WORCESTER POLYTECHNIC INSTITUTE

IQP BST 10i1:

Impacts and Limitations of Residential Geothermal Heating Systems

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Abstract:

This report looks at the impacts and limitations of ground-source heat pumps (GSHPs) for residential heating and cooling. While GSHPs could be a viable solution to the energy and environmental issues in the world, so far GSHPs have failed a widespread market penetration due to its high initial cost and space requirements. Through hybridization with other renewable technology it is however possible to lessen those limitations. Based on surveys we conducted, we believe that consumers are more interested in green technologies and that GSHPs will hold a larger market share in the future despite its limitations.

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CHAPTER 1: Introduction

It's been more than 3 centuries since steam engines have been introduced (1). A century later, electricity was invented (2). Courtesy of these 2 inventions, we are now enjoying high standard of material comfort. However we are now facing 2 main issues also due to these 2 inventions: the dependence of the current society on fossil fuels and global warming. The world energy consumption in 2007 was 495 quadrillion Btu according to the U.S. Energy Information Administration (EIA) (3). In 2035, it is predicted that the world energy consumption would increase by 49 percent (3). In Figure 1.1, the energy consumptions up to 2007 (blue) as well as the predicted values for energy consumption up to 2035 are also shown.

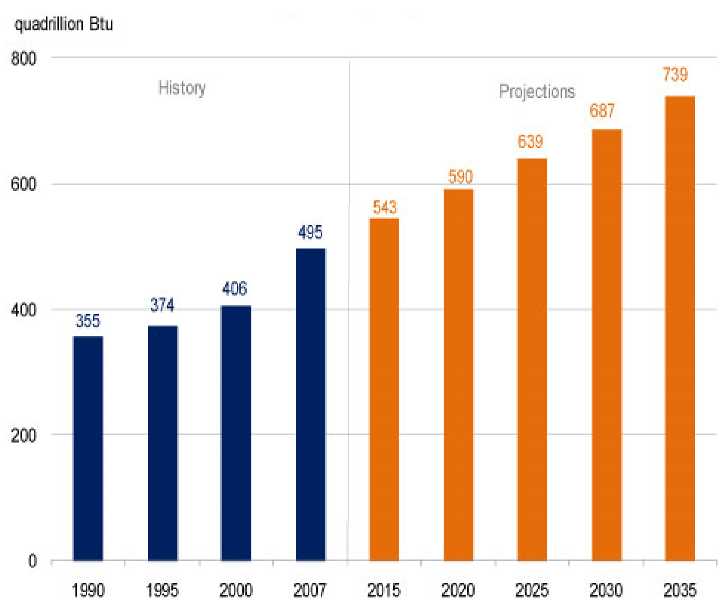


Figure 1.1: World marketed energy consumption, 1990-2035 (3)

Most of the energy is generated by fossil fuels (as shown in Fig 1.2): mostly coal and crude oil showing clearly the heavy dependence of modern society on fossil fuels. Countries' economies and politics are intrinsically related to fossil fuels. As a recent example of the current influence of fossil fuels, Oil Company BP in 2010 registered profits in 2010's 3rd quarter of about $1.8 billion (4) despite the charges and expenses associated to the Deepwater Horizon oil spill ($11.2 billion as of September 2010) (5). Moreover, while our dependence on fossil fuels is predicted to increase, the finite fossil fuels levels will eventually deplete. In addition, from the use of fossil fuels, greenhouse gases are emitted in the atmosphere. This in turn leads to global warming; the year 2010 has seen an increase in natural calamities and many have been attributing this increase to global warming (6). So far the only solution to these problems lies in the development of alternative and renewable sources of energy.

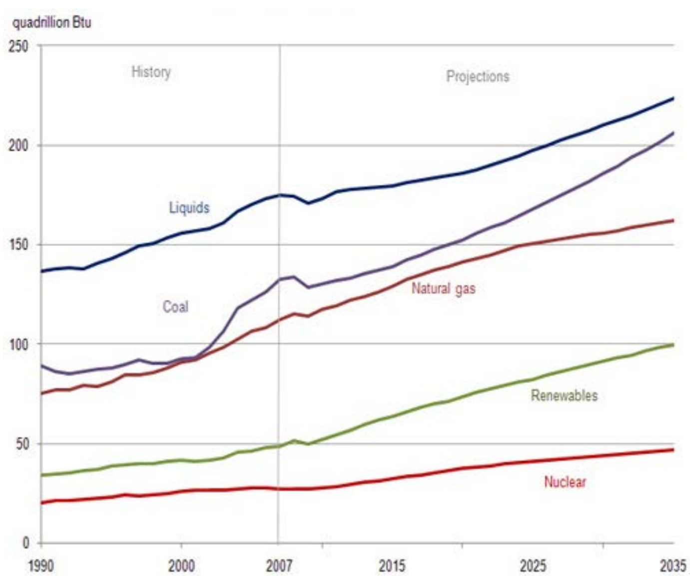


Figure1.2: World marketed energy use by fuel type, 1990-2035 (3)

Out of the total energy consumption, 14% is accounted for residential usage (3) of which a substantial amount is for space heating and air conditioning. In this report we look at the prospects of ground-source heat pumps (GSHPs) in addressing the fossil fuels and global warming issues.

The concept of the heat pump has been put forward as early as 1852 by Lord Kelvin and the idea of using the ground as the heat source was first introduced by Robert C. Webber in the late 1940's. However with the relatively low prices of the more established heat sources like fossil fuels and natural gas, few attempted to perfect the technology at that time. In the past 30 years however, GSHPs have enjoyed renewed interests due to concerns on increasing fuel prices, air pollution and greenhouse emissions.

In the U.S., the primary sources of energy have been wood (biomass), coal, oil, natural gas and nuclear power. Wood has been in use since the discovery of America itself. In 1880, wood provided 2/3 of the industrial and residential fuel used in the U.S (7). Most homes were heated using burnt wood in brick fireplaces and different types of cast iron Franklin Stoves. Starting from 1885 however, coal started to be used more than wood for heating (8). Although the use of wood has diminished since the 1880's, people still continue to use wood for home heating. The use and sale of wood has nonetheless fluctuated throughout the 20th Century. The 1973 oil crisis and the Three Mile Island incident for instance cause sharp and brief spikes in the use and the purchase of wood and wood stoves. As of 2006, wood was the sixth largest source of energy in the US (7).

With the rise of the industrial revolution in the early nineteenth century, coal became increasingly important in energy production. The advent of the coal-driven technology increased the demand for coal among industrialized countries. Great Britain, for instance, went from producing less than 3 million tons of coal in 1700 to over 15 million tons in 1800 and 30 million tons in 1830 (9). In terms of heat, by the end of the 19th century the use of low cost cast iron radiators allowed central heating into American homes with the boiler in the basement burning coal for energy. These boilers pumped hot water or steam to travel through the radiators where they release heat. Coal provided for most heating in the U.S. in the 19^{th} and early 20^{th}, but declined toward the latter part of the century even though it was still the world's primary energy source (9). Coal's massive abundance makes it a cheap and therefore viable source of energy (9). However with coal come significant greenhouse gas emissions and air pollution (9). This led to natural gas being favored over coal. It has higher hydrogen to carbon content making it much more efficient (9).

Another early 19^{th} century innovation was to pipe gas from a gas spring to be used in houses. Many tried to utilize potential of gas as a heating source, but without means to transport it through long distances very few were able to reap the benefits. Natural gas consisting of methane is released as a byproduct of oil production (10). It was only when Colonel Edwin Drake discovered oil in Titusville, Pennsylvania in 1859 (10) that natural gas became significant source of energy. The byproduct of natural gas was marketed to regional buyers and Drake was credited with the beginning of the U.S oil and natural gas industries (10). By the 1860's and 1870's natural gas was used for heating in a variety of industrial uses. When specialized gas pipelines were built the feasibility of natural gas increased exponentially.

In the 1850's, oil was discovered to be a very good lamp oil after Ignacy Lukasiewicz invented the process to distill kerosene from petroleum (11). It was a cheaper alternative to whale oil. Crude oil production skyrocketed from 2000 barrels in 1859 to 4.8 million barrels in 1869 and 5.35 million in 1871 (11). Early on, the main purpose for oil in the home was the kerosene used in lamps. Later on, new oil heating systems replaced the coal ones primarily because there was no need to stoke the fire like the coal systems. With the invention of the automobile, the use of oil became more increasingly driven by the automobile industry. Since around 1930, most of the industrialized nations' economies and politics were dependent on oil. The 20th and the 21st centuries have seen oil as the main fuel. Oil however emits greenhouse gases and supplies fluctuate greatly over time leading to fluctuating prices. As of now, oil is still the most popular source of energy but with decreasing reserves, there is a need for renewable source of energy (11).

One such source of energy is nuclear fission developed from advances made after the Manhattan project (12). It was originally met with great enthusiasm and the hope of cheap and abundant electricity (12). However since its development, Nuclear power has been one of the most controversial energy sources. It was started with the Atomic Energy Act of 1946, which established the institutional framework within which atomic energy decisions would be made for the next thirty years (12). In 1953, President Eisenhower launched an initiative known as "Atoms for Peace". This was to show the world the U.S was not just making bombs but peaceful applications as well. In 1963 at Oyster Creek, the first reactor was built without any direct government subsidy (12). The nuclear market increased after Oyster Creek. Seventy reactors were ordered between 1963 and 1967.

After the initial boom in nuclear power, a very strong anti-nuclear movement developed (12). These protestors were fueled by the nuclear meltdowns like Three Mile Island and Chernobyl and their disastrous consequences. Today in America, there are about 112 operational nuclear plants. The number has decreased from its prime but with tighter regulations the number is unlikely to grow. Although this energy is much cleaner than fossil fuels in terms of air pollution and greenhouse emission, it still produces radioactive byproducts.

Moreover it is highly unlikely that nuclear energy would be directly used for residential heating. Although hot water obtained as a by-product of nuclear fission could be used for heating, the radioactive nature of nuclear fission would lead to the reluctance of consumers although the water could be shielded entirely from radiation (13). Other renewable sources of energy such as solar energy in spite of their high prospects in terms of energy production are not yet capable of supplying houses as the primary heat source.

On the other hand heat pumps and especially GSHPs have proven to be able to supply enough heat during winter even in the upper parts of Northern America. In the late 1980’s to the beginning of the new millennium, the bulk of the research in GSHP was carried out in the U.S. leading to a large amount of GSHPs being installed throughout the country (14). The U.S. recognized the huge potential arising of GSHPs which through cycles of pumping and extraction of heat into and from the ground could be used for heating during winter months and cooling during warmer seasons. Furthermore, ground temperatures are in general less variable than ambient air temperatures. This leads to GSHPs being much more reliable than other heat pumps systems such as Air-Source Heat Pumps (ASHPs). However with respect to the latter, GSHPs also requires a higher initial investment and as such a longer period of time for any return on investment.

In addition, depending on the seasonal climates, the demand for heating (during winter) might exceed that of cooling (during summer). This load imbalance then causes a net decrease in temperature or vice versa in the case where the demands are inverted. With time, this change in ground temperature leads to a decrease in efficiency. GSHP system requires proper soil and climate analysis to determine the components to be used. For instance, larger houses require larger-capacity heat pumps. With changes in ground temperature, the components chosen may not be best-suited for the system anymore and therefore in order to provide the same amount of heat, more energy would have to be supplied.

As of now, the U.S. still possess the largest amount of GSHPs installed. However, Europe and South-east Asia are currently more involved in the development of GSHPs with market growths and demands higher than in the U.S (15). Despite the high efficiency ratings, the high initial cost and space requirement of GSHPs provided too much of a challenge to GSHPs promoters in the U.S. Studies in the 1990's put forward by U.S Environmental Protection Agency (EPA) concluded that despite the highly environmental –friendly figures of GSHPs consumers would instead opt for other technologies with lower initial cost and therefore faster returns such as ASHPs (16).

However GSHPs despite relatively low popularity in the U.S. could be a possible long-term solution to many of the current environmental and energy issues. GSHPs have no *in situ* emissions and no *in situ* fuel storage (17). The use of GSHP for space conditioning instead of other HVAC (Heating, Ventilating, and Air Conditioning) technologies would therefore decrease net greenhouse emissions. Furthermore, they would decrease the total energy production as there will be less energy consumption. To operate the heat pump would still require some substantial amount of energy but significantly less than gas distribution for instance.

With respect to consumers' reluctance to install GSHPs, hybrid systems were and are actively being developed. Hybrid systems make use of auxiliary sources, in general renewable, as an additional source/sink of heat energy. This in effect helps to reduce the size and capacity of the standard GSHP system which helps reduce the initial cost of installation. Furthermore GSHPs are sometimes unable to provide the net heat/conditioned air during extreme conditions. The auxiliary sources can then provide the additional energy required. Hybrid systems can also be optimized to have better performance than the traditional GSHP systems.

In an attempt to provide the reader with a thorough description of GSHPs for residential heating and cooling, we organized the report as follows: starting with Chapter 2, we look at how GSHPs work; their weaknesses and strengths. In Chapter 3, we explore possible hybridization of GSHP systems and how they can minimize the weaknesses discussed in Chapter 2. In Chapter 4, we look at the social and environmental aspects of GSHPs and we sum up in Chapter 5 with discussions on some issues pointed out in the previous chapters.

CHAPTER 2: Traditional GSHP Technology

Thermodynamics of Heat Pump

The idea of changing the temperature of a gas was first demonstrated by Joule in the 19th Century (18). Sadi Carnot later introduced the concept of heat engines in his 1824 book on Carnot Cycles (19). In 1852 Pr. William Thomson (Lord Kelvin) then described a system which through the use of compressors and expanders could be use to "multiply" the temperature of gas which could be use for either heating or cooling. However heat pump only started being developed in the 1940's when the first modern hydrocarbon refrigerants became available (20).

The concept of the heat pump uses the law of thermodynamics called a Carnot Cycle. From conservation of energy, it is possible to increase the temperature of a source of heat by applying mechanical work. As shown in Figure 2.1, by applying mechanical work to heat coming from a lower temperature heat source, we get back higher temperatures.

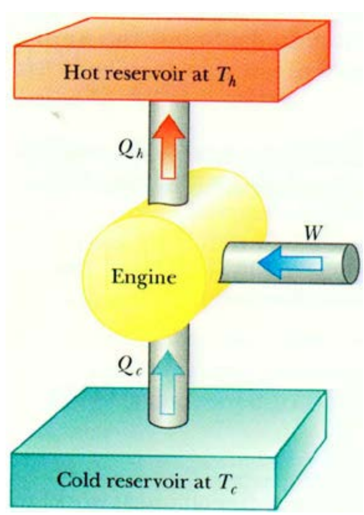


Figure 2.1 Heat Pump Energy Diagram (21). Applying mechanical work to a lower temperature heat source results in an increase in temperature.

However the heat pump cannot change the temperature above a certain limit for a certain amount of work. This arises from the conservation of energy law and also the 2nd Law of Thermodynamics which states there is a limit to the thermal efficiency. In Figure 2.2, we show a typical Carnot cycle which is similar to that in the refrigerant cycle in cooling mode. Transitions 1 to 2 and 3 to 4 are called isothermal expansion and contraction due to the change of volume that takes place. During the isothermal expansion, heat is absorbed by the system causing the expansion while in the isothermal contraction is absorbed from the system causing the contraction. In both process however the temperature is kept constant. If there is no heat loss during the process, transitions 2 to 3 and 4 to 1 are on the other hand called adiabatic expansion and contraction. Pressure, volume and temperature change simultaneously so that no heat loss occurs. For instance during the adiabatic expansion as there is no heat gain from the environment, the temperature of the source has to decrease to provide for the expansion in the fluid. In the same way, during adiabatic compression, there is an increase in temperature. In heating mode, the direction of the cycle in Figure 2.2 would be in the counterclockwise direction. In both cases however, the net work required during the compressions and expansions of the fluid is greater than the net heat gain or loss by the system.

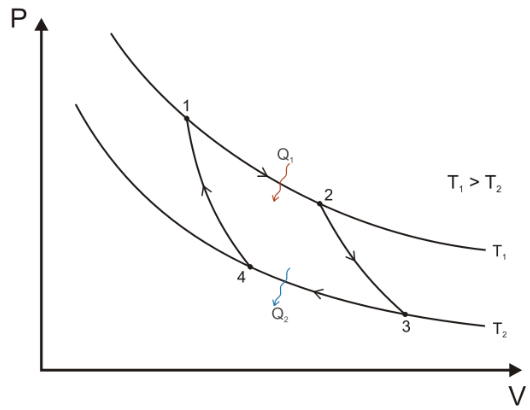


Figure 2.2: Pressure vs. Volume graph for a Carnot Cycle (22). The cycle consists of four transitions. The first one (1-2) is an isothermal expansion with same temperature and increase in volume. In the case where there is no heat loss during the second transition (2-3), the process is called an adiabatic expansion. The third transition is an isothermal compression (3-4) and the fourth (4-1) is an adiabatic compression returning the system in its original state.

As such the use of measures to gauge the efficiency of the heat pump became of importance. The most common measure is the coefficient of performance (COP) which is the ratio of the heat released (higher temperature) to the work applied.

$$COP = \frac{\text{Heat from High Temperature}}{\text{Work Applied}} = \frac{Q_H}{W}$$

Correspondingly for the refrigeration cycle, the COP is given by

$$COP_{refrigeration} = \frac{\text{Heat from Low Temperature}}{\text{Work Applied}} = \frac{Q_L}{W}$$

As mentioned above, there is a limit due to the 2nd Law of Thermodynamics to the COP of any heat pump and is given by the Carnot coefficient of performance

$$COP_{carnot} = \frac{T_H}{T_H - T_L}$$

Looking at Carnot COP also shows why the efficiency of Geothermal Heat pumps is normally higher than other heat pumps. In GSHPs, the temperature difference between the source temperature and the building temperature is normally smaller as the ground temperature (source temperature) is normally closer to the required building temperature.

Apart from COP, the Energy Efficiency Ratio (EER) is another commonly used efficiency measure. EER have been associated to cooling rather than heating.

$$EER = \frac{\text{Cooling Output in Btu}}{\text{Electrical Input in Watt-hours}}$$

Additionally, another commonly used measure is the Seasonal Energy Efficiency Ratio (SEER). SEER is similar to the EER but considers the performance over the full cooling season as compared to the performance at a specific instance in EER. SEER therefore takes into account fluctuations in cooling needs throughout the warmer periods.

$$SEER = \frac{\text{Total Cooling Output over Cooling Season in Btu}}{\text{Total Electrical Input in Watt-hours}}$$

In Figure 2.3 and 2.4, we show the temperature dependence of COP and EER values for a 3-ton ground-source heat pump.

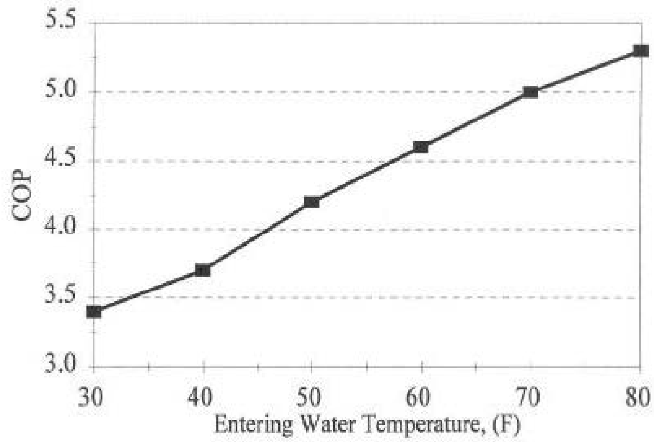


Figure 2.3: Variation of COP with water coming from ground loop (23)

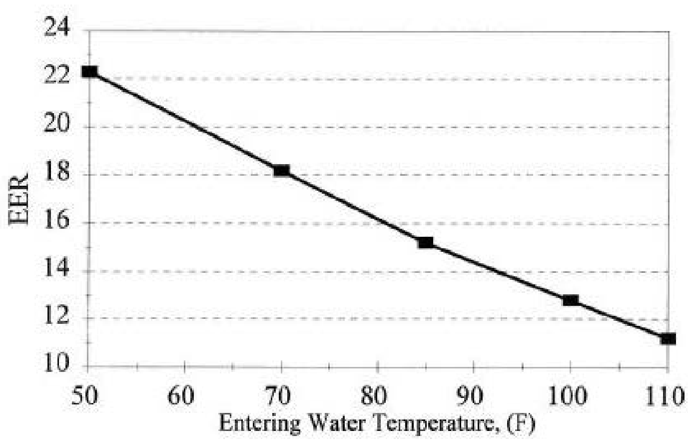


Figure 2.4: Variation of EER with water coming from ground loop (23)

Both the COP and EER show linear dependences with the temperature of the water coming from the ground. This is expected from the relation in terms of absolute temperature of the Carnot COP although the systems considered in Figure 2.3 and 2.4 are not ideal Carnot cycle.

