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Summary Ground source heat pumps 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 America and parts of Europe, but is at the demonstration stage in the United Kingdom. This paper provides a detailed literature-based review of ground source heat pump technology, concentrating on closed-loop, ground-coupled systems, and looks more briefly at applications and costs and benefits. It concludes with the prospects for ground source heat pumps in the United Kingdom.

Ground source heat pumps: A technology review

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1 Introduction

The first documented suggestion of using the ground as a heat source appears to have been in 1912 in Switzerland(1), but at that time the efficiency of heat pumps was poor and energy prices were low so the idea was not followed up. In the 1940s, investigation into ground source heat pumps started up again both in the UK and the US.

In the UK the ground as a source for a heat pump was first used by Sumner for space heating in a single-storey house in the mid 1940s(2). In 1948 he installed 12 prototype heat pump systems using ground collectors each with a 9 kW output. The average COP (coefficient of performance) of these installations was 3; however, this study was stopped after two years. The first ground source heat pump in North America was installed in a house in Indianapolis in 1945(3) and over the next few years virtually all the methods of exploiting the ground as a heat source/sink that are used today were investigated in the US(4).

Commercial use of the ground as a heat source/sink did not begin, however, until after the first oil shock in 1973, but it was well established by the end of the 1970s, 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 1970s(6,7) and from that time on has been used in various forms mainly in Sweden, Germany, Switzerland and Austria(8).

Today ground source heat pumps are an established technology with approximately 400 000 units installed worldwide (~62% in the US) and about 45 000 new units installed annually(9). 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 greenhouse gases and other pollutants.

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 ground temperatures are higher than the average air temperatures in winter, when heating is required, and lower in summer, when cooling is required.

This paper provides a detailed literature-based review of ground source heat pump technology and discusses applications of the technology and the costs and benefits.

2 The technology

The term 'ground source heat pump' (GSHP) can be applied to a variety of systems that use the ground, ground water and surface water as a heat source. Until recently, open-loop systems (i.e. using ground water pumped from a well) were the most widely used type, but increasingly restrictive environmental regulations covering the use of ground water and its limited availability have led to interest being focused on closed-loop ground-coupled systems. These, although more expensive than ground water systems, are more widely applicable. This paper will consider closed-loop ground-coupled systems in detail.

These systems consist of a sealed loop of pipe, buried in the ground and connected to a heat pump through which either refrigerant (direct system) or water/antifreeze (indirect system) is circulated. The collector loop can be installed horizontally or vertically.

2.1 Energy source: the ground

Ground source heat pumps make use of the energy stored in the earth's crust. Energy is transferred to and from the earth's surface by solar radiation, rainfall, wind, etc. Only a small part (less than 3%) of the stored energy in the earth's crust comes from its core. For a ground collector to remain effective it is important to consider the long-term energy balance in the ground. The energy balance can be maintained if

(*a*) the ground collector is used to provide balanced heating and cooling with the ground providing interseasonal storage;

(*b*) the ground collector is used to provide heating, provided that the heat extracted is replaced; i.e. for shallow collectors it will be replaced by solar energy from the surface and for deeper collectors it can be replaced by water movement.

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 may 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).

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). Kusuda(10) has developed an analytical equation for estimating the ground temperature at any time of year. Below 10 m the ground temperature remains effectively constant and can be represented by an empirical formula(11). The temperature is approximately equal to the annual average air temperature (~12°C in the UK).

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 1. The most important difference is between soil and rock because rocks have significantly higher values for thermal conductivity and diffusivity. For horizontal collectors the soil type can be determined from looking at and testing the excavated soil. EPRI(12) and collaborators have compiled a list of criteria and common test procedures that can be used to classify soil and rock types adequately for horizontal ground loop design. They have also prepared a video on Practical Soil and Rock in-Field Classification Techniques. Thermal conductivity can easily be measured. A vertical collector may pass through several soil layers and it is important that these are correctly identified. *In situ* methods for measuring the ground properties are being developed for vertical boreholes.

The moisture content of the soil has a significant effect on its thermal properties. When water replaces the air between particles it reduces the contact resistance. The thermal conductivity can vary from 0.25 W m^{-1}K^{-1} for dry soil to 2.5 W m^{-1}K^{-1} for wet soil. When heat is extracted there will be migration of moisture by diffusion towards the heat exchanger and the thermal conductivity will be increased.

Water movement will also have a significant impact on heat transfer through the ground as heat is transferred by convection due to moving water as well as conduction. When the ground around the heat exchanger freezes, latent heat is released, the thermal conductivity will be increased and heat will be transferred over a larger surface area than just the pipe.

Table 1 Typical thermal properties of soils

Material	Conductivity (W m^{-1} K^{-1})	Specific heat (kJ kg^{-1} K^{-1})	Density (kg m^{-3})	Diffusivity (m^2 d^{-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†	2.1–2.6	1.7–1.9	1440–1920	0.065–0.084

†Water movement will substantially improve thermal properties.

