



Pre-print version of a paper published as:

Preene, M and Powrie, W (2009). Ground energy systems – delivering the potential. *Proceedings of the Institution of Civil Engineers, Energy* 162, EN2, May, 77–84.

Ground energy systems: delivering the potential

KEYWORDS: Geothermal; Renewables

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Ground energy systems: delivering the potential

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ABSTRACT

Ground energy systems are increasingly considered as an alternative to traditional heating and cooling systems to reduce carbon emissions, control energy costs and improve the environmental performance of buildings. These systems use the ground and groundwater beneath a site as a heat source or sink, interacting through boreholes or pipes which exchange heat with the ground. This paper reviews the principles underpinning these systems, and describes the two main types of system – open loop and closed loop. Four potential barriers to wider scale application of ground energy systems are highlighted: thermal interference between neighbouring systems in densely developed urban areas; increased environmental regulation of below ground elements; capital cost; and the need to ensure that systems are sustainable in the long term. If the full potential of ground energy systems is to be realised, it is important that input from geotechnical and geological specialists to ensure that the below ground elements are designed using appropriate design tools and site-specific data. It is also important that appropriate post-occupancy monitoring is in place to provide feedback to designers on the long term performance of these systems.

INTRODUCTION

Rising energy costs and regulatory requirements to reduce carbon emissions mean that designers and operators of buildings must reduce their reliance on the traditional energy sources (derived primarily from fossil fuels) used to provide heating and cooling to buildings. A wide range of ‘alternative’ means of providing energy to buildings has been developed, known collectively as low or zero carbon (LZC) technologies. Ground energy systems – defined as those thermally coupled to the sub-surface environment, allowing heat energy to be extracted from and/or rejected to ground and groundwater – represent one subset of LZC technology.

Ground energy systems are not new, and worldwide there is a wealth of successful applications from single dwellings to major office buildings. There is clearly significant potential to apply ground energy systems to improve the environmental performance of buildings. However, ground energy systems differ from most other LZC technologies in that their successful design and operation requires an understanding of the likely thermal behaviour of the ground beneath a building; lack of such understanding can lead to problems later in the building design life. This paper reviews the background to ground energy systems, enumerates their principal constraints, and highlights the differences between them and other LZC technologies. Some potential barriers which may prevent

the full potential of ground energy systems being delivered, are identified, and possible measures to overcome these barriers are suggested.

COMPARISON WITH OTHER LZC TECHNOLOGIES

Ground energy systems are only one type of LZC technology that can be used to meet part of the energy demand of a building¹; these and other available technologies are summarised in Table 1. Table 1 shows that there is a wide range of systems available, some of which produce electricity and some of which produce heat; ground energy systems fall into the latter group. However, ground energy systems are the only technology where the ground beneath a site plays a significant role in the successful operation of the system. The importance of adopting suitable approaches to design and management of the below ground elements will be addressed later in this paper.

GROUND ENERGY SYSTEMS

In concept, ground energy systems are very simple. They involve using a sub-surface array of pipes (ground loops), boreholes or other structures such as piles to exchange heat with the ground. In the absence of external influences, and below the relatively shallow zone of annual temperature variation, the ground is assumed to act as a large, thermally stable mass, whose temperature varies little during the year (Figure 1). Ground temperatures within 200 m of the surface typically reflect the mean annual air temperature at a site (in the UK, 10 to 14°C). The stable ground temperature means that in the summer months the ground will be cooler than the surface air temperature, so heat can be rejected to the ground. Conversely, in winter the ground will be warmer than surface air temperature, and can be used as a heat source (Figure 2).

The nomenclature for these systems can be confusing to the non-specialist. In the current paper they are termed ground energy systems, but in much of the academic, professional and commercial literature they are referred to as geothermal systems. However, ground energy systems are distinct from traditional geothermal energy systems which tap into hot rocks at great depth, and produce hot liquid (water or brine) used for a range of purposes from power generation to district heating. In the UK such systems are rare. Prior to 2000 the only significant operational system was for district heating in Southampton, Hampshire². Since then a small number of traditional geothermal systems have been taken to the investigation stage in north eastern England.

A ground energy system can be divided conceptually into three key elements:

- i. The source side (the below ground elements such as boreholes, ground loops and associated infrastructure);
- ii. The load side (the building, its controls, users and the thermal load which results);
and

- iii. The heat transfer system (the heat pumps, heat exchangers and associated control systems).

Ground energy systems are categorised into two principal types: open loop and closed loop. Open-loop systems³ pump groundwater from the ground to the surface (Figure 3). The groundwater is then passed through a heat transfer system, before being disposed of (at a different temperature from before) either to waste or by re-injection back into the ground. In contrast, closed-loop systems do not abstract groundwater, but instead circulate a fluid through a loop of pipes (the ground loop) buried in the ground (Figure 4). The circulating fluid passes through a heat transfer system at the surface, and is then recirculated back through the buried ground loop, to exchange heat with the surrounding soil or rock. Characteristics of open and closed loop systems are summarised in Table 2.