Compression/Expansion Cycle

The compression and expansion cycle is the cycle in the heat pump where the temperatures rise occurs. The temperature rise is obtained by compressing the fluid adiabatically. Later in the cycle the fluid is cooled down by expanding the heat fluid to restore the lower temperature in the closed loop. The expansion and contraction are normally carried out through mechanical work.

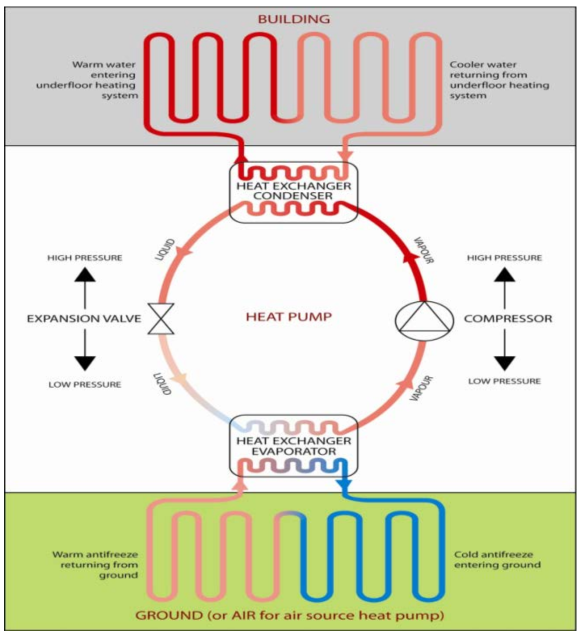


Figure 2.5: Compression and Expansion in Refrigerant Cycle (24). In heating mode the cycle is clockwise while in cooling mode the cycle is counterclockwise.

In Figure 2.5, we show the compressions and expansions in the heat pump. The isothermal processes occurs inside the heat exchangers (evaporator and condenser) while the adiabatic processes occurs at the expansion valve and the compressor. In heating mode, fluids coming from the ground exchange heat with the fluid in the compression and expansion cycle through the heat exchanger (evaporator). During the heat exchange, the temperature of fluid in the compression and expansion cycle at the exchanger is kept constant through an isothermal expansion. The expanded fluid then flows towards the compressor where its temperature is increased through an adiabatic compression. After passing through the compressor, the fluid which is at the higher temperature, exchange heat with the building loop in the other heat exchanger (condenser). This time the fluid inside the cycle is releasing heat to the building and the temperature is kept constant through an isothermal compression. The temperature is then decreased at the expansion valve to complete the cycle and return the fluid to its original state.

Heat Exchangers and Refrigerants

In the expansion and compression cycle (or refrigerant cycle), the fluid used has high compressibility and can be converted from gaseous state to liquid state easily. Such fluids are called refrigerants. The most common refrigerants used today are the hydrochlorofluorocarbons, HCFCs such as R22. In the past chlorofluorocarbons, CFCs such as Freon were used but due to their ozone depleting characteristic when leaked, HCFCs were preferred as they are not as damaging to the ozone layers (25). In recent years, there has however been some interest in hydrofluorocarbons, HFCs such as R-410A which do not affect the ozone layer but just as CFCs and HCFCs however contribute to global warming (26)

In GSHPs, typically the input temperature in the refrigerant cycle comes from the ground water loop. Therefore in order to transfer the heat coming from the water loop, a heat exchanger is used. Heat exchangers are devices that allow the transfer of heat from a warm fluid to a cooler fluid with any mixing of the two fluids by using an intermediate surface. The heat transfer occurs through convection and is given by the typical rate of heat transfer equation

$$\frac{\partial Q}{\partial t} = hA\Delta T$$

where $\partial Q/\partial t$ is the heat across the exchanger, h is the coefficient of heat transfer, A is the surface area in contact and ΔT is the temperature difference between the two loops. The heat transfer depends on the surface area in contact with the two fluids. This accounts for the generally complex geometries of heat exchangers. However some heat is lost during the heat transfer as the complex geometries also allows for heat transfer to the surroundings.

These heat losses have therefore led to interest in the so called direct exchange systems. Instead of having to transfer heat from the ground water loop and the refrigerant loop, the refrigerant is made to pass through the ground loop and the compression and expansion are carried out in the same loop. As such this limits the heat losses. However refrigerants are normally denser than water and therefore such system requires more power for sustaining the fluid flow. For smaller systems direct exchange has led to significant increases in efficiency but in larger systems the reduction of heat loss is counterbalanced by increasing power required to maintain fluid flow.

Types of GSHP systems

While the ambient temperature of the air varies from month to month, the ground temperature stays relatively constant. As seen in the Figure 2.6 and 2.7, the soil temperature varies less at greater depths at different times of the year. Soil temperature varies as a result of solar radiation, rainfall, type of soil, change in air temperature and even cover from local vegetation (27). The further down into the Earth the temperature is recorded the more constant it is. At depths greater than 30 feet underground, the soil temperature is relatively constant. This phenomenon is due to the fact that the heat capacity of soil is much higher than it is for air, and that the underground soil is insulated by vegetation and the above layers of soil (27). These conditions allow the soil to change very slowly in response to change in air temperature. This constant ground temperature is what allows the GSHP to heat space in the winter and cool it in the summer. At shallow depths, however, the soil temperature can change significantly in response to the air temperature.

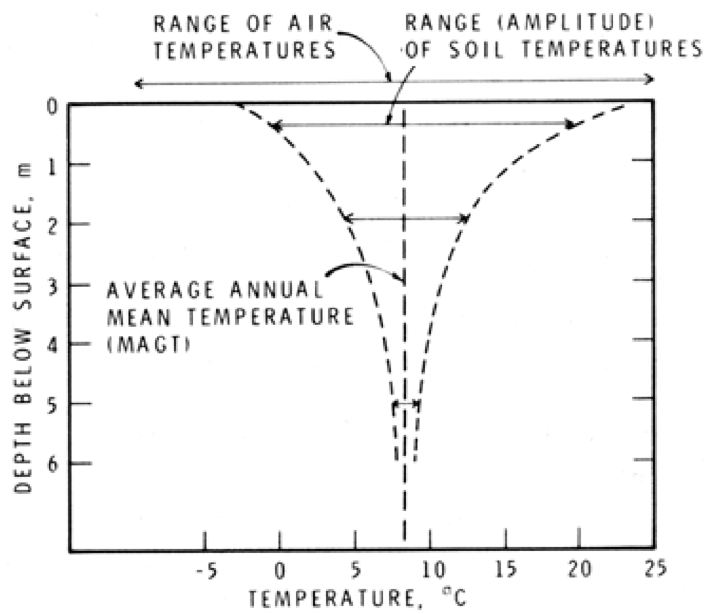


Figure 2.6: Depth dependence of the annual range of ground temperatures - Ottawa (28)

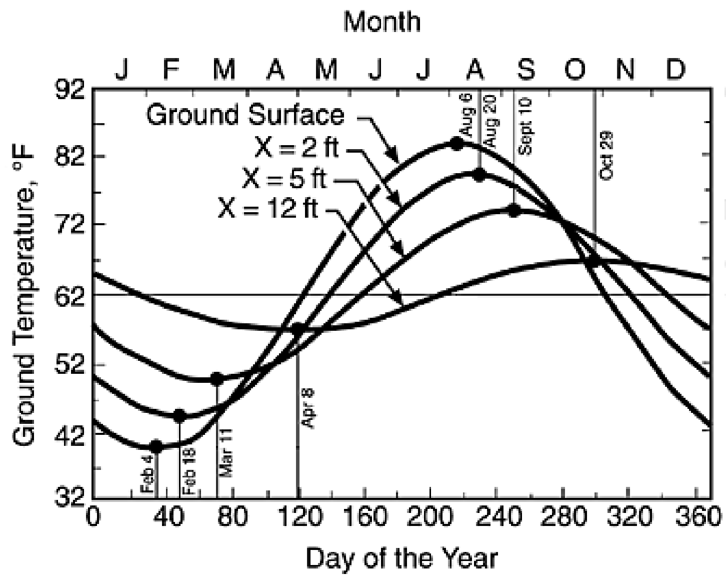


Figure 2.7: Year Round Ground Temperature at Different Depths (27)

It is clear that over the course of a year the ground temperature change is almost sinusoidal. As one goes deeper into the ground, it is shown in the graph above that the amplitude of these sine waves is much lower from only 12 feet of depth.

The GSHPs uses this thermal property of soil deep underground. The most common types of these GSHPs in use today are the open and closed loop systems. We outline the similarities, differences of these systems here. Aspects such as the piping systems, limitations, cost and overall feasibility of these two systems will be explained. These methods of GSHP harness the heat naturally produced by the Earth underground and transfer it to fluid circulated through the system. By using the fact that the ground temperature at a certain depth is relatively constant, the GSHP will cool the space in the summer and heat it in the winter.

Closed Loop Systems

Energy Transfer Mechanism

The science behind GSHP is based on the heat produced in the Earth and the ability to transfer it from soil to a fluid circulating through the system. The transfer of heat from the ground to the home is based off of principals of heat transfer and thermodynamics. For the closed loop GSHP, the heat is transferred through conductive heat transfer. Heat always goes down the gradient from areas of higher thermal energy to an area of lower thermal energy. So if the air is cooler than the ground the circulating fluid will absorb heat and bring it back into the system. During the summer, the excess heat in the air is transferred into the ground and the Earth acts as a heat sink. The heat is transferred from the soil to the pipes and then into the fluid before entering the house. This works on a subatomic level because of the movement of atoms and molecules. Atoms and molecules move and vibrate with an increase in thermal energy. These molecules interact with neighboring ones and they transfer some of their kinetic energy to the neighbor atoms. This means that atoms from the hotter soil move at a much higher rate than the atoms of the pipe. The thermal energy from the soil is transfer to the pipe until each are in equilibrium. The heat is then transferred from the pipe to the fluid by means of convective heat transfer.

There are 2 main types of closed-loop systems: namely horizontal loops and vertical loops. In horizontal loops, the piping is stretched over large surface areas while in vertical loops the piping goes deeper in the ground.

Horizontal Closed-Loop Systems

Horizontal closed loop systems are the most common layout wherever there is adequate land to use. To install this type of GSHP approximately 9000 square feet is required (29). This system has a much lower installation cost because trenching is much less expensive than drilling wells and is easier to install. The system is very flexible with many different types of piping arrangements and allows shorter trenches to absorb the same amount of heat as larger ones. This system is composed of parallel pipe arrangements that run horizontally in the ground. A trench is dug at depths between one and two meters and is about one meter wide. The trench is below the frost line and multiple trenches can be used to maximize power while minimizing load imbalance. The pipes range in diameter from 3/4 in to 1 1/2 in and are made of high-density polyethylene. Between 400 ft to 600 ft of pipe is installed per ton of heating and cooling capacity. A problem with horizontal GSHP is that these heat exchangers are more affected by weather and the temperature of the air due to the shallow depth at which they are buried (29). As seen in Figure 2.7, the shallow depth decreases the temperature difference in the system and thus decreases efficiency. The temperature of the ground is more easily affected by seasonal variance and the thermal properties are affected by seasonal changes, rainfall and burial depth. Another issue with the system is that the backfilling process in the trench can damage the piping system. When compared to the vertical closed loop, the horizontal loop requires more piping and more pumping energy which therefore increases the amount of work put in to the system and is less efficient because the temperature gradient between the ground and the ambient air is usually a lot smaller (29).

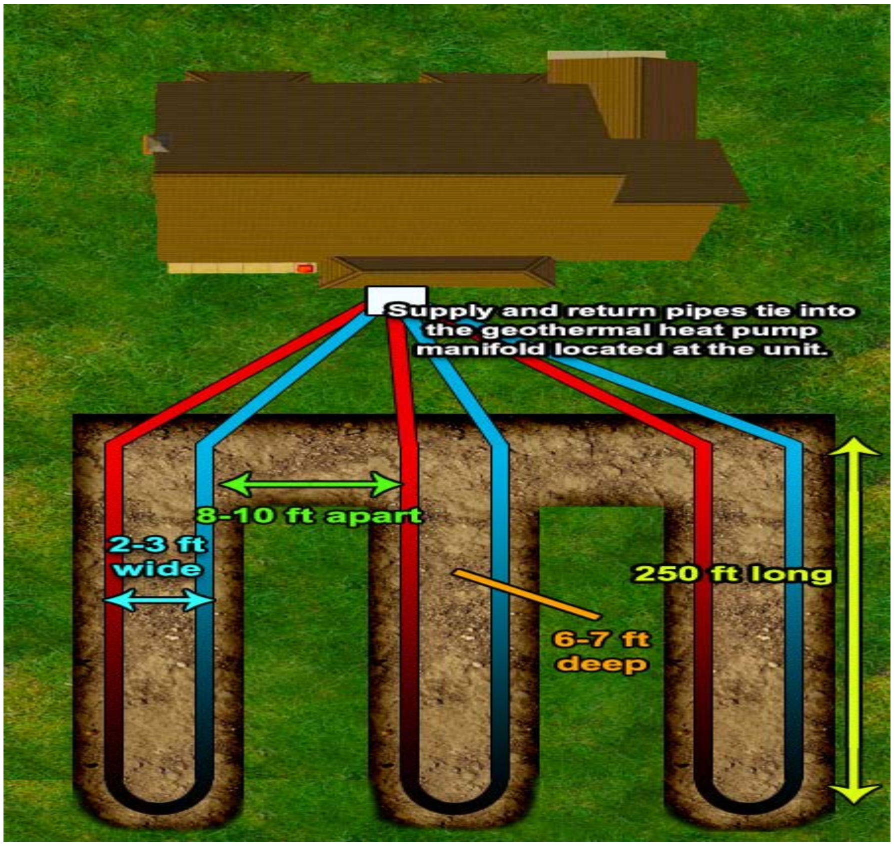


Figure 2.8: Piping Diagram for Closed-Loop Horizontal System (30). In closed-loop horizontal systems, the piping to extract heat from the ground covers a larger surface area but however goes only up to 7 ft underground. Water flows through the pipe, extracts the heat from the ground and enters the heat pump.

One very popular configuration of the horizontal closed-loop system is the “slinky”. The “slinky” and other spiral loops decrease the amount of trenching needed to install and therefore reduce the installation cost (31). Also this configuration reduces the amount of land needed while increasing the outside area of the piping per length. The increase in area because of the coiling increases the heat transfer while decreasing trench length. The coiling increases heat transfer by increasing the amount of contact with the ground because of more piping per length. The main thermal recharge for these systems is produced by solar radiation, and it’s important not to cover the ground above the system. Doing so will reduce the efficiency of the system and create a load imbalance.

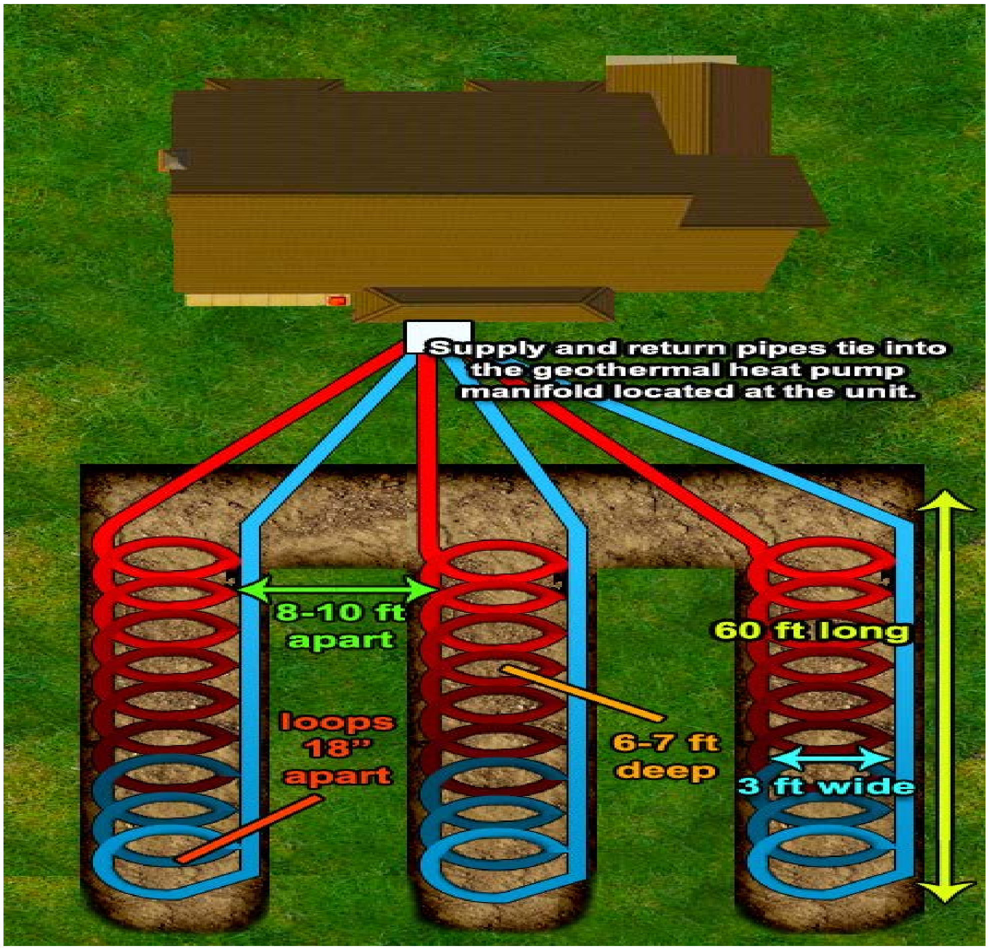


Figure 2.9: Pipe Diagram for Closed Loop "Slinky" Installation (30). The slinky coil provides with more surface area in contact with the soil and therefore allows for better heat exchange between the water in the pipes and the ground.

A variation of this system which is used in France and Austria is the direct expansion mentioned earlier. The direct expansion system uses a ground coil system (32). The working medium of the heat pump is circulated directly through the ground heat collector pipes. The heat pump's evaporator/condenser is extended into the ground where it can absorb heat during the heating mode or expel it into the ground during the cooling mode (32). The condenser in the ground is advantageous because it eliminates one heat transfer process and thus increases efficiency.

Vertical Closed-Loop Systems

When horizontal closed loop GSHP is unable to be installed, the contractors will normally turn to vertical loop GSHP. This type of GSHP is based on the same principle as the horizontal closed-loop systems but the trenches are replaced with boreholes going deep into the ground rather than a trench only a meter or two in the ground. Deep underground, the ground temperature remains more constant and creates a bigger temperature difference with the air above. Another major advantage with vertical closed-loop systems is that the space requirement is smaller compared to the horizontal loop. However, a major drawback is that the cost is higher because of the drilling cost.

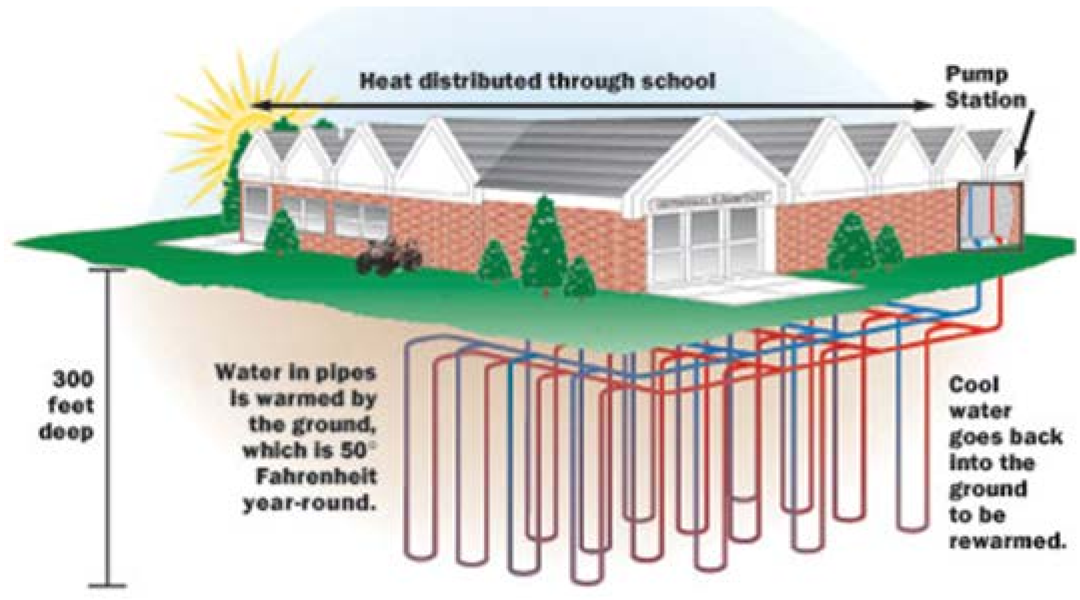


Figure 2.10: Piping System for a Vertical Closed-loop System (33). Water goes through the vertical boreholes absorbing heat from the ground and then goes to the heat pump.

