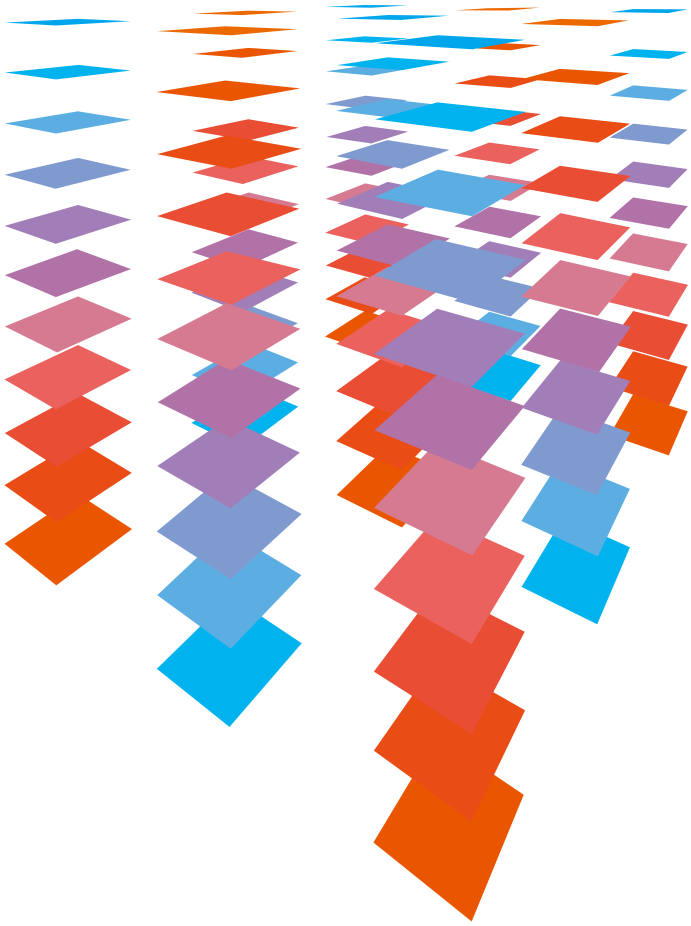
Buro Happold

Patterns

Ground Source Energy



Introduction

Welcome to this edition of Patterns, which focuses on ground energy.

For centuries many a fine wine has benefited from the stable environment afforded by a suitable cellar or cave, taking advantage of the great thermal capacity and inertia of the ground. With the advent of HVAC systems we have replicated this stable internal environment in our homes, work and leisure spaces, while interestingly the wine stays by and large underground!

Today, in a time where energy conservation is king, we find ourselves looking more closely at the temperature stability and thermal capacity of the ground as a source of free cooling and heating for our buildings.

Over the years we have developed a variety of techniques for coupling our buildings with the ground and exchanging heat back and forth between the two. The technology can take a number of forms using either water or air based systems.

As the drive to include a proportion of renewable energy into many public and private buildings increases, many see 'ground energy' as a viable means of energy conservation. At Buro Happold we have gathered a wealth of experience in these exciting techniques and have used the 'Geekfest' (see definition opposite) model to share and record this experience.

This sharing of experience is important as the process of design in this area is evolving fast. The thermal behaviour of the ground is a complex science which must be analysed in conjunction with the varying cooling and heating loads of the building and the characteristics of the HVAC system performance.

In the world of building design, prototypes are few and far between and solutions in a field such as this must be refined using solutions that at first are conservative and then are honed project by project as actual performance data is gathered. There simply is no substitute for experience!

We have split our discussion within Patterns into two areas, water and air based solutions – with the exception of Scott Baird's essay on the Burns Museum project which incorporates both earth tubes on the air inlet and a water based ground loop heat exchanger for heating/cooling.

Air based explores the use of thermal labyrinths and earth tubes.

Water based includes open loop ground water schemes and closed loop shallow (ground mat) and medium depth (piled) systems.

With water based systems used in conjunction with heat pumps for heating, or direct for cooling systems, it is also important to consider how such sources of heating and cooling are integrated with appropriate heating and cooling systems. This area is covered within a number of the essays contained in this edition of Patterns.

The topic of ground source heating and cooling is a fascinating one, being all the more rewarding as it fuses together Buro Happold's collective skills and experience in the fields of building services system design and analysis, ground engineering, sustainability and alternative technologies (SAT) and computational simulation and analysis (CoSA).

Geekfest:

A gathering of those engineers and consultants within Buro Happold who have specific experience in an area of growing importance to the firm and our industry. Held as a colloquium, all present must set out and discuss their relevant experience in terms of analysis, design, procurement, construction and post-occupancy evaluation. There are no spectators at a fest! By so doing, the gathering serves to share knowledge, educate others and close the all-important feedback loop to refine our analysis and design skills within a particular field.
The fest usually includes the opportunity to 'workshop' live projects at inception/feasibility stage to explore whether such technology can be successfully deployed.

PatternsGroundSourceEnergy

Ground energy options

When choosing liquid-based systems for ground source energy there are two main options – open or closed loop, and some variations. James Dickinson looks at the advantages of the approach and the key actions required.

Throughout the year the ground absorbs solar energy and below a depth of approximately 7-10m the temperature remains fairly constant at the mean ambient air temperature regardless of the time of year. Depending on the location and depth this temperature can vary, typically, from 7-13ºC in the UK. In general, the use of ground energy to provide heating and cooling in building requires equipment (heat pumps) to upgrade the temperature of the source temperature to a more useful temperature level using additional energy, see *figure 1* (opposite).

