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DIRECT EXPANSION GROUND SOURCE HEAT PUMPS FOR HEATING AND COOLING

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ABSTRACT

This article is an introduction to the energy problem and the possible saving that can be achieved through improving building performance and the use of ground energy sources. The relevance and importance of the study is discussed in the paper, which, also, highlights the objectives of the study, and the scope of the theme. This study discusses some of the current activity in the GSHPs field. The basic system and several variations for buildings are presented along with examples of systems in operation. Finally, the GCHP is presented as an alternative that is able to counter much of the criticism leveled by the natural gas industry toward conventional heat pumps. Several advantages and disadvantages are listed. Operating and installation costs are briefly discussed.

1. INTRODUCTION

The GSHPs can provide an energy-efficient, cost-effective way to heat and cool building facilities. Through the use of a ground-coupling system, a conventional water source heat pump design is transformed to a unique means of utilising thermodynamic properties of earth and groundwater for efficient operation throughout the year in most climates. In essence, the ground (or groundwater) serves as a heat source during winter operation and a heat sink for summer cooling. Many varieties in design are available, so the technology can be adapted to almost any site. The GSHP systems can be used widely in many applications and, with proper installation, offer great potential for the building sector, where increased efficiency and reduced heating and cooling costs are important.

The GSHP systems require fewer refrigerants than conventional air-source heat pumps or air-conditioning systems, with the exception of direct expansion type GSHP systems. Installation costs are relatively high but are made up through low maintenance and operating expenses and efficient energy use. The greatest barrier to effective use is improper design and installation; employment of well-trained, experienced, and responsible designers and installers is of critical importance. The new technology demonstration programme (NTDP) selection process and general benefits to the building sector are outlined. The GSHP operation, system types, design variations, energy savings, and other benefits are explained. Appropriate application and installation are presented to give the reader a sense of the actual costs and energy savings.

During the normal life span of a building the surplus of heat would lead to higher ground temperatures. This leads to less efficient heat pump operation and may result in insufficient capacity during cooling and peak demands. As a solution a hybrid system, incorporating a dry-cooler, was developed. The principle idea was to use the dry-cooler to store cold in the wellfield during early spring, when the required summer peak load cool can be generated very efficient and cheaply. A geothermal energy system uses the ground as a heat-source or heat sink, depending on whether the systems used in heating or cooling mode. The ground is principally suited for low temperature energy exchange. The usual operating temperature bandwidth is between -5^{o}C and 40^{o}C (not taking into account high temperature energy stores).

1.1 Background:

Globally, buildings are responsible for approximately 40% of the total world annual energy consumption. Most of this energy is for the provision of lighting, heating, cooling, and air conditioning. Increasing awareness of the environmental impact of CO_2, NO_x and CFCs emissions triggered a renewed interest in environmentally friendly cooling, and heating technologies. Under the 1997 Montreal Protocol, governments agreed to phase out chemicals used as refrigerants that have the potential to destroy stratospheric ozone. It was therefore considered desirable to reduce energy consumption and decrease the rate of depletion of world energy reserves and pollution of the environment.

One way of reducing building energy consumption is to design building, which are more economical in their use of energy for heating, lighting, cooling, ventilation and hot water supply. Passive measures, particularly natural or hybrid ventilation rather than air-conditioning, can dramatically reduce primary energy consumption [1]. However, exploitation of renewable energy in buildings and agricultural greenhouses can, also, significantly contribute towards reducing dependency on fossil fuels. Therefore, promoting innovative renewable applications and reinforcing the ground source energy market will contribute to preservation of the ecosystem by reducing emissions at local and global levels. This will also contribute to the amelioration of environmental conditions by replacing conventional fuels with renewable energies that produce no air pollution or greenhouse gases.

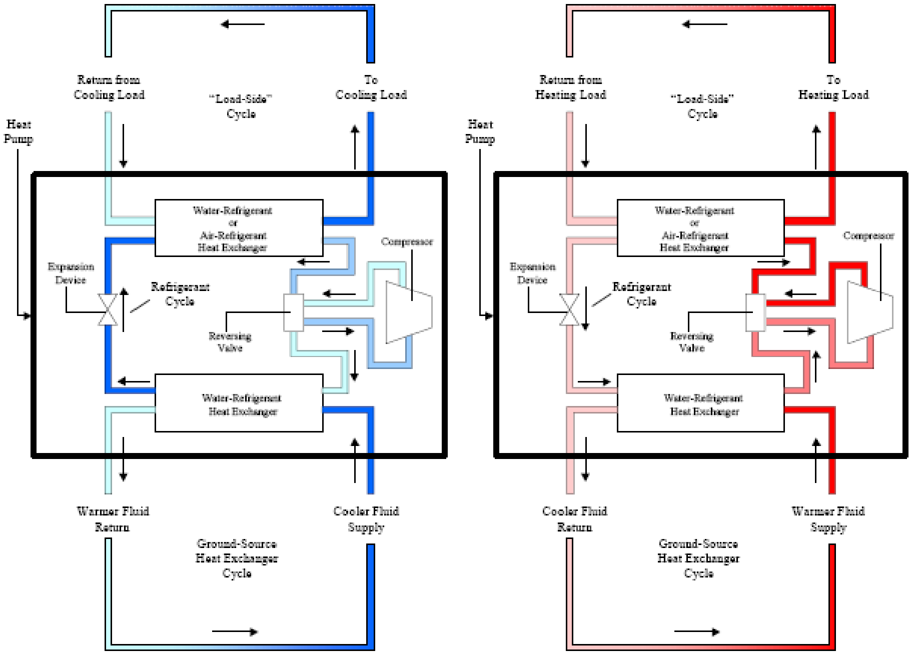
An approach is needed to integrate renewable energies in a way to meet high building performance. However, because renewable energy sources are stochastic and geographically diffuse, their ability to match demand is determined by adoption of one of the following two approaches [2]: the utilisation of a capture area greater than that occupied by the community to be supplied, or the reduction of the community's energy demands to a level commensurate with the locally available renewable resources.

1.2 Overview of ground source heat pump systems:

Ground source heat pump (GSHP) systems (also referred to as geothermal heat pump systems, earth energy systems, and GeoExchange systems) have received considerable attention in the recent decades as an alternative energy source for residential and commercial space heating and cooling applications. The GSHP applications are one of three categories of geothermal energy resources as defined by ASHRAE [2]. These categories are: (1) high-temperature (>302°F (>150°C)) electric power production, (2) intermediate- and low-temperature (<302°F (<150°C)) direct-use applications, and (3) GSHP applications (generally <90°F (<32°C)). The GSHP applications are distinguished from the others by the fact that they operate at relatively low temperatures.

The term "ground source heat pump" has become an all-inclusive term to describe a heat pump system that uses the earth, ground water, or surface water as a heat source and/or sink. The GSHP systems consist of three loops or cycles as shown in Figure 1. The first loop is on the load side and is either an air/water loop or a water/water loop, depending on the application. The second loop is the refrigerant loop inside a water source heat pump. Thermodynamically, there is no difference between the well-known vapour-compression refrigeration cycle and the heat pump cycle; both systems absorb heat at a low temperature level and reject it to a higher temperature level. The difference between the two systems is that a refrigeration application is only concerned with the low temperature effect produced at the evaporator, while a heat pump may be concerned with both the cooling effect produced at the evaporator as well as the heating effect produced at the condenser. In these dual-mode GSHP systems, a reversing valve is used to switch between heating and cooling modes by reversing the refrigerant flow direction. The third loop in the system is the ground loop in which water or an antifreeze solution exchanges heat with the refrigerant and the earth. The GSHPs utilise the thermal energy stored in the earth through either vertical or horizontal closed loop heat exchange systems buried in the ground. Many geological factors impact directly on site characterisation and subsequently the design and cost of the system. The solid geology of the United Kingdom varies significantly.

Furthermore there is an extensive and variable rock head cover. The geological prognosis for a site and its anticipated rock properties influence the drilling methods and therefore system costs. Other factors important to system design include predicted subsurface temperatures and the thermal and hydrological properties of strata. GSHP technology is well established in Sweden, Germany and North America, but has had minimal impact in the United Kingdom space heating and cooling market. Perceived barriers to uptake include geological uncertainty, concerns regarding performance and reliability, high capital costs and lack of infrastructure. System performance concerns relate mostly to uncertainty in design input parameters, especially the temperature and thermal properties of the source. These in turn can impact on the capital cost, much of which is associated with the installation of the external loop in horizontal trenches or vertical boreholes. The temperate United Kingdom climate means that the potential for heating in winter and cooling in summer from a ground source is less certain owing to the temperature ranges being narrower than those encountered in continental climates. This project will develop an impartial GSHP function on the site to make available information and data on site-specific temperatures and key geotechnical characteristics.



(a) (b)

Figure1: Schematic of cycles in a GSHP system in (a) cooling mode and (b) heating mode

The GSHPs are receiving increasing interest because of their potential to reduce primary energy consumption and thus reduce emissions of greenhouse gases. The technology is well established in North Americas and parts of Europe, but is at the demonstration stage in the United Kingdom. The information will be delivered from digital geoscience's themes that have been developed from observed data held in corporate records. These data will be available to GSHP installers and designers to assist the design process, therefore reducing uncertainties. The research will also be used to help inform the public as to the potential benefits of this technology.

The GSHPs play a key role in geothermal development in Central and Northern Europe. With borehole heat exchangers as heat source, they offer de-central geothermal heating at virtually any location, with great flexibility to meet given demands. In the vast majority of systems, no space cooling is included, leaving ground-source heat pumps with some economic constraints. Nevertheless, a promising market development first occurred in Switzerland and Sweden, and now also is obvious in Austria and Germany. Approximately 20 years of R&D focusing on borehole heat exchangers resulted in a well-established concept of sustainability for this technology, as well as in sound design and installation criteria. The market success brought Switzerland to the third rank worldwide in geothermal direct use. The future prospects are good, with an increasing range of applications including large systems with thermal energy storage for heating and cooling, ground-source heat pumps in densely populated development areas, borehole heat exchangers for cooling of telecommunication equipment, etc.

Efficiencies of the GSHP systems are much greater than conventional air-source heat pump systems. A higher COP (coefficient of performance) can be achieved by a GSHP because the source/sink earth temperature is relatively constant compared to air temperatures. Additionally, heat is absorbed and rejected through water, which is a more desirable heat transfer medium because of its relatively high heat capacity. GSHP systems rely on the fact that, under normal geothermal gradients of about 0.5^{o}F/100 ft (30^{o}C/km), the earth temperature is roughly constant in a zone extending from about 20 ft (6.1 m) deep to about 150 ft (45.7 m) deep. This constant temperature interval within the earth is the result of a complex interaction of heat fluxes from above (the sun and the atmosphere) and from below (the earth interior). As a result, the temperature of this interval within the earth is approximately equal to the average annual air temperature [2]. Above this zone (less than about 20 feet (6.1 m) deep), the earth temperature is a damped version of the air temperature at the earth's surface. Below this zone (greater than about 150 ft (45.7 m) deep), the earth temperature begins to rise according to the natural geothermal gradient.