The heat transfer system which allows the thermal loads from the building to be passed into the boreholes or ground loop often takes the form of one or more heat pumps. A heat pump is simply a mechanical device which uses a refrigerant vapour compression cycle to transfer heat efficiently from one reservoir to another. Ground energy systems are sometimes known as ground source heat pumps, but a heat pump (if used) is only one component of a successful system. Indeed, when used to provide cooling it may be possible for ground energy systems to use a plate exchanger for heat transfer, thereby avoiding the need for heat pumps.

ENERGY BALANCE IN GROUND ENERGY SYSTEMS

The reason that ground energy systems are attractive as a means of reducing energy consumption is that, when applied appropriately, they can produce greater amounts of heat energy than they consume in electricity. When heat pumps are used as part of a ground energy system, their performance is often assessed in terms of a coefficient of performance (COP). COP is the ratio of heat energy delivered to electrical energy used. In ground energy applications, heat pumps would typically be expected to operate with COPs of 3 to 5; in other words for every kilowatt hour (kWh) of electrical energy used, 3 to 5 kWh of heat energy is produced. Thermodynamically, the 'additional heat' in the equation – including energy lost – must be coming from or going somewhere, in this case into the ground. Ground energy systems operating in heating mode are net extractors of heat from the ground, and if operating in cooling mode dispose of the waste heat by injecting it into the ground.

Shallow soils and rocks are a huge thermal resource, receiving energy from above via solar radiation, and energy from below via geothermal flux from deep within the earth. Tapping into this resource via ground energy systems seems like a potential panacea to the problems of building energy. Unfortunately it is not that simple. The principles of thermodynamics dictate that if heat is extracted from a borehole then a temperature gradient will be created towards the borehole, and energy will flow from the surrounding ground to replenish the energy that has been extracted. Conversely, if heat is injected into a borehole then temperature gradients will act to dissipate the excess heat into the

surrounding ground. In practice, however, unless the net rate of energy extraction or input is very low, the rate of heat flow from or into the surrounding ground will be insufficient to replenish the energy extracted or injected by the system, and a zone of reduced or elevated temperature will grow.

These factors mean that many large scale ground energy systems which operate predominantly in either heating or cooling are potentially extracting (or injecting) far more heat energy than the ground locally beneath the building can sustain in the long term. These problems may not be apparent on the first day of operation, or even within the first few years of use, but as the years pass, there is a danger that ground temperatures around closed loop systems will gradually change (falling in the case of heating dominated systems or rising for cooling dominated system). Changes in ground temperature will affect the operational efficiency of the heat transfer system, and eventually the ground energy system may be rendered all but useless. If that happens, the building owner will be faced with an expensive and inconvenient retro-fitting exercise to install another heating or cooling system to last the remainder of the building life.

For closed loop systems, the impact of long term net extraction from or injection of heat to the ground will tend to result in temperature changes in the ground close to the system itself. This will have a detrimental effect on the performance of the system, **but in most cases is** unlikely to affect the site's neighbours and the wider environment. In contrast, open loop systems which actively pump groundwater can potentially have wider impacts. Also, the more systems there are operating in close proximity, the more likely it is that thermal overload of the ground will occur.

A common configuration of open loop system comprises an array of abstraction boreholes and an array or re-injection boreholes installed into an aquifer (a layer of soil or rock beneath the site, which is saturated and permeable and yields significant quantities of water to abstraction boreholes). The waste water from the heat transfer system is warmer or colder (for cooling and heating modes respectively) than the natural groundwater, and is re-injected back into the aquifer. If the rate of pumping is too great there is a risk that warmer/colder water will be drawn rapidly (within months or years) to the abstraction boreholes. 'Thermal breakthrough' is said to occur when the injected warmer/colder water reaches the abstraction boreholes (Figure 5). If this occurs the temperature of the abstracted water will change and the performance of the system will be detrimentally affected. Analytical tools are available to model thermal breakthrough (such as Gringarten and Sauty⁴); a wide range of hydrogeological tools relevant to ground energy problems are given by Banks⁵.

Even if thermal breakthrough does not occur, wider problems may arise if the injected warmer/colder water, instead of being drawn toward the abstraction boreholes, migrates off site, affecting neighbouring sites and possibly wider aquifer conditions. Where concentrations of open loop groundwater energy systems exist, there is evidence that cumulative effects from these systems can cause problems. Gustafsson⁶

reports that in Sweden open loop systems (used predominantly for heating) in densely developed areas have resulted in falling groundwater temperatures. Ferguson and Woodbury⁷ report a case in Canada where injected warmer water appears to have migrated between neighbouring open loop cooling systems, causing greater increases in groundwater temperature than might be expected from a single system operating in isolation.