1.2 Ground collector configuration

The ground collector may be installed vertically or horizontally. The choice depends on the available land, local soil type and excavation costs.

Horizontal collectors require a relatively large area free from hard rock or large boulders. They are generally most appropriate for small installations, particularly for new construction. The collector pipe is buried in a trench at a depth of between 0.5 m and 1.8 m (depths <1 m are most common in North America). In general, trenching costs are higher than piping costs per linear metre, so systems using multiple pipes (up to six) in one trench will be economic. The energy collected per metre length of pipe will be less, but the surface area needed for the collector will be reduced. A spiral coil is reported to reduce the surface area required further(13). Here the ground exchanger is made from an extended coil (about 60 cm diameter) of polyethylene tubing placed vertically in a narrow trench or laid horizontally at the bottom of a wider trench. The main advantage with this configuration is that the heat exchange surface is effectively a cylinder with the diameter of the coil. The required trench lengths are only 20–30% of those for a single pipe configuration, but pipe lengths may be twice as long for the equivalent thermal performance. Horizontal collectors are usually described as single-pipe, multiple-pipe or spiral.

Vertical systems are used where land area is limited and require less pipe and pumping energy. They can be installed in most soil and rock types except alluvial gravels with low thermal conductivity. A single U-tube is generally used in the US, whereas the most common type in Switzerland is a double U-tube. Concentric composite extruded vertical collectors have also been used there. Boreholes are generally 100–150 mm in diameter and between 15 m and 120 m deep. For deeper holes, problems can occur with backfilling, static pressure and insertion of the exchanger. Multiple boreholes are needed for larger residential and commercial installations. Adjacent boreholes need to be spaced far enough apart to ensure that there will be negligible thermal interference between them, and a separation of at least 5 m and preferably up to 15 m has been suggested(14). In general a smaller number of deeper holes will be most economical, will require least land and will take advantage of the fact that the undisturbed ground temperature increases with depth. The depth, however, may be limited by other factors such as the geology, the pumping energy or the presence of a drinking water aquifer.

Vertical exchange loops can also be incorporated into concrete piles where these are needed for support for a building, and 'energy piles' have been used in Austria and Switzerland. These can be very cost-effective as the additional cost of integrating plastic heat exchanger tubes is small.

If more than one horizontal loop or borehole are used they can be connected in series or in parallel. Series systems require larger-diameter pipe and thus greater fluid volumes than do parallel systems. The majority of horizontal loop installations use flow loops in parallel rather than a single loop so as to reduce pumping power. Although the total pipe length required is usually greater, the smaller pipe will be cheaper, so the total pipe cost will be less than for series configurations. To balance the flow rates, reverse return headers (common in the US) or manifolds with valves (preferred in Switzerland) can be used. The actual length of pipe will depend on the flow rate and the corresponding allowable pressure drop.

2.2 Collector materials

The choice of piping material is important as it has an impact on life, maintenance costs, pumping energy, capital cost and heat pump performance. The pipe materials and pipe jointing methods now available can provide reliable, leak resistant loops that can be installed without requiring any attention for long periods (some American companies are offering warranties of up to 50 years). For indirect circulation systems the most common pipe materials are high-density polyethylene or polybutylene. These are flexible and can be joined by heat fusion. The pipe diameter must be large enough to keep the pumping power small but small enough to cause turbulent flow so as to ensure good heat transfer between the circulating fluid and the inside of the pipe wall. The choice is thus a compromise. Pipe diameters between 20 mm and 40 mm are usual. Larger-diameter pipe is more expensive, requires a larger fluid volume and is more difficult to handle and install than smaller-diameter pipe.

For direct expansion systems, copper pipe ($\sim$12 mm diameter) is usually used for the ground collector coil and, depending on the soil conditions, it may need to be plastic coated externally to prevent corrosion. Good thermal contact with the ground combined with the elimination of a heat exchanger between the ground coil circulating fluid and the refrigerant means that these systems have high efficiencies. Using copper reduces the length of coil required, and the saving on installation costs helps to offset the higher material cost. Pumping power is also reduced.

2.3 Installation

The installation of ground coils is well documented and detailed manuals have been produced in the US and Canada(15,16). 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 exchangers i.e. bulldozers or backhoes and chain trenchers. In larger installations in Europe, track type machines have been used to plough in and backfill around the pipe in a continuous operation.

Methods used for installing vertical collectors have been comprehensively reviewed(17). Where there is soft ground, vertical heat exchangers can be installed by direct pressing or ramming. The advantages of these methods include one-step installation, good thermal contact with the ground without backfilling and the elimination of any problems with the stability of borehole walls. These methods are easy, fast and cheap, but they can only be used to depths of about 10 m or less and the areas where they are applicable are limited. Another alternative for soft, unconsolidated ground is a shallow, large-diameter hole and the use of a spiral heat exchanger.

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 2. 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 (DTH) can provide cost effective drilling, but the actual costs depend on geological conditions and local drilling industry experience.

Table 2 Drilling methods for the installation of vertical collectors.