The energy can be transferred to this equipment using a ground heat exchanger (closed loop systems). This new science usually comprises a number of pipe loops, vertical or horizontal, with a primary process medium of water, or more normally a glycol solution which eliminates the possibility of freezing within the application's seasonal temperature range. The alternative is to abstract and discharge ground water (open loop systems) from an aquifer beneath the building.

In the case of the closed loop system the energy in the ground is, if the ground loop is sized appropriately, replenished by solar irradiation, rain and, sometimes, for deeper vertical collector systems, underground water flow. With open loop systems it is necessary to consider the sustainable yield available from the wells.

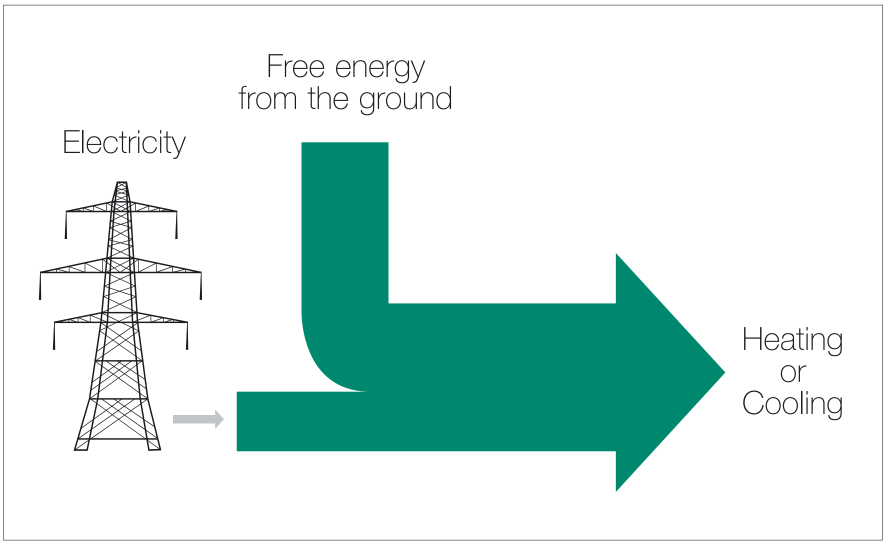


Figure 1 Heat pump technology

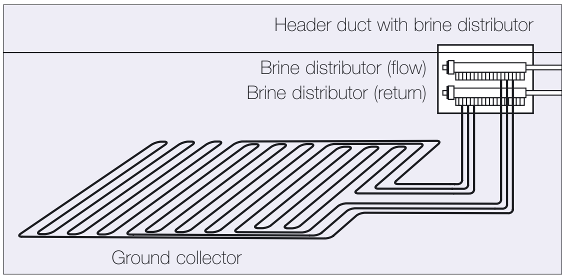


Figure 2 Horizontal closed loop system (Viessmann)

Variations of ground energy

Horizontal – closed loop

With this variation the energy or heat is transferred to the building using a series of ground collectors, laid horizontally at a depth of 1.5-2m, see *figure 2* (above). Each pipe run should be limited to 100m to avoid the need for more powerful circulation pumps. Pipe runs would normally be the same length to guarantee similar flow conditions, pressure drops and to ensure an even heat extraction from the ground.

The useable amount of heat or energy is dependent on the following:

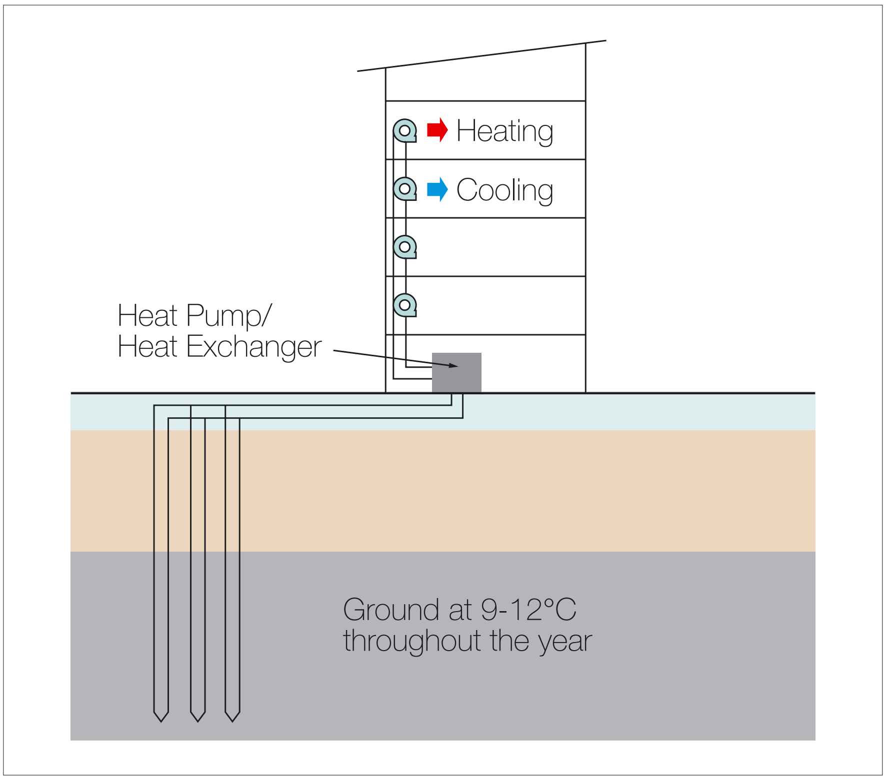
- Solar irradiation for the specific area
- Moisture content
- Soil type
- Size of pores.