The risk of long term temperature changes around closed loop systems and thermal breakthrough and off-site migration of heat for open loop systems can be reduced by using the ground energy system to provide the building with both heating and cooling, and carefully controlling the system to achieve an approximate annual balance between summer and winter thermal loads. This approach, known as aquifer thermal energy storage (ATES), uses the concept that during the annual energy cycle heat energy is stored in, and then recovered from, the ground⁸. During the summer season the system is operated in cooling mode the heat is rejected into the ground. During the winter season the system is used for heating and is effectively run in reverse so that heat is extracted from the ground.

Over the last decade detailed guidance on design and practice of ground energy systems has been produced in the United States⁹, and Canada^{10, 11}. A wide range of analytical and modelling approaches have been developed, as summarised by Banks⁵.

CONSTRAINTS AND BARRIERS

Ground energy systems have great potential to contribute to the delivery of reduced carbon emissions from buildings, but like any technology there are some potential barriers to their wider implementation. Some of these are discussed below.

Some of the key barriers to wide-scale development of ground energy systems might arise from the potential effects of their popularity. In the UK, during the first years of the 21st century, there has been a rapid expansion in the number of ground energy projects. Wang *et al.*¹² indicate that in 1999 there were probably only 10 significant ground energy systems in the UK, but by 2007 there may have been as many as 2000 in operation or under construction. There is a natural tendency for larger ground energy systems to be developed in city centres and urban areas where there is a greater density of development and more capital investment. It is likely that in the future in densely populated areas multiple ground energy systems will be developed on neighbouring or near-neighbouring sites. In these circumstances, a consideration of the effect of off-site migration of heat and long term temperature changes will become very important, to avoid the liability issues associated with a ground energy system on one site interfering with, and having a detrimental impact on, a neighbouring site.

As described earlier in this paper, there is some published evidence from Sweden and Canada of thermal interference between neighbouring open loop ground energy systems. In the UK there is no published evidence to date of thermal interference occurring, but

the environmental regulator for England and Wales (the Environment Agency) is beginning to raise concerns about the cumulative impacts of ground energy systems. In central London, there is already evidence that the net abstraction of groundwater from some open loop systems is impacting available water resources and causing groundwater levels in the Chalk aquifer to fall¹³. Ironically, only two decades ago the concern was rising groundwater levels in the Chalk¹⁴.

As a consequence, increased regulation of ground energy systems may become a perceived barrier. It is interesting to note that the recent update by the Environment Agency of the *Groundwater Protection Policy and Practice*^{15,16} introduced, for the first time, regulatory controls specific to closed loop and open loop ground energy systems. In the future, ensuring regulatory compliance of the below-ground aspects may become a much more onerous part of the development of ground energy systems.

An additional barrier to the development of ground energy systems is simply capital cost. Ground energy systems used to heat and cool buildings typically cost more to implement than traditional systems (such as gas-fired boilers for heating and electrically-driven cooling systems that exhaust heat to air). Ground energy systems, when designed and operated appropriately, offer operational savings relative to traditional systems, allowing the additional capital cost to be recouped, typically over a period of several years. The length of the 'payback period' required to recoup the additional capital cost is often a critical factor when project promoters and developers are selecting a ground energy system or other LZC technology. A payback period that is too long may result in a traditional heating and cooling solution being used instead of a ground energy system, with resultant loss of potential carbon savings.

It is important that the capital costs of ground energy systems are minimised, while still achieving the desired performance throughout the building life. The below ground elements (boreholes, ground loops, etc) have a disproportionate impact on the capital cost; if these elements can be designed to deliver appropriate thermal performance without excessive spare capacity, then significant capital efficiencies may be possible. This, or the use of hybrid systems meet a proportion of the peak thermal load by some other means (discussed later), could make ground energy systems financially viable on a wider range of projects than at present.

The final barrier to the wider implementation of ground energy system is the need to be able to demonstrate the long term sustainability of these systems. This means that the systems need to be capable of operating successfully for the entire building design life. This relates directly to the other barriers because to be successful a system needs to avoid unacceptable impacts on its neighbours, comply with the regulatory regime and be cost-effective. Until recently, the sustainability of ground energy systems (not merely the below ground elements, but also the relevant building elements) was rarely considered explicitly in design. This may have been because sustainability measures specific to

ground energy systems have not been available; however, this has recently changed with the publication of guidance by Preene³, Whitaker and Law¹⁷ and Younger¹⁸.