ASHRAE [2] groups GSHP systems into three categories based on the heat source/sink used. A fourth category is added here for the sake of completeness. These categories are: (1) ground-water heat pump (GWHP) systems, (2) ground-coupled heat pump (GCHP) systems, (3) surface water heat pump (SWHP) systems, and (4) standing column well (SCW) systems. Each of these is discussed in the following subsections.

1.2.1 Ground water heat pump systems:

Ground water heat pump (GWHP) systems, also referred to as open-loop systems, are the original type of GSHP system. The first GWHP systems were installed in the late 1940s [3]. The GWHP systems are not the focus of this theme, so they will only be briefly described here. A schematic of a GWHP system is shown in Figure 2. In GWHP systems, conventional water wells and well pumps are used to supply ground water to a heat pump or directly to some application. Corrosion protection of the heat pump may be necessary if ground water chemical quality is poor. The "used" ground water is typically discharged to a suitable receptor, such as back to an aquifer, to the unsaturated zone (as shown in Figure 2), to a surface-water body, or to a sewer. Design considerations for GWHP systems are fairly well established; well-drilling technologies and well-testing methods have been well known for decades. Design considerations include: ground-water availability, ground-water chemical quality, and ground-water disposal method. The main advantage of GWHP systems is their low cost, simplicity, and small amount of ground area required relative to other GSHP and conventional systems. Disadvantages include limited availability and poor chemical quality of ground water in some regions. With growing environmental concerns over recent decades, many legal issues have arisen over ground water withdrawal and re-injection in some localities.

1.2.2 Ground coupled heat pump systems:

Ground coupled heat pump (GCHP) systems, also referred to as closed-loop ground-source heat pump systems, were pioneered in the 1970s. Their main advantage over their water-well predecessors is that they eliminate the problems associated with ground water quality and availability and they generally require much less pumping energy than water well systems because there is less elevation head to overcome. The GCHP systems can be installed at any location where drilling or earth trenching is feasible. In GCHP systems, heat rejection/extraction is accomplished by circulating a heat exchange fluid through a piping system buried in the earth. This fluid is either pure water or an antifreeze solution and is typically circulated through high-density polyethylene (HDPE) pipe installed in vertical boreholes or horizontal trenches as shown in Figure 3. Thus, these systems are further subdivided into vertical GCHP systems and horizontal GCHP systems.

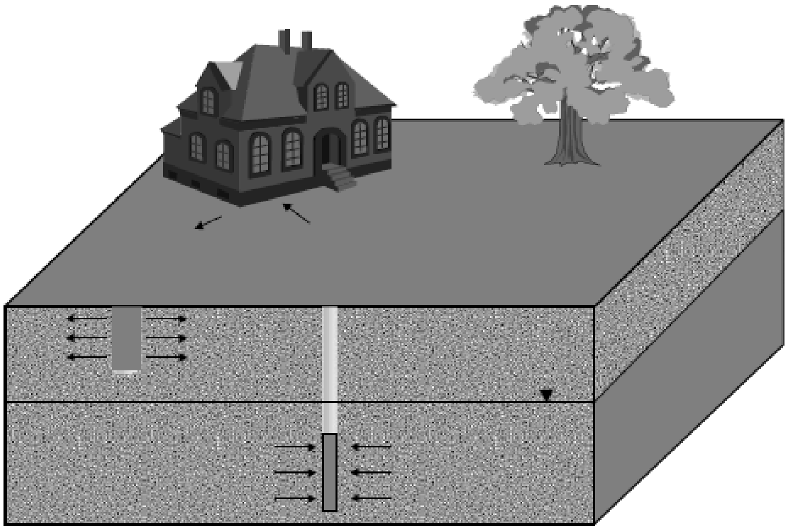


Figure 2: A schematic of a ground-water heat pump system

1.2.2.1 Vertical ground coupled heat pump systems:

Vertical borehole GCHP systems are the primary focus of this entire study. Therefore, they are described in some detail here and their design challenges are explained, laying the foundation for the motivation of this study. In vertical borehole GCHP systems, ground heat exchanger configurations typically consist of one to tens of boreholes each containing a U-shaped pipe through which the heat exchange fluid is circulated. Some Swedish applications use boreholes inclined from the vertical. A number of borehole-to-borehole plumbing arrangements are possible. Typical U-tubes have a diameter in the range of ¾ in. (19 mm) to 1 ½ in. (38 mm) and each borehole is typically 100 ft (30.5 m) to 300 ft (91.4 m) deep with a diameter ranging from 3 in. (76 mm) to 5 in. (127 mm). The borehole annulus is generally backfilled with a material that prevents contamination of ground water.

The design of vertical ground heat exchangers is complicated by the variety of geological formations and properties that affect their thermal performance [2]. Proper subsurface characterization is not economically feasible for every project. One of the fundamental tasks in the design of a reliable GCHP system is properly sizing the ground-coupled heat exchanger length (i.e., depth of boreholes). Particularly for large systems, an extensive effort is made to design the ground loop heat exchangers so that they are not too large (resulting in too high of a first cost) or too small (resulting in the building's thermal load not being met).

In the early days of GCHP technology, the task of sizing the ground-loop heat exchanger was accomplished using rules of thumb (i.e., 250 feet of bore length per ton of heating or cooling capacity). These rules were slightly modified on a case-by-case basis using some estimates of thermal conductivity of the formation or using previous design experience, but additional costs of more detailed testing or calculations was judged to outweigh the costs of a conservative design. This relatively simple approach proved to be successful in most residential and other small applications, but in larger-scale commercial and institutional applications, some ground-loop heat exchangers failed to meet their design loads after the first few years of operation. Further, the practice of greatly over-designing large GCHP systems was found to be unacceptable because the first costs were simply not competitive with the first costs of conventional systems.

Consequently, intensive research regarding methods to optimise ground-loop heat exchanger design has been ongoing for the last decade. Simple approaches to sizing the ground-loop heat exchanger in larger-scale applications are inadequate mainly because the heat transfer processes in the ground are complicated by thermally interacting boreholes and hourly periodic heat extraction/injection pulses. Annual heat rejection and heat extraction are usually not equal and peak temperatures rise or fall over a number of years. As a result, ground-loop heat exchanger designers need to consider hourly heating and cooling loads of the building and need to perform some simulation of the ground-loop temperatures over the life-cycle of the building. Recent research efforts have produced several methods and computer software programs for this purpose. However, none of the programs consider the effects of ground water flow on ground-loop heat exchanger performance; these effects have not been well understood, perhaps because of the lack of relevant investigations.

Another challenge in the design of GCHP systems arises from the fact that most commercial and institutional buildings, even in moderate climates, are generally cooling dominated and therefore reject more heat to the ground than they extract over the annual cycle. This load imbalance may require the heat exchanger length to be significantly greater than the length required if the annual loads were balanced. As a result, the GSHP system may be eliminated from consideration early in the design phase of the project due to excessive first cost. This has given rise to the concept of “supplemental heat rejecters” or so-called “hybrid GSHP systems”.

Supplemental heat rejecters have been integrated into building designs to effectively balance the ground loads and therefore reduce the necessary length of the ground-loop heat exchanger. In some applications, the excess heat that would otherwise build up in the ground may be used for domestic hot water heaters, car washes, and pavement heating systems. In cases where the excess heat cannot be used beneficially, conventional cooling towers or shallow ponds can provide a cost-effective means to reduce heat exchanger length. Design of these supplemental components adds to the challenge of designing the overall hybrid GCHP system because of their highly transient nature. Heat rejection systems are likely to operate more often during the nighttime hours or when the building is not in use. Therefore, it is essential that the hourly (or less) behaviour of these systems be examined during their design phase.

1.2.2.2 Horizontal ground coupled heat pump systems:

In horizontal GCHP systems, ground heat exchanger configurations typically consist of a series of parallel pipe arrangements laid out in dug trenches or horizontal boreholes about 3 ft (0.91 m) to 6 ft (1.83 m) deep. A number of piping arrangements are possible. “Slinky” configurations (as shown in Figure 1.3 (b)) are popular and simple to install in trenches and shallow excavations. In horizontal boreholes, straight pipe configurations are installed. Typical pipes have a diameter in the range of ¾ in. (19 mm) to 1 ½ in. (38 mm) and about 400 ft (121.9 m) to 600 ft (182.9 m) of pipe is installed per ton of heating and cooling capacity.

The thermal characteristics of horizontal GCHP systems are similar to those of vertical ones. The main difference is that horizontal ground-loop heat exchangers are more affected by weather and air temperature fluctuations because of their proximity to the earth’s surface. This may result in larger loop temperature fluctuations and therefore lower heat pump efficiencies. Recent research activities have focused on using these systems as supplemental heat rejecters with vertical borehole GCHP systems. A specific application (i.e., the use of a shallow cooling system) is the focus of this study.

Aside from the invention of the Slinky coil itself and the use of these systems as supplemental heat rejecters, horizontal systems have received much less attention than vertical systems with respect to recent research efforts. This may be due to the fact that vertical systems tend to be preferred in larger applications since much less ground area is required. Also, since horizontal systems are installed at shallow depths, geologic site characterisation is relatively easier because soils can be readily seen and sampled. Further, over-conservative designs are not as cost prohibitive as with vertical borehole designs because of the relatively low installation costs of the heat exchanger pipe.

1.2.3 Surface water heat pump systems:

The third category of GSHP systems is the surface-water heat pump (SWHP) system. A specific application of SWHP systems (i.e., the use of a shallow pond as a supplemental heat rejecter in vertical GCHP systems), and a schematic of a SWHP system is shown in Figure 4. The surface-water heat exchanger can be a closed-loop or open-loop type. Typical closed-loop configurations are the Slinky coil type (as shown in Figure 4) or the loose bundle coil type. In the closed-loop systems, heat rejection/extraction is accomplished by circulating a heat exchange fluid through HDPE pipe positioned at an adequate depth within a lake, pond, reservoir, or other suitable open channel. Typical pipe diameters range from ¾ in. (19 mm) to 1 ½ in. (38 mm) and a length of 100 feet (30.48 m) to 300 feet (91.44 m) per ton of heating or cooling capacity is recommended by ASHRAE [2], depending on the climate. In open-loop systems, water is extracted from the surface-water body through a screened intake area at an adequate depth and is discharged to a suitable receptor.