Ground	Method	Remarks
Soft, sand/ gravel	Auger	Sometimes temporary casing required
	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

† Down-the-hole-hammer.

‡ Overburden drilling equipment (Atlas Copco, Sweden).

Insertion of the vertical heat exchanger in a narrow borehole can be complicated. Normally it is expected that a plastic U-tube, which is filled with fluid before installation, will sink into the hole by its own weight; however, the pipes tend to bend and press against the borehole wall. One method of overcoming this, developed in Switzerland for double U-tube heat exchangers, is to use a series of removable steel rods to push the heat exchanger down the borehole.

It is very important for the performance of the ground collector to ensure good thermal contact with the ground, and thus careful backfilling of both horizontal and vertical installations is critical. For horizontal collectors the pipes are usually covered with sand before backfilling with the removed material. Vertical heat exchangers in drilled holes can be backfilled satisfactorily from the surface provided they are shallow, but for deep boreholes (>50 m) the backfill material has to be pumped to the bottom of the hole. Pumpable materials are bentonite (a generic name for the class of hydrophilic swelling clays used for grout) or fine-grained fluid concrete. Some thermally enhanced grouts are available. The choice of grout depends upon factors such as the subsurface conditions, material properties of the grout and the anticipated operating temperatures of the heat exchanger. The International Ground Source Heat Pump Association has published a very comprehensive manual on grouting procedures for ground source heat pump systems(18). It can be difficult to ensure that the grout fills the bottom of the hole. The Swiss have overcome this problem by using a plastic device to hold and separate the pipes at the base of a double U-tube heat exchanger; this has a hole in the centre through which a grout tremie can be run to ensure that grouting will be from the very bottom of the borehole. They have found that they can eliminate the grouting step altogether in some of their loop installations by using the same bentonites as used for making up grout to support the borehole and to remove drill cuttings. Bentonite is thixotropic and will not set as long as it is being sheared by pumping.

Grouting is important not only for heat transfer and to support the pipe but also to protect ground water (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).

2.4 Circulation

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 sytems use indirect circulation.

Direct expansion (DX) systems have inherently higher efficiencies because the secondary heat transfer fluid heat exchanger and circulating pump are eliminated, but they produce more system design and environmental problems (e.g. compressor starting, oil return, possible ground pollution and a requirement for more refrigerant charge). Until recently, DX systems were uneconomic; however, the development of better equipment and novel design approaches has led to renewed interest in these systems$^{(19)}$. This technology could be particularly appropriate for the retrofit market or where land areas are restricted. DX systems can be used with vertical collectors, but it is uncertain whether the increase in efficiency outweighs the increased complexity of design and control.

2.5 Circulating fluid

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 deg 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. Considerable work has been done to identify suitable antifreeze solutions and Table 3 lists those most commonly used and their properties. No single agent possesses superior properties in all areas.

Glycols in aqueous solutions (usually 20–30%) are commonly used in Europe; however, at low temperatures (below −10°C) they become viscous and need greater pumping power, reducing the efficiency of the heat pump system. Alcohols are popular in the US but are not used so much in Europe (e.g. Germany does not allow their use owing to the potential impact of spillage on ground water). Recently, potassium carbonate has been tested in Sweden because of its good thermal properties and in North America there is considerable interest in potassium acetate as an additive$^{(21)}$.

Many fluids are or can become corrosive to one or more of the wide variety of construction materials used in ground source heat pump systems; thus all antifreeze solutions require inhibitors. In general, these provide satisfactory protection except for potassium carbonate where glucose (the usual inhibitor) cannot provide protection for aluminium, zinc, tin and some brass alloys. Many corrosion inhibitors are toxic, so care must be taken to avoid a nontoxic antifreeze solution becoming toxic after the solution is inhibited. Environmental impact is important in case of accidents involving spillage of the antifreeze.

Table 3 Antifreeze agents and their properties

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. Adversely affects ground water.
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.	Eye/skin irritation. Single-dose oral toxicity is moderate. Excessive or long-term exposure may be hazardous.	Biodegrades when combined with CO_2 and H_2O. Non-persistent organic acids are formed.
Propylene glycol ($CH_3CHOHCH_2OH$)	70	135	Inhibitors required for cast iron, solder and aluminium.	Considered to be non-hazardous.	Same as ethylene glycol.
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_5OH)	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.

2.6 Heat pumps

The heat pump required is an extended range water-to-air or water-to-water unit, depending on the medium for heat distribution. The vapour compression cycle is by far the most common cycle for commercial heat pump equipment. It has been well tried in refrigeration equipment and combines efficiency, compactness, safety and reasonable cost. Its disadvantages are the need for high-capacity compressors and the sensitivity of the output to the evaporator temperature. This means that currently available compression heat pumps, although well suited to low temperature heating systems (e.g underfloor heating), have poorer COPs when used with conventional hydronic heating systems with circulation temperatures of 70°C or higher.