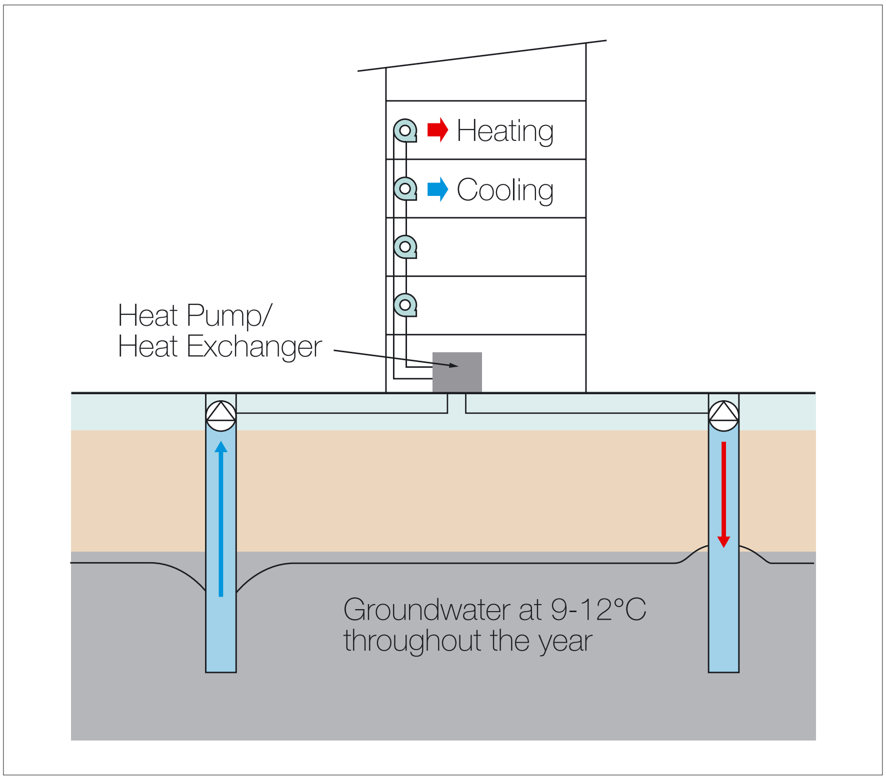
Extraction rates are generally in the order of between 10 W/m^2 for dry sandy soil, to over 30 W/m^2 for wetter loamy soils. Relatively inexpensive earth moving equipment is required for installation, although costs increase with greater depths. This type of collector is generally used for applications with lower power outputs where there is a large undeveloped area that is easy to excavate.

Vertical (probe) – closed loop

A vertical closed-loop system utilises vertical ground heat exchangers or probes that are inserted into specially drilled boreholes up to depths of 150m, see *figure 3 (*on page 3).

Extraction rates generally vary between 20 W/m for loose dry substrate to ~80W/m for damper sandstones, granites and basalts.





The useable heat or energy is dependent on similar factors to the horizontal system although more specialist geological analysis is generally needed. Deeper test-bores can ascertain the type and depth of each soil/rock layer, the heat transfer potential for the different layers over the length of the borehole, the presence and height of water table and underground water flow.

Due to the requirement for a test bore this type of system lends itself to larger applications where the initial testing costs can be justified. The data gathered help to reduce risk during the design stage as non-optimum sizing has serious cost implications.

Vertical – open loop

In this variation ground water is extracted direct from the underground water aquifer, eliminating the need for a closed loop ground heat exchanger. The used cooled or heated water can then be returned to the ground via a return well, see *figure 4*.

Prior to the consideration of such a configuration it is necessary to contact the Environmental Agency, initially to gain consent for a pumping test, and then for a final abstraction licence for a pumping test, and then for discharge consent. There is an additional requirement to consider the water quality of the water source as this can have an adverse effect on the materials used within the heat exchanger.

Figure 3 (top) Vertical closed loop system

Figure 4 Vertical open loop system

Feasibility and Evaluation

Generic guidelines for ground energy systems	
1	Start considering the technology at an early stage in the project.
	Complete a ground energy desktop survey to establish the suitability of the geology and hydrogeology underneath the site to different types of ground energy systems. Suitable sources include the British Geological Survey and site specific Geotechnical Investigation reports.
	Establish the spatial limitations around the building.
	What is the indicative foundation design and is it suitable to act as part of the ground energy heat exchanger?
2	Optimise the heating and cooling building circuits.
	Use high temperature cooling where possible (eg chilled beams and air based systems with over sized heat exchangers).
	Use low temperature heat emitters (large radiators, underfloor heating and air based systems with over sized heat exchangers).
	Simultaneous heating and cooling can be provided from the same heat pump unit.

Closed loop dos	
1	For larger commercial systems, ie greater than ~100kW, a thermal conductivity test is advised to confirm the insitu thermal properties.
2	Carry out a desktop simulation using recognised software to ensure the long term performance can be guaranteed.
3	Ensure boreholes are spaced adequately to reduce thermal interference.
4	Try to balance heat abstraction and rejection to the ground.
5	Consider using less expensive conventional plant for infrequent heating and cooling loads and/or higher relative seasonal heating and cooling loads.