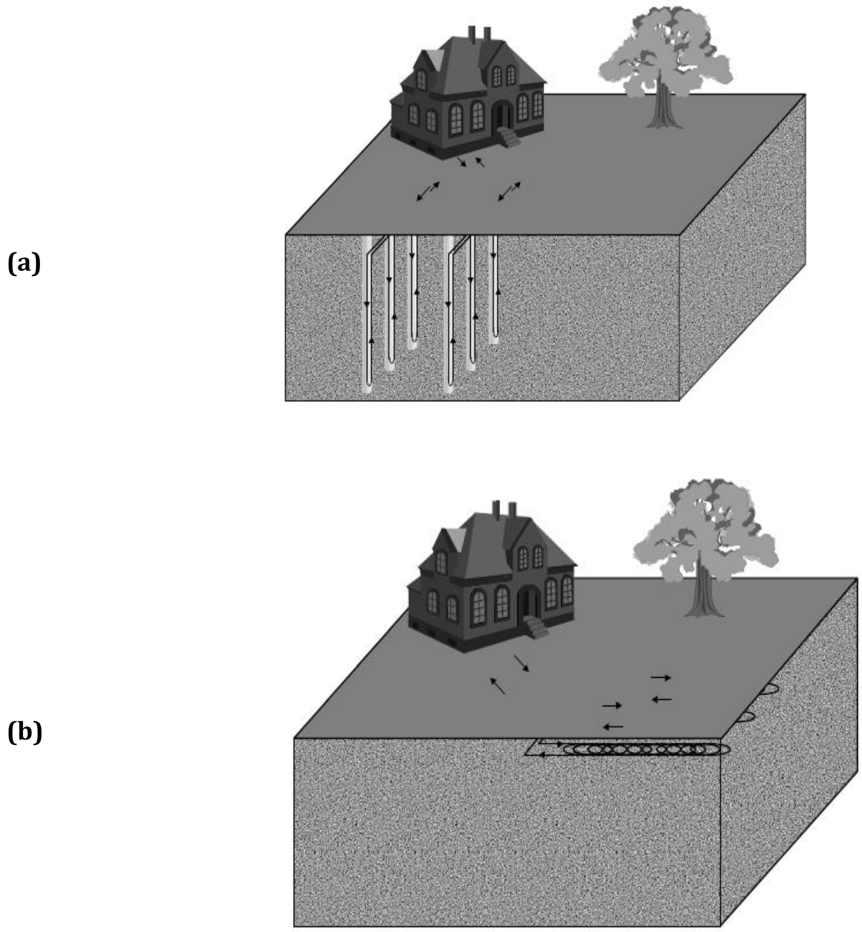


Figure 3: A schematic of (a) a vertical borehole ground-coupled heat pump system and (b) horizontal ground-coupled heat pump system

Heat transfer mechanisms and the thermal characteristics of surface-water bodies are quite different than those of soils and rocks. At the present time, design tools for surface-water heat pump systems are in their developmental infancy [3]. However, many successful installations are currently in operation and some guidelines do exist. In short, the loop design involves selection of sufficient length of coil for heat transfer, specifying adequate diameter piping, specifying a sufficient numbers of parallel loops, and locating the coil at a proper depth in a water body with adequate thermal capacity.

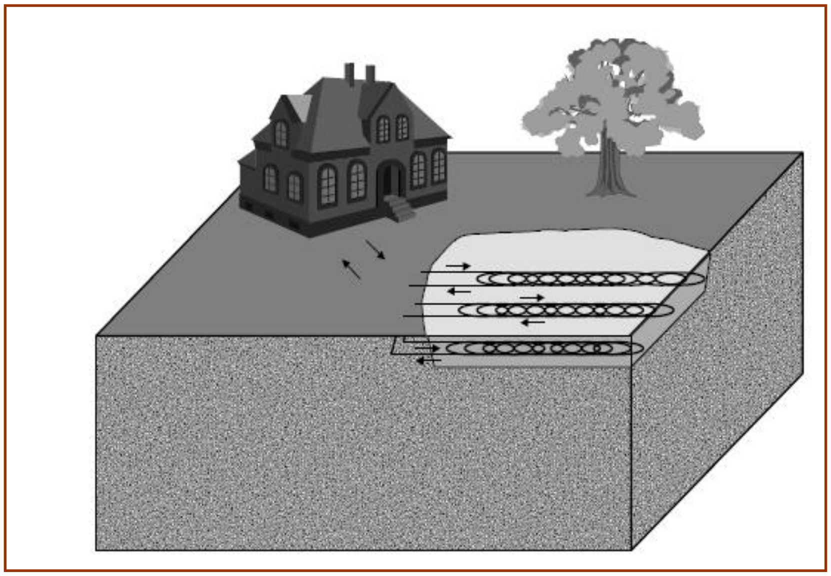


Figure 4:A schematic of a surface-water heat pump system

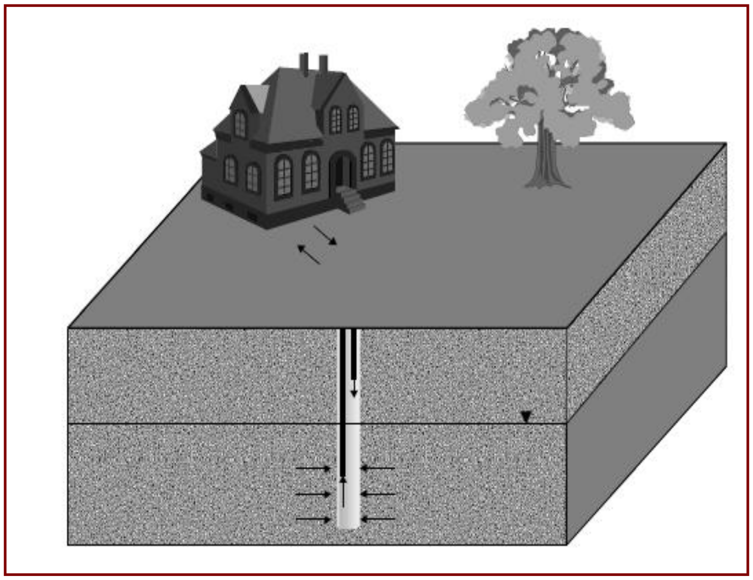


Figure 5: A schematic of a standing column well system

1.2.4 Standing column well systems:

The fourth category of GSHP systems is known as a standing column well (SCW) system. These systems are about as old as the ground-water heat pump systems, but are recently receiving much attention. Since these are not the subjects of this study, they are only briefly discussed here.

A schematic of an SCW system is shown in Figure 5. This type of GSHP draws water to a heat pump from a standing column of water in a deep well bore and returns the water to the same well. These systems, primarily installed in hard rock areas, use uncased boreholes with typical diameters of about 6 in. (15.24 cm) and depths up to 1500 feet (457.2 m). The uncased borehole allows the heat exchange fluid to be in direct contact with the earth (unlike closed-loop heat exchangers) and allows ground water infiltration over the entire length of the borehole. Properly sited and designed, SCW systems have been shown to have significant installation cost savings over closed-loop GCHP systems. Design guidelines for SCW systems are currently under development.

1.3 Objective of the study:

The main objective of the research is to stimulate the uptake of the GSHPs. The GSHPs are well suited to space heating and cooling, and can produce significant reduction in carbon emissions. To design a GSHP system, the tools that are currently available require the use of key site-specific parameters such as temperature and the thermal and geotechnical properties of the local area. This study deals with the modelling of vertical closed-loop and hybrid, ground source heat pump systems. The challenges associated with the design of these systems will be discussed in the later sections. A considerable amount of research in the past decade has been geared toward optimising the performance of these types of systems and this study is part of those efforts. Also, this project will establish services for GSHP users, installers and designers, providing them with the necessary key design parameters in order to help reduce design uncertainties. The School of the Built Environment, University of Nottingham has sponsored a project. There are three primary objectives of this study. These are to:

1) Examine the effects of ground-water flow on closed-loop GSHP systems.
2) Develop a design and simulation tool for modelling the performance of a shallow pond as a supplemental heat rejecter with closed-loop GSHP systems.
3) Develop a design and simulation tool for modelling the performance of a refrigeration system as a supplemental heat rejecter with closed-loop GSHP systems.

4) Identify current total and component costs of GSHPs, and compare the cost of GSHP equipment and installation with similar industry cost.

1.3.1 Goals:

Determine the suitability of ground source heat pumps (GSHPs) for heating and cooling. Verify and document the savings in energy use and demand that GSHPs may be expected to achieve.

1.3.2 Approach:

Long ago it was recognised that water source heat pumps were the only likely candidate for cold regions heat pump applications. Then, conducted demonstration projects for groundwater and sewage effluent source heat pumps on several facilities. In the early 2005s, the ground source heat pump (GSHP) was just installed at the School of Built Environment, and an experimental installation was undertaken. From this I have learned enough about the technology to propose further demonstrations.

1.3.3 Technology description:

Geothermal energy is the natural heat that exists within the earth and that can be absorbed by fluids occurring within, or introduced into, the crystal rocks. Although, geographically, this energy has local concentrations, its distribution globally is widespread. The amount of heat that is, theoretically, available between the earth's surface and a depth of 5 km is around 140 x 10^{24} joules. Of this, only a fraction (5 x 10^{21} joules) can be regarded as having economic prospects within the next five decades, and only about 500 x 10^{18} joules is likely to be exploited by the year 2020. Three main techniques are used to exploit the heat available: geothermal aquifers, hot dry rocks and ground source heat pumps.

1.3.4 Accomplishments:

The present ground source heat pump has been designed taking into account the local metrological and geological conditions, and then installed one of the first heat pump systems that used ground source as a heat source. This project yielded considerable experience and performance data for the novel methods used to exchange heat with the primary effluent. The heat pump have also fitted in dry, well-ventilated position where full access for service was possible and monitored the performance of a number of GSHP, including one so-called "hybrid" system that included both ground-coupling and a cooling tower. The site was at the School of the Built Environment, University of Nottingham, where the demonstration project and performance monitoring efforts. Then, obtained the performance data for GSHP.

2. GSHP DEVELOPMENT

The original GSHP technology published in 1995 [4]. As with the previous document, the focus of this material is on commercial application of the GSHPs in the building sector. While GSHPs are well established in the residential sector, their application in the federal sector is lagging, in part because of a lack of experience with the technology by those in decision-making positions. This technology provides the information and procedures that federal energy managers need to evaluate the potential for ground-source heat pump application at their facilities. The ground-source heat pump operation, system types, design variations, energy-savings, and other benefits are explained, and provided for appropriate application and installation.

Ground-coupled heat pumps (GCHPs) have been receiving increasing attention in recent years. In areas where the technology has been properly applied, they are the system of choice because of their reliability, high level of comfort, low demand, and low operating costs. Initially these systems were most popular in rural, residential applications where heating requirements were the primary consideration. However, recent improvements in heat pumps units and installation procedures have expanded the market to urban and commercial applications.

There are a variety of names for ground-coupled heat pumps. These include ground-source heat pumps, earth-coupled heat pumps, earth energy systems, ground source systems, geothermal heat pumps, closed-loop heat pumps, and solar energy heat pumps. Much of the confusion arises from local marketing needs. Sales people may wish to connect GCHPs to renewable energy sources (solar, geothermal), disassociate them from air heat pumps (GS systems), or connect them to environmental awareness (earth energy).

