensitivity Analysis

	Natural Gas Price Variation									GSHP*
	-50%	-25%	-10%	0%	10%	25%	50%	100%	200%	LCC
AL	$21,321	$23,650	$25,047	$25,979	$26,910	$28,307	$30,636	$35,293	$44,607	$24,848
AK	$19,775	$24,869	$27,926	$29,964	$32,002	$35,058	$40,153	$50,342	$70,720	$47,682
AZ	$19,754	$20,955	$21,676	$22,156	$22,636	$23,357	$24,558	$26,960	$31,764	$26,643
AR	$17,552	$19,573	$20,785	$21,593	$22,402	$23,614	$25,635	$29,676	$37,759	$21,497
CA	$18,475	$21,334	$23,049	$24,192	$25,335	$27,050	$29,909	$35,625	$47,059	$24,249
CO	$15,042	$17,839	$19,517	$20,636	$21,755	$23,433	$26,230	$31,823	$43,010	$19,301
CT	$24,472	$29,393	$32,346	$34,314	$36,283	$39,236	$44,157	$53,999	$73,684	$35,111
DE	$23,855	$28,397	$31,122	$32,939	$34,756	$37,481	$42,023	$51,107	$69,275	$25,580
DC	$25,216	$28,832	$31,002	$32,449	$33,895	$36,065	$39,682	$46,915	$61,381	$30,804
FL	$20,038	$21,250	$21,978	$22,463	$22,948	$23,675	$24,888	$27,313	$32,163	$24,838
GA	$19,763	$21,425	$22,422	$23,087	$23,751	$24,748	$26,410	$29,734	$36,381	$23,839
HI	$63,415	$63,415	$63,415	$63,415	$63,415	$63,415	$63,415	$63,415	$63,415	$72,666
ID	$15,718	$19,316	$21,475	$22,914	$24,354	$26,512	$30,111	$37,307	$51,699	$15,493
IL	$22,007	$25,755	$28,004	$29,503	$31,002	$33,251	$36,999	$44,495	$59,487	$26,814
IN	$18,570	$22,621	$25,052	$26,672	$28,293	$30,724	$34,775	$42,877	$59,081	$22,673
IA	$19,479	$23,718	$26,262	$27,957	$29,653	$32,196	$36,435	$44,914	$61,870	$24,265
KS	$18,783	$22,384	$24,545	$25,985	$27,425	$29,586	$33,187	$40,389	$54,793	$18,833
KY	$17,969	$21,123	$23,016	$24,277	$25,539	$27,432	$30,586	$36,894	$49,511	$18,688
LA	$20,594	$22,315	$23,347	$24,035	$24,723	$25,755	$27,476	$30,916	$37,798	$27,569
ME	$24,497	$31,469	$35,652	$38,441	$41,230	$45,413	$52,385	$66,330	$94,218	$33,017
MD	$22,965	$26,931	$29,311	$30,897	$32,484	$34,863	$38,830	$46,762	$62,627	$27,865
MA	$26,112	$31,245	$34,324	$36,377	$38,430	$41,509	$46,642	$56,906	$77,436	$33,154
MI	$20,940	$25,335	$27,971	$29,729	$31,487	$34,124	$38,518	$47,308	$64,886	$27,119
MN	$22,399	$27,367	$30,348	$32,335	$34,322	$37,303	$42,270	$52,206	$72,077	$32,237
MS	$19,130	$21,013	$22,142	$22,895	$23,648	$24,777	$26,659	$30,423	$37,952	$23,018
MO	$20,087	$23,917	$26,215	$27,747	$29,279	$31,577	$35,408	$43,068	$58,389	$22,465
MT	$17,911	$22,290	$24,917	$26,669	$28,420	$31,047	$35,426	$44,183	$61,698	$26,019
NE	$18,509	$22,254	$24,501	$25,999	$27,497	$29,744	$33,489	$40,978	$55,957	$22,483
NV	$21,180	$23,071	$24,205	$24,961	$25,718	$26,852	$28,742	$32,523	$40,085	$26,997
NH	$23,399	$29,448	$33,077	$35,496	$37,916	$41,545	$47,594	$59,691	$83,886	$31,224
NJ	$26,010	$30,101	$32,555	$34,192	$35,828	$38,282	$42,373	$50,554	$66,916	$32,538
NM	$15,865	$18,274	$19,720	$20,684	$21,648	$23,094	$25,504	$30,323	$39,962	$17,173
NY	$26,830	$30,526	$32,744	$34,222	$35,700	$37,918	$41,614	$49,006	$63,790	$34,735
NC	$17,589	$20,465	$22,190	$23,340	$24,490	$26,215	$29,091	$34,841	$46,342	$19,490
ND	$18,114	$22,717	$25,478	$27,319	$29,160	$31,922	$36,525	$45,730	$64,141	$25,884
OH	$20,060	$24,208	$26,698	$28,357	$30,017	$32,506	$36,655	$44,952	$61,547	$22,310
OK	$18,212	$20,877	$22,475	$23,541	$24,607	$26,205	$28,870	$34,198	$44,855	$19,311
OR	$18,862	$23,342	$26,030	$27,821	$29,613	$32,301	$36,781	$45,740	$63,659	$19,912
PA	$21,105	$25,799	$28,615	$30,493	$32,370	$35,186	$39,880	$49,267	$68,042	$25,328
RI	$24,021	$29,585	$32,924	$35,150	$37,376	$40,715	$46,279	$57,409	$79,668	$29,475
SC	$17,740	$19,993	$21,345	$22,246	$23,147	$24,498	$26,751	$31,257	$40,268	$20,397
SD	$16,097	$19,831	$22,071	$23,565	$25,058	$27,298	$31,032	$38,499	$53,434	$20,637
TN	$18,765	$21,751	$23,542	$24,737	$25,931	$27,722	$30,708	$36,680	$48,622	$19,408
TX	$21,384	$22,401	$23,011	$23,418	$23,825	$24,435	$25,453	$27,487	$31,556	$28,233
UT	$15,124	$17,814	$19,428	$20,505	$21,581	$23,195	$25,885	$31,266	$42,028	$18,164
VT	$20,652	$25,819	$28,919	$30,986	$33,052	$36,152	$41,319	$51,653	$72,319	$27,600
VA	$18,084	$21,090	$22,894	$24,097	$25,299	$27,103	$30,110	$36,123	$48,150	$20,394
WA	$16,903	$20,469	$22,608	$24,035	$25,461	$27,600	$31,166	$38,297	$52,559	$17,015
WV	$19,467	$23,672	$26,195	$27,877	$29,559	$32,082	$36,287	$44,697	$61,517	$17,756
WI	$20,761	$25,507	$28,355	$30,254	$32,153	$35,001	$39,747	$49,240	$68,227	$27,961
WY	$16,654	$20,786	$23,265	$24,918	$26,571	$29,050	$33,182	$41,446	$57,975	$19,508