Vertical loop is the most commonly used type because of its high efficiency and lower constraints on land area. The vertical systems are based on ground temperatures below approximately 15 to 20 meters in the ground remaining constant year round. Using this property of the ground this system has a temperature that's warmer than winter air and cooler than summer air. The system contains 1 to 10 boreholes each containing a U-shaped pipe where heat exchange fluid of water and antifreeze is circulated. The boreholes are spaced about 12 to 20 feet apart, depending on the climate of where it's installed. The diameter of the u-tubes ranges from 0.75 in to 1.5 in and each borehole is 100 ft to 300 ft deep with diameters ranging from 3 in to 5 in. In areas where there is greater cooling or greater heating needs a load imbalance can occur. A load imbalance can result in a change in the ground temperature and will decrease the efficiency of the system. A load imbalance can be minimized by increasing the size of the ground heat exchanger or increasing the distance between the boreholes. Although this will slow down the load imbalance, it will result in a higher cost for the system. The pipes inserted into the borehole are made from polyethylene or polypropylene. After insertion of the pipes and the u-tubes the borehole is commonly filled with a bentonite grout surrounding the pipe to provide a thermal connection to the surrounding soil or rock, thus improving the heat transfer to the system. This grout also provides protection from ground water contamination because it provides a seal between the pipe and the surrounding ground water. The thermal performance of the vertical system can be affected by geological formations and properties. This can complicate the installation of this system. For large systems the size of the heat exchangers is carefully determined to optimize the properties of initial cost and yet still meeting the building's thermal load. The major flaw of the systems is its comparatively high initial cost. This high cost is due to the need to drill to get the pipes down deep. Average drilling cost is between $5,000 to $10,000 depending on soil conditions, geology and the size of the system needed (34). However, the drilling costs can increase if drilling conditions are poor. The high initial cost can be mediated by the higher efficiency of the system. Of the 80,000 units installed annually in the United States 46% are vertical closed loops systems, 38% are horizontal closed loop systems and 15% are open loop systems (35).

Soil Conditions

The properties of the soil that the ground source heat pump is installed in plays a significant part in determining how much energy per unit of pipe, the relative efficiency of the system and the feasibility of installation. To install a GSHP, the soil needs to meet certain criteria. Some criteria for the soil that must be examined are depth of the bedrock, soil composition, moisture, thermal properties and ground temperature. The seasonal variation in soil temperature, heat capacity and thermal conductivity should be determined to quantify the heat transferred per unit of piping. The higher the thermal conductivity of the soil the more heat transferred per unit of piping. The main aspects of the soil that are of importance are the ground temperatures, soil composition and the thermal conductivity. In addition to that, the heat capacity is a factor in determining the feasibility of these systems.

The geologic properties and composition of soil can have a great effect on a geothermal system. The depth of soil cover, the types of soil and rock and the ground temperature are all important factors to consider when installing a geothermal system. If bedrock is within 1.5 meters of the surface it may be impossible to install a horizontal system. Large boulders also can prevent the installation of a horizontal closed-loop. A vertical system would be the only option in this case. For vertical closed-loop systems, however, the amount of soil directly impacts the cost. The less soil present means the more rock that has to be drilled through. This is very time consuming and expensive. Also the borehole has to be cased if it goes through rough ground. This leads to higher drilling costs and more time consumed for installation. With higher efficiency, the required amount of piping is greatly reduced to receive the same heat load.

In addition to the ground temperature, the heat capacity and thermal conductivity are crucial variables to observe when installing ground source heat pumps. Heat capacity is defined as the amount of heat required to raise the temperature of a substance one degree. As heat capacity increases, the substances can gain and lose more heat per change in temperature.

This measurement is very important for GSHP because the more heat that can be stored, the more heat can be released. In dry soil, the heat capacity is around 0.20 Btu per pound per degree change in Fahrenheit temperature (27). Water has a heat capacity of 1 Btu/lb/^{o}F. Due to this fact, moist soil has a higher average heat capacity. The average heat capacity is around 0.23-0.25 Btu/lb/^{o}F.

When installing GSHP another soil property to examine is the thermal conductivity. The thermal conductivity of a soil greatly impacts the efficiency of the system. Thermal conductivity is the rate at which the heat in the soil will be transferred into the ground loop and therefore how efficient the system works. The thermal conductivity has affects on the installation cost. Thermal conductivity varies between different types of soil. As the texture of soil becomes finer, the thermal conductivity tends to increase (27). Also much like heat capacity, the thermal conductivity increases as the soil becomes increasingly moist. The relative thermal conductivities for some soil examples are seen in the table below.

Table 2.1: Thermal Conductivity of Different Soils (27)

Texture Class	Thermal Conductivity, Btu/ft hr F
Sand	0.44
Clay	0.64
Loam	0.52
Basalt Rock	0.2
Dolomite Rock	0.22
Polyethylene	0.42-0.51
Polypropylene	0.1-0.22
Saturated Sand	1.44
Saturated Silt or Clay	0.96

By increasing efficiency, the thermal conductivity also impacts the sizing of the total system. This would cut costs on installation because fewer trenches or U tubes would need to be dug. If the soil has low conductivity, it may require as much as 50% more collector loops than highly conductive soil because the lack of conductivity means the fluid in the pipe needs to be in contact with the ground longer. The table below shows some examples of thermal conductivity and the amount of boreholes/ total length of piping for a ten ton load for a vertical closed loop GSHP system.

Table 2.2: Soil Conductivity and the Corresponding Amount of Piping Needed: (27)

Soil Thermal Conductivity, Btu/(ft hr F)	Number of U-Tubes	Effective Depth of U-Tubes, vert. feet	Total U-Tube Vert. Length, vert. feet
0.55	16	199	3,180
0.7	15	188	2,820
0.85	14	187	2,620
1	12	202	2,420
1.2	12	188	2,260
1.35	12	180	2,160
1.5	10	212	2,120

Open Loop

Energy Transfer Mechanism

In the open loop systems, the means of heat transfer is by convection. The open loop is where the water is taken directly from an underwater aquifer which has been previously heated from the ground. That water is taken up into the pipes and then up into the system. This is an example of forced convection, which is when fluid is forced to flow by an external force. The force in this case is the pump which makes an artificial convection current. This brings the warm water down the thermal gradient into the cooler air.

An open loop GSHP has a simple design concept. It consists of a piping system and a heat exchanger to deliver heat from the ground to the house, or from the house to the ground depending on the season. In Figure 2.11 we show the basic concept of an open loop GSHP.

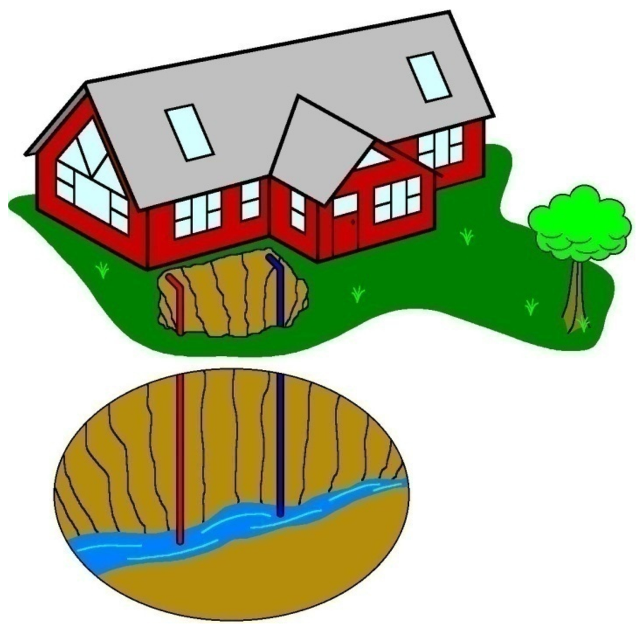


Figure 2.11: Open-loop system diagram (36). Water from an underground aquifer is pumped into the house from the ground to either warm the house or to take warmth from the house, and then it is returned to the ground.

Open loop GSHPs are slightly more efficient than closed loop because there are fewer heat transfer steps involved. Open-loop transfers heat from the ground to water to the heat exchanger, while closed loop transfers heat from the ground to a pipe to a circulating coolant to the heat exchanger. In each of these heat transfer steps a small amount of energy is lost, and is no longer available to heat the house. Using the underground water source also increases the rate of heat transfer because the underground water has a much greater surface area contacting the earth than the pipes in a closed loop system. Usually the return location is a sufficient distance from the source so that heat pollution (the addition or removal of enough heat in the ground to either effect the operation of the heat pump or the underground environment) in the ground is minimized. If not done, over time the ground temperature gets closer to the house temperature. This causes a drop in the efficiency of the heat pump and can also affect the habitat of animals and the environment for plant life (35).

Open-loop systems require by the presence of an underground aquifer. If there is not an available underground water source near the residence, an open loop system can't be used. While open loop GSHPs can be used with artificially made wells, it drives up the cost of installation. Artificially made wells have caused problems in the past with high pressures in the return well. The piping for open loop systems only needs to be long enough to get to and from the underground water source. Open loop systems can sometimes contaminate ground water or affect the underwater environment by adding or removing too much heat. Open loop systems are also more susceptible to damage from environmental causes such as buildup of sediment and minerals on piping, or corrosion due to acidity (37).

Desuperheater

In addition to heating and cooling, geothermal systems can also be used to heat the house's water supply. With the addition of a desuperheater, home owners can save even more money on monthly costs. A desuperheater is small, auxiliary heat exchanger that uses the hot steam from the heat pump's compressor to heat the home's water supply. The desuperheater works by using a circulating pump that moves cold water from the bottom of the hot water tank to the desuperheater itself. In the desuperheater, the heat from the geothermal system is used to heat the water. The water heated in the desuperheater goes through a pipe and is deposited in the home water tank. This heat recovery system can make about 60 percent of a house's hot water. The use of the desuperheater in a geothermal system will cost on average about 80 percent less in heating dominated climates, as well as about 95 percent less in a cooling dominating climate. This is compared to heating water with electric, oil or propane powered water heater. The hot water heater only heats the water when the geothermal system is heating or cooling the home. The heater is also good during the summer because it makes use of the heat that is normally expelled into the ground and wasted. This results in almost free hot water during the summer because the heat from the house is transferred to the hot tank. The only cost for the summer water heating is the cost of running the circulating pump that moves the water and this cost is very little. In colder climates, the heaters may require help to heat the water. Small electric resistance heaters can be used at the expense of about 30 or 40 dollars a year. This unit itself is about $500, but it will save money in the long run by cutting the water bill and in the summer helping to dissipate the excess heat. Many geothermal systems are installed with a desuperheater. Figure 2.12 below is a schematic of the desuperheater unit.

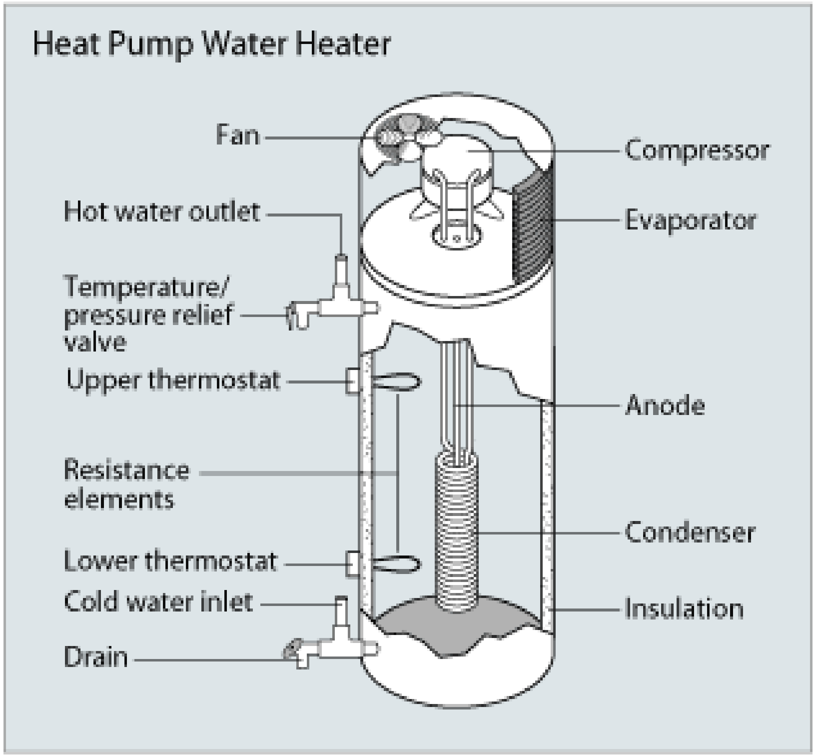


Figure 2.12: Schematic Drawing of the Desuperheater (38)

General Overview

In this chapter, we looked at the different types of GSHP systems: open and closed loop. The main problem with GSHP is its high initial cost of installation. With the high initial cost of ground source heat pumps it may seem like this technology cannot be put in the average home. Especially in the current economic downturn, many people fail to collect the money required for drilling to install the system. Looking at this problem by the numbers, you can see that the average resident of Massachusetts makes $52,710 dollars per year (39). The average mortgage in Massachusetts is $1,200 a month (40). Combining this with car payments, insurance food and other cost of living, It would be very difficult to afford GSHP which can range from about

$6,000 to $10,000 or higher depending on house size. However thanks to federal and state incentives program to help improve our environment, energy-efficient and green technology are eligible for tax cuts and loan rebate. The federal tax credit is worth up to 30% with no upper limit and the offer expires December 31, 2016 (41). Although this credit applies to both existing homes and new construction rental homes of any kind do not qualify for a tax credit. This tax credit can open access to GSHP even for people without the money on hand to do so. Another way a homeowner can afford the high installation cost is through financing. If the GSHP is being installed in a new construction or a major addition, the cost can be financed through a mortgage.

Another consideration when installing GSHP is the space needed if you are installing a horizontal system. The average area needed for a horizontal system is approximately 9000 square feet depending on load requirements (29). In more suburban areas like Needam, Natick and Sudbury, they have average lot sizes of 0.93 acres, 0.95 acres and 3.25 acres respectively (42). With the houses only averaging about 2500 square feet and an acre being about 43000 square feet these towns are perfect candidates for horizontal systems (42). In more urban areas such as South Boston, Dorchester and downtown Worcester, there is very little space to build anything on already built up lots. In these areas, even installing a vertical loop might be difficult because of this lack of space. Unless GSHP is installed before the house is built there will be very limited space.

Soil characteristics also determine the feasibility of a geothermal system in certain areas. Different types of soil have different properties, and one of the most important is its thermal conductivity. The higher its thermal conductivity, the more efficient the system will be.

In addition to its thermal properties the composition of the soil can also impact the GSHP systems. If the soil is too rocky, has boulders or has bed rock within about 1-2 meters from the surface a horizontal loop may be impossible or impractical. Along that point, the rockier rocky soil the higher the drilling cost for vertical loop and that raise in the initial cost could make it not feasible or cost effective. Also for extremely lost soils, the pipes can shift in the vertical loop and break. So in places with sandy soil like the towns around Cape Cod vertical loop GSHP may not be feasible.

However despite the limitations, GSHP systems are still appealing as they in general require low maintenance and are highly reliable. The components of the systems are normally installed inside and therefore suffer low wear and tear throughout the years. Thus the performance of the system with respect to the components status is not expected to deteriorate with time. The only possible source of damage would be in the piping system. Choosing an inappropriate ratio of refrigerant to water determines the work required by the pump. A higher concentration would reduce the risk of cracking in pipes but at the same time would require a higher energy input from the pump to set up the fluid flow. With a proper selection of the ratio of refrigerant to water, one can therefore reduce the risk of pipe cracking to being insignificant and at the same time minimize the energy input required. In a general sense, the reliability of GSHPs depends mainly on the installation. If a proper analysis of the climate and ground condition is made before the installation, then the components to be installed can be properly selected. Such optimization would correspond for example to choosing the right borehole length, proper grouting materials and heat pump capacity for the expected usage. The first two for instance would help in reducing the load imbalance and as such reduce the efficiency drop due to changing ground temperature. However not only will the performance of the system be maintained throughout the years but the expected lifetime would consequently also increase. To sum it up, GSHPs are intrinsically not prone to major wear and tear as they are not exposed to extreme conditions. Therefore they are able to operate with the same efficiency and over a longer period as seen in Figure 2.13.

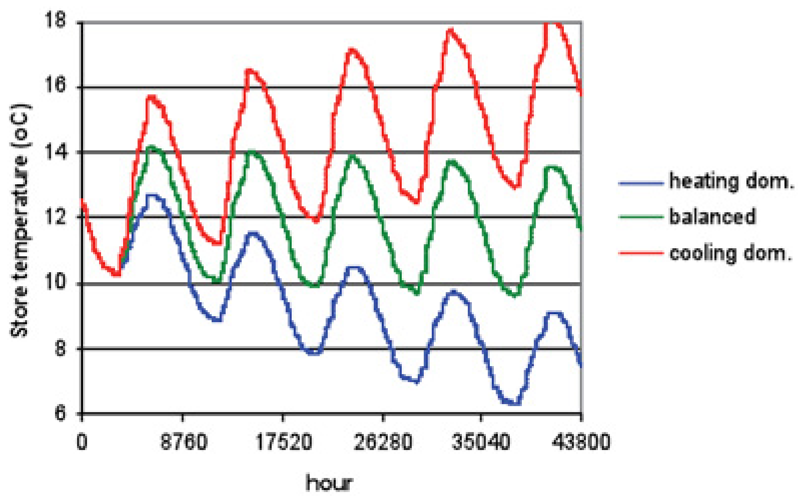


Figure 2.13: Long-term temperature in the BHE under unbalanced (heating or cooling only) or balanced annual loads (43)

However optimization normally comes at a higher price. For instance to optimize the system, longer borehole length might be required which in turn would require more drilling and a higher initial cost of installation.

Also the underlying concept behind geothermal heat pumps allows them to produce similar level of performance throughout the year as we have seen earlier that the ground temperature remains almost constant for sufficiently deep wells. Therefore during heating seasons, the source temperature for heating is always higher than the ambient temperature and similarly during cooling seasons; the source temperature for cooling is lower than the ambient temperature. This consistency of source temperature allows for an easier analysis of the system required and therefore the system can be designed to be efficient throughout the whole year.

In Chapter 3, we look at the possibility of hybridization of GSHP systems with other heating and cooling technologies. We also look at how hybridization can deal with the limitations and weaknesses of GSHPs mentioned above

CHAPTER 3: Hybrid Ground-Source Heat Pumps

Despite initially enjoying success and being hailed as one of the greenest and energy-efficient technology (16), GSHPs had since fallen short on the expectations while other technologies such as ASHP systems, or gas and coal have been increasing their global market shares (15) (14). The lack of success of GSHP systems can be mainly attributed to their higher initial cost and space requirements as compared to other heating and cooling technologies (14) (15).

In the previous chapter, we looked over the traditional GSHP systems and came up with the following list of limitations and weaknesses in GSHP systems:

1. High initial cost – on top of the purchase of the heat pump, a geothermal heating and cooling system requires drilling and grouting. This lead to more thorough and expensive post-installation ground and climate analysis as well as increase in raw material and labor cost compared to other technologies.
2. Space requirement – for open loop system, in general a water source should be already available while in closed loop system, depending on the amount of land available and the soil properties, installation of trenches or borehole might not be possible.
3. Load Imbalance – locations with different cooling and heating loads would suffer from increase or decrease in the ground temperature. This in turn would lead to decrease in efficiency of the system thereby affecting the predicted net savings on the GSHP installation.

In this chapter we go through the concept of hybridization and how it helps resolve environmental and social issues as well as providing solutions to the limitations mentioned above. We then provide a general overview of hybridization, its strengths and its weakness.

Concept of Hybridization

For several decades, two of the main worldwide issues have been global warming (44) and decreasing reserves of fossil fuels (45) (46). GSHPs directly reduce the use of fossil fuels by providing an alternative to heating through oil and coal. Furthermore, the higher efficiency of GSHPs reduces the net electricity consumption for heating and cooling by up to 50% (47). This reduced use of electricity usage in turn decreases the net oil and coal usage and correspondingly pollution and greenhouse emissions. It can be further argued that this net energy consumption reduction minimizes the energy consumed in energy transport: as less electricity is used, there is energy loss during electricity distribution and also less energy is spent through actual transportation of fossil fuel.

In order to overcome the hurdles faced by GSHP systems, the notion of hybrid geothermal systems was introduced. The concept lies in using additional heat sources or heat rejecter; by combining technologies, mostly renewable ones, the strengths of one technology are used to offset the weaknesses in the second. With the additional heat being pumped inside the ground or increase in excess heat being rejected, the problem of load imbalance that the traditional GSHP systems faced can be easily taken care of by either allowing more heat in through the additional heat source or by releasing more excess heat. This is not entirely novel concept as traditional GSHP systems are normally connected to auxiliary energy sources such as oil or air conditioner units so as to provide for surplus heat or cold air during days with extreme temperatures. With hybrid systems, the additional heat source or rejecter provides the additional energy required from renewable sources and there is no use for the usually less efficient auxiliary sources. However with the addition of the new components, the heat pump systems become more complex in the case of hybrid system. In order to use the hybrid system to its full capacity, a more thorough analysis is required before installation to determine the correct type and size of components to be used. Also the system requires complex real-time monitoring accounting for changes climatic conditions. However when optimized for the expected usage, hybrid systems can successfully reduce the initial cost, increase significantly the efficiency, any load imbalance, and reduce the size of the components (borehole or trenches).