The GCHPs are a subset of the GSHPs. GSHPs; also include groundwater and lake water heat pumps. The distinguishing feature of GCHPs is that they are connected to a closed-loop network of tubing that is buried in the ground. The most common method of ground coupling is to bury thermally fused plastic pipe either vertically or horizontally. A water or antifreeze solution is circulated through the inside of the tubing and heat is released to or absorbed from the ground. No water enters the system from the ground. Water- to-air heat pumps are located inside the building and are connected to the water loop with a circulator pump. This type of system is referred to as a secondary fluid GCHP since there is an intermediate liquid between the refrigerant and the ground.

A less frequently used system is referred to as a direct expansion (DX) GCHP. Refrigerant lines are buried in the ground in either a vertical or horizontal arrangement. Thus the intermediate heat exchanger and fluid are eliminated. The possibility of higher efficiency than secondary fluid GCHPs does exist. However, larger charges of refrigerant are required and system reliability is compromised. Therefore, the future of DX GCHP is not clear because of environmental concerns. The major barriers to rapid implementation of this technology involve awareness and acceptance by users and HVAC designers (which is growing rapidly) and higher initial implementation costs than other options. In addition, there is a limited infrastructure and availability of skilled and experienced designers and installers of ground-source heat pump systems.

2.1 Technology and application domain:

Commercial use of the ground as a heat source/sink did not begin until after the first oil shock in 1973 but was well established by the end of the seventies by which time there were over 1000 ground source heat pumps installed in Sweden [5]. The vertical earth heat exchanger was introduced into Europe in the late 70s [6] and from that time on has been used in various types mainly in Sweden, Germany, Switzerland and Austria [7]. Since 1980 there have not been any major technological advances in the heat pump itself except for improved reliability. However, considerable progress has been made in other areas such as system integration, reducing costs for the ground heat exchanger, improving collector configuration and control systems and strategies. Today GSHPs are an established technology with over 400,000 units installed worldwide (around 62% of which are in the US) and about 45,000 new units installed annually. They are receiving increasing interest in North America and Europe because of their potential to reduce primary energy consumption and thus reduce the emission of GHGs and other pollutants. Studies carried out [7] identified ground source heat pumps as the technology for space heating and cooling which had the highest potential energy efficiency. The Geothermal Heat Pump Consortium was thus set up in 1994 with the aim of stimulating uptake of the technology and increasing the number of installations from approximately 40,000 units/year to 400,000 units/year by the year 2000. It was estimated that this could save over 300 x

10^9MJ/year and reduce GHG emissions by 1.5 million metric tons/year of carbon equivalent. Although this target was very ambitious, and will not be met, there has been sustained interest in the technology. Overall efficiencies for ground source heat pumps are high because the ground maintains a relatively stable source/sink temperature, allowing the heat pump to operate close to its optimal design point.

Efficiencies are inherently higher than for air source heat pumps because the air temperature varies both daily and seasonally and air temperatures are lowest at times of peak heating demand and highest at times of peak cooling demand. This theme provides a detailed literature based review of the GSHP technology and looks more briefly at applications of the technology, applicable standards and regulations, financial and other benefits and the current market status.

In 1999, an estimated 400,000 GSHPs were operating in residential and commercial applications, up from 100,000 in 1990. In 1985, it was estimated that only around 14,000 GSHP systems were installed in the United States. Annual sales of approximately 45,000 units were reported in 1997. With a projected annual growth rate of 10%, 120,000 new units would be installed in 2010, for a total of 1.5 million units in 2010 [8].

In Europe, the estimated total number of installed GSHPs at the end of 1998 was 100,000 to 120,000 [8]. Nearly 10,000 ground-source heat pumps have been installed in U.S Federal buildings, over 400 schools and thousands of low-income houses and apartments pumps, although electrically driven, are classified as a renewable-energy technology. The justification for this classification is that the ground acts as an effective collector of solar energy. The renewable-energy classification can affect the goals and potential funding opportunities. An environmental benefit is that GSHPs typically use 25% less refrigerant than split-system air-source heat pumps or air-conditioning systems. The GSHPs generally do not require tampering with the refrigerant during installation. Systems are generally sealed at the factory, reducing the potential for leaking refrigerant in the field during assembly.

GSHPs also require less space than conventional heating and cooling systems. While the requirements for the indoor units are about the same as conventional systems, the exterior system (the ground coil) is underground, and there are no space requirements for cooling towers or air-cooled condensers. In addition, the ground-coupling system does not necessarily limit future use of the land area over the ground loop, with the exception of siting a building. Interior space requirements are also reduced.

There are no floor space requirements for boilers or furnaces, just the unitary systems and circulation pumps. Furthermore, many distributed groundsource heat pump systems are designed to fit in ceiling plenums, reducing the floor space requirement of central mechanical rooms. Compared with air-source heat pumps that use outdoor air coils, ground-source heat pumps do not require defrost cycles or crankcase heaters and there is virtually no concern for coil freezing.

Cooling tower systems require electric resistance heaters to prevent freezing in the tower basin, also not necessary with ground-source heat pumps. It is generally accepted that maintenance requirements are also reduced, although research continues directed toward verifying this claim. It is clear, however, that ground-source heat pumps eliminate the exterior fin-coil condensers of air-cooled refrigeration systems and eliminate the need for cooling towers and their associated maintenance and chemical requirements. This is a primary benefit cited by facilities in highly corrosive areas such as near the ocean, where salt spray can significantly reduce outdoor equipment life.

GSHP technology offers further benefits: less need for supplemental resistance heaters, no exterior coil freezing (requiring defrost cycles) such as that associated with air source heat pumps, improved comfort during the heating season (compared with air-source heat pumps, the supply air temperature does not drop when recovering from the defrost cycle), significantly reduced fire hazard over that associated with fossil fuel-fired systems, reduced space requirements and hazards by eliminating fossil-fuel storage, and reduced local emissions from those associated with other fossil fuel-fired heating systems. Another benefit is quieter operation, because GSHPs have no outside air fans.

Finally, ground-source heat pumps are reliable and long-lived, because the heat pumps are generally installed in climate controlled environments and therefore are not subject to the stresses of extreme temperatures. Because of the materials and joining techniques, the ground coupling systems are also typically reliable and long-lived. For these reasons, GSHPs are expected to have a longer life and require less maintenance than alternative (more conventional) technologies.

2.2 Ground-coupled system types:

The ground-coupling systems used in GSHPs fall under three main categories: closed-loop, open loop and direct-expansion. These systems are common in residential applications but are not frequently applied to large-tonnage commercial applications because of the significant land area required for adequate heat transfer.

2.3 Direct-expansion systems:

Each of the ground-coupling systems described above uses an intermediate heat transfer fluid to transfer heat between the earth and the refrigerant. Use of an intermediate heat transfer fluid necessitates a higher compression ratio in the heat pump to achieve sufficient temperature differences in the heat transfer chain (refrigerant to fluid to earth). Each also requires a pump to circulate water between the heat pump and the ground couple. Direct-expansion systems remove the need for an intermediate heat transfer fluid, the fluid-refrigerant heat exchanger, and the circulation pump. Copper coils are installed underground for a direct exchange of heat between refrigerant and earth. The result is improved heat transfer characteristics and thermodynamic performance. The coils can be buried either in deep vertical trenches or wide horizontal excavations. Vertical trenches typically require from 100 to 150 square feet of land surface area per system cooling ton (2.6 to 4.0 m2/kW) and are typically 9 to 12 feet (2.7 to 3.7 m) deep. Horizontal installations typically require from 450 to 550 square feet of land area per system cooling ton (11.9 to 14.5 m2/kW) and are typically 5 to 10 feet (1.5 to 3.0 m) deep. Vertical trenching is not recommended in sandy, clay or dry soils because of the poor heat transfer. Because the ground coil is metal, it is subject to corrosion (the pH level of the soil should be between 5.5 and 10, although this is normally not a problem).

If the ground is subject to stray electric currents and/or galvanic action, a cathodic protection system may be required. Because the ground is subject to larger temperature extremes from the direct-expansion system, there are additional design considerations. In winter heating operation, the lower ground coil temperature may cause the ground moisture to freeze. Expansion of the ice buildup may cause the ground to buckle. Also, because of the freezing potential, the ground coil should not be located near water lines. In the summer cooling operation, the higher coil temperatures may drive moisture from the soil. Low moisture content will change soil heat transfer characteristics.

2.3.1 GSHP advancements:

Ground source heat pumps are receiving increasing interest in North America and Europe because of their potential to reduce primary energy consumption and thus reduce the emission of greenhouse gases and other pollutants. This technical note provides a detailed, literature-based review of ground source heat pump (GSHP) technology then looks more briefly at applications of the technology, applicable standards and regulations, financial and other benefits and the current market status. Heat pumps are widely used in buildings for space heating and cooling and for water heating. The majority of heat pumps currently in operation use air as the heat source, however, interest in using the ground as a source has been growing. Relatively stable ground temperatures, approximately equal to the average air temperature, mean that heat pumps which use the ground as a source are inherently more efficient than those using ambient air. Interest is focused on closed loop systems, which consist of a sealed loop of polyethylene or polybutylene pipe buried in the ground either in a shallow trench or vertically in a borehole and connected to the heat pump. Either refrigerant (direct system) or awater/antifreeze mixture (indirect system) is circulated through the ground coil. Direct circulation systems are more efficient than indirect systems but the design is more complex and there is the risk of refrigerant leaks. The majority of systems are indirect. The components of the system, the energy source, the ground collector and the heat pump and how these affect the system performance are discussed in detail. Efficiencies of heat pumps used to supply low temperature water-based heating systems (e.g., underfloor heating) are high. Coefficients of performance of between 3 and 4 are common for indirect systems and, for direct systems, are higher (3.5 to 5.0). The reliability of heat pump components is good, with expected lifetimes of 10 to 15 years. The expected lifetime for polyethylene or polybutylene ground coils is much longer, with warranties being offered for up to 50 years.

A typical seasonal performance factor for a ground source heat pump system with an electrically driven vapour compression cycle heat pump is 3.0 and high efficiency, heating only heat pumps can give seasonal performance factors of 3.8. The highest seasonal performance factors are for systems with horizontal collectors with direct circulation supplying low temperature heating systems, for which seasonal performance factors often exceed 4.0 and are expected to reach 5.0 in the near future. Capital costs are higher than for alternative systems, mainly because of the costs associated with the ground coil, but costs are being reduced. For commercial applications where heating and cooling are provided, the additional cost of the ground coil can be substantially offset by the elimination of other plant and a reduction in the space needed for plantroom. Capital costs appear to vary considerably between countries and direct comparisons are difficult. For residential systems, costs appear to be lowest in North America and Sweden, which may be partly due to economies of scale. In Britain there are currently too few installations to permit accurate cost assessment. Average energy savings of over 50% compared with direct electric heating and 33% compared with air source heat pump systems have been found for residential systems in the US, implying a simple payback of between 3 and 7 years with respect to direct electric systems. Domestic systems in Scandinavia providing heating only, have similar payback periods. In Switzerland, although capital costs are much higher than in the US, they are only about 25% higher than the alternative oil fired system and running costs are about 25% lower. Payback periods are longer at between 10 and 12 years, but still well within the lifetime of the system. For commercial systems, studies in the US and Canada suggest a simple payback period of under 3 years when compared with a water loop heat pump system and that maintenance costs will be reduced. Other benefits include low noise, good aesthetics and good security. The use of ground source heat pumps also has wider benefits. Utilities are promoting the technology as it can help to reduce their internal costs through the ability to reduce both peak and average load demands. There will also be benefits to the community as the consumption of fossil fuels reduces and emissions of GHGs and other pollutants also reduce and become more centralised. Detailed studies in the US, Switzerland and the Netherlands have all concluded that ground source heat pumps already have an advantage environmentally over gas or oil heating.