In general, developments in ground source heat pumps follow on from developments in the much larger market for air source equipment. Substantial improvements in ground source heat pump technology were made in the US in the early 1990s(21). More recently, the approach has been to look for improvements in the total heat pumping system, and technology procurement competitions in Sweden(22), Switzerland and, most recently, the Netherlands(23) have led to the development of equipment specifically for the northern European market.

The other main areas of research, common to all heat pumps, have been into environmentally acceptable, chlorine-free replacement refrigerants (for instance the R-22 Alternative Refrigerants Evaluation Program(24)) and into reducing refrigerant charges, especially for flammable or toxic refrigerants. In the US, flammable refrigerants are considered unacceptable because of the liability laws, and the most promising alternatives are seen as R-34a, R-407C and R-410A, with R-410A probably the favourite. Although these hydrofluorocarbon (HFC) refrigerants do not contain chlorine and have zero ozone depletion potential (ODP), they still have significant global warming potential (GWP), and their use is likely to be restricted at some time in the future. Thus, work in Europe on replacement refrigerants has concentrated on 'natural' refrigerants (i.e. hydrocarbons, ammonia, water or CO_2) that have no ODP and no GWP(25). The hydrocarbon propane is being tested as a replacement for R-22 for smaller ground source heat pumps in Europe, especially in Germany, Austria and Sweden. Hydrocarbon refrigerants are commercially available and a number of manufacturers in Europe are currently offering a range of low-charge water-to-water heat pumps in the range 2–100 kW that use these refrigerants. The main problem with hydrocarbons and ammonia is flammability.

Advances have also been made in controls. Sophisticated microprocessor controls are being introduced that help to optimise operation and improve energy savings, comfort and reliability. Status and fault indication help with trouble shooting, and some units incorporate a 'smart card' that in the case of failure can be sent to a service centre, allowing remote diagnosis of the problem based on information on the card.

3 Applications

Providing domestic space heating is currently the most common application of GSHPs. In North America, however, the market developed out of the need for space cooling, so the majority of systems use reversible heat pumps that can provide heating and cooling. Even in Canada the fact that heat pump systems can provide cooling increases their market. Systems in North America are usually sized to meet the cooling load as cooling often has a larger peak load than heating, even though the total annual energy consumption for cooling may be considerably less than for heating. The most common distribution medium is air, except in the North East US and Canada where water distribution systems are often used.

In central and northern Europe, heat pumps are typically used for heating only and the distribution medium is usually water. In central and northern Europe, the demand for air conditioning in domestic buildings is very small; however, the market has been growing. Systems that provide heating and cooling with a single unit are likely to be increasingly important. A GSHP can also provide direct cooling by bypassing the evaporator and circulating fluid from the ground coil through a water-to-water or water-to air heat exchanger.

The heat pump may be integrated into a ducted forced air system or a hydronic heat distribution system with floor heating or radiators or can be a single room unit. One of the aims of the recent Nordic Heat Pump Competition was to encourage the development of a heat pump room heater to replace direct electric heating. A highly efficient system using a precharged DX horizontal ground collector was the winner(26). Studies on single room systems are also being carried out as part of IEA Annex 23—Heat Pumping Systems for Single Room applications.

The main market so far has been new housing, where high insulation levels result in low heating demand and air distribution temperatures can be minimised or low-temperature hydronic systems (i.e. designed for delivery temperatures of 45–55°C) or underfloor heating systems (distribution temperature 30–45°C) can be used.

The retrofit market is potentially much larger, but market penetration has been limited because of the higher distribution temperatures of conventional central heating systems. In Canada and the US, however, GSHPs have been installed for retrofit bivalently with existing heating systems, with the GSHP providing a large proportion of the annual heating at reduced operating temperatures and reducing the energy required for the conventional system during periods of peak demand. The economics of such systems are dependent on the relative fuel prices.

Even with new build, because of the high capital cost of the ground collector, it is common to size the ground coil to meet only a proportion of the design load, with supplementary heating provided by a secondary system. This is usually electrical resistance heating, but in Switzerland wood burning stoves have been used. Recommendations for the proportion of the design load to be met from the heat pump vary (50% in Sweden, ~70% in the US) and depend on the demand pattern and the heat pump and fuel costs. If the heat pump supplies at least 65% of the design heat loss, the use of supplementary heating can depend more on the occupants than on the weather(27).

In general, both horizontal and vertical ground collectors can be used for domestic applications; however, there may not always be sufficient surface area available for a horizontal collector.

Water heating is often provided in addition to space heating; this provides a year-round load and therefore can improve the load factor for the heat pump. The output from the heat pump can provide indirect heating via an exchange coil in the domestic hot water cylinder or a desuperheater may be used. This is a refrigerant hot gas-to-water heat exchanger that is installed between the compressor and the reversing valve of a space conditioning heat pump. The IEA Heat Pump Centre has carried out a comprehensive analysis of domestic hot water heat pumps for residential and commercial buildings(28).