DELIVERING THE POTENTIAL

The huge potential for ground energy systems to contribute to carbon emissions reductions is reflected in their recent rapid uptake. However, if the full potential is to be delivered, it is important that the design of the ground energy system is fully integrated into the building design, and that building designers understand the specific characteristics of ground energy systems. Some design aspects relevant to effective ground energy systems are discussed below.

At the moment the design of ground energy systems is often led by building services engineers with input from geotechnical specialists considered as a secondary issue and sometimes left until relatively late in the project. In the future it should be recognised that avoiding over-design and achieving cost-effectiveness of the below ground elements (boreholes, ground loops etc) will be vital if ground energy systems are to be widely applied. Geotechnical design input can contribute the most if it is involved from the very outset of schemes to allow the ground energy concept to be matched to the likely ground conditions identified at desk study stage. Later during site investigation, the opportunity should be taken to obtain site-specific data on thermal properties, for example by carrying out in-situ thermal response tests¹⁹ or by thermal testing of soil samples²⁰. Such site specific data can be obtained at reasonable cost, will reduce uncertainty in design and are ultimately likely to give clients increased confidence in the design process.

Designers need to be aware that the below ground elements of these systems are subject to environmental regulation by bodies such as the Environment Agency. At this stage in the development of ground energy systems there is an opportunity for designers to embrace best practice and to engage in a positive dialogue with environmental regulators, to develop future designs which explicitly consider the environmental impacts. If this is not done, there is a risk that additional, more onerous, regulation may be imposed in response to perceived problems with existing systems.

The long term sustainability of system operation should be assessed in the design of any significant ground energy system. According to Preene³, if it is assumed that the building energy demand has been minimised through design in accordance with energy conservation principles, then sustainability can be demonstrated by ensuring that a ground energy system will:

- i. be effective for most if not all of the building life (e.g. avoid problems with loss in system performance through long term changes in ground temperature in closed loop systems, or thermal breakthrough between boreholes in open loop systems);
- ii. be flexible in response to future changes in operation; and

- iii. not have unacceptable indirect impacts (e.g. avoid off-site migration of heat which has the potential to affect neighbouring sites).

Specific design approaches that can be used to ensure sustainability are given in Preene³, Whitaker and Law¹⁷ and Younger¹⁸. All these approaches recommend that consideration be given to ensuring an annually balanced thermal load, where during one annual cycle the amount of cooling energy rejected to the ground in summer is approximately balanced by the amount of heat energy extracted in winter.

One approach to ensuring that a ground energy system under a balanced load and is flexible in its future operation is to use a hybrid or bivalent system in which a relatively constant baseload (of less than 100% of the peak heating/cooling load) is applied to the ground energy system, with the remaining short term peaks above the baseload dealt with by supplementary traditional heating/cooling systems. This will allow significant reductions in energy costs and carbon dioxide emissions to be achieved, while substantially reducing capital costs compared to the case where the entire building load is applied to a ground energy system designed to cope with peak demands that might occur for just a tiny fraction of the design life. Hybrid systems offer flexibility if the building is subjected to higher thermal loads (for example due to climate change or different occupancy patterns) than assumed by the designer. A suitably controlled hybrid system subjected to an increased thermal load would 'cap' the load applied the ground at the design values, with the excess load dealt with by increasing use of the traditional plant. This will avoid long term temperature changes in the ground and will ensure that the system does not violate the conditions of any environmental permits which may be in place.

An aspect of design that is sometimes neglected is to ensure that designers receive feedback on how a building performs in practice. Building industry guidance²¹ highlights the need for effective in-use energy management and for post occupancy evaluation, to determine whether the building and the ground energy system perform as intended and meet the user's needs. The availability of post-occupancy information may allow the development of more sustainable designs in the future.

CONCLUSION

Ground energy systems are a LZC technology for heating and cooling which offer real potential to improve the environmental performance of a wide range of buildings. The below ground elements (boreholes and ground loops) are significant factors in the capital cost of these systems. It is important that these elements are designed taking into account the latest developments in design and regulation, and are fully integrated into the building design.

Obtaining appropriate input from geotechnical and geological specialists, and ensuring that long term sustainability of systems is addressed are key steps in delivering the full potential of ground energy systems. In particular,

- a. systems should ideally be designed on the basis of a substantially balanced annual energy cycle so that the ground is used primarily as a heat bank rather than as a long-term source or sink;
- b. consideration should be given to meeting periods of peak demand that are very short in comparison with the lifetime of the system by other means, through the adoption of hybrid systems;
- c. interactions and the cumulative effects of neighbouring systems in densely developed urban areas must be considered in design; and
- d. data on in-service performance is required to feed back into the design process to enable the development of more realistic and reliable design tools.