Optimization of hybrid system

1. Cooling-oriented vs. Heating-oriented environment

When devising a suitable hybrid system to be implemented, we first need to consider whether the system is going to be used in a cooling-oriented or a heating-oriented environment. By cooling-oriented, we mean one with more cooling needs than heating needs. As such we would expect with time a gradual increase in the ground temperature due to excess heat. Similarly a heating oriented environment would require more heating than cooling and this would eventually leads to a decrease in temperature of the GSHP. In general, when deciding the capacity of the GSHP and the size of the borehole field or trench size, one bases their final choice on factors such as the thermal properties of the soil and the average ground temperature as discussed in Chapter 2. However as the ground temperature varies with time as well as possibly and subsequently the thermal properties of the soil, the efficiency of the pump decreases. With continuous decrease in efficiency, the long-term savings from using GSHP system will also decrease. At the same time, this could also cause a reduction in the expected lifetime of the system.

Hybrid systems offer solutions to both decrease in efficiency due to load imbalance and space limitations but however require different schemes for each. For instance, in the cooling-oriented system the use of a heat rejecter is required. As such the excess heat accumulated during the warm seasons can be removed from the system. This keeps the temperature constant and there will not be any deteriorations of the system performance. On the other hand, for the heating-oriented environment, we require an additional heat source that will take into account the additional heat required during cool seasons. The heat from the additional source and the ambient air will be combined to cope with cooler periods' heating demands. In doing so, the net loads throughout the whole season are insignificant and will not affect the ground temperature.

2. <u>Efficiency vs. Cost</u>

Hybridization of systems involves more complex analysis and optimization. These involve choosing the best components to be used according to the climatic and geographical conditions. The choice of the type of hybridization could also be geared towards cost rather than efficiency. After choosing the components which would suit the customer the best, the system must be configured so as to minimize any excess energy usage. Hybridized systems involve adding more components to a traditional system. Often these components are less efficient in terms of generating heat than GSHPs but are financially more affordable. However without any proper configuration running the combined system could end up reducing the efficiency as well as reducing the net financial gain over time. Furthermore the additional components would in general be more prone to damage as they are exposed to changing and extreme conditions unlike GSHP’s components.

In the next section, we will look at different hybridization schemes proposed in literature. For locations with higher cooling needs, there have been extensive research in the addition of cooling towers as heat rejecters while for locations with higher heating needs, the combination of solar collectors and GSHPs have been of utmost interest.

Cooling-Oriented Locations

As mentioned above, most research in hybridization of cooling-oriented system has been made towards the addition of a cooling tower to the system and the development of control schemes to optimize the performance of the system (48).

Cooling towers are used to reject heat from a system to the ambient air. The concept consists of passing the fluid to be cooled down a tower. In the process, the fluid is sprayed so as to provide for more contact with a forced air flow so that there is as much heat transfer as possible from the fluid to the air.

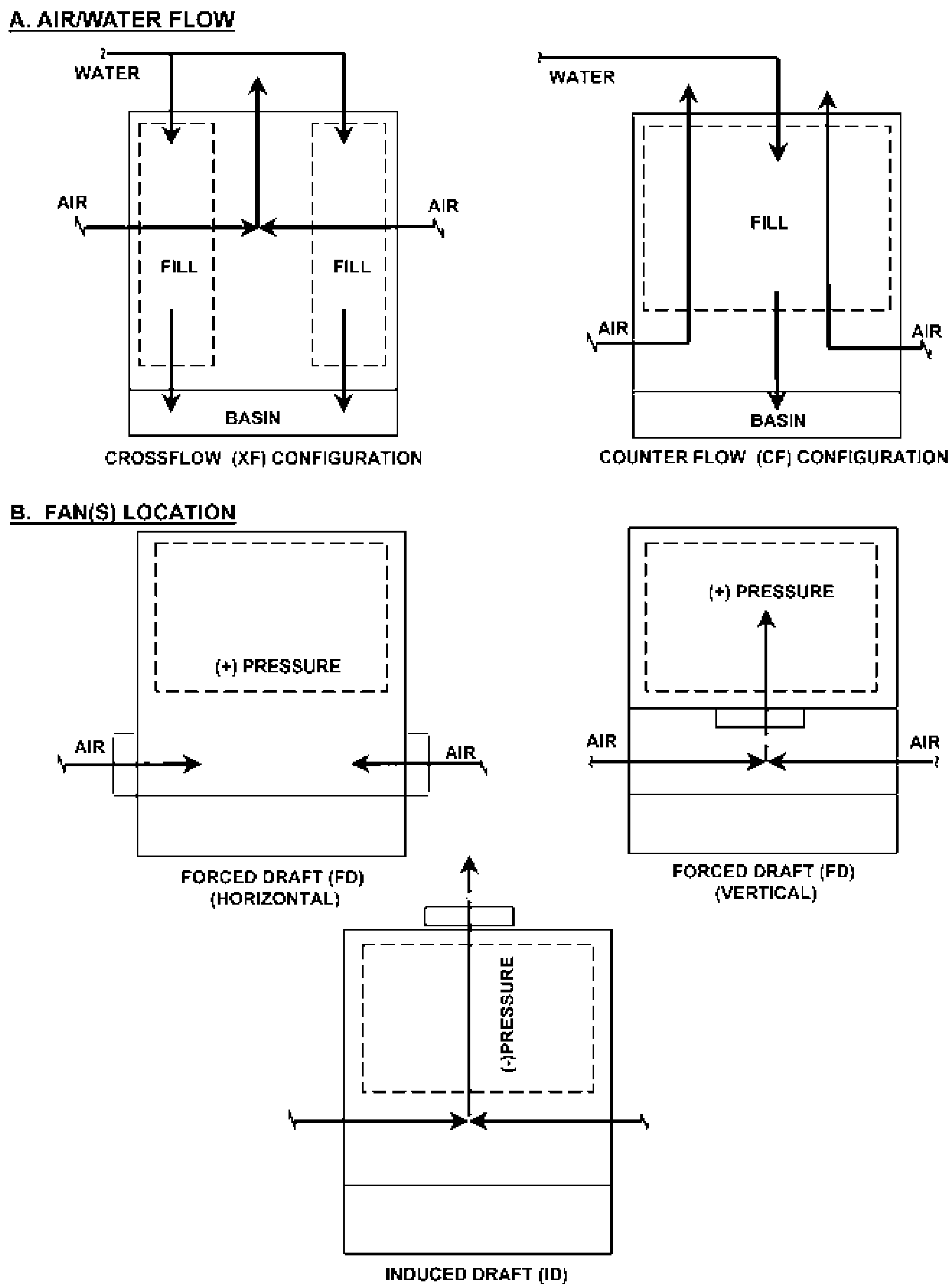


Figure 3.1: Cooling Tower Configuration. The water to be cooled town is injected from the top. Two different schemes are shown for the air flow (crossflow and counter flow). The cooled water is recovered at the bottom of the tower.

Cooling towers performance are dependent on entering ambient air temperature, the flow rate of the fluid to be cooled and the temperature of the fluid. There is a wide range of cooling towers developed by manufacturers so as to accommodate any cooling system. The required characteristics of the tower can be easily determined from the ambient air temperature, the flow rate of the fluid to be cooled and the temperature of the fluid. However any change in these factors could necessitate a change in the tower as well.

In a paper in 2000, Yavuzturk and Spitler (49) identified the addition of a cooling tower as a possible way of reducing energy consumption and overall cost for cooling-oriented locations. They proposed three different control schemes for the cooling tower.

1. In one scheme, a specific set point temperature is chosen initially and when the fluid temperature from the heat pump exceeds this threshold temperature, the cooling tower is brought into operation.
2. In the 2nd scheme, the authors use the difference between the fluid temperature coming from the heat pump and the building temperature. The tower is operated only when the temperature difference is between 2.7^{o}F to 3.6^{o}F.
3. In the last scheme, they propose a daily 6 hours operation to release excess heat from the ground, thereby balancing the cooling and heating loads. The scheme is also combined with the first one so as to account for extreme conditions.

Yavuzturk and Spitler carried out their calculations using the TRNSYS code (50). They carried out simulations for a building in Houston, TX and another in Tulsa, OK with a higher cooling to heating load ratio for the building in Houston. The use of the cooling tower helped reduce the size of the loop (borehole) to be used, thereby reducing cost of ground heat exchanger. Their results are presented in Figure 3.2 and 3.3.

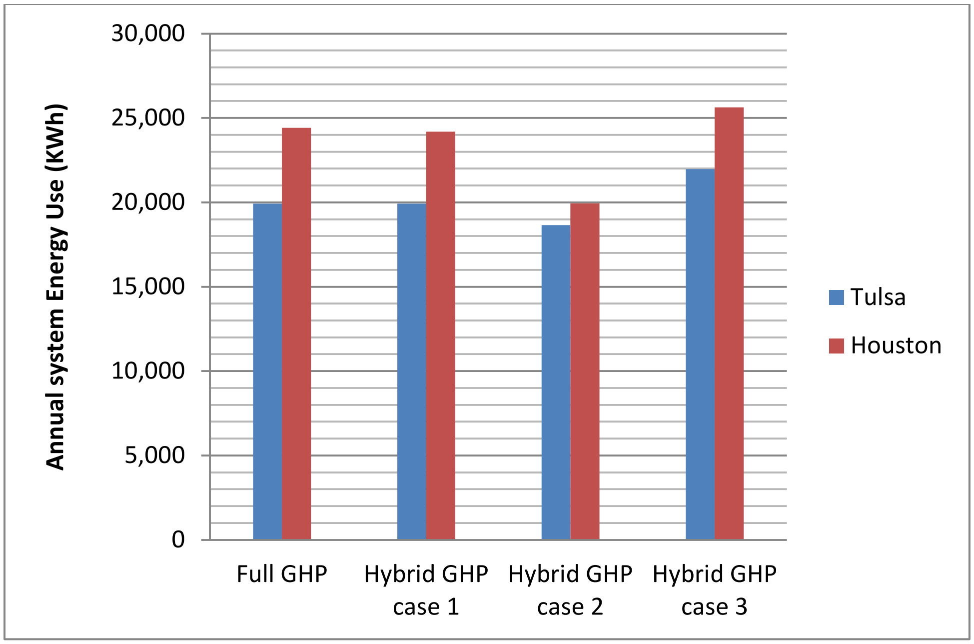


Figure 3.2: Full vs. Hybrid GHP system energy use for 14,025 ft^2 office building (51)

Although the heat pump required less energy in the hybrid cases due to the decrease in size and lower output requirement, the energy used in operating the cooling tower pump and fan kept the total energy use the same.

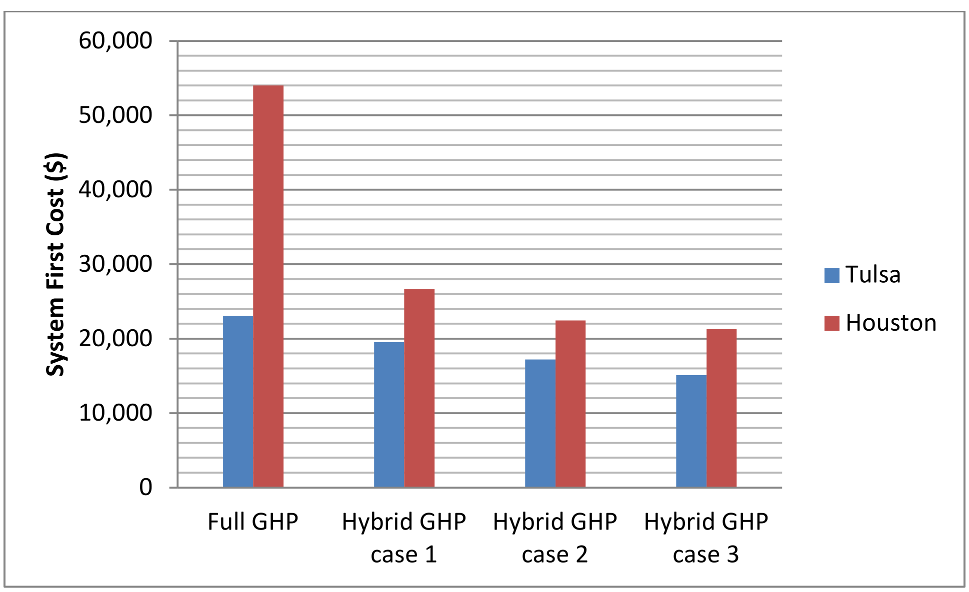


Figure 3.3: Full vs. Hybrid GHP first cost for 14,025 ft^2 office building (51)

Although in both case, we clearly observe benefits from hybridization of the system, the addition of a cooling tower is the most beneficial for locations with high cooling demands like the building in Houston with clear decrease in first cost and similar annual energy use. The different performances for the 2 locations and the 3 different schemes highlight the need for proper optimization. A similar study by Thornton (52) showed similar results for a 21,000 ft^2 office and classroom space. Thornton describes systems with water flows piped in series and in a parallel to the ground heat exchanger (Figure 3.4 and Figure 3.5)

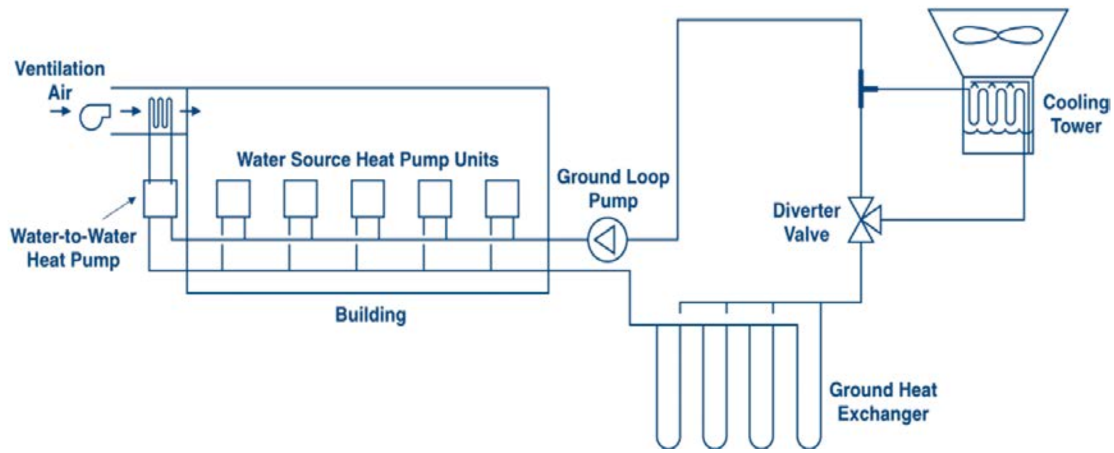


Figure 3.4: Hybrid GHP system schematic - tower unisolated from ground and building loop (51)

1. In the first case, he considers a cooling tower connected in series to the ground heat exchanger and similar to the previous example, the cooling tower is brought into operation only when the temperature exceeds a preset temperature which was for this example 80^{o}F.

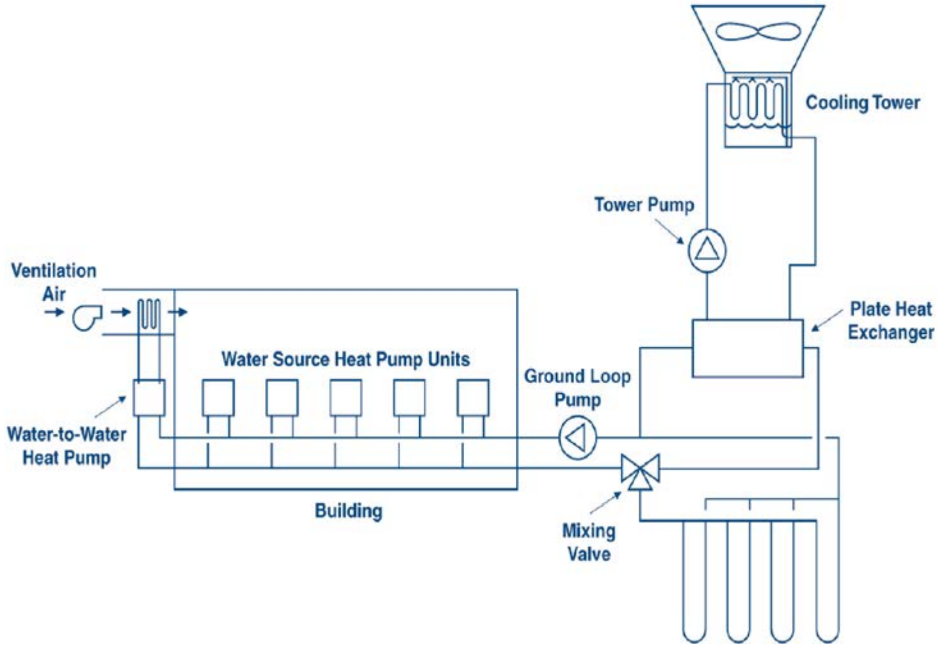


Figure 3.5: Hybrid GHP system with tower isolated from building and piped in parallel with ground heat exchanger (51)

Then Thornton considered the additional two cases for which the tower is isolated from the ground-source loop with a plate heat exchanger. The tower is then switched on when the temperature exceeds the threshold temperature of 70^{o}F. In the 2nd case (1st parallel), the flow of water from one loop to another was controlled such that the total heat rejection in summer was the same as the heat pumped in winter. In the third and last case (2nd parallel) the flow was instead split so that the maximum fluid temperature entering the building was kept below 95^{o}F. Figure 3.6 shows the first cost difference results obtained by Thornton.

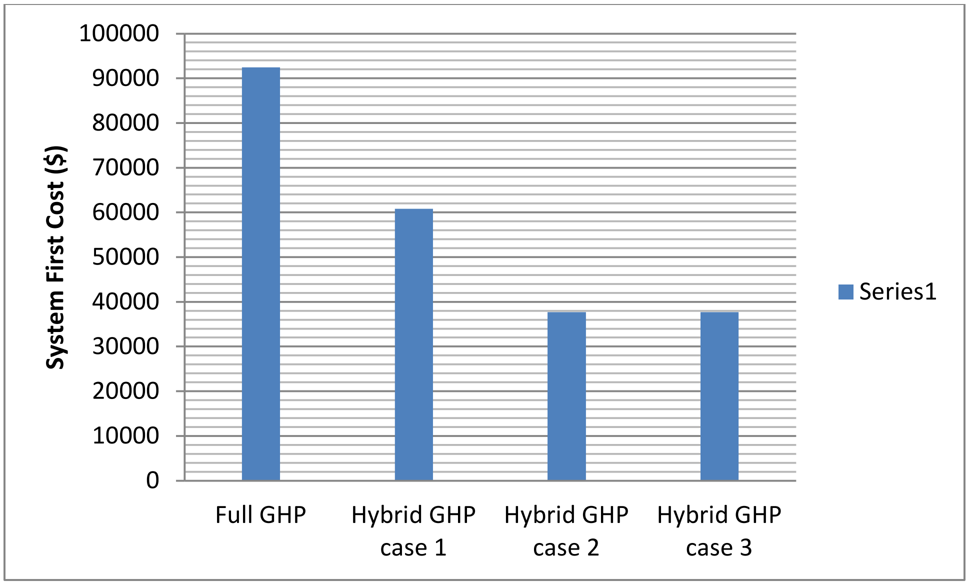


Figure 3.6: Full vs. hybrid GHP system first cost comparison with cooling tower in series and in parallel (51)

Further calculations by Chiasson and Spitler (53) confirmed the results obtained. However, the paper also pointed out the need to implement optimization scheme in selecting the proper components and control schemes as they explored different systems with different borehole lengths.

Heating-Oriented Locations

Similar to how cooling towers help balance the load imbalance from higher cooling needs, using solar collectors can help balance the heat loads in a heating-oriented system.

Solar Energy and Solar Collectors

It can be argued that solar energy is the most basic form from which we can extract energy. Without the Sun, there would never have been any life on Earth and consequently no fossil fuel reserves. Even winds arise from the heating of the atmosphere. Moreover, the sun is still presently showering the Earth with large amount of energy. The average solar energy incident on any horizontal surface in the U.S is around 150-200 W/m^2 (54). As such over 100 m^2, it is possible to collect up to 20kW which is of the same order as the net energy consumption per house in the U.S. (55). There are 2 main ways of harnessing solar energy: by using photovoltaic cell for electricity generation or by using solar collectors that gather the heat from the solar rays. Even among solar collectors, there exist different types of collectors: flat plate collectors and evacuated tube collectors. We will focus on the parallel plate collectors.

The flat plat collector consists of a dark absorber which can either be polymer based or metal based. There is also a glass cover that allows for infrared rays responsible for heating to enter but prevents it from leaving. A fluid which can be water, air or antifreeze is then used to absorb and carry the collected heat to the main space heating system.