A market study estimated the total worldwide stock of ground source heat pumps to be approximately 400,000 in 1996 with total annual sales of about 45,000 units. The market has been mainly new housing but the number of commercial installations is growing fast. Systems operating in parallel with conventional heating systems are also beginning to be installed in existing houses, which theoretically form the largest potential market. Between 1996 and 1998 the rate of installation in Europe more than doubled but generally the market growth has been slow. In Britain the technology is still at a demonstration stage with approximately 50 installations. Barriers to the wider uptake of the technology appear to be:

- Lack of awareness of the technology and its benefits.
- Capital cost.
- Low energy prices.
- Lack of manufacturers, suppliers and installers.

In most of the countries, which have a significant market, initiatives to overcome these barriers and encourage the use of ground source heat pumps have been taken. Usually the government has played an active part, with initiatives forming part of a national energy policy. An increasingly important factor is concern for the environment not only at government level but also, particularly in Switzerland, it appears to influence the choice of heating system for individual house owners. In North America electric utilities have been very instrumental in the promotion of ground source heat pumps, and utilities in Europe have also taken an active interest. Direct financial incentives have been used and can have a big impact but their use in future by the utilities is less likely in an increasingly competitive market. Future activities are likely to focus on education, marketing, technical advice and favourable tariffs or innovative forms of financing (leasing, etc.).

The prospect for GSHPs looks attractive. In Europe and the UK the demand for space cooling is growing, especially in commercial buildings. This trend could favour the use of the GSHPs, which can provide low operating costs for heating, and the extra comfort of cooling in summer. There is considerable potential for both heat pump efficiencies and electricity generation efficiency to improve. A heat pump coefficient of performance of 4.0 combined with a generation efficiency of 55% (gas combined cycle plant) would result in an energy efficiency factor of 2.2. Ground source heat pumps thus have a large potential to reduce both primary energy consumption and CO_2 emissions. As the proportion of renewable sources used for electricity generation increases CO_2 emissions will be further reduced and the introduction of replacement refrigerants will also reduce the global warming effect. For the market for ground source heat pumps to become established in countries such as the UK, governments and utilities need to work together to promote this technology, which effectively provides a continuous, high performance source of solar energy.

For an air-source heat pump its COP is limited by its need to pump the heat into the house from outside - and so they work less well in very cold climates where there is less heat density outside to pump in. Typically the COP decreases markedly once outside temperatures go below around -5 or -10 degrees Celsius, though this limit varies from one model to another. Those buying an air-source heat pump should look closely at the heat pump's COP, at what outside temperature range that COP is effective for, at the cost of installation of the pump, at how much heat it can pump (measured in kilowatts), and at the noise generated (in decibels). Because a ground-source heat pump draws heat from the ground, which below a depth of about 8 feet is at a relatively constant temperature year round, its COP is higher than for an air-source heat pump and its COP is constant year round. The penalty for this improved performance is that a ground-source heat pump is significantly more expensive to install than an air-source heat pump. Heat pumps are also becoming more commonly used to heat swimming pools and to heat hot water for household use.

2.3.2 Technology procurement:

Ground-sourceand water source heat pumps work the same way, except that the heat source/sink is the ground, groundwater, or a body of surface water, such as a lake. (For simplicity, water-source heat pumps are often lumped with ground-source heat pumps, as is the case here.) The efficiency or coefficient of performance of Ground-source heat pumps is significantly higher than that of air-source heat pumps because the heat source is warmer during the heating season and the heat sink is cooler during the cooling season. Ground-source heat pumps are also known as geothermalheat pumps, though this is a bit of a misnomer since the ultimate heat source with most ground-source heat pumps is really solar energy, which maintains the long-term earth temperatures within the top few meters of the ground surface. Only deep-well ground-source heat pumps that benefit from much deeper earth temperatures may be actually utilizing geothermal energy.

Ground-source heat pumps are environmentally attractive because they deliver so much heat or cooling energy per unit of electricity consumed. The COP is usually 3 or higher [9]. The best ground-source heat pumps are more efficient than high-efficiency gas combustion, even when the source efficiencyof the electricity is taken into account.

2.3.3 Opportunities:

GSHPs are generally most appropriate for residential and small commercial buildings, such as small-town post offices. In residential and small (skin-dominated) commercial buildings, ground-source heat pumps make the most sense in mixed climates with significant heating and cooling loads because the high-cost heat pump replaces both the heating and air-conditioning system.

In larger buildings (with significant internal loads), the investment in a ground-source heat pump can be justified further north because air-conditioning loads increase with building size. Packaged terminal heat pumps, used in hotels and large apartment buildings, are similar except that the heat source is a continuously circulating source of chilled water-the individual water-source heat pumps provide a fully controllable source of heat or air-conditioning for individual rooms.

Because ground-source heat pumps are expensive to install in residential and small commercial buildings, it sometimes makes better economic sense to invest in energy efficiency measures that significantly reduce heating and cooling loads, then install less expensive heating and cooling equipment-the savings in equipment may be able to pay for most of the envelope improvements. If a ground-source heat pump is to be used, plan the site work and project scheduling carefully so that the ground loop can be installed with minimum site disturbance or in an area that will be covered by a parking lot or driveway.

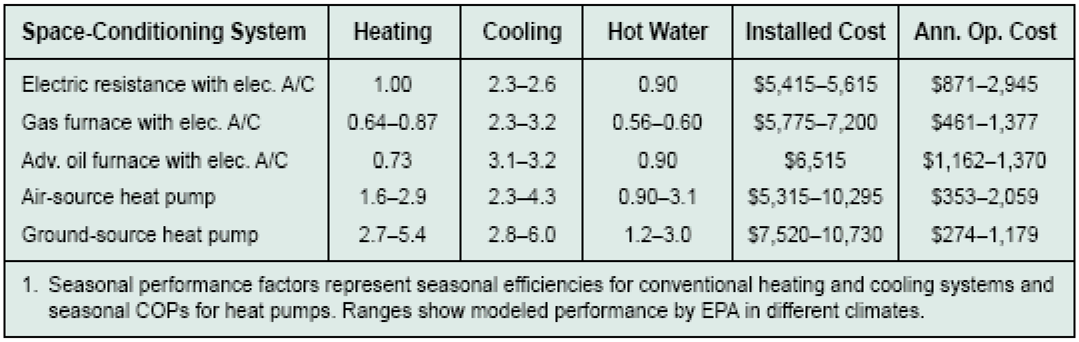
3. CHARACTERISTICS OF GROUND HEAT

Ground-source heat pumps are generally classified according to the type of loop used to exchange heat with the heat source/sink. Most common are closed loop horizontal and closed loop vertical systems. Using a body of water as the heat source/sink is very effective, but seldom available as an option. Open-loop systems are less common than closed-loop systems due to performance problems (if detritus gets into the heat pump) and risk of contaminating the water source or in the case of well water-inadequately recharging the aquifer. Ground-source heat pumps are complex. Basically, water or a nontoxic antifreeze-water mix is circulated through buried polyethylene or polybutylene piping. This water is then pumped through one of two heat exchangers in the heat pump. When used in the heating mode, this circulating water is pumped through the cold heat exchanger, where its heat is absorbed by evaporation of the refrigerant. The refrigerant is then pumped to the warm heat exchanger, where the refrigerant is condensed, releasing heat in the process. This sequence is reversed for operation in the cooling mode.

Direct-exchange ground-source heat pumps use copper ground-loop coils that are charged with refrigerant. This ground loop thus serves as one of the two heat exchangers in the heat pump. The overall efficiency is higher because one of the two separate heat exchangers is eliminated, but the risk of releasing the ozone-depleting refrigerant into the environment is greater (Table 1).DX systems have a small market share [10].

The energy supplied for space and water heating by the heat pump, its auxiliary heater and the immersion heater over the first year of operation of the system (Table 2). The total annual energy supplied for space heating was 15 255 kWh, and domestic water heating was 3425 kWh. However, the total electricity consumed to provide the space and water heating was only 7825 kWh, as the heat pump provided 10 855 kWh of ‘free’ energy from the ground. Use of the heat pump saved the emission of approximately 5 tones of CO_2 compared with conventional electric heating. The heat pump provided 91.7% of the energy for space heating and 55.3% of the energy for water heating.

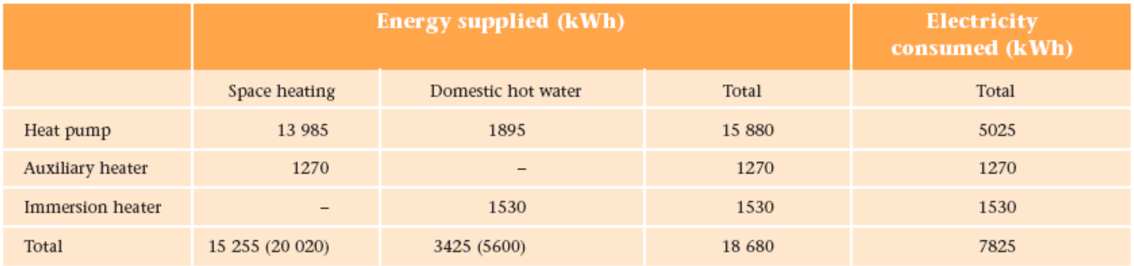
The two main factors affecting heat transfer from the ground to the collector are the collector’s surface area and the thermal properties of the ground. Unfortunately, the thermal properties of the ground are not well understood because they can be affected by many factors and very little measured data is available (e.g., thermal resistance many vary with time of year or amount of rainfall and the operation of the heat pump can even alter the thermal properties by altering the moisture content around the collector).



Space-Conditioning System	Heating	Cooling	Hot Water	Installed Cost	Ann. Op. Cost
Electric resistance with elec. A/C	1.00	2.3–2.6	0.90	$5,415–5,615	$871–2,945
Gas furnace with elec. A/C	0.64–0.87	2.3–3.2	0.56–0.60	$5,775–7,200	$461–1,377
Adv. oil furnace with elec. A/C	0.73	3.1–3.2	0.90	$6,515	$1,162–1,370
Air-source heat pump	1.6–2.9	2.3–4.3	0.90–3.1	$5,315–10,295	$353–2,059
Ground-source heat pump	2.7–5.4	2.8–6.0	1.2–3.0	$7,520–10,730	$274–1,179

1. Seasonal performance factors represent seasonal efficiencies for conventional heating and cooling systems and seasonal COPs for heat pumps. Ranges show modeled performance by EPA in different climates.