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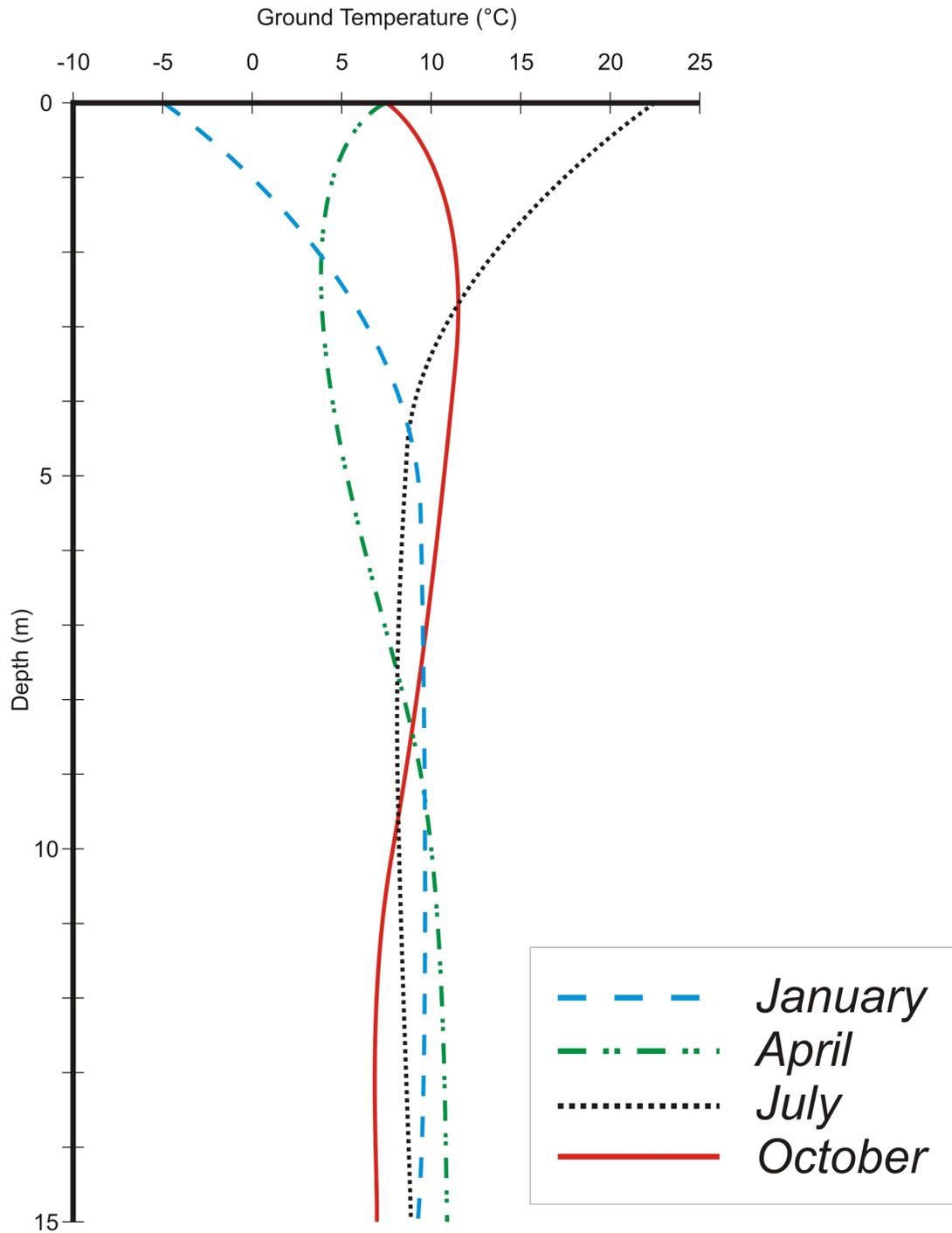


Figure 1: Typical ground temperature profile (redrawn from Wang *et al.*⁶)

A zone of seasonal temperature variation exists within a few metres below ground level, however, below the zone of seasonal variation the ground temperature varies little during an annual cycle