*GSHP systems do not consume natural gas

Appendix M. NPV LCC GSHP Installed Cost Reduction Sensitivity Analysis

	GSHP Installed Cost Reduction Percentage					NGAC LCC
	0	10%	25%	50%	75%	
AL	$25,648	$24,738	$23,373	$21,097	$18,822	$31,072
AK	$46,667	$44,719	$41,798	$36,929	$32,060	$33,274
AZ	$26,228	$25,128	$23,478	$20,729	$17,979	$26,284
AR	$21,764	$20,854	$19,490	$17,216	$14,942	$25,642
CA	$23,365	$22,460	$21,102	$18,839	$16,576	$27,139
CO	$18,728	$17,810	$16,434	$14,140	$11,846	$24,150
CT	$35,289	$34,184	$32,527	$29,764	$27,002	$39,161
DE	$26,074	$25,184	$23,849	$21,624	$19,400	$37,839
DC	$31,792	$30,810	$29,338	$26,884	$24,429	$37,469
FL	$26,134	$25,334	$24,133	$22,132	$20,131	$27,429
GA	$24,612	$23,725	$22,395	$20,177	$17,960	$27,372
HI	$31,726	$29,698	$26,657	$21,588	$16,519	$32,490
ID	$21,697	$20,961	$19,856	$18,016	$16,175	$26,852
IL	$27,223	$26,171	$24,592	$21,962	$19,331	$33,477
IN	$22,982	$22,012	$20,557	$18,131	$15,706	$30,684
IA	$24,692	$23,683	$22,170	$19,648	$17,126	$30,884
KS	$19,326	$18,572	$17,441	$15,555	$13,670	$29,995
KY	$18,772	$17,968	$16,763	$14,754	$12,746	$28,254
LA	$28,386	$27,300	$25,671	$22,957	$20,242	$28,404
ME	$33,437	$32,367	$30,762	$28,088	$25,413	$43,889
MD	$28,854	$27,947	$26,587	$24,320	$22,052	$35,707
MA	$32,874	$31,759	$30,086	$27,299	$24,511	$40,585
MI	$27,320	$26,225	$24,583	$21,847	$19,110	$33,812
MN	$31,861	$30,284	$27,919	$23,976	$20,034	$36,319
MS	$24,144	$23,360	$22,185	$20,225	$18,266	$27,481
MO	$22,687	$21,737	$20,312	$17,936	$15,561	$31,682
MT	$26,092	$24,826	$22,928	$19,764	$16,599	$30,854
NE	$22,730	$21,750	$20,279	$17,828	$15,376	$29,888
NV	$26,602	$25,565	$24,009	$21,417	$18,824	$28,069
NH	$31,702	$30,729	$29,269	$26,836	$24,403	$40,530
NJ	$32,702	$31,723	$30,255	$27,807	$25,360	$38,483
NM	$17,224	$16,546	$15,528	$13,832	$12,135	$24,209
NY	$34,211	$33,091	$31,411	$28,612	$25,812	$37,744
NC	$19,990	$19,197	$18,007	$16,025	$14,042	$27,517
ND	$25,983	$24,737	$22,868	$19,752	$16,637	$31,385
OH	$22,682	$21,790	$20,452	$18,222	$15,991	$32,486
OK	$19,810	$19,060	$17,934	$16,059	$14,183	$27,441
OR	$19,039	$18,083	$16,650	$14,261	$11,872	$31,708
PA	$25,028	$24,007	$22,477	$19,925	$17,374	$34,804
RI	$29,371	$28,322	$26,748	$24,125	$21,502	$39,751
SC	$21,089	$20,298	$19,111	$17,134	$15,156	$26,553
SD	$21,066	$20,165	$18,813	$16,559	$14,306	$27,525
TN	$19,727	$18,954	$17,795	$15,863	$13,931	$28,809
TX	$29,090	$28,090	$26,590	$24,090	$21,590	$27,597
UT	$17,876	$17,061	$15,839	$13,801	$11,764	$23,995
VT	$28,262	$27,403	$26,115	$23,969	$21,822	$35,941
VA	$20,415	$19,495	$18,116	$15,817	$13,519	$28,147
WA	$16,257	$15,433	$14,198	$12,139	$10,081	$27,503
WV	$17,543	$16,720	$15,487	$13,430	$11,374	$32,047
WI	$27,891	$26,690	$24,889	$21,888	$18,886	$34,040
WY	$23,420	$22,501	$21,123	$18,826	$16,529	$29,089