Open loop dos	
1	For almost all open loop systems Environment Agency (EA) approval is needed for both abstraction and discharge of ground or surface water.
2	A pumping test will be needed to confirm the yield and to get permission from the EA to abstract and discharge a specified volume of water per hour/day/year.
3	Start the process to obtain an abstraction licence and discharge consent as early as possible (this process can take from eight to nine months in the UK).

Closing the loop

In this report Alan Shepherd describes the need for dynamic thermal modelling of Closed Loop Geothermal Heat Pump (CLGHP) systems. He looks at the various CLGHP system permutations and how they are applied and outlines the relative merits of the analysis tools available.

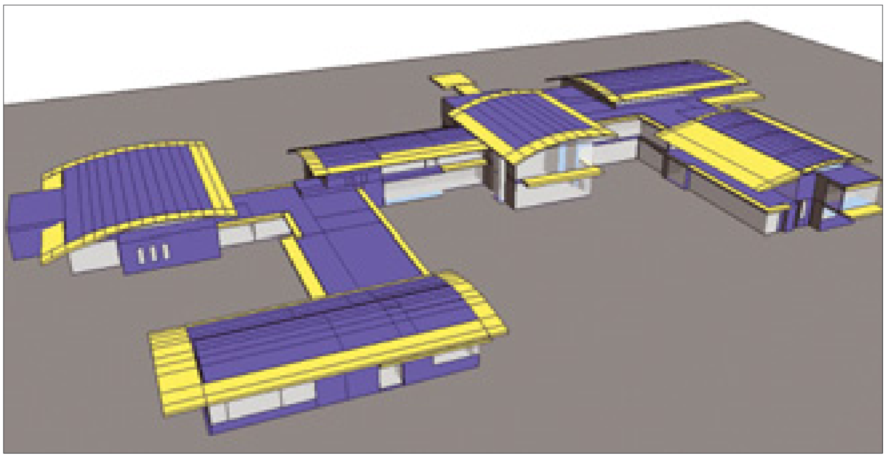


Figure 1 3D rendering of an IES building model

Why dynamic thermal modelling is so vital to CLGHP system design

A 'traditional' gas fired boiler and vapour compression chiller based HVAC system design can be sized with a reasonable level of confidence simply by determining the peak heating and cooling load of a given building. This is not the case for CLGHP systems. The heat source and sink for a CLGHP system is the rock and earth that surrounds the ground loops. Over the course of a year the ground temperature varies sinusoidally as heat is either rejected into the ground (cooling operation) or abstracted from the ground (heating operation).

The operating efficiency of a heat pump depends largely upon the temperature differential between the source-side entering water temperature from the ground loops and the system-side (CHW/LTHW) water temperature. The smaller the temperature differential, the more efficiently the heat pump will operate. To understand the seasonal efficiency of a CLGHP system it is therefore necessary to be able to simulate the seasonal variation in the ground temperature surrounding the geothermal loops.

Furthermore, it is important that there is a reasonable balance between the total annual heat energy rejected into the ground and that abstracted. A significant imbalance will result in the gradual increase in ground temperature over successive years in the case of a cooling dominated load profile, or a gradual decrease in temperature for a heating dominated load profile.

An increase in ground temperature over successive years will eventually result in a drop in heat pump cooling efficiency (as the differential between geothermal water and CHW temperature increases) as well as a reduction in heat pump cooling capacity and vice versa for heating operation.

CLGHP simulation process

The following steps describe a methodology that was used by Buro Happold to develop an in-house CLGHP analysis tool. The methodology lends insight into the factors that affect CLGHP performance and also exposes some of the internal workings of alternative commercially available CLGHP analysis tools on the market.

Step 1: Generating annual heating and cooling load profiles

The first step in simulating the performance of a CLGHP installation is to establish the annual heating and cooling load profiles. Deriving accurate annual heating and cooling load profiles requires the use of sophisticated simulation tools used in conjunction with realistic estimates of dynamic occupancy, lighting and equipment loads.

For peak load analysis occupancy, lighting and equipment loads are often assumed to be at a constant peak – this is of course highly unrealistic and, if used for annual energy analysis, will result in a gross over-estimation of cooling energy consumption and an equal under-estimation in heating.

Engineers should exercise caution in the use of the more basic Dynamic Thermal Modeling (DTM) software that is available on the market. *Figure 1* (above) shows a 3-dimensional rendering of a building model generated using IES DTM software.

It is also important that the DTM accurately models the HVAC system and controls. The use of generic system templates can result in significant inaccuracies and should be used with caution. *Figure 2* is an excerpt from a system model generated in ApacheHVAC that incorporates an air-side economiser, cooling coil with wrap-around heat pipe, evaporative humidifier with face and bypass dampers, along with all associated controls. *Figure 3* graphically displays the full hour by hour heating and cooling load results calculated by IES for the building and system model shown in *figures 1* and *2*.