The expansion of the GSHP market started in the residential sector, but in the US, where the market is mature, growth in recent years has been primarily in the commercial sector. In 1996, 30% of all closed-loop GSHP units sold in the US were estimated to be to the commercial sector. As in the residential sector, the need for cooling drives the market and so the majority of systems are reversible. The commercial sector is much more diverse than the residential sector and GSHPs have been used in a wide range of applications (offices, schools, shops, hotels, sports centres, institutional buildings, military complexes. etc.). A list of case studies is available from the Geothermal Heat Pump Consortium(29).

GSHPs can be used with a range of heating and cooling systems: central, distributed (e.g. a water loop system), modular or hybrid (GSHP plus conventional heating or cooling equipment). In general, because of the larger size of commercial systems, horizontal ground collectors are not suitable and multiple boreholes are required. One of the largest installations, at Richard Stockton College, New Jersey, uses 400 × 130 m boreholes providing an installed capacity of just under 5000 kW.

In mid and northern Europe, the main demand is for space heating; however, improved insulation and rising internal heat gains from increased occupation density and radical office automation have led to an increasing demand for cooling. Some countries, however, are introducing regulations aimed at constraining the use of cooling (e.g. in Switzerland and parts of Germany regional building codes require that mechanical ventilation is reduced to a minimum).

Where GSHPs are used to provide heating and cooling, the ground can provide interseasonal underground thermal energy storage (UTES). There is no significant borderline between ground source heat pumps and true thermal storage plants. Large ground source heat pump plants like the one at Stockton College store energy within the borehole field as well as extracting and rejecting heat from and to the surrounding ground. The ground can be used for heat or cold storage; however, the main application is to store cold from the winter to the summer as the ground temperatures at 10 m of 5–15°C in northern and moderate climates are ideal for supplying cooling provided that sufficient cooling has occurred during the winter(30). The IEA Energy Storage Programme Annex 8 has produced a state-of-the-art report on UTES(31).

4 System design

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. A comprehensive review of the written and electronic tools used to design, install and market GSHP systems available in North America was recently carried out for the Geothermal Heat Pump Consortium(32) (DynCorp, 1996). This concluded that a good range of material was available as reference and training material for dealers and installers. It did, however, identify a lack of marketing-orientated design tools aimed more at decision makers, especially for commercial/institutional applications.

The most widely used written design manual in the US is the NRECA/OSU *Closed-loop/Ground-Source Heat Pump Systems: Installation Guide*(15). This covers residential and small commercial installations. It was produced in 1988 and so some important topics are not included, but these are mostly found in separate, more recent, publications by OSU. The main problem with using this guide for European applications is that hydronic distribution systems are not covered.

A comprehensive written guide for commercial applications in the US has been produced by ASHRAE(16) and does include hydronic distribution systems. This was published in 1995, but revisions and additions are already planned. Another problem with the US design tools is that some do not use SI units; however, the Canadian Guides do.

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 4. Software is generally in the public domain or has been developed by the largest manufacturers. However, programs are often niche tools that perform quite narrowly focused analyses.

5 Performance

For electrically driven heat pumps the steady-state performance at a given set of temperatures is referred to as the coefficient of performance (COP), defined as the ratio of the heat delivered by the heat pump to the electricity supplied to the compressor (electricity to auxiliary components including pumps and fans is usually also included)(33).

The performance of heat pumps is steadily improving. National standards for minimum equipment efficiency, where applied, generally adopt a minimum COP of 3 for brine source electrically driven vapour compression cycle heat pumps(34), but advanced reversible (brine-to-air) units with COP of 3.8 are available. Considerable advances have also been made in developing non reversible heat pumps designed for northern European conditions. The two winning systems of the recent Scandinavian technology procurement competition more than met the minimum performance requirement of a $\text{COP}_{0/35}$ (i.e. at a brine temperature of 0°C and a distribution temperature of 35°C) of 3.5 and $\text{COP}_{0/50}$ of 2.8 and showed a 30% improvement in energy efficiency along with a 30% reduction in cost. They also met other stringent requirements for size, noise, etc.(22). In Japan, research aimed at developing a high-performance Super Heat Pump has resulted in prototype water source units with COPs in operation of up to 6.

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 highest SPFs are from systems with DX horizontal collectors combined with low-temperature underfloor heating, for which SPFs often reach 4, can be over 4.5 and are expected to reach 5.0 in the near future(34).