Appendix N. NGAC NPV LCC Carbon Dioxide Emission Offset Cost Sensitivity

	Net Present Value Life Cycle Cost									
	$0/ton	$2/ton	$5/ton	$10/ton	$50/ton	$100/ton	$200/ton	$500/ton	$1,000/ton	$2,000/ton
AL	$31,072	$31,353	$31,774	$32,477	$38,095	$45,118	$59,164	$101,301	$171,530	$311,989
AK	$33,274	$33,582	$34,044	$34,814	$40,975	$48,675	$64,077	$110,281	$187,288	$341,303
AZ	$26,284	$26,551	$26,950	$27,617	$32,948	$39,612	$52,940	$92,924	$159,564	$292,845
AR	$25,642	$25,915	$26,325	$27,008	$32,474	$39,307	$52,971	$93,966	$162,289	$298,936
CA	$27,139	$27,281	$27,494	$27,849	$30,690	$34,240	$41,342	$62,646	$98,153	$169,168
CO	$24,150	$24,349	$24,648	$25,146	$29,132	$34,115	$44,080	$73,974	$123,798	$223,446
CT	$39,161	$39,404	$39,768	$40,375	$45,233	$51,305	$63,448	$99,879	$160,596	$282,031
DE	$37,839	$38,080	$38,443	$39,046	$43,875	$49,911	$61,983	$98,200	$158,561	$279,284
DC	$37,469	$37,764	$38,205	$38,942	$44,832	$52,194	$66,919	$111,094	$184,720	$331,971
FL	$27,429	$27,646	$27,971	$28,514	$32,853	$38,278	$49,126	$81,672	$135,914	$244,399
GA	$27,372	$27,635	$28,029	$28,686	$33,940	$40,508	$53,645	$93,054	$158,736	$290,100
HI	$32,490	$32,889	$33,489	$34,487	$42,477	$52,464	$72,438	$132,361	$232,232	$431,974
ID	$26,852	$27,029	$27,294	$27,735	$31,268	$35,684	$44,516	$71,012	$115,172	$203,492
IL	$33,477	$33,778	$34,230	$34,984	$41,011	$48,545	$63,613	$108,817	$184,157	$334,837
IN	$30,684	$30,943	$31,332	$31,981	$37,169	$43,654	$56,624	$95,533	$160,382	$290,079
IA	$30,884	$31,138	$31,520	$32,156	$37,246	$43,607	$56,331	$94,500	$158,117	$285,349
KS	$29,995	$30,258	$30,654	$31,312	$36,582	$43,169	$56,343	$95,865	$161,735	$293,476
KY	$28,254	$28,503	$28,877	$29,500	$34,482	$40,709	$53,165	$90,531	$152,807	$277,361
LA	$28,404	$28,653	$29,027	$29,650	$34,635	$40,865	$53,327	$90,711	$153,019	$277,634
ME	$43,889	$44,119	$44,464	$45,038	$49,635	$55,381	$66,872	$101,348	$158,806	$273,724
MD	$35,707	$35,947	$36,306	$36,905	$41,698	$47,689	$59,672	$95,619	$155,531	$275,354
MA	$40,585	$40,800	$41,122	$41,658	$45,952	$51,320	$62,055	$94,260	$147,935	$255,284
MI	$33,812	$34,048	$34,401	$34,990	$39,702	$45,591	$57,370	$92,708	$151,604	$269,397
MN	$36,319	$36,626	$37,087	$37,855	$43,997	$51,675	$67,031	$113,098	$189,878	$343,436