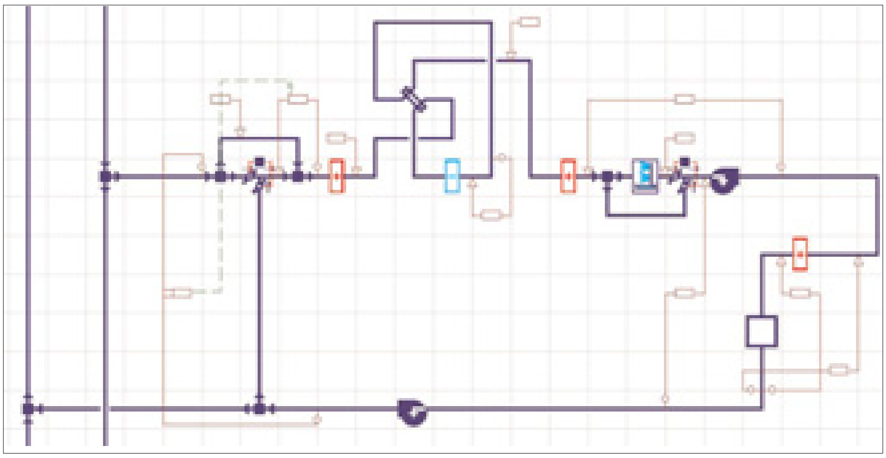


Figure 2 An excerpt from an HVAC system simulation model using IES ApacheHVAC software

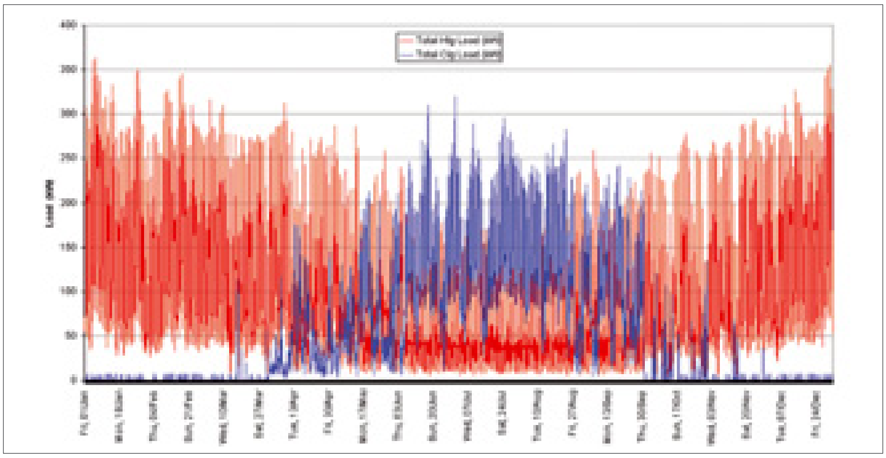


Figure 3 Annual heating and cooling load profiles – hourly data

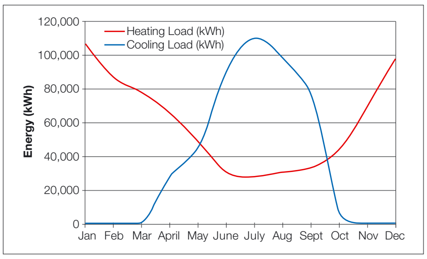


Figure 4 Annual heating and cooling load profile – monthly data

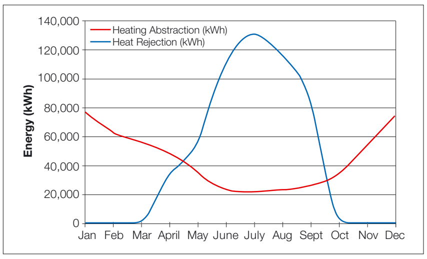


Figure 5 Annual heat of abstraction/ rejection profile – monthly data

Step 2: Calculating the abstraction and rejection of heat between the heat pumps and the bore field

Having derived the annual heating and cooling load profiles of the HVAC system, the next stage in the analysis is to calculate the abstraction and rejection of heat from and to the geothermal bore field.

When in heating mode the heat abstracted from the ground ($Q_{\textbf{Abstraction}}$) is calculated as follows:

$$Q_{\textbf{Abstraction}} = Q_{\textbf{Heating}} - Q_{\textbf{Compressor}}$$

where $$Q_{\textbf{Compressor}} = \frac{Q_{\textbf{Heating}}}{COP_{\textbf{Heating}}}$$

When in cooling mode the heat rejected to the ground ($Q_{\textbf{Rejection}}$) is calculated as follows:

$$Q_{\textbf{Rejection}} = Q_{\textbf{Cooling}} - Q_{\textbf{Compressor}}$$

where $$Q_{\textbf{Compressor}} = \frac{Q_{\textbf{Cooling}}}{COP_{\textbf{Cooling}}}$$

The calculation of the heat of abstraction and rejection creates a ‘chicken and egg’ situation as it requires that the operating COP of the heat pumps be known. However, the heat pump operating COP can only be determined from knowledge of the geothermal bore field temperature which, in turn, is calculated from rates of heat abstraction and rejection. The problem is circular. In order to break this stalemate it is necessary to make an initial estimate of heat pump operating COP. *Figure 4* above shows the annual heating and cooling load profile (from *figure 3*) displayed in monthly ‘bins’ for clarity. *Figure 5* shows the heat of abstraction and rejection.

Noticeably apparent when comparing the two graphs is that the relatively balanced heating and cooling load profiles displayed in *figure 4* actually result in an imbalance in heat exchange with the bore field, with the heat of rejection dominating over the heat of abstraction. The simple reason for this is the fact that the heat emitted by the compressor assists the heat pump when in heating mode, but hampers performance in cooling mode.