Table 4 Some models and their properties

Name	Supplier	Residential	Commercial	Vertical	Horizontal	Sizing	Performance	Economics	Comments
CLGS	GSHPA, USA	✓		✓	✓	✓		Operating cost + alt. systems	Developed by OSU, based on OSU/NRECA method
DIBSIM	TNO, Netherlands	✓		✓		✓	Annual COP of heat pump and system	Operating cost + alt. systems	Developed by TNO, Netherlands
ECA	Elite Software, Inc. USA	✓		✓	✓		annual COP		Requires heating/cooling loads Provides detailed design info.
EED	University of Lund, Sweden			✓ Multiple boreholes		✓	SPF by month		Lund Univ software under trial
GchpCalc	Energy Information Systems, USA		✓	✓ Multiple boreholes		✓	10-y period SPF by zone		Developed by Alabama Univ. Requires heating/cooling loads library of equipment
GLHEPRO	GSHPA, USA		✓	✓		✓	Heat extraction		Requires heating/cooling loads Uses Lund University method
GL-Source	Kansas Electric Utilities Research Programme, USA			✓	✓	✓	SPF	Installed cost; operating cost	
Geocalc	HVACR Programs, USA	✓	✓			✓		Annual operating cost	
Geodesigner	ClimateMaster Inc., USA				✓			Operating cost + alt. systems	Database of ClimateMaster's products
GS2000	Caneta Research, Inc. Canada	✓		✓	✓	✓			Requires heating/cooling loads
Right-loop	Wright Associates, USA			✓	✓	✓			
W-Calc	InfoEnergie, Switzerland	✓		✓		✓	✓		Swiss programme. Generates daily load demand profiles
WFEA	WaterFurnace International, Inc., USA	✓		✓	✓	✓	SPF	Operating cost + alt. systems	Database of WaterFurnace products

Considerable data has been collected on operating experience with GSHP systems. A study of commercial systems in 1994 for ASHRAE(36,37) identified approximately 350 installations in the US and Canada, from which 23 detailed case studies were prepared. These provided details of the design, performance and economics of systems in a wide range of building types with installed capacities from 88 kW up to 4920 kW. For the systems in this study, the heat exchanger length varied between 10 and 25 m of borehole (20–50 m of pipe) per kW of installed capacity.

Comprehensive sets of monitored data for residential systems are scarce but were included in an extensive analysis carried out by Lienau(38), who collected information from 217 case studies on residential, commercial and school systems throughout the US. Details of the design, performance and economics of 65 of these systems, where the system had been compared with another energy source, were compiled in a database with the main aim of determining the annual energy usage and peak demand savings. This study found that residential and commercial systems provided average energy savings of ~52% compared with electric resistance heating as shown in Table 5. In addition to these studies the list of case studies that the Geothermal Heat Pump Consortium has compiled(29) includes some performance data.

Canada has been particularly active in collecting performance data and a survey of GSHP owners (residential) carried out in 1988(39) found that the reliability of GSHPs was considerably higher than for air source heat pumps (ASHPs) of the same era and that levels of customer satisfaction were high, with 80% of respondents willing to buy another system of the same type. A follow-up survey has been started. For Europe, a considerable amount of performance data is available(8) especially on the increasing number of commercial systems.

Table 5 Measured energy savings from GSHP systems (Lienau)

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

6 Costs

6.1 Capital costs

The capital costs for a GSHP system are made up of the equipment costs for the heat pump unit, the ground coil and the distribution system, the drilling or trenching costs and installation costs. Of these, the costs for the ground coil and its installation are specific to a GSHP system and typically form between 30% and 50% of the total. The total cost for an installed ground collector (including materials, drilling and backfilling, etc.) is between US\$45 and US\$70 per metre in the US. For vertical collectors, the drilling costs can vary between US\$20 and US\$50 per metre of borehole(17,40,41). The actual costs will be dependent on the ground conditions.

Table 6 Typical costs for residential GSHP systems

Country	Costs (US$)	Cost (US$)/kW installed capacity	Comments
Austria	21 000 (inc. underfloor heating) 13 000 (excl. distribution system)	1500 930	Horizontal DX
Canada	9500–13 000 (inc. ~2900 for air distribution system + DHW)	700–1000	Lowest: horizontal DX Highest: vertical
Norway	7500–10 000 (excl. distribution system)	1500–2000	Vertical: underfloor heating ~5 kW (sized to meet 50% of design load)
Sweden	6300 (excl. distribution system) 7100 (inc. distribution system)	1250–1420	As above
Switzerland	20 000 (excl. distribution system) 27 000–36 500 (inc. distribution system)	1900 2800–3800	Vertical: underfloor heating
US	7500–10 000	700–1000	Vertical: air distribution

Note: Scandinavian systems are sized to meet 50% of the design load. North American systems are sized to meet 75–80% of the design load.

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 6 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. Capital costs for residential systems appear to be lowest in the US, Canada and Sweden, which may be due partly to economies of scale. There are too few installations as yet in the UK to establish typical system costs.

6.2 *Running costs*

The running costs for a system will depend on the electricity costs. Typical running costs for an electrically driven GSHP are about 50% less than for electric resistance heating and about 33% less than for an air source heat pump (ASHP)(38) L'Ecuyer, in a report for the US Environmental Protection Agency(42), concluded that GSHP systems had the lowest operating costs of any system for the US (i.e. the highest SPF for heating and for cooling of all systems).

Maintenance costs for GSHPs are low and so may also result in cost savings compared with alternative systems. For the US, the cost of maintenance for a commercial GSHP system is between \$1.08 and \$2.36/m^2/y compared with a mean value of \$5.38/m^2/y for an 'average' commercial heating and cooling system(43).