MS	$27,481	$27,746	$28,143	$28,804	$34,098	$40,714	$53,948	$93,647	$159,814	$292,147
MO	$31,682	$31,951	$32,354	$33,026	$38,404	$45,126	$58,570	$98,903	$166,124	$300,566
MT	$30,854	$31,092	$31,449	$32,043	$36,800	$42,746	$54,637	$90,312	$149,771	$268,687
NE	$29,888	$30,177	$30,610	$31,331	$37,104	$44,319	$58,750	$102,043	$174,198	$318,509
NV	$28,069	$28,279	$28,595	$29,120	$33,324	$38,580	$49,090	$80,622	$133,175	$238,281
NH	$40,530	$40,759	$41,103	$41,676	$46,261	$51,992	$63,454	$97,840	$155,150	$269,769
NJ	$38,483	$38,708	$39,045	$39,607	$44,103	$49,723	$60,964	$94,685	$150,886	$263,290
NM	$24,209	$24,415	$24,725	$25,241	$29,368	$34,527	$44,845	$75,800	$127,391	$230,574
NY	$37,744	$37,961	$38,285	$38,827	$43,159	$48,574	$59,404	$91,894	$146,043	$254,343
NC	$27,517	$27,748	$28,096	$28,674	$33,304	$39,091	$50,665	$85,387	$143,257	$258,997
ND	$31,385	$31,682	$32,127	$32,870	$38,809	$46,233	$61,081	$105,625	$179,866	$328,347
OH	$32,486	$32,731	$33,099	$33,712	$38,617	$44,749	$57,012	$93,800	$155,115	$277,744
OK	$27,441	$27,665	$28,002	$28,563	$33,053	$38,666	$49,891	$83,565	$139,689	$251,937
OR	$31,708	$31,890	$32,163	$32,618	$36,258	$40,809	$49,909	$77,212	$122,715	$213,722
PA	$34,804	$35,033	$35,377	$35,951	$40,537	$46,270	$57,736	$92,135	$149,466	$264,128
RI	$39,751	$39,947	$40,240	$40,729	$44,643	$49,536	$59,320	$88,674	$137,598	$235,445
SC	$26,553	$26,785	$27,134	$27,715	$32,361	$38,170	$49,787	$84,638	$142,723	$258,893
SD	$27,525	$27,773	$28,145	$28,766	$33,728	$39,931	$52,337	$89,554	$151,583	$275,642
TN	$28,809	$29,043	$29,395	$29,980	$34,666	$40,522	$52,236	$87,376	$145,943	$263,076
TX	$27,597	$27,826	$28,171	$28,744	$33,334	$39,071	$50,545	$84,967	$142,338	$257,078
UT	$23,995	$24,213	$24,541	$25,086	$29,452	$34,909	$45,822	$78,564	$133,132	$242,270
VT	$35,941	$36,179	$36,536	$37,130	$41,886	$47,832	$59,722	$95,394	$154,848	$273,754
VA	$28,147	$28,387	$28,747	$29,347	$34,147	$40,147	$52,147	$88,146	$148,145	$268,142
WA	$27,503	$27,662	$27,902	$28,300	$31,489	$35,474	$43,446	$67,359	$107,216	$186,929
WV	$32,047	$32,273	$32,612	$33,177	$37,697	$43,348	$54,648	$88,551	$145,054	$258,061
WI	$34,040	$34,302	$34,696	$35,351	$40,596	$47,152	$60,264	$99,600	$165,160	$296,280
WY	$29,089	$29,308	$29,636	$30,183	$34,558	$40,027	$50,964	$83,777	$138,465	$247,842