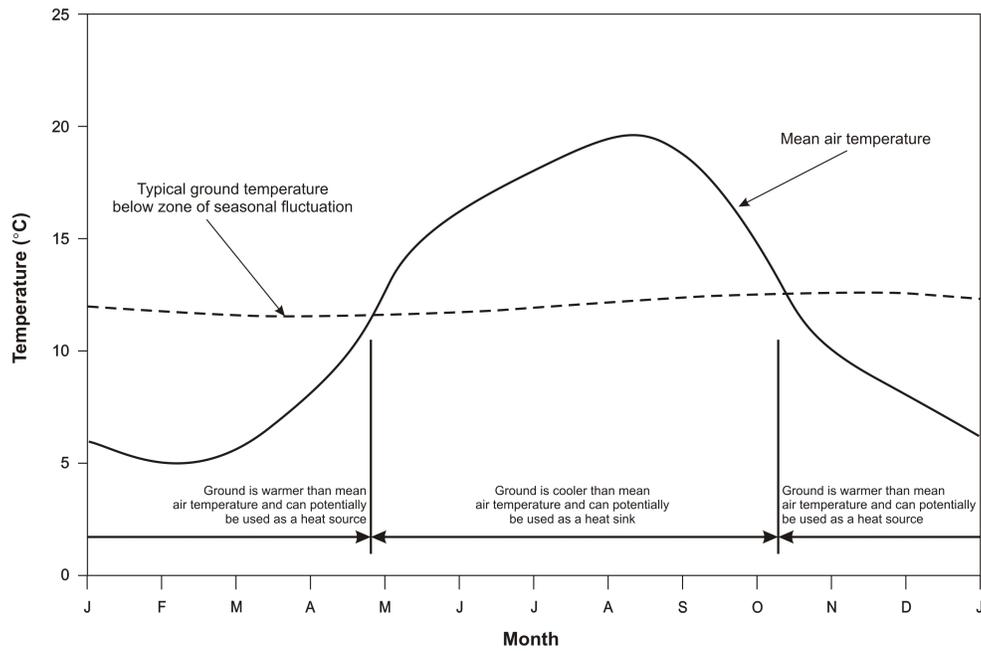


Figure 2: Relationship between surface air temperature and ground temperature

At depths of more than a few metres the annual variation in ground is much less than the annual variation in mean air temperature. In the summer the ground is cooler than the air temperature and can potentially be used as a heat sink. In the winter the ground is warmer than the mean air temperature and can potentially be used as a heat source.

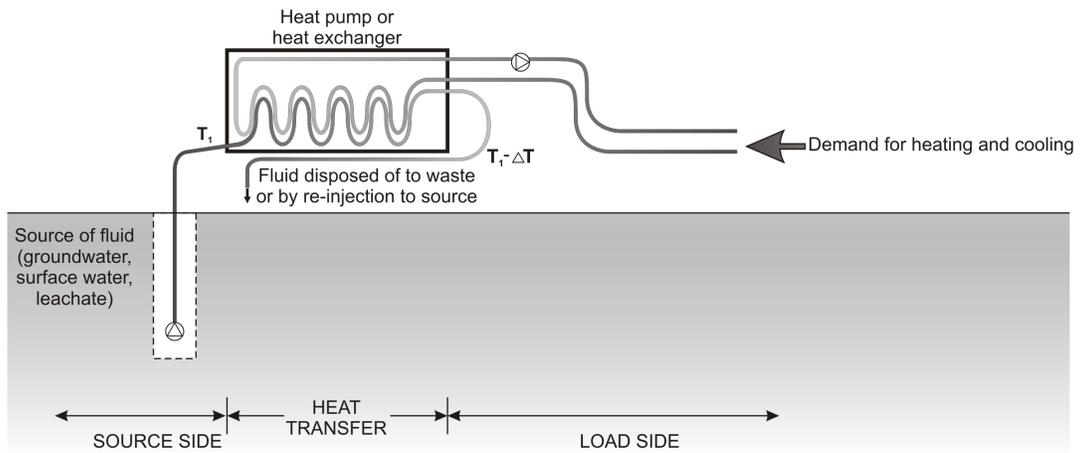


Figure 3: Open loop ground energy system

Groundwater is abstracted from the source (typically one or more boreholes), passed through a heat pump or heat exchanger and disposed of to either to waste (sewer or watercourse), or by re-injection to the source (typically by one or more aquifer re-injection boreholes)