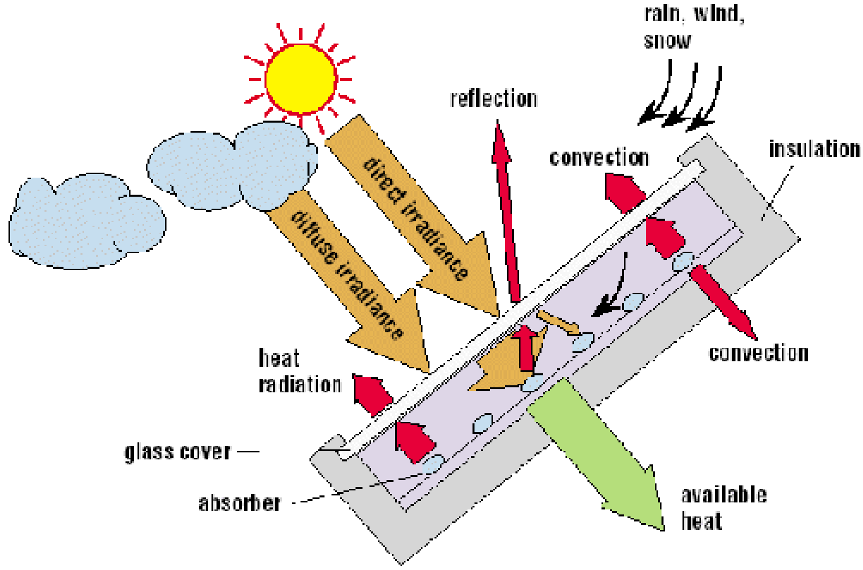


Figure 3.7: Flat Plate Collectors (56)

In a hybrid system, the solar collector loop can then be connected to the ground source heat pump loop to provide for additional heat when required. Moreover, the excess heat collected through the solar panels can be used to heat up domestic water through a desuperheater. Figure 3.8 shows a simplified schematic of a solar assisted GSHP system

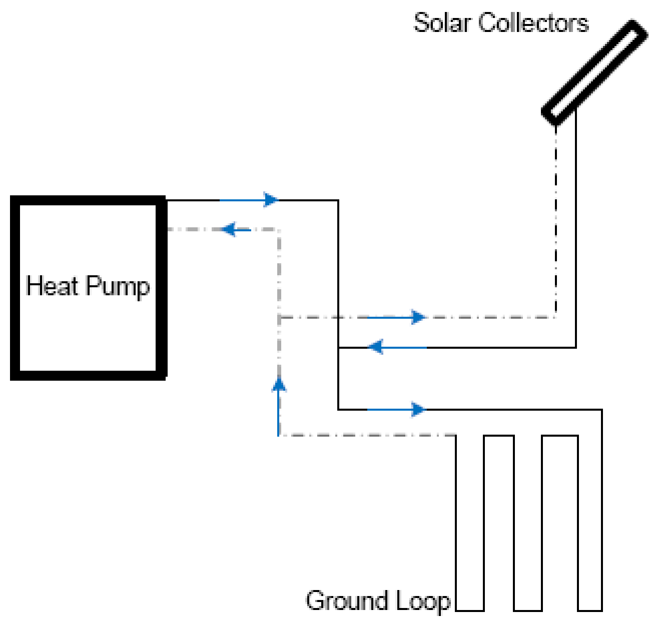


Figure 3.8: Simplified Schematic for Solar Assisted GSHP system (57). In this simplified scheme, water from the ground loop is sent to both the heat pump and the solar collectors. During the day, the solar collectors can be used to provide partially for heating and the heat pump can operate at a lower power.

Rad et al (58) analyses the addition of solar collectors. They propose a scheme where the ground heat exchange loop is connected in parallel to the solar collectors. The system is also connected to a desuperheater for domestic water. The solar collectors only receive a percentage of the total flow from the ground loop exchanger. Both a seasonal and thermostat controls are used for the operation of the heat pump. Figure 3.9 shows how solar panels can help decrease the borehole length in terms of space conditioning capacity

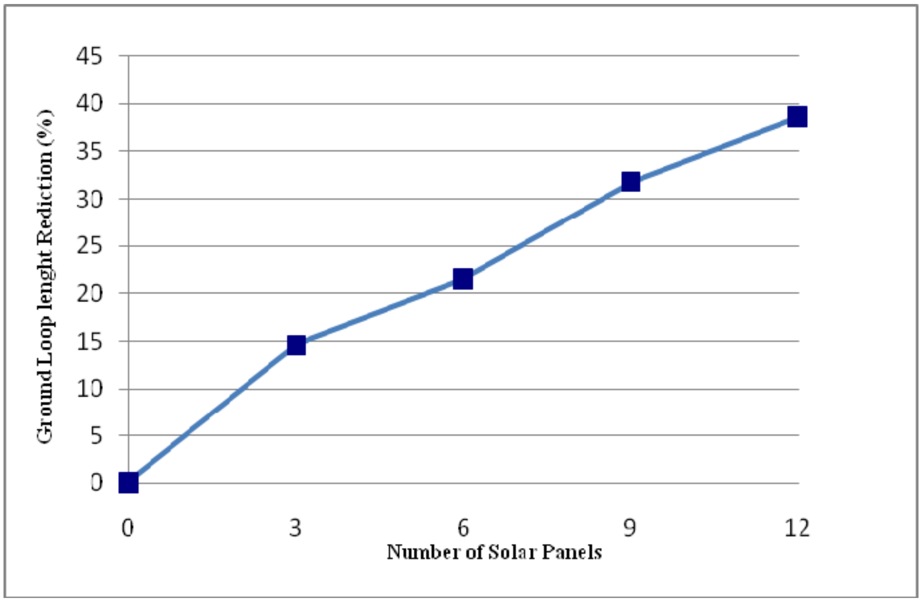


Figure 3.9: Ground loop length reduction % vs. number of Solar Panels (58)

However in terms of cost, for a 2 storey building having 5,360 ft^2, the most optimum number of panels is three. This is shown in Table 3.1.

No. of Panels	Area of Solar Panels (m^2)	Length of Borehole (m)	Initial Solar Cost	Initial GSHP cost	Annual Operating Cost	Present Operating Cost	Net Cost
0	0	380	$0	$19,040	$2,050	$23,514	$42,554
0	0	220	$0	$13,760	$2,330	$26,721	$40,481
3	6.81	188	$851	$12,704	$2,330	$26,723	$40,278
6	13.62	172.8	$1,703	$12,202	$2,334	$26,776	$40,681
9	20.43	150	$2,554	$11,450	$2,337	$26,804	$40,807
12	27.24	135	$3,405	$10,955	$2,335	$26,786	$41,146

Table 3.1 Cost Analysis of SAGSHP (58)

From the table it is also clear that with solar panels, it is not necessary that the net cost in the long term is lower. However according to the customers, it is possible to reduce substantially the initial cost of installation. In places with space limitations and drilling is limited, hybridization through addition of solar collectors also allows the use of GSHP through reduction of borehole length.

However it is clear that the performance of a solar assisted GSHP is clearly dependent on the location. In Figure 3.10 and 3.11 we show different solar radiation data.

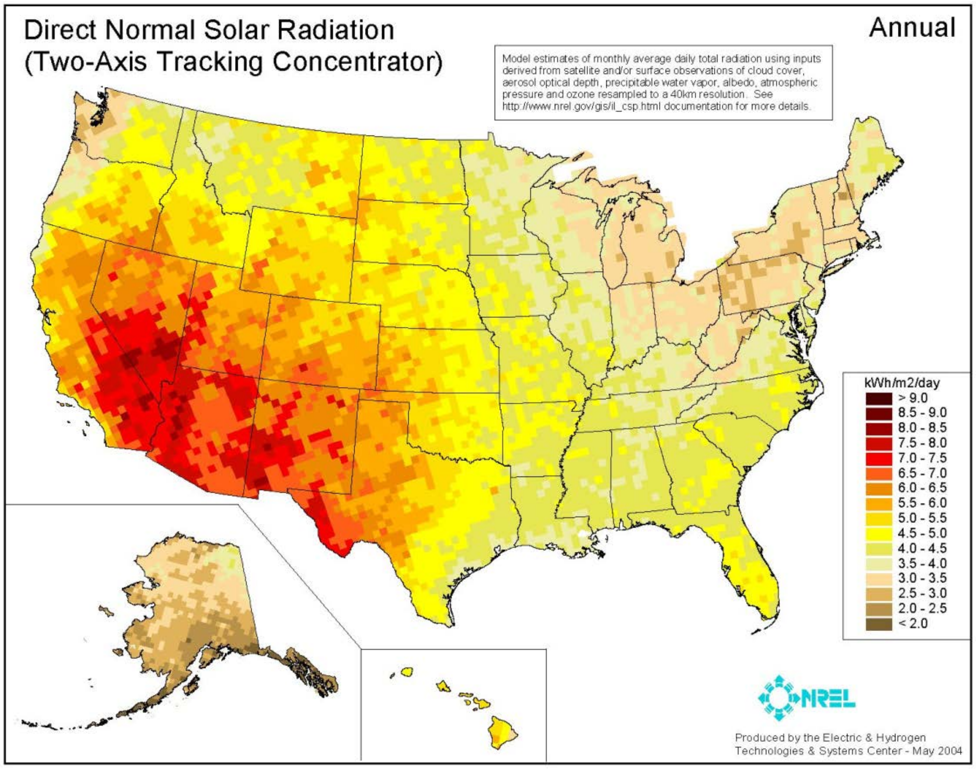


Figure 3.10: Mean Annual Solar Radiation for the U.S. (59)

As it can be seen, from Figure 3.10, the South Western region receives more solar energy and therefore possesses higher prospects in extracting energy from the sun. However in such cooling oriented region, the use of solar collectors to assist GSHP as an additional heat source is rather pointless and addition of solar collectors would only help with water heating for domestic source. In heating-oriented regions such as the North Eastern one, however the annual solar radiation is relatively lower but is still a significant source of heat.

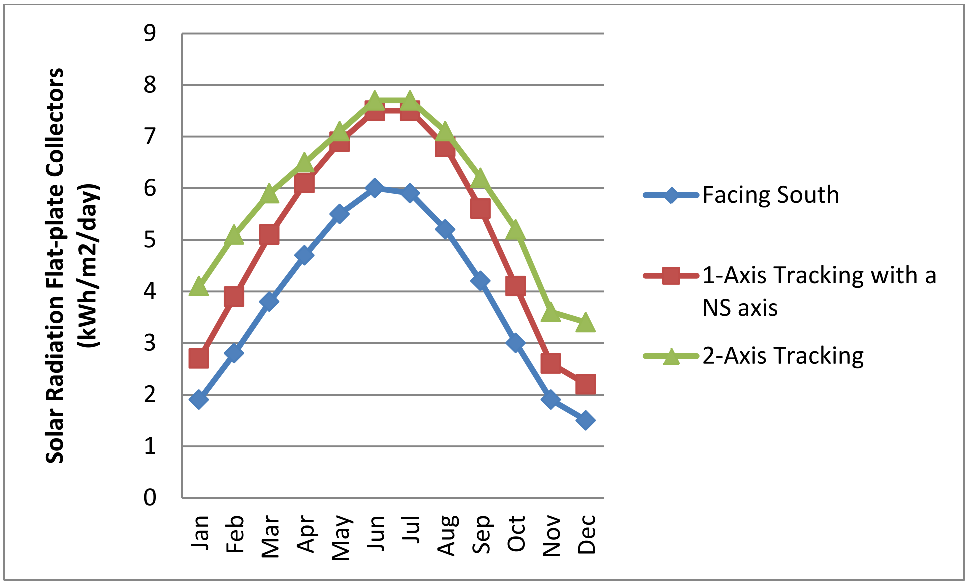


Figure 3.11: Graph of Solar Radiation for Worcester for Flat-plate Collectors based on data from the National Renewable Laboratory (NREL) (60)

Figure 3.11 shows monthly variation in solar radiation available in the city of Worcester, MA. During winter, the solar radiation available is halved as compared to the solar radiation available during summer. This reduction coincides with an increase in heating needs. As such, this shows that when implementing solar collectors to a GSHP system, there is a need for a thorough climatic analysis of the region and proper optimization with respect to the components and the control schemes to be used.

Alternatively instead of using solar energy as an additional heat source or a cooling tower as a heat releaser, GSHPs can be instead combined with an Air-source heat pump

Hybrid Air and Ground-Source Heat Pump

The idea of combining Air-source heat pump with GSHP is to combine the less costly ASHPs with the highly efficient GSHPs. Although ASHPs have higher initial cost than other HVAC technologies, ASHPs do not include drilling cost and grouting making it significantly more economical than GSHPs. However ASHPs depend on ambient temperature and could fail to provide enough space conditioning under extreme climatic conditions. Moreover unlike GSHPs, ASHPs components are directly exposed to the changing conditions and therefore subject to possible damage. Thus an air and ground-source heat pump could help reducing the initial cost by reducing the borehole or trench length. GSHPs which use the relatively constant underground temperature would then provide for more steady performance and the air source heat pump could be use to balance the heating and cooling loads as well as provide additional heating and cooling when required.

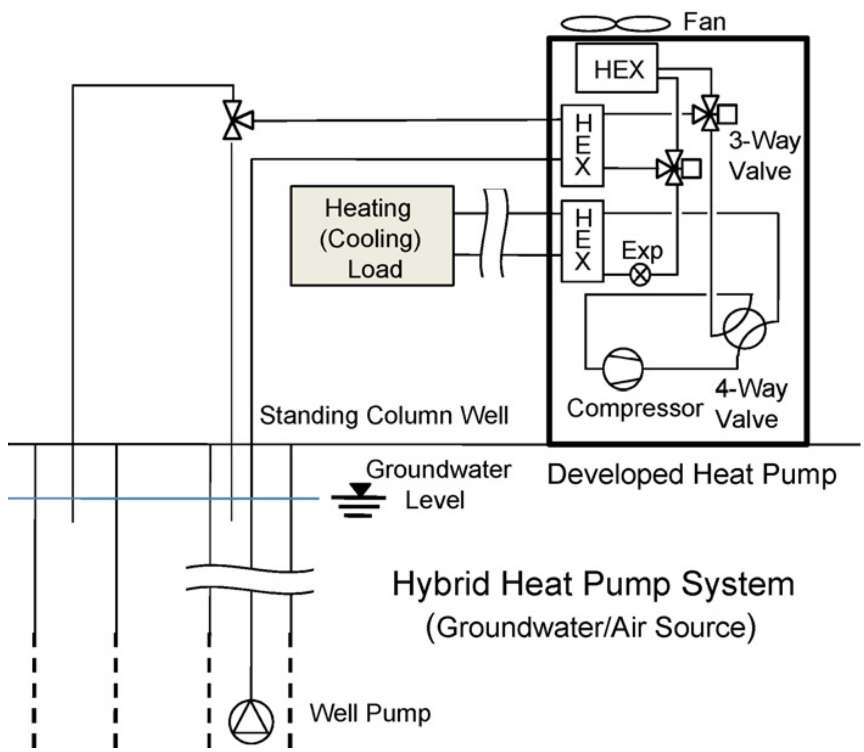


Figure 3.12: Schematic of Air and Ground Source Heat Pump (61)

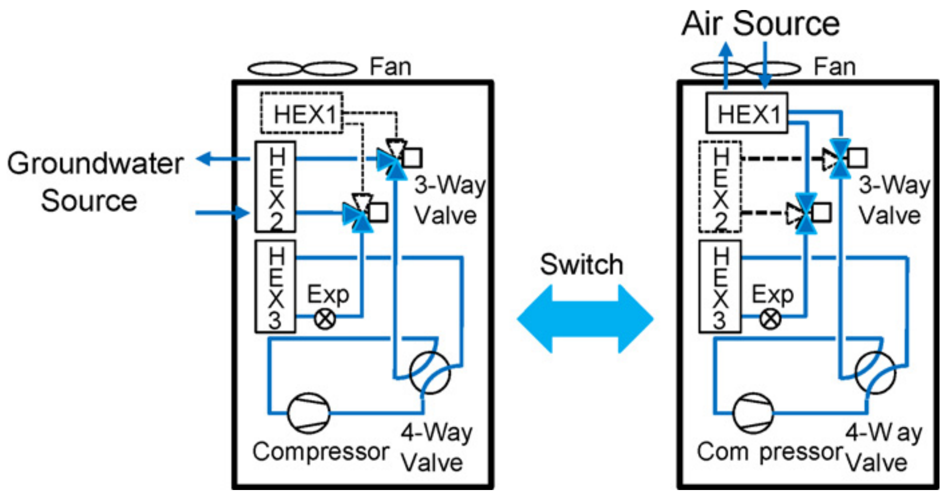


Figure 3.13: Switching of Heat Sources (GSHP to AHSP and vice-versa) (61)

Works carried out by Nam et al (61) and Pardo et al (62) showed that such systems can effectively increase the efficiency and while the initial price would be higher than that of the ASHP, the system can be properly optimized to obtained faster payback.

General Overview

As it has been outlined so far, the type of hybridization together with the geographical conditions of the location for the installation of the GSHP system can greatly influence the performance obtained. Also we have seen that the control schemes also influence the overall performance. Therefore as more and more research are being carried out in alternative sources of energy and mainly heating and air conditioning, the possibility of hybridization increases. However as more components are added to the GSHP system, the system becomes more complex and in order to determine if such hybridization are viable, there is a need for thorough computer simulation and if possible data collection from actual implementation of the system.

So far, most research on hybridization has involved solar collectors, cooling towers or air-source heat pump. Other research currently being done also involves the use of an underground heat storage, chemical dehumidifiers and the different possible control schemes involved with the combinations of technology (63). There is also an increasing interest in combination of geothermal heat pump as a space conditioning system together with photovoltaic cells and wind turbines. This makes use of the high efficiency rating of GSHP in terms of output over electrical input. These have been called the zero-energy buildings, ZEB which ideally would be able to provide for its own energy demand with the electricity being supplied by the photovoltaic cells and/or the wind turbines and the GSHP would provide for the space conditioning. In Chapter 5, we go over ZEBs in more details.

In the next chapter, we look more into the social aspects and environmental aspects of GSHP system. GSHP systems are not the most affordable systems. While hybrid systems can sometimes reduce the initial cost, they are most effective in increasing annual savings and in taking care of any geographical limitations. However when considering social and environmental issues together, GSHP systems might provide the easiest solutions to both them.

CHAPTER 4: Social and Environmental Impacts

Heating and cooling account for the majority of energy used by a typical U.S. home and as such making it the highest energy expense for homes. Homeowners have therefore long identified heating and cooling as a potential source of savings. In that respect GSHPs are an attractive candidate with higher monthly savings than other heating and cooling technologies. However with their higher initial cost and the recent financial crisis, homeowners are reluctant to install a GSHP system and prefer to either continue using their already installed lower energy-efficient and less green system or to install systems with lower initial cost.

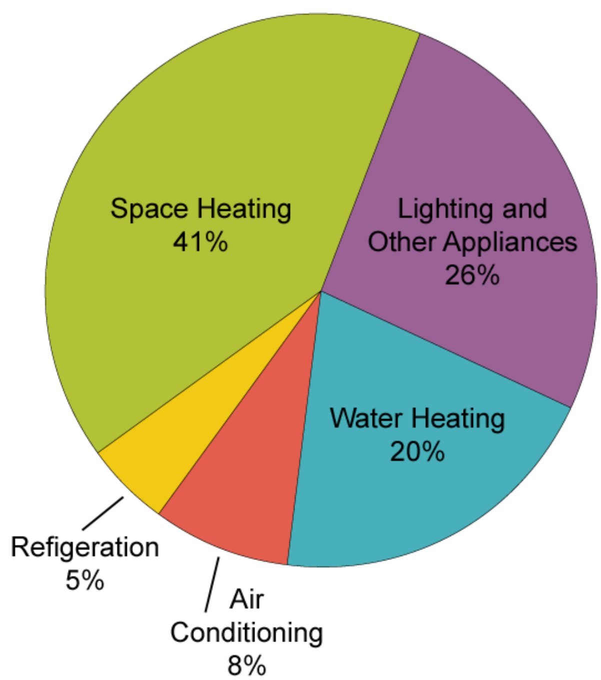


Figure 4.1: Typical Energy Use in U.S. homes (64)

Despite its higher initial cost, GSHPs is one of the few technologies capable of simultaneously addressing the current environmental and energy issues that the world is facing. By taking a stand to use more energy-efficient technologies like GSHPs despite possibly higher installation cost, we will move one step towards trying to regulate the ecological equilibrium. Furthermore this will save the fossil fuel for applications in which they are indispensable. Making efforts now can help future generations go through the eventual energy crisis and climatic change or possibly to avoid what seems to be inevitable.