Step 3: Sizing the geothermal bore field

Having calculated the annual heat of abstraction and rejection, the annual variation in the temperature of the geothermal bore field can be determined. The relative capabilities of available CLGHP analysis tools will be discussed later in the report; however, for this particular analysis GS2000 was used. The input data required by GS2000 and other CLGHP sizing software is broadly similar; requiring the user to define the following:

- Bore field configuration (vertical, horizontal etc)
- Ground temperature properties
- Ground layer description (depth, material properties etc)
- Ground heat exchanger pipe properties
- Geothermal circulation fluid properties (ethylene/propylene glycol etc)
- Heat pump details (peak capacity, COP etc)
- Abstraction/rejection heat loads.

There are no hard and fast rules that govern the sizing of a geothermal bore field, although heat pump manufacturers recommend that bore field leaving water temperature should not be allowed to stray outside a minimum of 5°C and a maximum of 32°C.

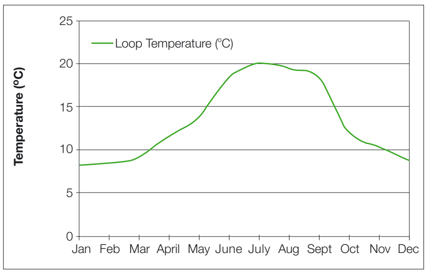


Figure 6 Annual geothermal bore field leaving water temperature profile – monthly data

For the annual abstraction and rejection heat loads displayed in *figure 5*, and with minimum and maximum leaving water sizing limits of 8°C and 30°C respectively, GS2000 calculated an annual leaving water temperature profile as shown in *figure 6* and a required borehole length of 9097m (72 bores, each 128m deep).

Step 4: Establishing heat pump COP and peak capacity

Having established the annual geothermal bore field leaving water temperature profile, it is possible to determine the annual variation in heat pump operating COP as well as the variation in peak heat and cooling capacity. *Figures 7* through to *10* (right) were derived using manufacturer's data for a Climate Master WW360 water/water heat pump. *Figures 7* and *8* show the relationship between entering geothermal water temperature (source temperature) and COP. *Figures 9* and *10* show the relationship between entering geothermal water temperature and peak heating/cooling capacity.

Using the expressions given in *figures 7* and *8* in conjunction with the annual bore field leaving water temperature profile given in *figure 6* it is now possible to derive the annual variation in heating and cooling COP as shown in *figure 11* on page 8.

Using the expressions given in *figures 9* and *10* in conjunction with the annual bore field leaving water temperature profile also allows us to derive the annual variation in peak heating and cooling capacity of an individual heat pump as shown in *figure 12* on page 8. This allows us to determine the maximum number of heat pumps required and also how the number of on-line heat pumps varies over time – a key factor in determining the parasitic pump power associated with the system.

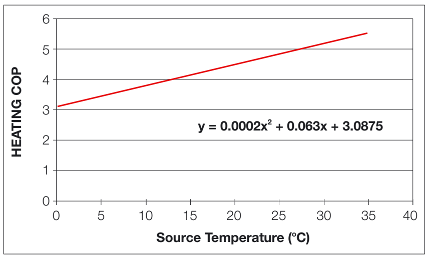


Figure 7 Relationship between heating COP and entering source water temperature

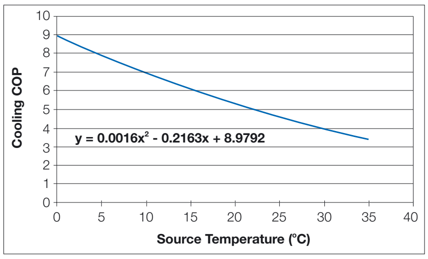


Figure 8 Relationship between cooling COP and entering source water temperature

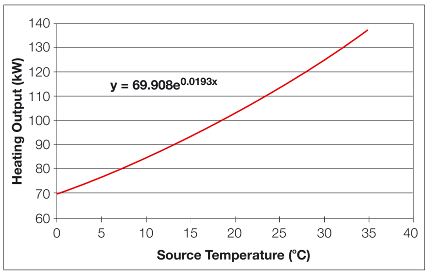


Figure 9 Relationship between heating capacity and entering source water temperature

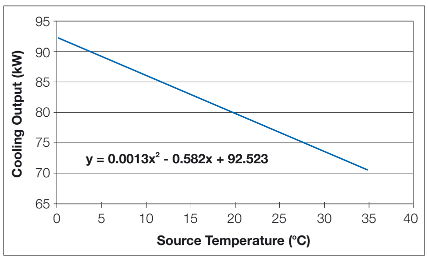


Figure 10 Relationship between cooling capacity and entering source water temperature

In Step 2 of the analysis methodology the necessity to estimate initial COP values was discussed. Having completed the first iteration of the analysis and derived a complete annual variation in COP (*figure 11*), these values should now be plugged back into Step 2 of the analysis in order to obtain more accurate heat of abstraction and rejection figures. This iterative procedure should be repeated until such time that the COP values entered in Step 2 match those calculated in Step 4.

Step 5: Parasitic Loads

When conducting a comparative analysis of potential heating and cooling plant options it is essential that the parasitic loads (pump power, cooling tower fans etc) associated with each option are accounted. The Buro Happold in-house CLGHP analysis tool incorporates a parasitic load calculation spreadsheet. Depending upon whether a constant or variable speed pumping strategy is implemented the contribution of parasitic loads to the overall CLGHP system energy consumption can be significant. *Figure 13* opposite shows the annual variation in Geothermal, CHW and LTHW pump energy consumption.