7 Benefits

7.1 *Financial savings*

Studies in the US have shown that the simple payback period for residential GSHP systems when compared with direct electric heating ranges from 2 to 7 years(38). Similar payback periods are being achieved in Sweden for heating-only systems. For comparison with alternative systems using other fuels, the economics depend on the relative capital costs and fuel prices. In Austria, systems using horizontal DX collectors are reported as being fully competitive with conventional fossil fuel systems for new dwellings(35). In Switzerland, although running costs are ~25% lower than for oil fired systems, the payback time is longer (~12 years) as capital costs are approximately 25% higher than for oil systems. The simple payback time can be long compared with that for a system using a substantially cheaper fuel.

The economics are generally more favourable for commercial systems. The systems are used to provide heating and cooling, so the use of a GSHP can save the cost of both a boiler and cooling equipment; systems are larger, so there are economies of scale and the space required for the plant room is reduced. Economic analyses carried out in Canada showed GSHP systems to have a simple payback time when compared with water loop heat pump systems of between 0.5 and 3.5 years for offices, schools, etc. over a wide range of floor areas. In addition to savings due to reduced energy consumption, there may also be substantial cost savings because of reduced maximum demand. The lifetime of the heat pump would normally be taken as 15 years, but the lifetime of the ground coil is expected to be substantially longer, possibly in excess of 50 years.

7.2 *Other user benefits*

The use of GSHPs can have benefits in addition to the financial ones discussed above. These include

- low noise—no external fans
- good aesthetics
- no roof penetrations (commercial applications)
- high reliability—no exposure to weather
- high security—no outside unit vulnerable to vandals
- increased safety—no combustion or explosive gases within the building
- no local pollution.

7.3 *Benefits to utilities*

Many power utilities view GSHPs as a significant technology that can help to reduce the cost of providing power and to attract and retain customers while protecting the environment. Heat pumps have a useful role in Demand-Side Management and this has been reviewed by Steadman(44). Using GSHPs to replace fossil fuel-fired systems will increase electricity demand and electric utilities have a clear incentive to encourage this. Using heat pumps to replace resistance heating can be less attractive to utilities as it may result in reduced revenue, but it can have operational advantages by helping to minimise internal costs through the ability to reduce both peak and average load demands. In a competitive market a utility must meet customer needs at lowest cost. In addition, GSHPs with their low running costs, long system lifetimes and good reliability could result in increased customer satisfaction and thus customer retention. Some utilities have used them to create a business opportunity by providing consultancy services and assistance with installation, leasing equipment or even providing the system and selling the final energy. A substantial proportion of the energy sold would then be provided from a renewable source.

Table 7 Energy efficiency factors for a range of heating systems

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 (eff. 42%) + GSHP	1.26 (1.68)
Gas fired combined cycle plant (eff. 52%) + GSHP	1.57 (2.1)
Combined cycle CHP plant (max. eff. 89%) + GSHP	1.7 (2.3)

Note : SPF for the GSHP is 3.0 (figures for SPF = 4 are given in brackets). Figures are for electrically driven vapour compression heat pumps and newer power plants and boilers.

For gas utilities the main benefit is likely to be the opportunity to enter the market for cooling if suitable gas-driven equipment becomes widely available.

7.4 Community benefits

Benefits to the community at large will result from the reduction in fossil fuel consumption and the resulting environmental benefits. Gilli(45) 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 the heat pump is supplied from a single power station. Energy efficiency factors for a range of systems are given in Table 7. These figures suggest that GSHPs can reduce primary energy consumption by between 15% and 50% compared with conventional oil- and gas-fired boilers and agree with figures suggested by Laue in 1994 based on practical experience and simulation programmes of the whole fuel cycle. In practice, electricity would be supplied from a national grid system and the effect on both primary energy and CO_2 emissions is more complex. The fuel mix for generation will thus be a factor.

By reducing primary energy consumption, the use of GSHPs has the potential to reduce the quantity of CO_2 produced by the combustion of fossil fuels and thus to reduce global warming. The impact of heat pumps on the greenhouse effect has been the subject of considerable research. An analysis report produced by the Heat Pump Centre(45) provides a comprehensive overview of the knowledge up to 1993. Studies in the US(42), in the Netherlands(46) and most recently in Switzerland(48) have all concluded that heat pumps are cost effective for providing high CO_2 reductions.

A GSHP with an SPF of at least 3 will always reduce CO_2 emissions compared with an oil-fired boiler, independently of the local electricity generation mix. When used in place of a high-efficiency gas fired boiler it will reduce overall emissions of CO_2 provided that mean specific CO_2 emissions from electricity generation do not exceed 0.63 $kgCO_2/kWh_{el}$. Since 1990 the CO_2 emitted per unit of electricity for the UK has fallen over 20% as a result of the substantial switch from coal- to gas-fired generation and the average specific CO_2 emission from electricity generation in the UK is currently about 0.54 $kgCO_2/kWh_{el}$.