Appendix O. GSHP NPV LCC Carbon Dioxide Emission Offset Cost Sensitivity

	Net Present Value Life-Cycle Cost									
	$0/ton	$2/ton	$5/ton	$10/ton	$50/ton	$100/ton	$200/ton	$500/ton	$1,000/ton	$2,000/ton
AL	$25,648	$25,940	$26,379	$27,110	$32,960	$40,272	$54,897	$98,770	$171,893	$318,137
AK	$46,667	$46,959	$47,396	$48,125	$53,956	$61,244	$75,822	$119,554	$192,441	$338,215
AZ	$26,228	$26,517	$26,951	$27,675	$33,462	$40,696	$55,163	$98,566	$170,904	$315,580
AR	$21,764	$22,056	$22,493	$23,222	$29,056	$36,348	$50,932	$94,685	$167,606	$313,447
CA	$23,365	$23,451	$23,579	$23,794	$25,509	$27,653	$31,941	$44,804	$66,243	$109,121
CO	$18,728	$18,929	$19,231	$19,735	$23,763	$28,797	$38,866	$69,073	$119,418	$220,108
CT	$35,289	$35,554	$35,951	$36,613	$41,909	$48,529	$61,770	$101,491	$167,692	$300,095
DE	$26,074	$26,299	$26,637	$27,201	$31,707	$37,339	$48,605	$82,401	$138,729	$251,384
DC	$31,792	$32,124	$32,621	$33,451	$40,087	$48,381	$64,970	$114,738	$197,684	$363,576
FL	$26,134	$26,361	$26,701	$27,268	$31,805	$37,476	$48,818	$82,845	$139,556	$252,978
GA	$24,612	$24,882	$25,286	$25,960	$31,350	$38,088	$51,564	$91,992	$159,372	$294,132
HI	$31,726	$32,091	$32,640	$33,553	$40,861	$49,996	$68,266	$123,076	$214,426	$397,126
ID	$21,697	$21,917	$22,247	$22,798	$27,201	$32,705	$43,714	$76,739	$131,780	$241,864
IL	$27,223	$27,537	$28,009	$28,795	$35,083	$42,943	$58,663	$105,824	$184,425	$341,627
IN	$22,982	$23,262	$23,683	$24,384	$29,993	$37,004	$51,025	$93,090	$163,199	$303,416
IA	$24,692	$25,006	$25,476	$26,261	$32,536	$40,380	$56,068	$103,132	$181,572	$338,451
KS	$19,326	$19,587	$19,980	$20,633	$25,861	$32,396	$45,467	$84,678	$150,031	$280,736
KY	$18,772	$19,014	$19,377	$19,982	$24,823	$30,873	$42,974	$79,277	$139,783	$260,793
LA	$28,386	$28,645	$29,032	$29,679	$34,849	$41,312	$54,238	$93,015	$157,645	$286,903
ME	$33,437	$33,599	$33,842	$34,248	$37,492	$41,546	$49,655	$73,983	$114,528	$195,620
MD	$28,854	$29,093	$29,451	$30,048	$34,822	$40,789	$52,724	$88,529	$148,204	$267,555
MA	$32,874	$33,054	$33,324	$33,775	$37,378	$41,882	$50,889	$77,912	$122,950	$213,027
MI	$27,320	$27,539	$27,869	$28,417	$32,805	$38,291	$49,261	$82,173	$137,027	$246,733
MN	$31,861	$32,239	$32,807	$33,753	$41,319	$50,776	$69,692	$126,437	$221,014	$410,166
MS	$24,144	$24,411	$24,811	$25,479	$30,817	$37,490	$50,836	$90,874	$157,604	$291,065
MO	$22,687	$22,973	$23,403	$24,119	$29,846	$37,004	$51,322	$94,273	$165,860	$309,033
MT	$26,092	$26,386	$26,827	$27,562	$33,440	$40,788	$55,484	$99,571	$173,050	$320,009
NE	$22,730	$23,047	$23,522	$24,315	$30,653	$38,577	$54,424	$101,964	$181,198	$339,665