Table 1: Seasonal performance factors [10]



	Energy supplied (kWh)			Electricity consumed (kWh)
	Space heating	Domestic hot water	Total	Total
Heat pump	13 985	1895	15 880	5025
Auxiliary heater	1270	–	1270	1270
Immersion heater	–	1530	1530	1530
Total	15 255 (20 020)	3425 (5600)	18 680	7825

Table 2: Energy supplied and electricity consumed for space and water heating with predicted consumption in parenthesis [10]

The ground temperature is important, as it is the difference between this and the temperature of the fluid circulating in the heat exchanger that drives the heat transfer. At depths of less than 2 m the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases, the seasonal swing in temperature reduces and the maximum and minimum soil temperatures begin to lag the temperatures at the surface (e.g., a time-lag of approximately one month at 1.5 m, two months at 4 m). The two-rock/soil properties that most affect the design of a heat pump system are the thermal conductivity (k_s) and the thermal diffusivity (α). The thermal properties of common ground types are given in Table 3. The most important difference is between soil and rock because rocks have significantly higher values for thermal conductivity and diffusivity.

The main consideration with installation of the ground coil is to ensure good long-term thermal contact. Only standard construction equipment is needed to install horizontal ground heat exchanger i.e., bulldozers or backhoes and chain trenchers. In larger installation in Europe, track type machines have been used to plough in and backfill around the pipe in continuous operation. Drilling is necessary for most vertical heat exchanger installations. The drilling equipment required is considerably simpler than the conventional equipment for drilling water wells. Drilling methods commonly used are listed in Table 4.

Material	Conductivity ($Wm^{-1}K^{-1}$)	Specific heat ($kJkg^{-1}K^{-1}$)	Density (kgm^{-3})	Diffusivity (m^2d^{-1})
Granite	2.1-4.5	0.84	2640	0.078-0.18
Limestone	1.4-5.2	0.88	2480	0.056-0.20
Marble	2.1-5.5	0.80	2560	0.084-0.23
Sandstone				
Dry	1.4-5.2	0.71	2240	0.074-0.28
Wet	2.1-5.2			0.11-0.28
Clay				
Damp	1.4-1.7	1.3-1.7		0.046-0.056
Wet	1.7-2.4	1.7-1.9	1440-1920	0.056-0.074
Sand				
Damp		1.3-1.7		0.037-0.046
Wet*	2.1-26	1.7-1.9	1440-1920	0.065-0.084

Table 3: Typical thermal properties of soil

* Water movement will substantially improve thermal properties

Conventional rotary drilling is not a good choice for shallow holes in hard rock because the drilling rate will be very slow with a light-drilling rig. Easy methods such as use of a tractor mounted auger or light, mobile rigs suitable for both rotary and down-the-hole-hammer can provide cost effective drilling, but the actual costs depend on geological conditions and local drilling industry experience.

Grouting is important not only for heat transfer and to support the pipe but also to protect groundwater (i.e., to prevent leakage through any defective joints, to prevent leakage downwards of contaminated surface water or upwards from artesian formations, to prevent migration between aquifers or to seal off formations that are contaminated) [10]. Circulation in the ground coil can be direct i.e., the refrigerant circulates in the ground coil, or indirect, where a secondary heat exchange fluid (water/antifreeze) circulates in the ground coil and heat is transferred via a heat exchanger to the heat pump. The majority of systems use indirect circulation. For an indirect system the circulating fluid is water or a water/antifreeze solution. The freezing point of the circulating fluid needs to be at least 5°C below the mean temperature of the heat pump (i.e., the average of the inlet and outlet temperatures); thus in northern Europe an antifreeze solution is normally required. The ideal fluid should have good heat transfer properties and low viscosity, be environmentally acceptable, safe, and cheap and have a long life. Table 5 lists the most commonly used antifreeze solutions and their properties.

Ground	Method	Remarks
Soft, sand	Auger	Sometimes temporary casing required
Gravel	Rotary	Temporary casing or mud additives required
Soft, silt/clay	Auger	Usually the best choice
	Rotary	Temporary casing or mud additives required
Medium	Rotary	Roller bit, sometimes mud additives required
	DTH*	Large compressor required
Hard	Rotary	Button bit, very slow
	DTH	Large compressor required
	Top hammer	Special equipment
Very hard	DTH	Large compressor required
	Top hammer	Special equipment
Hard under soft	ODEX#	In combination with DTH

Table 4: Drilling methods for the installation of vertical collectors [10]

* Down-the-hole-hammer

Overburden drilling equipment (Atlas Copco, Sweden)

Antifreeze solution	Heat transfer (%)	Pump energy (%)	Corrosivity	Toxicity	Environmental impact
Salts					
Calcium chloride ($CaCl_2$)	120	140	Unacceptable with stainless steel, aluminium, mild steel, zinc or zinc based solders.	Potential skin/eye irritation from dust, strong salt taste will prevent ingestion of contaminated ground water.	Impact on ground water quality.
Sodium chloride (NaCl)	110	120	No inhibitors provide protection for mild steel, copper and aluminium.	Potential skin/eye irritation from dust, strong salt taste will prevent ingestion of contaminated ground water.	Travels quickly owing to high solubility.
Potassium carbonate (K_2CO_3)	110	130	Inhibitors required for mild steel and copper. No protection available for tin, bronze or zinc.	Caustic nature makes handling somewhat hazardous. Long-term human ingestion is of concern.	Carbonate precipitates out. Not considered a problem.
Organics					
Glycols					
Ethylene glycol ($HOCH_2CH_2OH$)	90	125	Inhibitors required to protect mild steel, cast iron, aluminium and solder.	Skin/eye irritation. Single-dose oral toxicity is moderate. Excessive or long-term exposure may be hazardous. Considered to be non-hazardous.	Biodegrades when combined with CO2 and H2O. Non-persistent organic acids are formed.
Propylene glycol ($CH_3CHOHCH_2OH$)	70	135	Inhibitors required for cast iron, solder and aluminium.	Same as ethylene.	Same as ethylene.
Alcohols					
Methanol (CH_3OH)	100	100	Biocide should be used to prevent fouling.	Highly toxic by inhalation, skin contact and ingestion. Long-term effects are cumulative, prolonged exposure can be harmful.	Biodegrades into CO_2 and H_2O. Non-persistent organic acids are formed.
Ethanol (C_2H_3OH)	80	110	Anti-oxidant should be used to minimise corrosion.	Vapours burn throat and eyes. Ingestion in high quantities can cause sickness. Prolonged exposure may exacerbate liver damage.	Unavailable.
Other					
Potassium acetate (CH_3CHOOK)	85	115	Inhibitors required for aluminium and carbon steels. Low surface tension requires special pipe doping materials to prevent leakage.	Some eye/skin irritation may occur. Relatively non-toxic.	Same as methanol.

Table 5: Antifreeze agents and their properties

Accurate sizing is important for GSHP systems. A high proportion of the capital cost is for the ground collector and because there are few economies of scale, oversizing carries a high cost penalty. Undersizing, however, can result in comfort conditions not always being met. The detailed analysis of building loads, energy consumption and cost effectiveness associated with GSHP systems is best carried out using electronic computer based design tools. These are evolving rapidly and manual methods of analysis are being overtaken by increasingly sophisticated, easy to use and reliable computer software systems. A summary of models and their characteristics is given in Table 6. Software is generally in the public domain or has been developed by the largest manufacturers. However, programmes are often niche tools that perform quite narrowly focused analysis.

For systems the seasonal performance factor (SPF) defined as the ratio of the heat delivered to the total energy supplied over the season, is of interest. It takes into account the variable heating and/or cooling demands, the variable heat source and sink temperatures over the season, and includes any energy demands for circulation, for instance fans and pumps (to circulate the fluid round the ground collector), etc. Careful design of the whole system is required to ensure that this is as high as possible. SPFs for ground source systems are typically greater than 3.0 and high-efficiency heating only heat pumps can give SPFs of 4. The residential and commercial systems provided average energy savings of 52% compared with electric resistance heating as shown in Table 7.

Name	Supplier	Residential	Commercial	Vertical	Horizontal	Sizing	Performance	Economics
CLGS	GSHPA, USA	X		X	X	X		Operating cost+alt. Systems.
DIBSIM	TNO, Netherlands	X		X		X	Annual COP of heat pump and system.	Operating cost+alt. Systems.
ECA	Elite Software,	X		X	X		Annual COP.	Requires heating/cooling loads.
EED	Inc., USA Lund, Sweden			X		X	SPF by month	Lund Univ. software under trial.
GchpCale	Energy Information Systems,		X	X		X	10-y period SPF by zone	Provides detailed design information
GLHEPRO	USA		X	X		X	Heat extraction	Required heating/cooling loads
GL-Source	GSHPA, USA USA			X	X	X	SPF	Annual cost = Operating + Alt. Costs
		X	X			X		
Geocalc					X			As above
Geo-designer	USA USA	X		X	X	X		As above
GS2000				X	X	X		
Right-loop	Canada USA	X X		X X	X X	X X		
W-calc	Switzerland						SPF	
WFEA	USA							

Table 6: Models and their properties [11]

In general, capital costs are higher than for alternative systems mainly because of the costs associated with the ground coil, but costs are being reduced. Table 8 shows some typical capital costs for residential systems. The cost per kW of installed capacity appears to vary considerably between countries, but direct comparison is difficult. There are too few installations as yet in the UK to establish typical system costs.

Building type	**Percentage energy savings**		
	Versus ASHP range	**Mean**	**Versus electric resistance range**
Residential	13-60	25-70	53
Schools		15-50	32
Commercial	22-44	40-68	52

Figure 7: Energy savings from GSHP systems [12]

Country	**Costs (US$)**	**Cost (US$/kW) installed capacity**	**Comments**
Austria	21000 including underfloor heating	1500	Horizontal DX
	13000 excluding distribution system	930	
Canada	9500-13000 including 2900 for air distribution system + DHW	700-1000	Lowest: horizontal DX Highest: vertical
Norway	7500-10000 excluding distribution system	1500-2000	Vertical: underfloor heating
Sweden	6300 excluding distribution system	1250-1420	
	7100 including distribution system		As above
Switzerland	20000 excluding distribution system	1900	
	27000-36500 include distribution system	2800-3800	Vertical: underfloor heating
USA	7500-10000	700-1000	
			Vertical: air distribution

Table 8: Typical costs for residential GSHP systems

* Scandinavian systems are sized to meet 50% of the design load. North American systems are sized to meet 75-80% of the design load

Benefits to the community at large will result from the reduction in fossil fuel consumption and the resulting environmental benefits. Gilli [13] suggests that an energy efficiency factor (the equipment based COP or SPF multiplied by the power system generation efficiency) can be used to compare systems if it is assumed that heat pump is supplied from a single power station. Energy efficiency factors for a range of systems are given in Table 9.