Environmental Impacts

In Chapter 1, we discuss the importance of fossil fuels in the current society. The high level of consumption of fossil fuels comes from their high energy content. According to the American Petroleum Institute, coal contains between 5,000 and 15,000 Btu per pound and a barrel of oil (42 gallons) can yield about 6 million Btu (65). Massive amounts of coal and oil are burned to up to provide energy, but in addition to energy many harmful agents are also released. Carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perflourocarbons and sulfur hexafluoride, more commonly known as “greenhouse gases”, are released and lower the quality of the air and may lead to global warming (64). Until recently, the United States has been the biggest consumer of oil and coal. The United States now sits at second in the world but still uses about 17 million barrels of oil every day and produces over 1.7 million metric tons of carbon dioxide into the air a year (66). The massive emissions of greenhouse gases are detrimental to the planet’s ecosystem as well as us, its inhabitants. The World Health Organization (WHO) estimates that air pollution causes approximately 2 million premature deaths per year around the world (3). Air pollution has been linked to a number of health problems such as a decrease in lung function, aggravation of respiratory and cardiovascular disease, increased severity of symptoms of asthma, cancer and negative effects on the nervous system (67). The air pollution also causes massive damage to the environment. The current conventional energy sources are a double edged sword in that they provide a bountiful supply of energy but at the cost of the health of our planet and the people living on it.

As a renewable source of energy, geothermal heat pumps are very efficient and environmentally friendly. A major selling point to geothermal heat is that it is on average 40% more efficient than air source heat pumps, 48% more efficient than natural gas furnaces and 75% more efficient than oil furnaces (68). This efficiency would save consumers money and decrease the amount of fossil fuels burnt. Another positive factor for geothermal heating is that it does not emit harmful greenhouse gases like most of our current heating systems. Currently geothermal systems used for heating and cooling save more than 80 Mt of carbon emissions from entering the atmosphere a year (69). That number is estimated to equal the savings of 13.1 Mt of fuel oil per year (69). In addition to the reduction of carbon emissions, these efficient systems use much less power than conventional heating systems. One system in Indiana saved more than 17,000 KWh per year, which equates to nine tons of coal that would have been burnt at a power plant (68).

GSHPs however have disadvantages as well. One concern is water contamination. This problem is more common in open loop systems because unlike the closed loop systems the heat exchanging fluid is not contained within a pipe. The fluid is free to interact with ground and the outside environment, and this can lead to contamination. Geothermal systems can affect both surface and ground waters. The primary problems are caused by geothermal brines. The contaminated brines are injected into wells or stored in holding ponds. The brines contain a myriad of metals and other elements that can be harmful. They infect groundwater from the well and infect surface water in the holding ponds. Brine water can also contaminate soil and affect local agriculture. For example, phytotoxic boron is a main concern with respect to agriculture (70). Another type of harmful byproduct of geothermal systems is solid wastes. Although not harmful to the environment, calcite and silica buildups in the pipes can affect permeability of developing aquifers and can block your pipes preventing the system from working well (70). Also these systems can release hydrogen sulfide which is toxic at high concentrations, but it is usually in small doses and makes an obnoxious odor.

An additional environmental impact is heat pollution. When a geothermal system runs, the waste water is hotter than before and could raise temperatures if it runs off into a river or pond. Aquatic ecosystems are fragile and slight rises in temperature could be very harmful to the wildlife. For example, a rise in temperature as small as one or 2^{o} C can drastically affect the wildlife (71). The main issue with thermal pollution is that an increase in water temperature leads to a decrease in the amount of oxygen dissolved in the water. The effects on immobile wildlife like plants and shellfish are much worse than on mobile aquatic lie. The immobile animals are usually the first to die. The fish will leave the area to find cooler waters or they would also die too from a lack of oxygen in their system. The results of the fish leaving is new fish adapted to the warmer water enter the ecosystem and drastically alter it. With the dominance of this new species biodiversity could be lowered (71). Moreover with an increase in water temperature, the metabolic rates of the fish also increase. This increase in fish population leads to food shortages because of the increase in their food consumption (71). However not all organisms are harmed by the increase in temperature. Algae and certain plants thrive in warm water. They grow faster, but they also die faster. The problem is that the bacterium that dissolves the dead algae consumes oxygen so the oxygen levels drop even more making the water unlivable. This phenomenon is called eutrophication and it can cause the taste and smell of the water to turn bad.

Most of the current heating and cooling systems popular today have negative effects on the environment. The impact on the environment, the air and even the health of the people will continue to increase with the increasing demands for heating and cooling throughout the world. GSHP is a solution to these problems. With no greenhouse emissions from the system and minimal risk to the environment, GSHP may be the solution to combat the environmental crisis left by fossil fuels.

Market Analysis

Current Trends:

In the past year, the U.S. energy market continued to show the impact of the economic downturn that began in late 2007. In the 60 years that the EIA has recorded energy use, the generation of electricity has declined in two straight years. The electrical generation in 2008 fell 1% from the previous year and dropped 3% in 2009. This can be attributed to the wave of legislation restricting the amount of power used in home appliances. The lower-energy electric appliances being sold will allow the amount of power used in homes to decrease. The U.S. energy market in the upcoming years will increase as the nation's economy increases. The world's oil prices are sensitive to the demand expectations. The Organization of the Petroleum Exporting Countries (OPEC), with their decision regarding production and supply, can have great impacts on the price of oil. All of the producers, consumers and traders are vigilant for an indication of upturn in the world economy and the inevitable increase in oil demand. The current price is around $100. The price of oil, according to the EIA, is estimated to average about $93 a barrel in 2011. This is $14 higher than the average price in the previous year. This is in response to a projected 3 percent increase in the U.S. real gross domestic product. The EIA also is forecasting an increase in expenditures on space-heating fuels for the average household. The average is estimated at approximately $991 during the winter of 2010-2011. This is $24 higher than last winter.

The world oil market has tightened over the past few years and is predicted to continue to tighten. The consumption of oil in the world is predicted to increase by 1.5 million barrels of oil per day (bbl/d) for the year and into 2012. Unfortunately, the non-OPEC countries supply average about .3 million bbl/d and is predicted to remain at this level. The world market will be forced to rely on the oil production and oil reserves of the OPEC members to meet the world demand.

The world consumption of crude oil and liquid fuels grew by an estimated 2.4 million bbl/d in 2010, to around 86.7 million bbl/d. This is the second largest increase in consumption in the last 30 years. In the U.S., total consumption of petroleum and non-petroleum liquid fuels increased by 360,000 bbl/d (1.9 percent) to 19.1 million bbl/d in 2010. The major source of this consumption growth were distillate fuel oil (diesel and heating oil), which grew by 140,000 bbl/d (3.8 percent).

Currently the bulk of home heating is done through oil, propane, and natural gas. In New England, the market share of oil is even higher than the average because of the cold winters. These methods of heating use nonrenewable resources, which will eventually run out. These more popular heating systems emit copious amounts of greenhouse gases. The current trends of the heating market are not good. Such a large amount of fossil fuels are burnt up and large quantities of carbon dioxide and other harmful gases are released into the atmosphere. Unfortunately, in this market oil heat is favorable over GSHP because of the lower initial cost. In this economy people cannot afford to install GSHPs and prefer less expensive options.

Ground source heat pumps, as of 2008 had a market share of about 0.3%. Over the years, GSHPs have slowly increased in popularity. Around the world, the global installed capacity has reached around 15,400 MW (72). Although the GSHP market share is comparatively miniscule to the major space conditioning technology, annual growth rates of this technology has exceeded 10 percent over the previous ten years. As of 2005, 33 countries have installed 100 MW of GSHP capacities at minimum. The majority of GSHP are installed in North America (56 percent), and Europe comes in second with 39 percent of the GSHP installations. Asia contributes 5 percent. The European market for GSHP has grown at a significant rate over the past 10 years. Europe has seen over 690,000 GSHP systems installed since 2006. As of now, Sweden is the leader in Europe in the adoption of GSHP. Sweden has been penetrating the retrofit market with a market penetration of over 75 percent (15). This has led to an increase in GSHP retrofit markets in Norway, Finland and Switzerland. The Swiss have used GSHP extensively in their new construction market (15).

The market shares for GSHPs are low for a variety of reasons. The main challenge for GSHP marketability is the extremely high installation cost in comparison to conventional heating systems, and even ASHP (15). It is also very difficult to install in certain areas. Urban areas are especially difficult to install because of the space constraints. Low production volumes of GSHP systems lead to a higher cost. In New England, the high price of electricity would increase operating cost and make the system less desirable. Also the extensive digging required for installation is something that can be an annoyance for some people. In addition, the lack of qualified trained installers and the low market awareness among the potential customers is a reason for a smaller market share.

Predicted Trends:

In the future, the market share for GSHP is expected to increase. According to the Annual Energy Outlook 2010 (73), the implementation of the current incentives will cause the numbers of installations to increase greatly from 2008 to 2016. The amount of GSHP installed may increase from 47,000 units in 2008 to an average of about 150,000 units in 2016. 2016 is when the tax credit expires. Even with the massive increase in sales and installation, GSHP would still only control about 2.3% of the market shares by 2035. This number could go as high as 4% if the tax credits are extended (73).

It is clear that GSHPs provide a suitable solution. Currently the market share of GSHP anywhere else from the U.S. is increasing with more and more installation and ever increasing demands. This is mainly due to the worldwide trend towards greener energy. Every other country is now recognizing the benefits of GSHP and is working towards reducing its limitation to a minimum. However unlike practically anywhere else, the U.S while still the country with the most amount of installed units, the current trend seems towards more lucrative systems such as ASHPs that are more likely to be accepted by customers due to its lower cost. If however the U.S. was to instead try to push the more energy-efficient GSHP system this will show the country's determination towards a worldwide awareness to the imminent ecological and energy crisis. This would also lead to more focused research towards a specific goal and potentially towards ground-breaking results; with combined research from countries throughout the world in GSHP, more funds could be attributed to GSHP and increasing interest could lead to faster progress.

We have so far discussed the traditional GSHP systems as well as the hybrid GSHP systems that can be used to bypass some of the limitations and weaknesses of the traditional systems: both those of the traditional GSHP system and those of the other technology used in the hybrid system. In this chapter, we looked at the environmental and social impacts of GSHP system. We identified some of the causes for the low market penetration of GSHP technology as a heating and cooling technology. In the next chapter, we discuss some of these causes with respects to some of the results from surveys we carried out to get more insight. We also discuss the possible contribution of GSHPs in zero-energy buildings (ZEBs).

CHAPTER 5: Discussion

Surveys

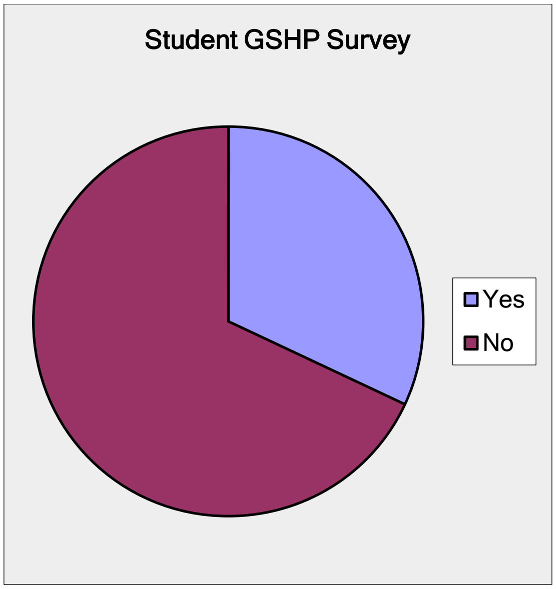
From December 2010 to February 2011, we conducted surveys over students at Worcester Polytechnic Institute (WPI), WPI alumni and contractors operating in the North Eastern region. Despite GSHPs being termed as one of the greenest technologies available, they have not been as popular as other traditional heating and cooling technologies. Through the surveys of various demographics, we sought to find the principal reasons underlying this relatively low popularity. The objectives of the surveys were to:

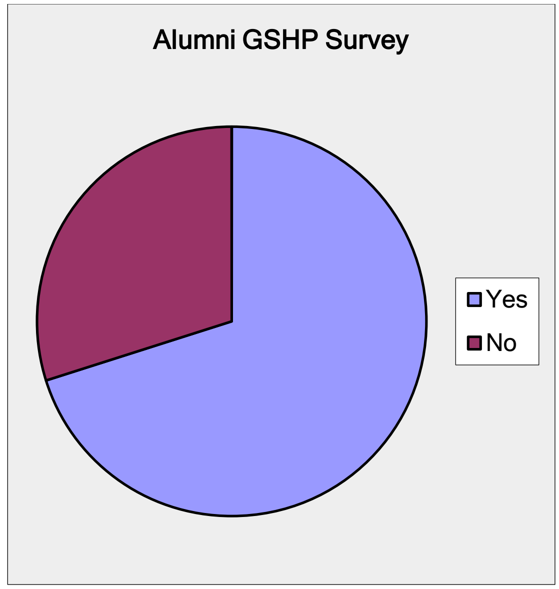
1. gauge public knowledge of GSHPs.
2. identify main causes for and against installing GSHP system as space conditioning system from different perspectives (students, alumni, contractors).
3. identify possible solutions to help increase awareness of GSHP systems.

Public Knowledge of GSHPs

Several reports have identified the public knowledge of the benefits of GSHPs as one of the main barriers for market penetration (23) (15) (14) (72). In our surveys, we targeted students and alumni of an engineering school like WPI; we expect the samples we chose to have higher awareness of GSHP than the general public. Towards that end, we asked several questions:

- **Have you heard of GSHPs before?**



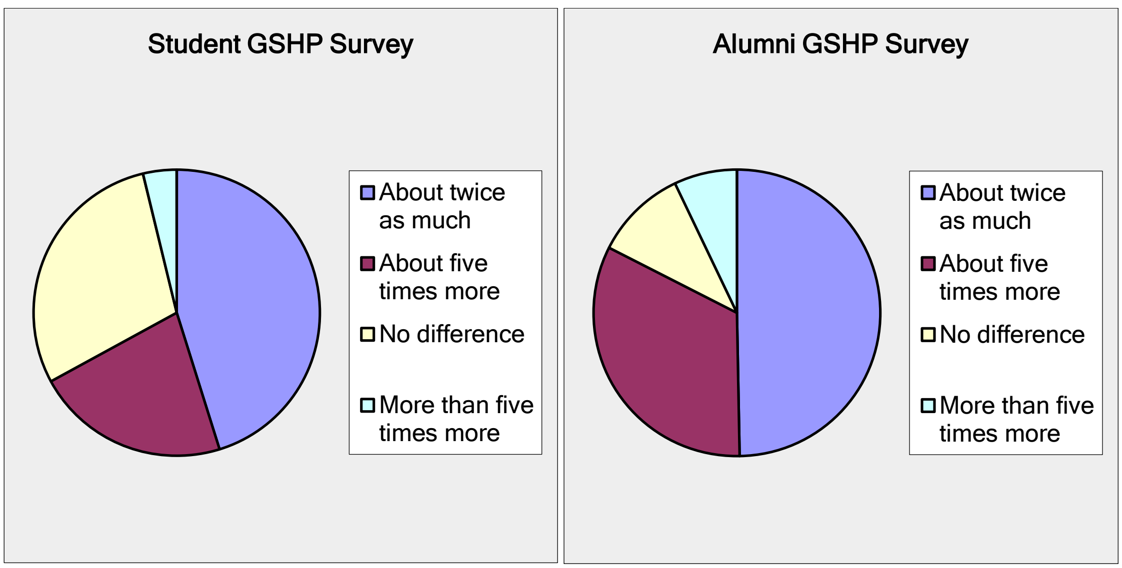


We obtained a positive response of only 32.0% from students but up to 70.1% from the alumni. Among those that responded positively, we asked them how many residences they know that use GSHP systems. For the students most knew on average only one house installed with a GSHP system. For the alumni, the average is slightly higher with the exception of a couple alumni knowing around 100 houses with GSHPs installed.

Even among students aiming towards engineering degrees, there were only 32.0% of them that heard of GSHPs before the survey. The numbers were twice as great for the alumni. This can probably be attributed to the fact that students have not yet been looking for a permanent residence. If this is the case, then when considering the general population of college graduates looking for permanent housing after school we would expect from our results that much less than 32.0% heard of GSHPs before. Moreover of the few portion that knows only a smaller portion understand their environmental and long-term benefits.

The possibility that people only interested in temporary housing are not interested in the different heating and cooling technologies available could be a possible barrier to implementation of GSHPs on a larger scale. Around 33% of the total household units in the U.S. are rented homes (74). Utilities are usually paid by the house occupants themselves. Landlords are then often not concerned about neither the energy or cost efficiency of the heating and cooling systems used while the occupants are not willing to invest into technologies with high initial cost like GSHP as they are only renting their house temporarily.

- **What is the installation cost of a GSHP relative to a traditional oil heating system**



About half of the students and the alumni responded with the cost of installation of a GSHP system being twice as much as that of a heating oil system. The installation cost of the heating oil system consists mainly of the cost of the furnace. The typical values for installation cost are around $2000. On the other hand for GSHPs, the installation cost would most of the time require a proper analysis of the location, drilling, grouting, piping and purchase of the heat pump. This could sum up to values from $10,000 to $30,000 depending on the performance required and the soil qualities. In general this would amount to the initial cost of GSHPs being at least 5 times more than heating oil systems. In the survey, they were also asked what they would expect the time required for them to obtain some return on investment (ROI) if they were to install a GSHP. The mean time obtained was 7.6 years while both the mean and mode were 5 years. This agrees with the typical expected time for returns of 5 to 10 years. From the previous results on the initial cost of GSHP, we expected shorter expected time for returns from the students and alumni. We can therefore argue that the students and alumni underestimate the energy and monthly utilities savings obtained from using GSHPs. The survey results show that only a small portion of the population knows the real specifics and financial benefits of a GSHP system.

Barriers Faced by GSHP Systems

In Chapter 2 and 4, we discussed the limitations and barriers faced by GSHPs. Through surveys conducted among students, alumni and local contractors, we tried to find which ones are the most important and the why are they the most important.

According to the survey addressed to local contractors, the main factor deterring customers from choosing GSHP is the high initial cost. The contractors also seem to agree among that the monthly savings from using GSHPs provides the most incentive for their installation over other technologies. These are shown from the following 2 results from our contractors' survey.

- **How do customers rank the factors when deciding whether or not to implement a GSHP system?**

Answer: Each was rank least to greatest (1 least and 7 greatest)

Factor	Average Rating
Environmental Picture- Reduction of Greenhouse Emissions	4.4
Initial Cost	5.4
Monthly Savings	6.4
Time Required for Installation	1.4
Expected Lifetime of Systems	4.2
Space Availability	2.8
Performance	6.2

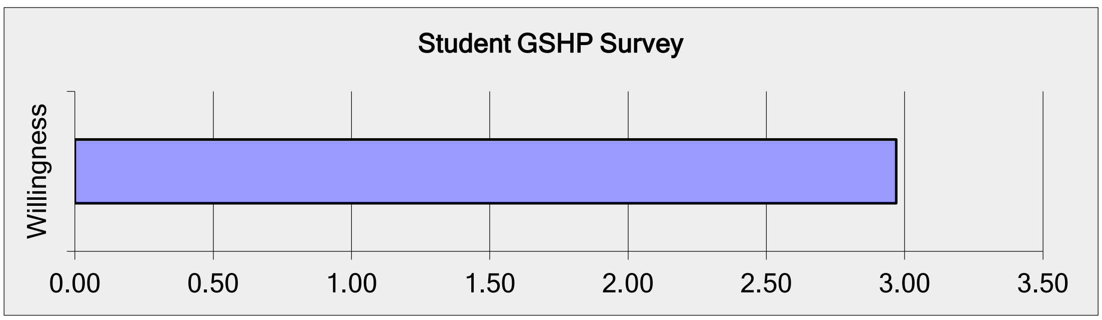
- **What factors most deter customers from installing GSHP systems?**

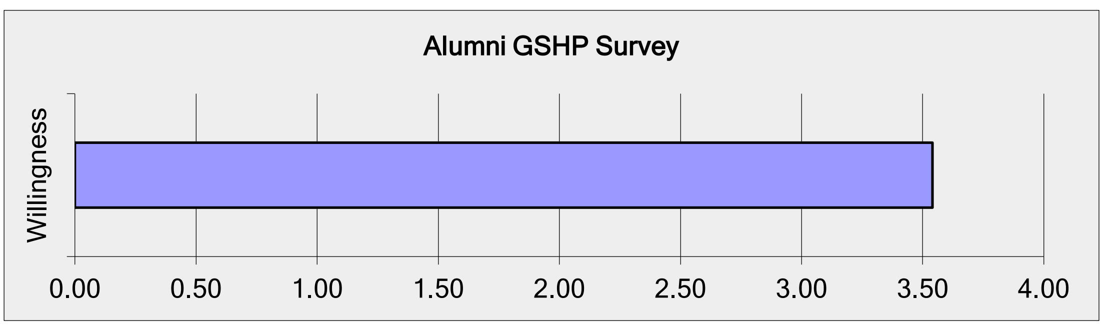
Answer: Each was rank least to greatest (1 least 6 greatest)

Factor	Average Rating
High Initial Cost	5.8
Pollution (Water Contamination, Thermal Pollution)	1.4
Space Constraints	2.2
Time for Return on Investment	3.6
Compatibility with Current Heating and Cooling Systems	2.8
Power Output of the System	2

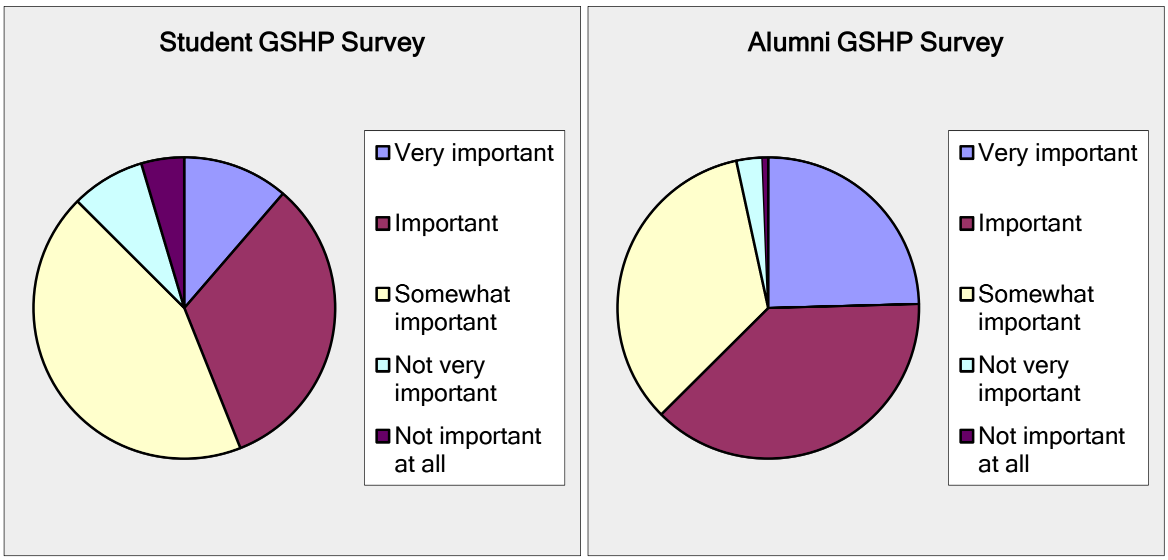
These two results show that in general the financial aspect plays the most important part in deciding whether or not to install a GSHP system. However we also observe growing concerns on environmental aspects. This agreed to results obtained in the student and alumni surveys, where we observed some willingness to consider GSHP despite their higher initial cost due to their eco friendliness.