NV	$26,602	$26,818	$27,142	$27,682	$32,001	$37,400	$48,198	$80,591	$134,580	$242,559
NH	$31,702	$31,982	$32,402	$33,103	$38,706	$45,710	$59,718	$101,743	$171,784	$311,865
NJ	$32,702	$32,875	$33,136	$33,569	$37,037	$41,373	$50,043	$76,055	$119,407	$206,112
NM	$17,224	$17,420	$17,715	$18,206	$22,135	$27,047	$36,870	$66,338	$115,453	$213,681
NY	$34,211	$34,394	$34,668	$35,124	$38,778	$43,344	$52,478	$79,878	$125,545	$216,880
NC	$19,990	$20,232	$20,594	$21,199	$26,033	$32,075	$44,160	$80,415	$140,840	$261,691
ND	$25,983	$26,368	$26,946	$27,909	$35,612	$45,242	$64,501	$122,278	$218,573	$411,163
OH	$22,682	$22,915	$23,264	$23,846	$28,504	$34,326	$45,970	$80,901	$139,120	$255,559
OK	$19,810	$20,012	$20,316	$20,821	$24,866	$29,923	$40,036	$70,375	$120,940	$222,069
OR	$19,039	$19,163	$19,350	$19,661	$22,150	$25,260	$31,482	$50,146	$81,254	$143,468
PA	$25,028	$25,269	$25,630	$26,233	$31,052	$37,077	$49,126	$85,273	$145,518	$266,008
RI	$29,371	$29,495	$29,680	$29,989	$32,463	$35,555	$41,738	$60,289	$91,207	$153,043
SC	$21,089	$21,331	$21,693	$22,298	$27,132	$33,176	$45,262	$81,522	$141,954	$262,819
SD	$21,066	$21,346	$21,767	$22,467	$28,073	$35,081	$49,096	$91,140	$161,215	$301,363
TN	$19,727	$19,944	$20,271	$20,814	$25,162	$30,597	$41,467	$74,077	$128,428	$237,129
TX	$29,090	$29,329	$29,687	$30,285	$35,063	$41,035	$52,980	$88,816	$148,542	$267,995
UT	$17,876	$18,097	$18,428	$18,979	$23,393	$28,910	$39,944	$73,045	$128,215	$238,554
VT	$28,262	$28,553	$28,989	$29,716	$35,533	$42,804	$57,346	$100,972	$173,682	$319,102
VA	$20,415	$20,655	$21,016	$21,616	$26,422	$32,428	$44,441	$80,481	$140,547	$260,680
WA	$16,257	$16,405	$16,628	$16,998	$19,963	$23,668	$31,080	$53,314	$90,371	$164,485
WV	$17,543	$17,753	$18,068	$18,592	$22,789	$28,035	$38,528	$70,004	$122,466	$227,388
WI	$27,891	$28,198	$28,659	$29,427	$35,573	$43,256	$58,620	$104,715	$181,538	$335,186
WY	$23,420	$23,687	$24,087	$24,755	$30,094	$36,768	$50,116	$90,159	$156,899	$290,378

Bibliography

AFCESA. (1999). *A-Gram 99-23 Accounting for Energy Saving Contracts.* Air Force Civil Engineer Support Agency.

AHRI. (2008). *ARI 210-240 2008 Standard for Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment.* Arlington: Air-Conditioning Heating and Refrigeration Institute.

ASHRAE. (2007). *2007 ASHRAE Handbook HVAC Applications.* Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

ASHRAE. (2008). *2008 ASHRAE Handbook HVAC Systems and Equipment.* Atlanta: American Society of Heating, Refrigeration, and Air Conditioning Engineers.