Step 6: Comparative Analysis

In order to gain some relative perspective on the performance of a CLGHP it is, of course, necessary to obtain comparative data for alternate heating and cooling system options. Ideally that data should be derived from the same annual heating and cooling loads used in the analysis of the CLGHP. The Buro Happold in-house analysis tool includes two alternate system options; air cooled chiller and water cooled chiller. Either option can be coupled with a gas, oil or LPG fired boiler. The results of a typical analysis are shown in *figures 14* through to *16* on page 9.

Imbalanced annual heating and cooling loads

The simulation process described in the previous section uses as its example a somewhat idealised scenario in which the annual heat of abstraction is almost exactly equal to the annual heat of rejection. This results in an annual geothermal leaving water temperature profile that starts on 1 January at 8°C and ends on 31 December at the same 8°C (see *figure 6*). It is infrequently the case that a building will exhibit such a fortuitously balanced heating and cooling load profile.

Heating dominated loads

Figure 17 on page 10 shows an annual heating and cooling load profile that is heavily heating dominated. This imbalance will result in a far greater quantity of heat being abstracted from the ground during the heating season than is replenished during cooling. As is clearly shown in *figure 18* this results, over successive years, in a gradual drop in the temperature of the earth surrounding the geothermal bores.

The drop in leaving water temperature from the bore field will be accompanied by a gradual drop in heating COP (see *figure 19*) and a consequential increase in operating costs. The peak heating capacity of the heat pumps will also gradually fall.

The drop in earth temperature will actually improve the cooling COP of the heat pumps. However, since the load profile is so heavily heating dominated, the reduction in annual cooling energy consumption is relatively insignificant compared to the increase in heating energy.

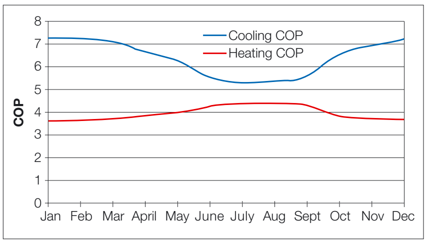


Figure 11 Annual variation in heat pump COP – monthly data

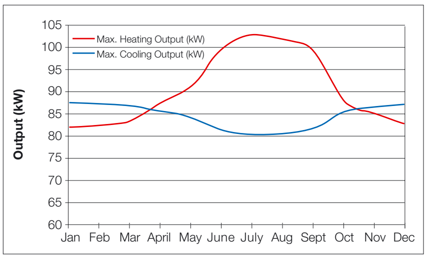


Figure 12 Annual variation in peak heating and cooling capacity – monthly data

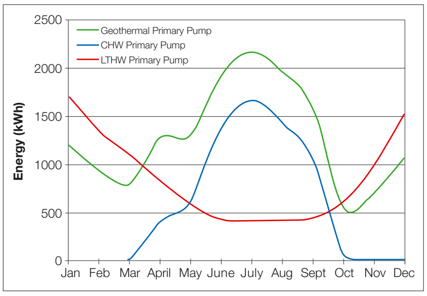


Figure 13 Annual circulation pump energy consumption – monthly data

Cooling Dominated Loads

The impacts of a heavily cooling-dominated load profile are fundamentally similar but in reverse. There is a gradual rise in earth temperature over successive years, and consequential reduction in cooling COP. The increase in earth temperature and the reduction in COP are non-linear. As the temperature of the ground increases the heat loss to its surroundings also increases. Furthermore, at higher geothermal leaving water temperatures the quantity of heat rejected into the ground will begin to level off as the heat pumps are no longer able to meet peak cooling load requirements. The result of these phenomena is that the mean annual earth temperature will eventually reach a balance point: in one recent simulation this was reached after approximately 12 years of operation.

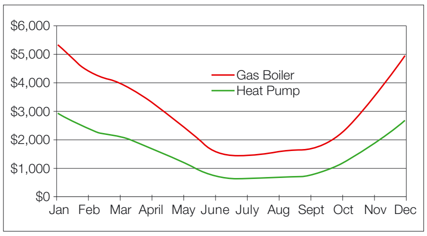


Figure 14 Comparative system heating energy cost profile – monthly data

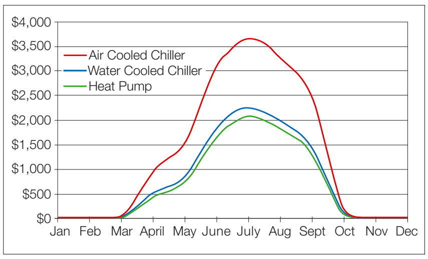


Figure 15 Comparative system cooling energy cost profile – monthly data

Despite the negative impacts described above, an imbalanced load profile need not preclude the use of a CLGHP system. Described under the following headings are various mitigating measures that can be taken when dealing with imbalanced loads.

Increase the size of the geothermal bore field

A 'solution' that is often proposed when faced with the problem of imbalanced heating and cooling load profiles is to increase the size of the geothermal bore field. This is a costly option and not the most effective. An increase in the size of the bore field does nothing to address the imbalance in load, it merely slows down the inevitable increase/decrease in earth temperature.

Load shifting by modifying the MEP system design

A far more effective approach is to purposefully manipulate the heating and cooling load profiles by modifying the MEP system design.

For example, a cooling dominated load profile can be brought back into balance, at least in some part, by making a design change from electric resistance humidifiers to evaporative type.