System	**Energy efficiency factor**
Small coal or oil-fired boiler	0.6-0.65
Gas-fired boilers	0.7-0.9
Condensing gas-fired boiler + low temperature system	1.0
Coal-fired condensing power station	1.26
Gas-fired combined cycle plant	1.57
Combined cycle CHP plant	1.7

Table 9: Energy efficiency factors for a range of heating systems

4. VENTILATION-HEALTH ASPECTS

Since the early 1980s, there has been much discussion about Sick Building Syndrome (SBS). This refers to allergic disorders, and even illness symptoms, which frequently occur in certain buildings and rooms. This can lead to chronic illness, reducing the person's ability to work and function in general. This, in turn, results, not only in the individual concerned loses his or her quality of life, but it also has a major detrimental impact on the economy and incurs huge costs. Basically, the following potential risks jeopardising people's health could be found inside buildings:

1) Toxic pollution caused by harmful chemical substances and dust.
2) Effects of noise, light, odours, dampness and climate.
3) Accumulation of microbes (bacteria, viruses, mould) in terms of infection risks.
4) Exposure to allergens.

These pollutants vary considerably according to the inside climate conditions, state of ventilation, design and use of the inside area. When energy-saving measurements were introduced in the early 1970s, considerable efforts were made to improve the insulation used in the construction industry. This led to a reduction in the air exchange rate inside buildings. From a health and allergy perspective, the ideal air exchange rate would be 0.5 - 1.0, but in actual fact, air exchange rates in appropriately insulated houses are only between 0.3 and 0.5, which means that the polluted inside air is exchanged far too infrequently. Based on the reasons given above, an increase in the incidence of complaints affecting the population health is inevitable. Significant carbon dioxide savings can be gained by displacing fossil fuels. Even compared to the most efficient gas or oil condensing boilers, a well-designed heat pump with COP of 3 to 4 will reduce CO_2 emissions by 30–35%. Further carbon savings can be made if the electricity required to power the pump comes from a renewable energy source such as photovoltaics or a renewable electricity tariff. Refrigerants such as hydrochloroflurocarbons (HCFCs) are present in GSHP systems. These are potentially toxic, flammable and can lead to increased global warming. This is where controlled domestic ventilation can have a particular role to play. Its purpose is to control temperature and dampness, while ensuring that the quality of the inside air is totally hygienic. The relevant technical guidelines and hygiene regulations are stipulated by DIN 1946 [5].

4.1 Controlled domestic ventilation:

Nowadays, the public generally spend around 90% of the time indoors. This undoubtedly places great demands on the climate inside. The inside climate is affected considerably by odours, harmful substances, noise and temperature.

There is a certain amount of basic ventilation in every building, even if it is only produced by air coming through windows, doors, pipe ducts and walls. This type of ventilation, in older houses in particular, provides the necessary exchange of air. Ventilation is also provided through opening windows and doors, perhaps also when one or more windows are opened at an angle. Strong wind pressure and a difference in temperature between inside and outside also increase the exchange of air. On the other hand, a weak wind or small temperature difference will reduce the required air exchange rate. This uncontrolled ventilation also accounts for a significant part of the heating costs and causes a considerable proportion of non-renewable energy resources to be wasted.

4.2 Low-energy house:

In contrast to this, there is the low-energy house concept. A construction design is used in this type of house, which prevents heat from escaping through effective thermal insulation. This also means that low-energy houses benefit the environment. But even with this construction design, there is still the problem that the required hourly air exchange rate of 0.5-1.0 is not achieved.

To achieve the required air exchange rate either the windows would have to be opened, which would run counter to the whole low-energy house concept, or installing a controlled domestic ventilation system with heat recovery would have to be considered.

4.3 Controlled domestic ventilation:

Controlled domestic ventilation can be used in both low-energy and older houses. In low-energy houses the controlled ventilation system guarantees the required air exchange rate, even with the doors and windows closed. When older houses are renovated better thermal insulation could be used, along with fitting new windows to enable controlled domestic ventilation to achieve the necessary air exchange rate. These types of older building are often affected by street noise. A ventilation system would therefore be beneficial in these cases too.

4.4 Controlled domestic ventilation with heat recovery:

When ventilation based on opening windows and controlled domestic ventilation without heat recovery are used, the energy from the inside air is not used. The ventilation heat requirement accounts (40–50%) of the total heat requirement. In contrast to this, controlled domestic ventilation with heat recovery (Figure 6) reuses the energy from the exhaust air. Not only that, the additional heat generated internally from lighting, people and domestic appliances is also utilised through heat recovery. FIGHTER exhaust air heat pumps facilitate heat recovery and supply the energy recovered from exhaust air for the domestic hot water and even the heating. The diagram below (Figure 7) illustrates what proportion of the total heat requirement is provided by domestic ventilation with heat recovery supplied by the FIGHTER 315P and FIGHTER 600P pumps. Using the FIGHTER 600P, it is possible to supply a far greater proportion of the total heat requirement with the heat pump. In this case, energy recovery ensures a healthy and comfortable form of heating, while the system also produces considerable savings in terms of heat energy, along with CO_2 emissions.

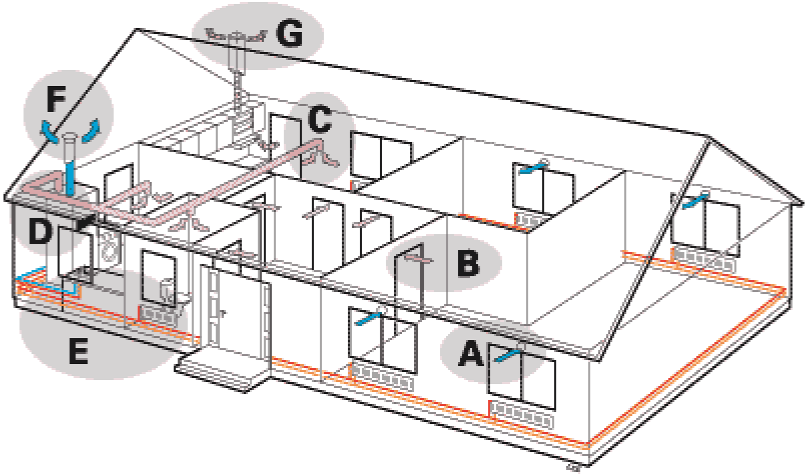


Figure 6: Domestic ventilation

Functions:

- **A.** Fresh outside air is supplied to the house through cleanable outside vent holes.
- **B.** The air overflow occurs under the door or through the overflow vent holes.
- **C.** The warm inside air (exhaust air) is drawn into the ventilation system.
- **D.** Warm exhaust air is supplied to the heat pump for heat recovery.
- **E.** The heat pump provides the house with domestic hot water and/or hot water for the radiators.
- **F.** When the exhaust air has passed through the heat pump the discharge air is released into the open air. Before this, the heat pump has extracted so much energy from the exhaust air that the temperature of the discharge air is only about 0°C (depending on the system).
- **G.** Extractor hood.

4.5 Exhaust air heat pumps:

Ventilation, which means totally hygienic inside air, is a basic requirement for living in a healthy house. Controlled domestic ventilation with heat recovery reuses the energy from the exhaust air. Furthermore, the additional heat generated internally from lighting, people and domestic appliances is also utilised through heat recovery.

4.6 Energy extraction from cold water:

Climate change is a real threat to the planet’s future, and a major cause for it is the use of fossil fuels to power homes and businesses. Renewable energy, combined with energy efficiency, offers a viable and potent solution to countering the effects of global warming. By installing any of the available renewable energy technologies, one will be making a major personal contribution to the well-being of future generations and could also benefit from lower fuel bills.

In heating applications, heat pumps save energy by extracting heat from a natural or waste source, using a mechanism similar to that found in a refrigerator. They can be used for any normal heating need. However, this technology is not new. Several heat pumps were installed in the 1950's in a bid to save energy and fuel costs. One of the most famous of these was used to heat the Royal Festival Hall in London by extracting heat from the River Thames [6].

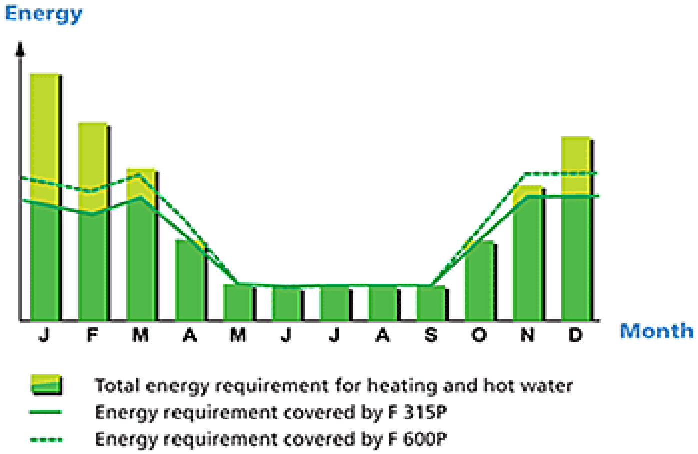


Figure 7: Energy requirements for heating and hot water

Humans’ natural sense of heat is based more on instinct than science. Humans are warm-blooded and judge "heat" by comparing it to touch. Since the body temperature needs to be maintained to within a few degrees Celsius, the natural senses have evolved to make extremes of temperature uncomfortable. Hence, a hot summer's day feels many times "hotter" than the freezing mid-winter. But in reality the earth's surface does not vary in "heat energy" as much as one might imagine. Scientifically speaking, there is only 11% less energy in cold river water at 5°C (40°F) compared to hot bath water at 40°C (105°F).

The most familiar form of heat pump is the domestic refrigerator. Here heat is extracted from the cabinet to keep food fresh and the extracted heat is expelled through the radiator grill at the back of the unit.

In this case, the heat is merely a waste product. The heat pump, utilises this heat, and put the "cold part" outside. To make this more understandable, imagine that the "ice box" of a refrigerator is immersed in a small garden stream and the hot grid from the back is placed inside a house. The "ice box" will attempt to freeze the stream and, if the stream stopped from flowing, freezing of the water would naturally occur. But the passing water will constantly warm up the very cold "ice box". Hence, the temperature of the stream will be reduced immeasurably. So, heat is extracted from the stream, which ends up as heat in the radiator grill, available to warm the house. In every case, the useful heat output will be greater than the energy required to drive the heat pump itself. Therefore, the heat was extracted from the stream for "free". Another way to think of it is as follows. If an electric kettle element was immersed in the stream, then water will rapidly absorb any warmth from the element. This would be a one-way loss of energy to the stream. If, conversely, the element is colder than the stream, then the stream will warm it up. Therefore, the surrounding will absorb, hence gaining energy.

There are various types of heat pump with many different uses. Nearly all heat pumps use electricity as the form of energy input. Types using gas engines are almost unheard-of in the UK. These can save significant amounts of energy, and are a thing for the future. The heat pump usually delivers heat in the form of hot water. To maintain high-energy efficiency, the system should be designed so that the water temperature is not too high. For this reason, radiators with larger than average surface area (or more of them) should be used. Water temperatures within the pipes of an underfloor heating system can be as low as 35 Celsius (95°F); this gives a very high efficiency. Such systems are very comfortable, and are especially good when used in well-insulated houses.