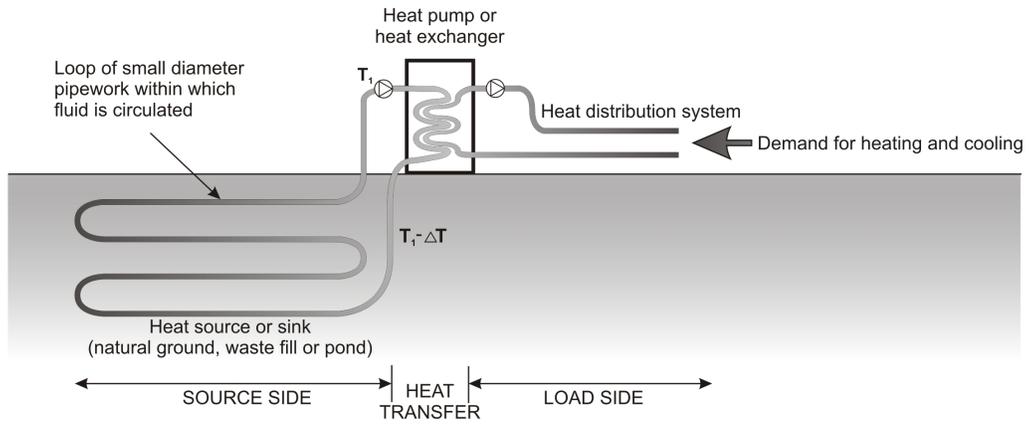
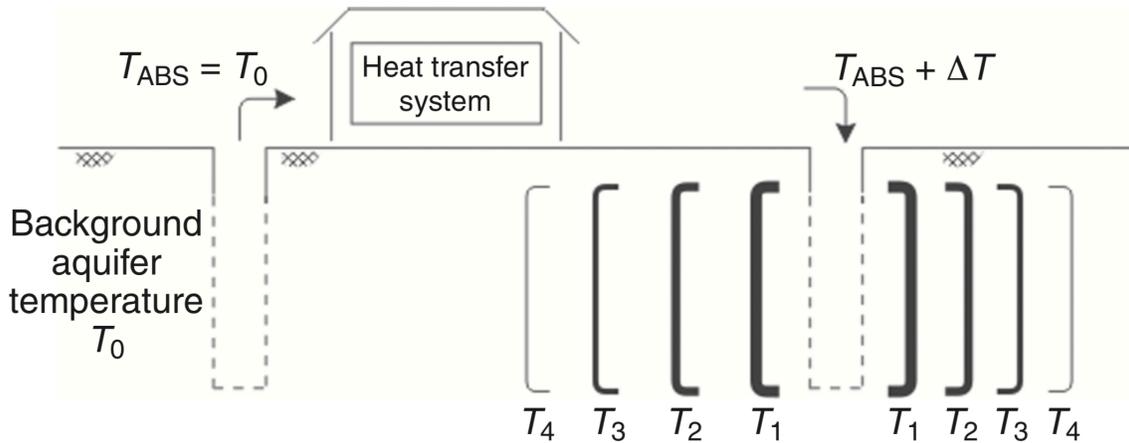


Figure 4: Closed loop ground energy system

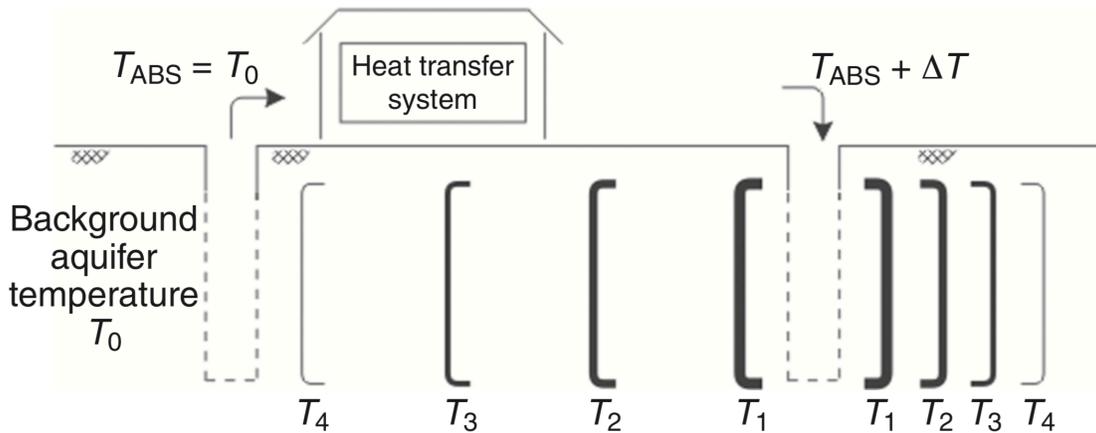
A thermal transfer fluid is circulated through a closed circuit of pipework embedded in the ground, thereby allowing the building heat pump system to reject or extract heat from the ground. The ground loop can be configured into shallow trenches, an array of vertical boreholes, or can be incorporated into the building piles and other foundations



$$T_{ABS} + \Delta T > T_1 > T_2 > T_3 > T_4 > T_0$$

a) After short term pumping (cooling mode shown)

Pumping from the abstraction boreholes draws the injected warmer water preferentially toward the abstraction boreholes (the front of warm water is shown schematically, in reality the front of warm water will form an irregular plume, drawn toward the abstraction boreholes)



$$T_{ABS} + \Delta T > T_1 > T_2 > T_3 > T_4 > T_0$$

b) After longer term pumping (cooling mode shown)