In addition to their positive effect on reducing CO_2 emissions (indirect effect), heat pumps can also have a negative effect on ozone depletion and global warming due to their refrigerant (direct effect). However, when these effects are combined using the total equivalent warming impact (TEWI) it is found that the direct impact of all non-CFC refrigerants is negligible compared to the energy related CO_2 emissions.

Apart from the effect of reducing fossil fuel consumption, electrically driven heat pumps allow centralised removal of atmospheric pollutants such as sulphur dioxide, oxides of nitrogen, etc. from the flue gas and fuels before and while they are burned compared with the decentralised emission from individual heating systems.

8 Conclusions and future prospects in the UK

Although the technology is well established elsewhere, GSHPs are currently at the demonstration stage in the UK. A recent analysis of the wordwide market for GSHPs carried out by the Building Services Research and Information Association (BSRIA)[9] identified some of the reasons for this. It found that in the majority of countries where sales of GSHPs are significant the government has played an active part in stimulating the market either by directly subsidising systems and installation or by subsidising research and development, promotion or through tax incentives. Government schemes usually are part of a national environmental and energy policy where the objective is to increase renewable energy's share of the total energy supply and thus promote sustainability and reduce greenhouse gas emissions. The utilities have also been a driving force in the US, Canada, Austria and Germany. The study also found that the attitude of end users and specifiers was very important; for instance, in Switzerland and Scandinavia clients were generally prepared to pay more for high-quality environmentally friendly systems. The study included a survey of specifiers and users in the UK, which identified the main barriers to uptake of the technology as the relatively high capital cost, doubts about reliability, the lack of qualified installers and, most importantly, lack of awareness of the technology.

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 space 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 (4.9 million households). A niche market could also emerge for the provision of 'green air conditioning' in larger individual houses. 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.

At present there are manufacturers of water source heat pump equipment in the UK but not of equipment specifically designed for use with ground collectors. Equipment is available from manufacturers in Europe and there are also UK agents for some of the largest US manufacturers but it is possible that some development work would be necessary to optimise systems for UK conditions. The installation of horizontal ground collectors does not require specialist equipment; however, the installation of vertical collectors requires drilling expertise. A few installers have undergone training in the US or Europe, but in general there is no infrastructure yet in the UK in terms of experienced designers and installers. It would be necessary to establish product testing and training for consultants and installers in order to ensure quality products and good standards of design and installation.

It is difficult to estimate what the additional capital cost of a GSHP system might be over a conventional system because of the limited number of systems installed to date. Estimates from one company suggest that the cost of drilling a borehole and installing a vertical collector is $\sim$£10 per metre of borehole but the figure is dependent on the ground conditions. For a domestic space heating installation the capital cost appears to be 2–3 times higher than that for a conventional condensing gas boiler or electric storage heating. To help offset this increased capital cost, one electricity supply company provides subsidies (it obtained approval from the Energy Savings Trust to include these subsidies in its energy saving programme and thus use 'Standards of Performance' money). For commercial applications the cost differential would be less and one company suggests £135–165 per m^2 of conditioned space for a ground source heat pump system operating with a closed water loop system with individual heating/cooling modules. With the optimisation of equipment for the UK and an increase in the market, prices are likely to fall.

With system SPFs of between 3 and 4 there would be considerable savings in delivered fuel for the user. The financial savings depend on the relative costs of the fuels used by the heat pump and the alternative system. The financial savings will be similar to the fuel savings if the heat pump and the alternative system both use electricity charged at the same rate. However, if the alternative fuel is gas, which is substantially cheaper than electricity, then the heat pump system would probably need a SPF greater than 3.2 to achieve any fuel cost savings. The introduction of favourable electricity tariffs could make electrically driven heat pumps more competitive compared with gas-fired equipment and one electricity supply company is already offering a 'total living tariff' specially for use with ground source heat pumps. This offers eight hours of electricity at a cheap rate but does not limit this period to overnight.

The use of GSHPs in the UK already has the potential to reduce primary energy consumption. Assuming steam generation (average efficiency 37.4%) and a low SPF for the GSHP of 3, the saving would be 12% but for gas fired combined cycle generation (average efficiency 44.3%) and an SPF of 4 for the GSHP, the savings rise to 77%. 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%. There is thus still considerable scope for improving the efficiency of both power stations and heat pumps. By comparison there is virtually no potential for improving the efficiency of a condensing gas boiler.

The reduction in primary energy consumption leads to a reduction in CO$_2$ emissions. This is of particular importance since the UK is legally committed to reducing CO$_2$ emissions by 12.5% from 1990 levels by the year 2010 and energy use in buildings is a major source of emissions. A condensing gas boiler operating at a seasonal efficiency of 85% delivers heating at 0.25 kgCO$_2$/kWh$_{th}$; however, the use of a GSHP for heating results in CO$_2$ emissions of around 0.15 kgCO$_2$/kWh$_{th}$ (assuming an average emission rate of 0.54 kgCO$_2$/kWh for electricity generation); a reduction of 40%. 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.

In conclusion it would appear that the increasing interest in GSHPs in the UK is more than justified.

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