- **Compared to other heating and cooling technologies, GSHP's tend to have a higher initial cost. With the potential for global warming, and the uncertainty in conventional energy costs, how willing would you be to install a GSHP as your primary heating and cooling technology?**





- **How important is it to you to get your ROI (Return on Investment) quickly?**



There is some coherence in general in between the alumni and the students when considering environmental and financial aspects.

<u>Summary of Results</u>

From the results of the surveys, while they do not provide a precise statistical picture of the general population but of more specific demographics, we observe that the major barrier to a successful market penetration of GSHPs is the high initial cost. While environmental issues are growing in importance in decisions made by customers, the financial aspects still have the last word. This opinion is also shared by the contractors as they identified in our survey federal tax cuts and loan incentives as the main causes for future increase in market shares of GSHP as a heating and cooling technology together with the most probable decrease in availability and subsequent increase in price of oil. However as mentioned in the previous chapters, hybridization of the system in some cases can help reduce the initial cost. In other cases, hybridization can greatly increase monthly savings and this could despite the high initial cost still convince customers as we observed in the survey results. As such we believe that the environmental aspects would be playing a more and more important role in the future of GSHP as space conditioning technology.

Zero-Energy Buildings, ZEBs

We discuss briefly ZEBs in this section as a possible motivation to further develop GSHP. The concept of ZEBs is actively being promoted by U.S DOE to offset the growing energy demands (75). Just like the hybrid GSHP systems described in Chapter 3, zero-energy buildings while categorized under one specific term can have different purpose. As defined by National Renewable Energy Laboratory, NREL and U.S. DOE (P. Torcellini, August 14−18, 2006), there are

- **Net Zero Site Energy:** A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site.
- **Net Zero Source Energy:** A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.
- **Net Zero Energy Costs:** In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
- **Net Zero Energy Emissions:** A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

All these different ZEBs have as motto that efficiency is of utmost importance.

- In ZEBs, any unnecessary loads are discarded and the remaining loads are minimized. This is evidently best accomplished with new buildings in construction.
- Any wasted energy in one appliance is used for another purpose
- Most energy is generated on site and should be preferentially renewable.

GSHP systems fit to these guidelines. GSHP system is one of the most efficient heating and cooling technology requiring approximately only 1/4th of its energy output to operate. GSHP system can also be incorporated with control system such that it operates with respect to day-to-day needs. Moreover any excess heat can be used for water heating using desuperheater.

Not only are GSHPs suited for ZEBs, it turns out that ZEBs are suited for GSHP systems. ZEBs have lower heating and cooling needs due to the optimization in insulation and ventilation system. Therefore with ZEBs there is a lesser need for large capacity GSHP systems. Corresponding, there will be less drilling and grouting. This will then significantly reduce the cost of the GSHP system as well as any space requirement.

There are already many case-studies of ZEBs (Zero Energy Buildings, 2008). So far most of these are located in cooling-oriented region. These buildings are mainly based on energy generation through photovoltaic cells and only some of the case-studies mentioned above also have incorporated a GSHP system acting as the HVAC system. The reason for this is due to the fact that they are cooling-oriented systems and the cooling needs can be supplied by highly efficient AC unit nowadays available. (Air Conditioning, Central). However when considering heating-oriented region, GSHP system could be the most promising choice as HVAC system. GSHP systems as mentioned in the previous sections use the constant temperature ground as their source and are able to provide for more reliable performances as compared to ASHPs which uses the varying temperature ambient air. Furthermore GSHP systems is also capable of providing for cooling needs during the warmer seasons which is a huge advantage over the more cost-effective high efficiency furnace for natural gas.

Conclusion

Residential heating and cooling contribute significantly to the energy consumption and greenhouse emission in the U.S. With the increasing energy consumption, there will be correspondingly an increase in greenhouse gases and fossil fuel consumption. With the level of fossil fuels decreasing, this could lead to serious energy shortage as well as non-reversible changes due to global warming. GSHP used for residential heating could solve these problems. The environmental issues related to GSHPs are minimal and GSHPs are highly rated in terms of energy-efficiency. However GSHPs have limitations as well. GSHPs have higher initial cost of installation as compared to other space conditioning technologies. In the absence of water source like a well, drilling and grouting are required for the trenches or boreholes. Therefore GSHPs is limited by the geography of the location. Moreover as the heating loads and cooling loads are usually not equal, there will be a gradual change in ground temperature which would in turn affect the performance of the GSHPs. These limitations are the causes of reluctance from customers to install GSHP system in their houses.

Hybridization with other heating and cooling technologies can solve these problems. Hybridization involves drawing out the best of each technology and therefore increasing the performance of the system. Depending on the auxiliary technology used as well as the control scheme set up, hybridization could lead to reduction in initial cost, better performance and even decrease in space requirement. Hybridization by minimizing these limitations also provides GSHP with more market potential. The problem with hybridization is that with the addition of other technologies, the system becomes dependent on more factors like incident solar energy in solar aided hybrid GSHP or ambient temperature in combined ground/air-source heat pump systems. This makes the system more complex and optimization towards one goal could lead to new limitations. For instance in trying to reduce load imbalance through the use of solar collectors could lead to an increase in initial cost. However with advances in the different technologies and the development of more elaborated control schemes these new arising limitations could be avoided and hybridization of GSHP could be both a financially and environmentally viable heating and cooling technology.

We believe that GSHP should be supported to occupy a bigger market share for heating and cooling technology. With the growing interest in the public in green technology, GSHP could provide for a larger portion of residential heating and cooling through widespread promotion of its long-term financial and environmental benefits. GSHP system when combined with other technologies and concept in hybridization and ZEBs provides further motivation towards further research in the field.

APPENDIX A – Acronyms and Units

Organizations

- DOE U.S. Department of Energy
- EIA U.S. Energy Information Administration
- EPA U.S. Environmental Protection Agency
- NREL National Renewable Energy Laboratory
- OPEC Organization of Petroleum Exporting Countries
- WHO World Health Organization

Terms

- AGSHP Air and ground source heat pump
- ASHP Air-source heat pump
- COP Coefficient of performance
- EER Energy efficiency ratio
- GSHP Ground-source heat pump
- HVAC Heat, ventilation and air conditioning
- SEER Seasonal energy efficiency ratio
- ZEB Zero-energy building

Units Used and Units Conversions

Length

- Meter (m)
- Foot (ft)
- Inch (in)

Length conversions

- 1 ft = 12 in
- 1 m = 3.28 ft

Mass

- Kilogram (Kg)
- Pound (lb)
- Ton (t)

Mass conversions

- 1 kg = 2.205 lbs
- 1 ton (t) = 2000 pounds

Volume

- Cubic Meter (m^3)
- Gallon
- Barrel (bbl)
- Liters (L)

Volume conversions

- 1 bbl of oil = 42 gallons
- 1 gallon = 3.79 L
- 1 m^3 = 1000 L
- 1 m^3= 6.29 bbl

<u>Energy</u>

- Joule (J)
- Kilowatt-hour (KWh)
- British thermal unit (Btu or BTU)

Energy conversion

- 1 Btu = 1055 J
- 1 KWh = 3.6 MJ = 3.6×10^6 J
- 1 KWh = 3414 Btu

<u>Power</u>

- Watts (W)

<u>Temperature</u>

- Fahrenheit (^oF)
- Celsius (^oC)
- Kelvin (K)

Temperature conversions

- $[K] = [\,^oC] – 273.15$
- $[°F] = [K] \times {}^9\!/_5 − 459.67$
- $[°F] = [°C] \times 9/5 + 32$

Appendix B

Contractor Survey:

As part of our study of ground source heat pumps, as survey of some local installers of these systems was undertaken. The purpose of this survey was to see what professionals thought of the different types of GSHP, their strengths and weaknesses, and how their customers felt about different aspects of GSHP. The questions discussed topics including their preferred type of GSHP, what types they offer, customer satisfaction, future market shares and if the individual companies offer hybrid systems. This survey was sent to several local installers of GSHP. Some of the companies included Earth Comfort Company, Terraclime Geothermal, Altren Consulting, Coneco, and Redmond Hvac. The information provided by this survey further supplemented our understanding of the current state of GSHP and the probable future of its popularity. It also provided more information of the demand among customers, their satisfaction and their interests. Below are the questions asked in this survey and the answers provided.

1. **What type of GSHP would you most recommend to a customer if all the options were available? Please provide a brief explanation.**

Answer: Of the five responses, four answered Closed Loop Horizontal and one answered Closed Loop Vertical. The explanations were:

- "Closed loop horizontal systems cost less than vertical or pond loops and don't have the environmental and zoning issues associated with open loop systems. Vertical systems are recommended only where space doesn't allow for a horizontal installation."

- “Where land and overburden are available and behave, less expensive than drilling. Vertical is 2nd good choice.”
- “A closed system is secure and not subject to possible fluctuations in aquifer flow rate or recharge rate. The ground exchange portion of a horizontal loop field is less expensive, by about half, than vertical wells. If space allows, this is a cost effective option. In a well insulated home, its cost is repaid in savings against a new high efficiency fossil fuel heating system/central air conditioning system in about three years.”
- “Better performance. More reliable.”
- “this often is less up front costs and provides the most value to clients. As w/ everything, it generally depends on the site restrictions.”

2. **How do customers rank the factors when deciding whether or not to implement a GSHP system?**

Answer: Each was rank least to greatest (1 least and 7 greatest)

Factor	Average Rating
Environmental Picture- Reduction of Greenhouse Emissions	4.4
Initial Cost	5.4
Monthly Savings	6.4
Time Required for Installation	1.4
Expected Lifetime of Systems	4.2

Space Availability	2.8
Performance	6.2

By the answers it is clear that performance, savings and initial cost are very important to the customers. While time required and space are negligible to the customers.

3. **What factors most deter customers from installing GSHP systems?**

Answer: Each was rank least to greatest (1 least 6 greatest)

Factor	Average Rating
High Initial Cost	5.8
Pollution (Water Contamination, Thermal Pollution)	1.4
Space Constraints	2.2
Time for Return on Investment	3.6
Compatibility with Current Heating and Cooling Systems	2.8
Power Output of the System	2

Again the cost is by far the most important aspect to the customer, with return on investment at second place. The rest of the potential factors had very low ratings of importance.

4. **What types of GSHP do you install?**

Answer:

Types of GSHP	Percent
Open Loop	40%
Closed Loop Vertical	80%
Closed Loop Horizontal	80%
Hybrid Systems	60%
Other	60%

Of the companies surveyed, few offered open loop or hybrid. Open loop would not be offered by many because of the necessity of an aquifer for installation. The closed loops are the usual standard.

5. **Approximately what percent of all your installations is some form of GSHP?**

Answer:

Percent of GSHP Installation	Percent
0-20%	0%
20-40%	0%
40-60%	0%
60-80%	0%
80-100%	100%

All of the companies are primarily GSHP installers and this is reflected in the responses.

6. **Do you expect GSHP systems to have a bigger market share in the future with regards to heating/cooling technology?**

Answer:

Yes	100%
No	0%

7. **Rank which market forces you think would most influence the market growth of GSHP systems in the near future?**

Answer:

Market Force	Average Rating
Decrease Level of Fossil Fuel	4.2
Greenhouse Emission and Global Warming	3.6
Better Awareness of General Public on GSHP Systems	4
More Federal and State Tax Cuts	4.6
Other	5

Under other they said:

- "cost of home heating oil / propane"
- "Greater federal and state incentives, to potential system owners or to utility involvement in installing the ground exchange, as a permanent infrastructure, and leasing the cost to residents of the building over extended time periods, since the ground connection lasts virtually indefinitely."

- “Cost of fossil fuels”

8. Do you offer installation of hybrid GSHP systems?

Yes	80%
No	20%

Brief explanations were provided:

- “Propane or natural gas furnace when the furnace already exists in the home.”
- “We always offer some sort of makeup/backup. We are believers in solar thermal, PV and wind where appropriate”
- “We don't install hybrid system to increase performance, since a geothermal system in a well insulated and air-sealed home combined with a properly sized system will attain efficiencies of well over 300%. The client will receive a faster payback by investing in insulation or solar thermal or photovoltaic to offset geothermal running costs. However, we have clients who are concerned about loss of power to the electrical grid. We can design systems for them where their heating needs would be switched to a fossil fuel heating appliance whose electrical needs are powered by a generator.”
- “with recent declines in new construction we've seen increases in the retrofit existing market and a large portion of that work involves hybrid...so fossil furnaces, hydro coils off fossil boilers or water tanks, though much of this is used for backup or 2nd stage heat.”

9. **As an installer of GSHP systems, what reason would there be to not offer installation of hybrid systems?**

Answer: There responses to the question were:

- "It all boils down to initial cost, recurring costs, renew-ability."
- "only reason I can see is mainly new construction where there is a greater possibility of designing to full load as the distribution system is part of the design."

Alumni and Student Survey:

We also conducted a survey of WPI alumni and student as a part of our research. WPI is an engineering school and as such we expect the results to not describe the general public opinion and knowledge on GSHP. We expect on average a better knowledge of the general idea behind GSHPs. Nonetheless, the student survey provided us with insight into how the next working generation which will be looking for jobs and settling down perceive GSHP as a HVAC technology. On the other hand, the alumni survey helped us understand how people who have already settled down or are still looking to settle down value GSHPs. The survey begins by briefly assessing their knowledge of GSHPs, and then goes on to seek their opinions on various forms of energy as well as GSHPs. Below are the questions along with the answers and a brief analysis of each question.

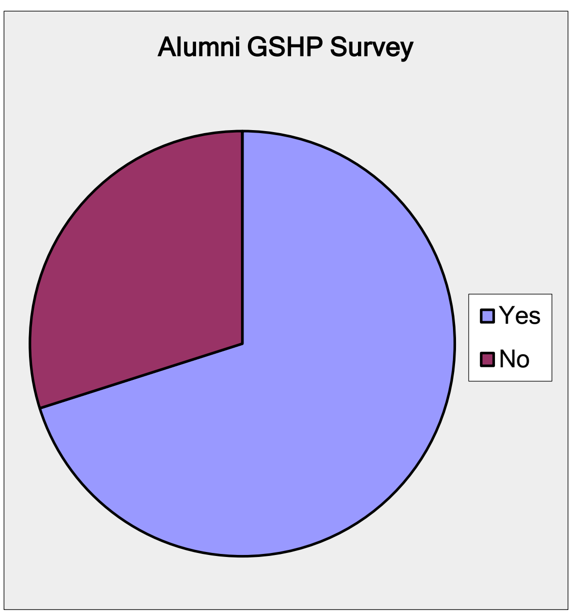
- **Question 1**

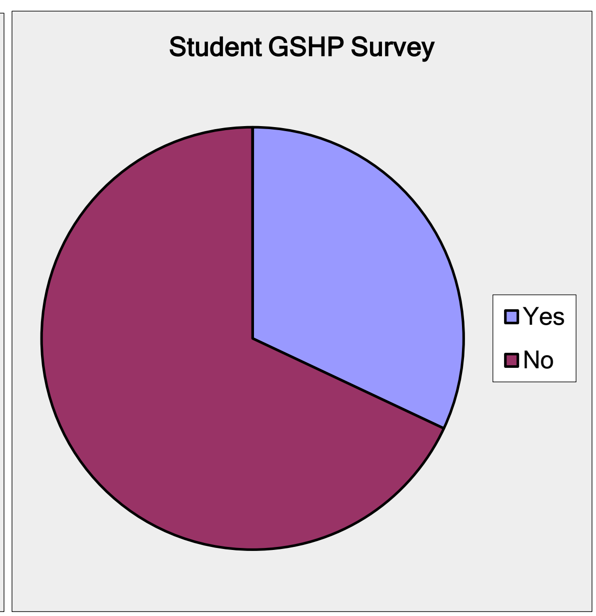
Alumni GSHP Survey

Have you ever heard of Ground Source Heat Pumps?		
Answer Options	**Response Percent**	**Response Count**
Yes	70.1%	148
No	29.9%	63
If yes, how many residences do you know of which use a GSHP?		138
	answered question	**211**
	skipped question	**0**

Student GSHP Survey

Have you ever heard of Ground Source Heat Pumps?		
Answer Options	**Response Percent**	**Response Count**
Yes	32.0%	129
No	68.0%	274
If yes, how many residences do you know of which use a GSHP?		108
	answered question	**403**
	skipped question	**1**





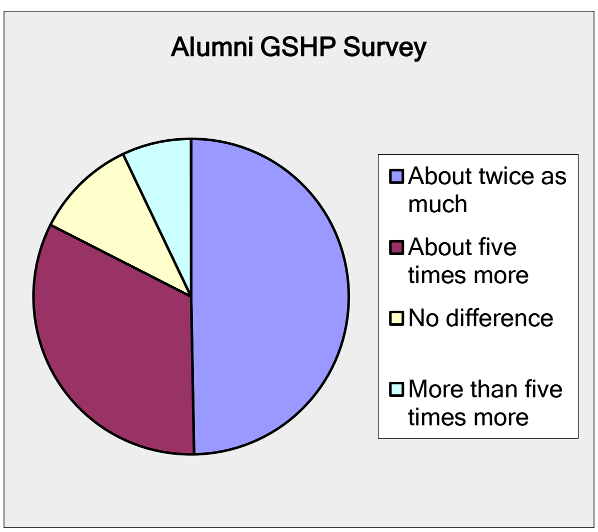
Question 2

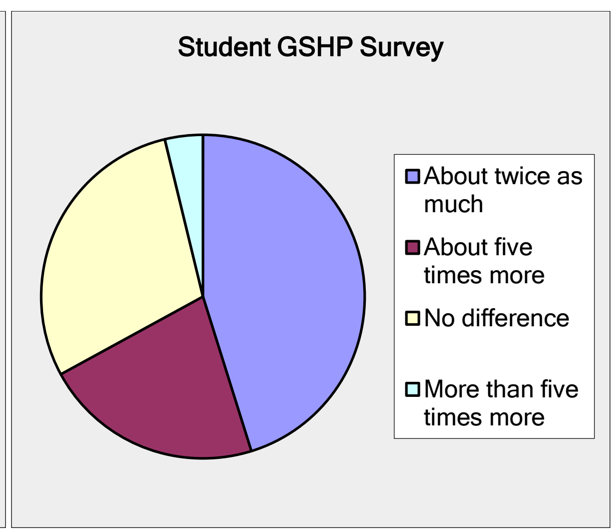
Alumni GSHP Survey

To your knowledge, the installation cost of a GSHP relative to a traditional oil heating system is:		
Answer Options	**Response Percent**	**Response Count**
About twice as much	49.7%	91
About five times more	32.8%	60
No difference	10.4%	19
More than five times more	7.1%	13
	answered question	**183**
	skipped question	**28**