ASHRAE. (2008). *ASHRAE Owning and Operating Cost Database ASHRAE Research Project 1237 TRP*. Retrieved December 17, 2008, from ASHRAE Web Site: http://xp20.ashrae.org/publicdatabase/system_service_life

Baroid Industrial Drilling Products. (2008). *IDP-357 One Sack Thermally Conductive Grout.* Houston: Baroid Inc.

Bush, G. W. (2007). *Energy Independence and Security Act of 2007.* Washington, D.C.: U.S. Government Printing Office.

Bush, G. W. (2001). *National Energy Policy.* Washington, D.C.: U.S Government Printing Office.

Bush, G. W. (2005). *National Energy Policy Status Report.* Washington, D.C.: U.S. Government Printing Office.

Bush, G. W. (2007). *Strengthening Federal Environmental, Energy, and Transportation Management.* Washington, D.C.: U.S. Government Printing Office.

U. S. Supreme Court, (2007, April 2). *United States Supreme Court Decisions.* Retrieved December 17, 2008, from Unites States Supreme Court: http://www.supremecourtus.gov/opinions/06pdf/05-1120.pdf

Department of Energy. (2005). *Air Conditioning Usage Indicators by Type of Housing Unit, Table HC2.7, 2005.* Washington, D.C.: Department of Energy.

EIA. (2007). *Commercial Electricity Prices.* Washington, D.C.: Energy Information Administration.

EIA. (2007). *Commercial Natural Gas Prices.* Washington, D.C.: Energy Information Administration.

EIA. (2007). *Electricity Flow, Annual Energy Review 2007.* Washington, D.C.: Energy Information Administration.

EIA. (2000). *Energy Information Administration Historical Data.* Retrieved December 15, 2008, from Energy Information Administration: http://www.eia.doe.gov/emeu/aer/eh/total.html

EIA. (2007). *Natural Gas Flow, Annual Energy Review 2007.* Washington, D.C.: Energy Information Association.

EPA. (1998). *AP 42, Fifth Edition, Volume I, Chapter 1:External Combustion Sources.* Washington, D.C.: Environmental Protection Agency.

Esch, M. (2008, September 29). *Nation's first greenhouse gas auction nets $38.5M.* Retrieved September 29, 2008, from Chicago Tribune : www.chicagotribune.com
Eschenbach, T. G. (2003). *Engineering Economy Applying Theory to Practice.* New York: Oxford University Press.

Fuller. (2005, April). *United States Department of Energy Energy Efficiency and Renewable Energy Home Page.* Retrieved December 13, 2008, from Guidance on Life-Cycle Cost Analysis Required by Executive Order 13123: http://www1.eere.energy.gov/femp/pdfs/lcc_guide_05.pdf

Fuller, S. K., & Peterson, S. R. (1996). *Life Cycle Costing Manual for the Federal Energy Management Program.* Washington, D.C.: U.S. Department of Energy.

Geo Heat Center. (2008). *Geo Heat Center*. Retrieved December 13, 2008, from Geo Heat Center Geothermal Heat Pump Terminology: http://geoheat.oit.edu/images/ghp/ghpterm.gif

Geo Pro Incorporated. (2008). *Thermal Grout Lite.* Elkton: Geo Pro Incorporated.

Geo Pro Incorporated. (2008). *Thermal Grout Select.* Elkton: Geo Pro Incorporated.

Haines, R. W., & Wilson, L. C. (2003). *HVAC Systems Design Handbook.* New York: McGraw-Hill.

Hughes, P. J. (2008). *Geothermal (Ground Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers.* Oak Ridge: Oak Ridge National Laboratory.

Kavanaugh, S. P., & Rafferty, K. D. (1997). *Ground-Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Kavanaugh, S. (1985). *Simulation and experimental verification of a vertical ground-coupled heat pump system.* Stillwater: Oklahoma State University.

Lekov, A., Franco, V., & Meyers, S. (2006). *Electricity and Natural Gas Efficiency Improvements for Residential Gas Furnaces in the U.S.* Berkeley: Lawrence Berkeley National Laboratory.

Mathias, J. A., & Bolling, A. L. (2008). *Investigation of Optimal Heating and Cooling Systems in Residential Buildings.* Atlanta: ASHRAE.