Thermal breakthrough occurs when the injected warmer water reaches the abstraction boreholes. If pumping continues the temperature of the abstracted water will rise, affecting the efficiency of the groundwater energy system (the front of warm water is shown schematically, in reality the front of warm water will form an irregular plume, drawn toward the abstraction boreholes)

Figure 5: Thermal breakthrough between abstraction and re-injection boreholes for intergranular flow conditions

Table 1: Summary of low or zero carbon technologies (adapted from Thorne¹)

Technology	Primary output	Carbon savings	Cost effectiveness	Local impact
Photovoltaics	Electricity	Low	Low	Low
Wind power	Electricity	Low-medium	Medium	Medium-high
Combined heat and power, fuelled by:				
- gas	Heat and electricity	Medium	Medium	Low-medium
- biomass	Heat and electricity	Medium-high	Medium	Low-medium
Solar thermal systems	Heat	Low-medium	Medium	Low-medium
District heating and cooling	Heat	Medium-high	Medium	Low
Biomass boiler	Heat	High	Medium	Medium
Ground energy systems				
- open loop	Heat	Depends on building type	Depends on building type	Low
- closed loop	Heat	Medium	Medium	Low

Table 2: Characteristics of open loop and closed loop ground energy systems

Characteristic	Open loop systems	Closed loop systems
Requirements for groundwater abstraction and re-injection	All open loop systems involve abstraction of groundwater. For many open loop systems it is impracticable or unsustainable to discharge the water to sewer or surface water; in those circumstances the water must be re-injected into the aquifer.	Groundwater abstraction and re-injection not required.
Regulatory constraints	In many countries the abstraction and discharge of groundwater is closely regulated. Open loop systems will be subject to the constraints of any such legislation.	In many countries there is currently little or no regulation of the ground element of closed loop ground energy systems. One issue that is sometimes be regulated is to ensure that boreholes are adequately sealed or grouted to avoid the creation of seepage pathways from the surface and between different geological units.
Dependence on favourable hydrogeological conditions	Open loop systems are only practicable when significant water-bearing strata (which collectively form a continuous water bearing layer of soil or rock – termed an ‘aquifer’) are present beneath a site.	Closed loop systems do not require the presence of an aquifer, and can be practicable in a wide range of geological settings.
Number and capacity of boreholes	Under favourable hydrogeological conditions, where borehole water yields are significant, relatively small number of abstraction boreholes can supply large peak demands. For example a borehole yielding 25 l/s could provide a peak thermal output of 500 kW.	The peak thermal capacity of an individual closed loop borehole is typically much less than that of an open loop borehole. Closed loop systems typically require much greater number of boreholes than equivalent open loop systems. A typical 100 m deep closed loop borehole could have peak thermal output in the range 4 to 7 kW.
Requirements for heat transfer system	Depending on the water temperatures required by the building system, open loop systems can operate in cooling mode using a heat exchanger only, without the need for a heat pump. This improves energy efficiency as there is no additional energy requirement to power the heat pump compressor.	Closed loop systems almost always use heat pumps as the heat transfer mechanism.
Ability to handle annual imbalanced thermal load	Where open loop systems discharge to waste they can operate successfully with very unbalanced thermal loads, where heating or cooling demand dominates during the annual cycle. Where aquifer re-injection is used open loop systems work best where the annual total of heating energy and annual total of cooling energy are approximately balanced. If the thermal load is unbalanced there is a risk that warmer/cooler water from the injection boreholes will migrate to the abstraction boreholes (a phenomenon termed ‘thermal breakthrough’) which will affect system efficiencies.	Closed loop systems work best where the annual total of heating energy and annual total of cooling energy are approximately balanced. If the thermal load is unbalanced there is a risk of long term year-on-year changes in ground temperature which will affect system efficiencies.

Characteristic	Open loop systems	Closed loop systems
Potential for off-site thermal impacts	Where open loop systems discharge to waste, there is potential that that the discharge of warmer/cooler water to a surface water course will cause environmental impacts. Where aquifer re-injection is used advective flow of warmer/cooler groundwater over extended periods (typically several years) can potentially result in plumes of warmer/colder groundwater migrating off-site.	For many closed loop systems heat flux in the ground is predominantly by conduction. Resulting zones of ground heating and cooling migrate only slowly, reducing the risk of significant off-site thermal impacts.
Constraints on locating boreholes making up the ground element	Although open loop systems typically require relatively modest numbers of boreholes, it is preferable that boreholes be spaced as widely apart as practicable to minimize interference between boreholes. This is especially the case where aquifer re-injection is used, when the distance between abstraction and re-injection boreholes has a direct influence on the risk of thermal breakthrough.	Because of the large number of boreholes typically required for closed loop systems, and the need to arrange them on a grid pattern to maintain a minimum horizontal separation between boreholes, significant site areas may be needed to accommodate the borehole array.