Student GSHP Survey

To your knowledge, the installation cost of a GSHP relative to a traditional oil heating system is:		
Answer Options	**Response Percent**	**Response Count**
About twice as much	45.2%	155
About five times more	21.9%	75
No difference	29.2%	100
More than five times more	3.8%	13
	answered question	**343**
	skipped question	**61**

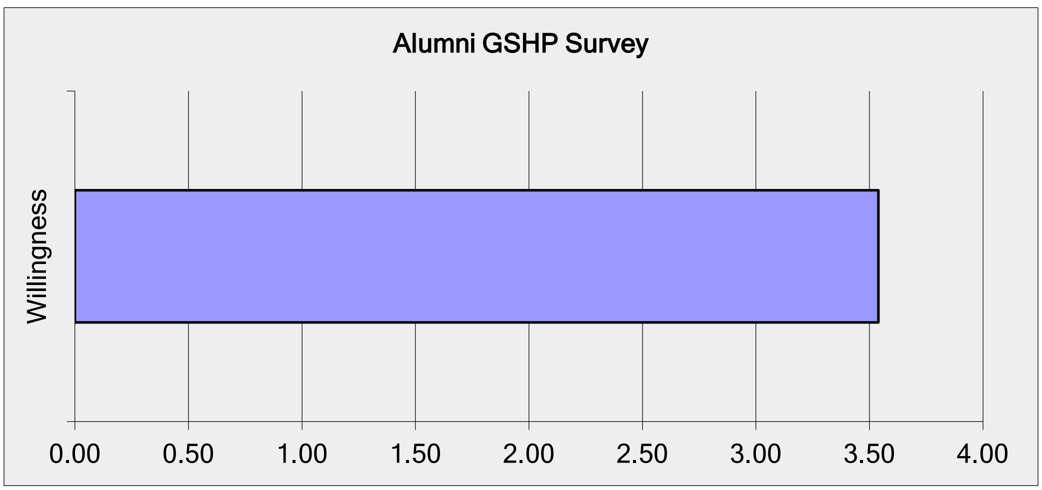




Question 3

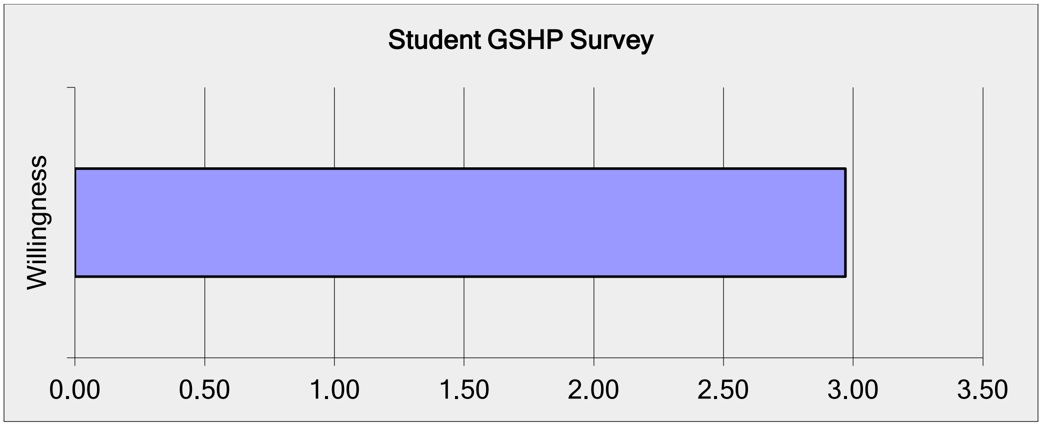
Alumni GSHP Survey

Compared to other heating and cooling technologies, GSHP's tend to have a higher initial cost. With the potential for global warming, and the uncertainty in conventional energy costs, how willing would you be to install a GSHP as your primary heating and cooling technology? Please rate."								
Answer Options	**I plan to do so**		**I would consider it**		**I would not strongly consider it**		**I would not do so**	**Rating Average**	**Response Count**
Willingness	4	21	94	22	22	5	11	3.54	179
								answered question	**179**
								skipped question	**32**



Student GSHP Survey

Compared to other heating and cooling technologies, GSHP's tend to have a higher initial cost. With the potential for global warming, and the uncertainty in conventional energy costs, how willing would you be to install a GSHP in the future as your primary heating and cooling technology? Please rate."									
Answer Options	**I plan to do so**		**I would consider it**		**I would not strongly consider it**		**I would not do so**	**Rating Average**	**Response Count**
Willingness	20	47	133	22	10	3	7	2.97	242
								answered question	**242**
								skipped question	**162**



- **Question 4**

Alumni GSHP Survey

Despite their high initial cost, GSHP's significantly reduce energy consumption, resulting in a lower operating cost than other heating and cooling technology. Please Provide a reasonable time estimate for return on investment in years.	
Answer Options	**Response Count**
	172
answered question	**172**
skipped question	**39**

Student GSHP Survey

Despite their high initial cost, GSHP's significantly reduce energy consumption, resulting in a lower operating cost than other heating and cooling technology. Please Provide a reasonable time estimate for return on investment in years.	
Answer Options	**Response Count**
	208
answered question	**208**
skipped question	**196**

We list below the mean, median and mode of the answers obtained:

Column1	Alumni Survey	Student Survey
Mean	6.09	7.66
Median	5	5
Mode	5	5

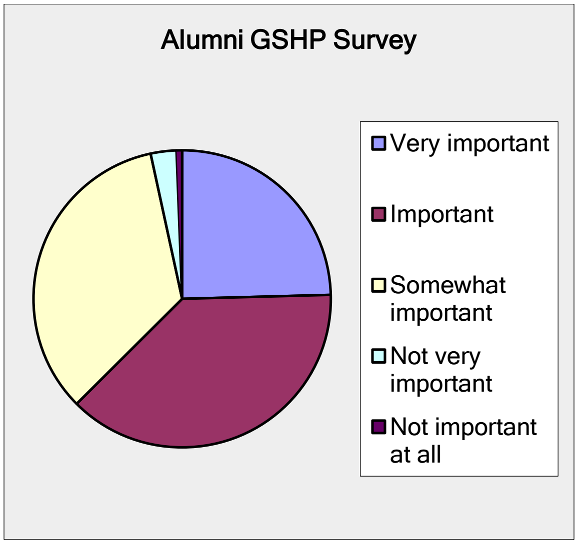
- **Question 5**

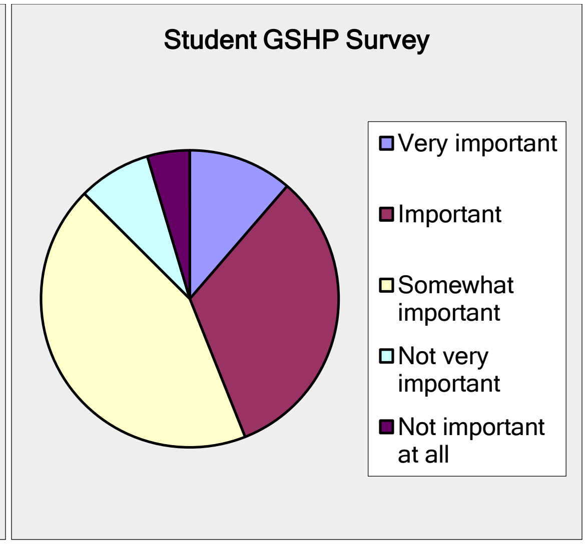
Alumni GSHP Survey

How important is it to you to get your ROI quickly?		
Answer Options	**Response Percent**	**Response Count**
Very important	24.6%	44
Important	38.0%	68
Somewhat important	34.1%	61
Not very important	2.8%	5
Not important at all	0.6%	1
	answered question	**179**
	skipped question	**32**

Student GSHP Survey

How important is it to you to get your ROI quickly?		
Answer Options	**Response Percent**	**Response Count**
Very important	11.3%	27
Important	32.6%	78
Somewhat important	43.5%	104
Not very important	7.9%	19
Not important at all	4.6%	11
	answered question	**239**
	skipped question	**165**

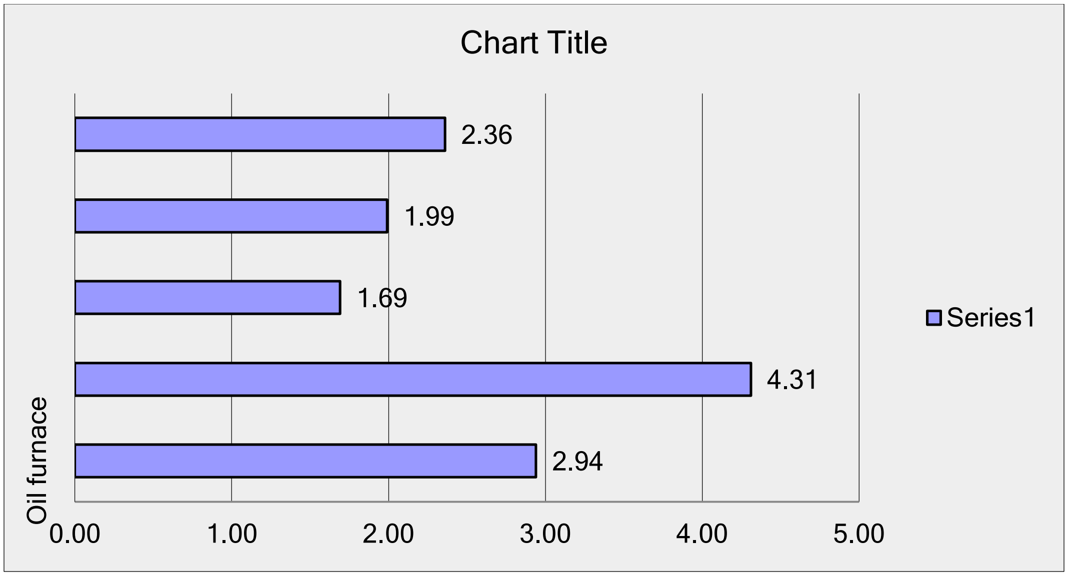




Question 6

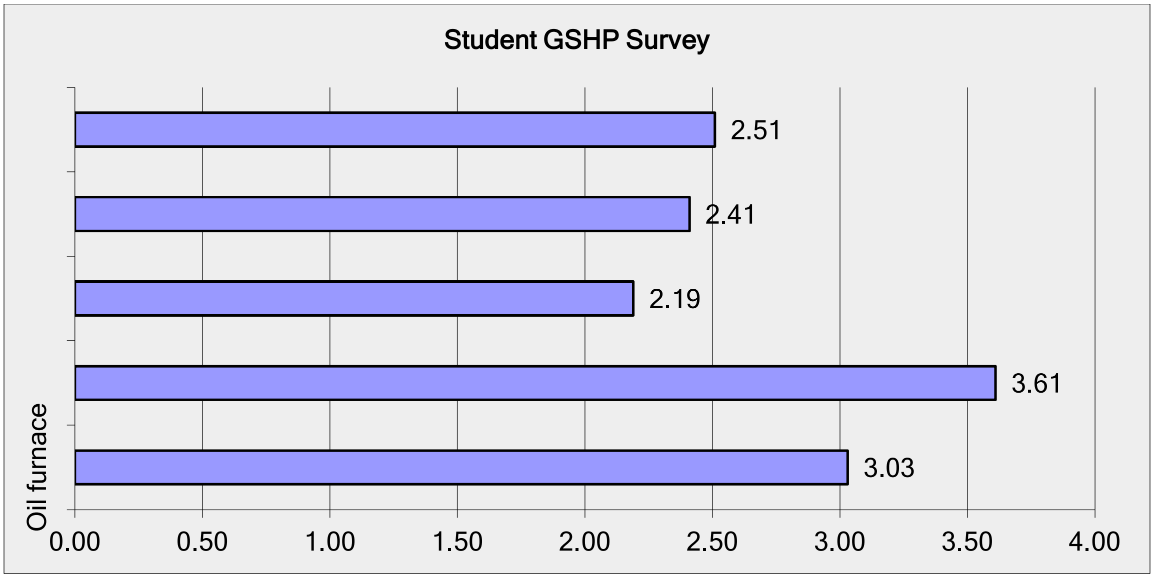
Alumni GSHP Survey

Please rate the following systems in terms of their ease of use, remembering to account for cleaning, fueling and maintenance factors.							
Answer Options	**Easiest**				**Hardest**	**Rating Average**	**Response Count**
Oil furnace	20	37	61	55	6	2.94	179
Wood stove	3	8	22	43	102	4.31	178
Electric floor board radiators	98	46	24	8	1	1.69	177
Natural gas	47	92	36	3	1	1.99	179
GSHP	34	62	48	17	4	2.36	165
						answered question	**180**
						skipped question	**31**



Student GSHP Survey

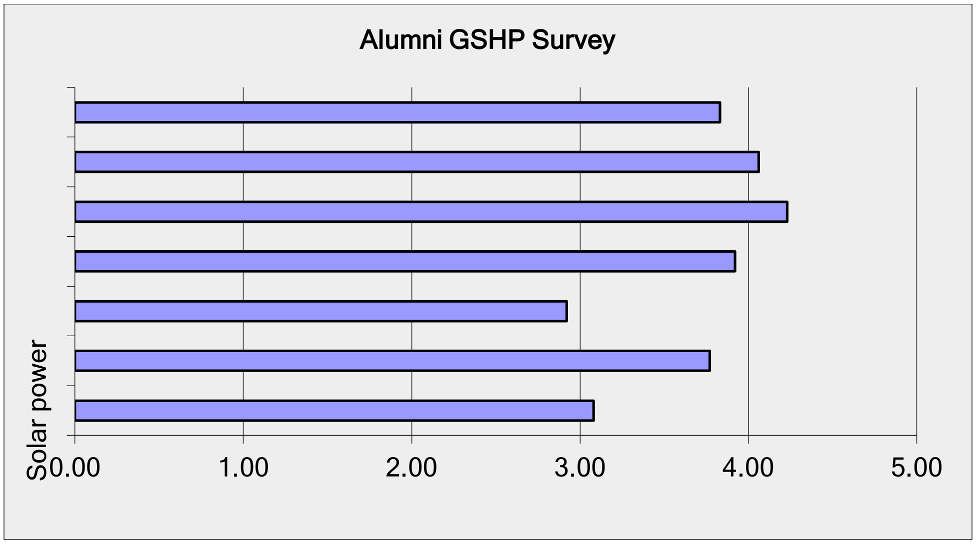
Please rate the following systems in terms of their ease of use, remembering to account for cleaning, fueling and maintenance factors.							
Answer Options	**Easiest**				**Hardest**	**Rating Average**	**Response Count**
Oil furnace	22	53	65	62	21	3.03	223
Wood stove	18	24	56	55	70	3.61	223
Electric floor board radiators	70	66	63	16	6	2.19	221
Natural gas	39	83	73	21	5	2.41	221
GSHP	46	52	91	19	9	2.51	217
						answered question	**224**
						skipped question	**180**



Question 7

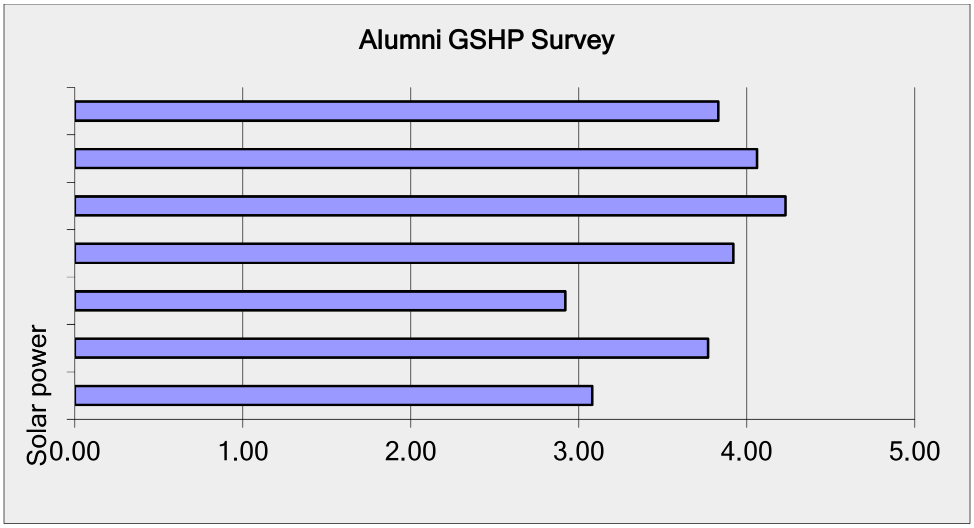
Alumni GSHP Survey

Please rank the following technologies according to how much money you would devote to them if you were in a position in the government to do so.									
Answer Options	**Most money**						**Least Money**	**Rating Average**	**Response Count**
Solar power	40	51	27	8	14	15	16	3.08	171
Wind power	16	35	44	19	12	21	23	3.77	170
GSHP	26	50	46	21	15	3	7	2.92	168
Fuel cell	8	34	35	35	21	16	20	3.92	169
Biomass/Biofuel	13	17	29	36	29	23	22	4.23	169
Hydro power	12	27	36	24	22	32	17	4.06	170
Other	19	11	11	10	4	3	22	3.83	80
Other (please specify what your other is)									62
								answered question	**172**
								skipped question	**39**



Student GSHP Survey

Please indicate how you would budget money for the following technologies if you held a government position.									
Answer Options	**Most money**						**Least Money**	**Rating Average**	**Response Count**
Solar power	66	64	37	22	11	6	5	2.46	211
Wind power	37	65	47	32	15	6	9	2.89	211
GSHP	34	67	55	35	10	5	4	2.77	210
Fuel cell	33	38	45	46	25	17	7	3.34	211
Biomass/Biofuel	14	35	41	38	34	33	15	3.96	210
Hydro power	32	37	46	32	29	23	8	3.43	207
Other	20	6	9	18	7	7	27	4.22	94
Other (please specify what your other is)									42
								answered question	**211**
								skipped question	**193**



Both alumni and students chose nuclear energy in general as the other technology

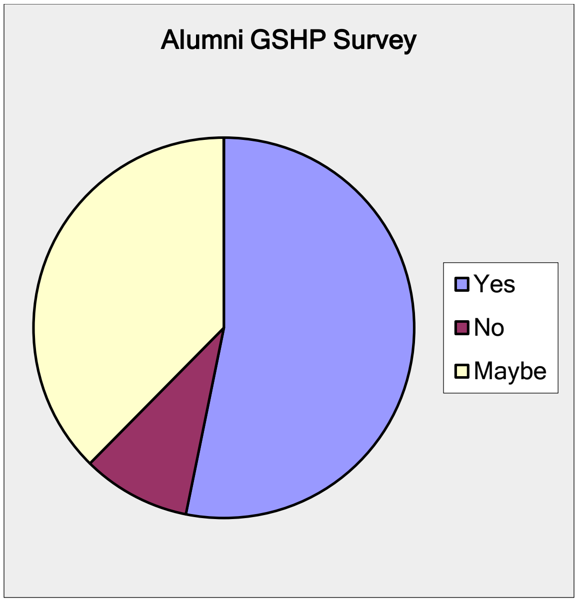
- **Question 8**

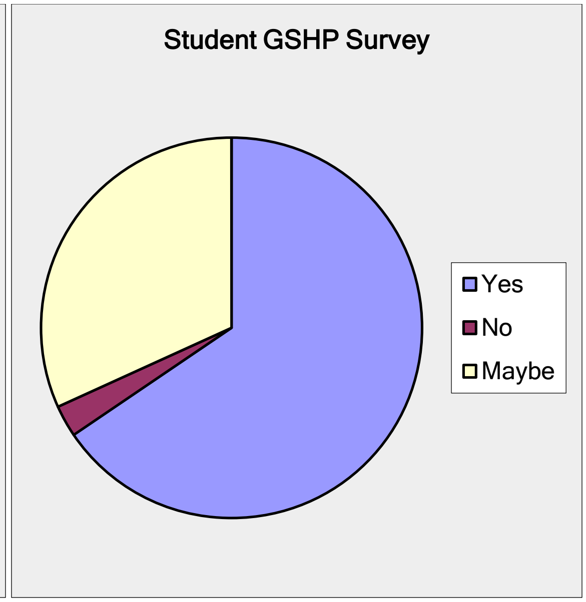
Alumni GSHP Survey

Would you consider implementing a GSHP in the future?		
Answer Options	**Response Percent**	**Response Count**
Yes	53.2%	92
No	9.2%	16
Maybe	37.6%	65
Conditions of you maybe?		73
	answered question	**173**
	skipped question	**38**

Student GSHP Survey

Would you consider implementing a GSHP in the future?		
Answer Options	**Response Percent**	**Response Count**
Yes	65.5%	144
No	2.7%	6
Maybe	31.8%	70
Conditions of you maybe?		46
	answered question	**220**
	skipped question	**184**





When they chose maybe, both alumni and student’s reasons were related to time for return on investment.

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