Minnesota Department of Commerce. (2008). *Performance, Emissions, Economic Analysis of Minnesota Geothermal Heat Pumps.* St. Paul: Minnesota Department of Commerce.

Oklahoma State University. (1988). *Closed Loop/Ground-Source Heat Pump Systems:Installation Guide.* Oklahoma City: Oklahoma State University.

Oklahoma State University. (1991). *Grouting Procedures for Ground-Source Heat Pump Systems.* Stillwater: Ground Source Heat Pump Publicaitons, Oklahoma State University.

OMB. (1992, October 29). *Office of Management and Budget Circular No. A-94.* Retrieved December 17, 2008, from Office of Management and Budget: http://www.whitehouse.gov/omb/circulars/a094/a094.html

Pickens, T. B. (2008, November 25). *www.pickensplan.com*. Retrieved November 2008, from PickensPlan.

Plastics Pipe Institute. (2008). *Rate Process Method for Projecting Performance of Polyethylene Piping Components TN-16/2008.* Irving: Plastics Pipe Institute.

U.S. Senate. (2008). *A bill to direct the Administrator of the Environmental Protection Agency to establish a program to decrease emissions of greenhouse gasses, and for other purposes.* Washington, D.C.: U.S. Government Printing Office.

United Nations. (1997). *Kyoto Protocol to the United Nations Framework.* New York, New York: http://unfccc.int/resource/docs/convkp/kpeng.pdf.

U.S. Green Building Council. (2008). *Green Building Facts. U.S. GreenBuilding Council Fact Sheet.* Washington, D.C.: U.S. Green Building Council.

Vanderburg, D. (2002). *Comparative Energy and Cost Analysis Between Conventional HVAC Systems and Geothermal Heat Pump Systems.* Dayton: Air Force Institute of Technology.

Vita

Captain Paul W. Fredin graduated from Comfrey Public High School in Comfrey, Minnesota in 1996. He attended South Dakota State University in Brookings, South Dakota where he graduated with a Bachelor of Science degree in Civil Engineering in 2001. He was commissioned as a 2nd Lieutenant through the Air Force Reserve Officer Training Corps, Detachment 780, in Brookings, South Dakota.

His first assignment was at Eielson, AFB where he served as a Civil Engineer in the 354th Civil Engineer Squadron. As a Civil Engineer, he worked in Maintenance Engineering as the Base Pavement Engineer and was later selected as the Chief of GeoBase. While stationed at Eielson, he deployed to Manas AB, Kyrgyzstan in support of Operation Enduring Freedom and served as the lead Civil Engineer in the Engineering Flight. In June 2004, he was assigned McGuire AFB where he served in the C-17 Program Office of the 305th Air Mobility Wing. Once the C-17 military construction was complete, he was reassigned to the 305th Civil Engineer Squadron where he continued to work in military construction. While stationed at McGuire, he deployed to New Orleans, Louisiana in support of Hurricane Katrina relief efforts. Following that mission, he was deployed on a Joint Engineer Tasking to Iraq in support of Operation Iraqi Freedom as an advisor to the Iraqi Army. In August 2007, he entered the Graduate School of Engineering and Management of the Air Force Institute of Technology.

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14. ABSTRACT

The world is undergoing a dramatic transformation with regard to how it produces and consumes energy due to increasing demand from developing nations and diminishing new resource discoveries. In addition, there has been increased concern over the effect of carbon dioxide emissions on the environment. All of these issues have created a combined pressure to force the world to begin to redefine how energy is utilized. Geothermal or ground source heat pumps (GSHPs) may provide one potential solution to these problems. This research investigated vertical borehole closed-loop GSHP systems in direct comparison to natural gas furnaces combined with traditional air-conditioning (NGAC) for 51 locations in the United States. The study utilized Trane Trace 700, Geothermal Loop Design, and Building Life-Cycle Cost 5 software packages for analysis. Although the installation costs for GSHP systems were 257% higher than NGAC systems, the operating costs were 33% lower. The mean simple and discounted payback periods for the GSHP system were 10 and 15 years, respectively. Carbon dioxide emissions were found to be 2.2% higher for the GSHP systems due to their use of coal-fired electricity in most locations. The overall life-cycle cost was 19.0% lower when selecting the GSHP system over the NGAC system.

15. SUBJECT TERMS

Ground Source Heat Pump, Ground Coupled Heat Pump, Geothermal, Economic Analysis, Greenhouse Gas Emission Analysis

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