Swimming pool applications are very energy-efficient and fairly common. These are mostly air-source, taking heat from the air. An air source system, however, will be less effective in winter since the air temperature fluctuates and becomes very cold. For a year-round heating, a river, stream or spring is much more stable and better heat source, offering higher efficiency. The water source should ideally be close to the property. The water flow required is less than one litre per second for a 10 Watt output heat pump, so the smallest of streams can be utilised. Springs and boreholes can often deliver water at a steady 10 degrees Celsius (50°F) throughout the winter, making them excellent heat sources. Ground pipes, buried either vertically or horizontally, are good heat sources. This type is often referred to as geothermal. This system is particularly suited if cooling is also required since in cooling mode (air-conditioning), the energy efficiency is significantly better as compared to a conventional air cooled systems (Figure 8).

Unlike the outside air, the temperature of the ground remains fairly constant. As a result, the potential output of an Earth-Energy System (EES) varies little throughout the winter. Since the EES's output is relatively constant, it can provide almost all the space heating requirement - with enough capacity left to provide hot water heating as an "extra". As with air-source heat pump systems, it is not generally a good idea to size an EES to provide all of the heat required by a house. For maximum cost-effectiveness, an EES should be sized to meet 60 to 70 percent of the total maximum "demand load" (the total space heating and water heating requirement). The occasional peak-heating load during severe weather conditions can be met by a supplementary heating system. A system sized in this way will in fact supply about 95 percent of the total energy used for space heating and hot water heating.

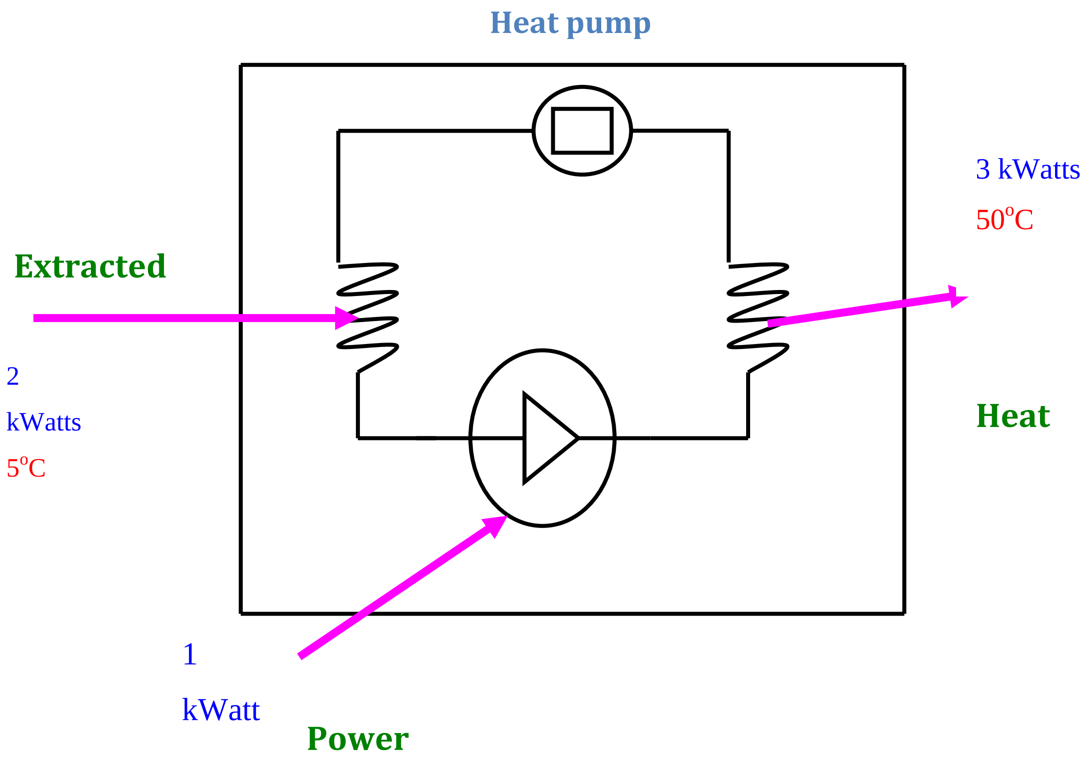


Figure 8: Schematic diagram of ground source heat pump

Useful Heat Output = Extracted Heat + Power Input --------------- (1)

4.7. Performance/costs:

The GSHPs energy cost savings vary with the electric rates, climate loads, soil conditions, and other factors. In residential building applications, typical annual energy savings are in the range of 30 to 60 percent compared to conventional HVAC equipment. Unlike air source units, GSHP systems do not need defrost cycles nor expensive backup electric resistance heat at low outdoor air temperatures. The stable temperature of a ground source is a tremendous benefit to the longevity and efficiency of the compressor.

A residential GSHP system is more expensive to install than a conventional heating system. It is most cost-effective when operated year-round for both heating and cooling. In such cases, the incremental payback period can be as short as 3–5 years. A ground source heat pump for a new residence will cost around 9-12% of the home construction costs. A typical forced air furnace with flex ducting system will cost 5-6% of the home construction costs. Stated in an alternative form, the complete cost of a residential ground source heat pump system is \$3,500-\$5,500 per ton [6]. Horizontal loop installations will generally cost less than vertical bores. For a heating dominated residence, figure around 550 square feet/ton to size the unit. A cooling dominated residence would be estimated around 450 square feet/ton. The Table 10 below compares three types of systems.

Central system type	Concern for safety	Installation cost	Operating cost	Life-cycle cost
Combustion-based	Some concern	Moderate	Higher	Moderate
Heat pump	Less concern	Moderate	Low	Moderate
GSHP	Less concern	High	Lower	Moderate to low

Table 10: Comparisons of central heating systems

The GSHPs can be applied to virtually any size residential building as well as specialised applications such as swimming pools. The vertical ground loops average 400 feet in length per ton of capacity; so limited site area is usually not a problem. Horizontal loops may be 600 to 1000 feet per ton, depending on soil type. GSHPs tend to be the most cost effective in the following situations:

- New construction.
- Climates characterized by high daily temperature swings, or where winters are quite cold or summers quite hot.
- Areas where electricity costs are over \$.07/kWh.
- Areas where natural gas is unavailable or where cost is high compared with electricity.

When considering an open-loop system, check with local environmental authorities to ensure compliance with regulations. There are one-to-two-million GSHPs are operating in homes, schools, and commercial buildings in the United States. They are adaptable to virtually any kind of building; the Federal government has installed many thousands of GSHPs, mostly in residential applications [6].

The heat pump works by promoting the evaporation and condensation of a refrigerant to move heat from one place to another. Horizontal trenches are drilled to a depth of 1 to 2 metres and can cost less than boreholes, but require a greater area of land. Placing coiled piping in horizontal trenches will enhance the performance compared with straight piping. A borehole is drilled to a depth of between 15 to 100 metres and will benefit from higher ground temperatures than the horizontal trench, although installation costs will be greater. A heat exchanger transfers heat from the water/antifreeze mixture in the ground loop to heat and evaporate refrigerants, changing them to a gaseous state. A compressor is then used to increase the pressure and raise the temperature at which the refrigerant condenses. This temperature is increased to approximately 40°C. A condenser gives up heat to a hot water tank, which then feeds the distribution system. Because the GSHPs raise the temperature to approximately 40°C they are most suitable for underfloor heating systems, which require temperatures of 30 to 35°C, as opposed to conventional boiler systems, which require higher temperatures of 60 to 80°C. GSHPs can also be combined with radiator space heating systems and with domestic hot water systems. However, top-up heating would be required in both cases in order to achieve temperatures high enough for these systems. Some systems can also be used for cooling in the summer.

5. CONCLUSIONS

Although the technology is well established elsewhere, GSHPs are currently at the demonstration stage in the UK. Currently there are approximately ten installations in operation in the UK but over 30 are planned and interest is steadily increasing. The majority of the installed systems provide domestic heating and applications range from social housing where the issue is 'affordable warmth' to larger individual housing where the owner's priority is 'whole life cost'. The market potential for GSHPs providing domestic heating is greatest in areas not provided with gas. In commercial/institutional buildings the main potential market is where both heating and cooling are required. In the UK the demand for space cooling in the commercial sector is growing at about 6% per annum and this trend could favour use of GSHPs, which could provide low operating costs for heating, and the extra comfort of cooling in summer. The use of GSHPs in the UK already has the potential to reduce primary energy consumption. Significant efficiency increases have been possible for gas turbines and internal combustion engines and modern combined-cycle plants are now available with net efficiencies of 55%. However, still considerable scope for improving the efficiency of both power stations and heat pumps. The reduction in primary energy consumption leads to a reduction in CO_2 emissions. The comparison will become even more favourable in the future as generation efficiencies improve and more use is made of renewable energy sources that do not result in CO_2 emissions.

REFERENCES

1. Cantrell, J., and Wepfer, W. Shallow Ponds for Dissipation of Building Heat: A case Study. ASHRAE Transactions 90 (1): 239-246. 1984.
2. ASHRAE. Commercial/Institutional Ground Source Heat Pump Engineering Manual. American Society of heating, Refrigeration and Air-conditioning Engineers, Inc. Atlanta, GA: USA. 1995.
3. Kavanaugh, S., Rafferty, K. Ground source heat pumps. Design of Geothermal Systems for Commercial and Institutional Buildings. American Society of heating, Refrigeration and Air-conditioning Engineers, Inc. Atlanta, GA: USA. 1997.
4. U.S.A Environmental Protection Agency. Space Conditioning: The Next Frontier. Washington, DC. 1993.
5. Boulder, C. Space Heating Technology Atlas: Energy Source, Inc. (303) 440-8500. 1996. www.esource.com.
6. Brattleboro, V.T. GeoExchange in Federal Facilities. Building Green (800) 861-0954. 2000.
7. Malin, Nadav, and Alex Wilson. "Ground-Source Heat Pumps: Are They Green?" Environmental Building News Vol. 9, No. 7/8, July 2000.

8. Granryd, E. Ground source heat pump systems in a northern climate. 15th IIR Congress. Venice. Paper No. E1-82. 1979.

9. Rosenblad, G. Earth heat pumps system with vertical pipes for heat extraction and storage. Proc. Nordic Symposium of Earth Heat Pump Systems. Goteborg. P.102-110. 1979.
10. Sanner, B., Kabus, F., and Ritter, W. Practical experiences in Europe of the combination of geothermal energy and heat pumps. Toronto. 1996.
11. Lienau P. Geothermal heat pump performance and utility programmes in the UAS. Proceedings of the International Geothermal Association World Geothermal Congress. Florence. 1995.
12. Rybach and Sanner. Ground-source heat pumps installed in Europe in 1998. 2000.

13. International Ground Source Heat Pump Association (IGSHPA). Grouting procedures for ground-source heat pumps systems. IGSHPA: 1995.
14. Lund and Boyd. Ground sources heat pumps operating in residential and commercial applications. 2000.
15. Gilli, P. The impact of heat pumps on the greenhouse effect. IEA Heat Pump Centre. 1992.