Bivalent systems – load side

Imbalances in annual heating and cooling load can also be addressed by sizing the CLGHP system to meet a base load, while top-up boilers and/or chillers are used to meet peak load requirements. This dual approach is commonly referred to as a 'bivalent system'.

Aside from load balancing purposes a bivalent system design approach often results in the optimum payback period for a CLGHP installation. The problem with a bivalent approach is that it requires the reintroduction of equipment such as chillers, cooling towers, flues etc, the elimination of which may have been one of the drivers for selecting a CLGHP system in the first place.

Bivalent system – source side

An alternative bivalent system approach to the problem of imbalanced loads is to target the source side of heat pumps rather than the load side. This means that the heat pumps provide 100% of the heating and cooling load but that the geothermal bore field is supplemented in dealing with the heat of abstraction and rejection.

An example of this approach (shown in *figure 20)* is for a cooling dominated load profile the heats of abstraction and rejection from and to the bore field can be put into balance by rejecting a portion of the heat via the cooling tower.

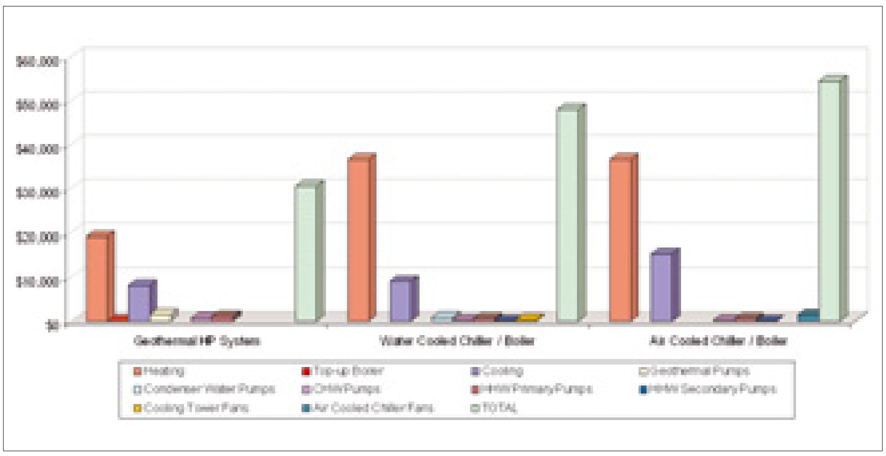


Figure 16 The three systems – annual energy cost comparison

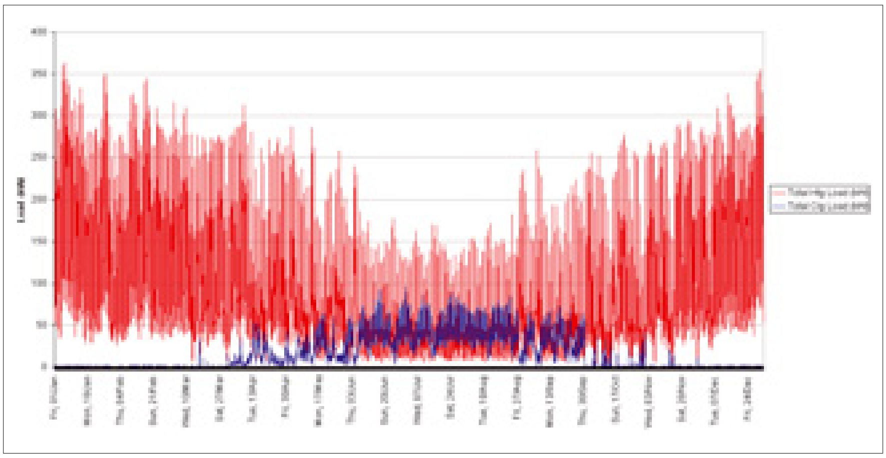


Figure 17 Heating-dominated annual load profile – hourly data

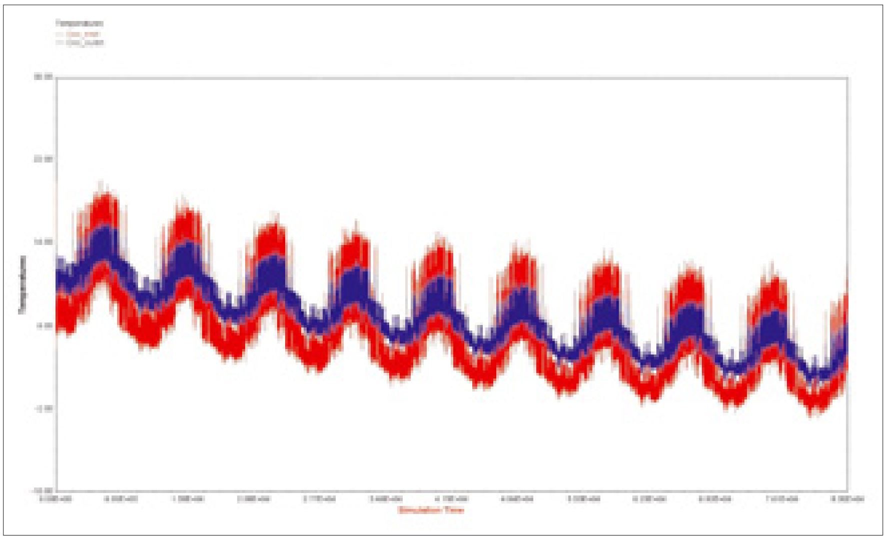


Figure 18 Geothermal inlet and outlet water temperature – 10 year simulation

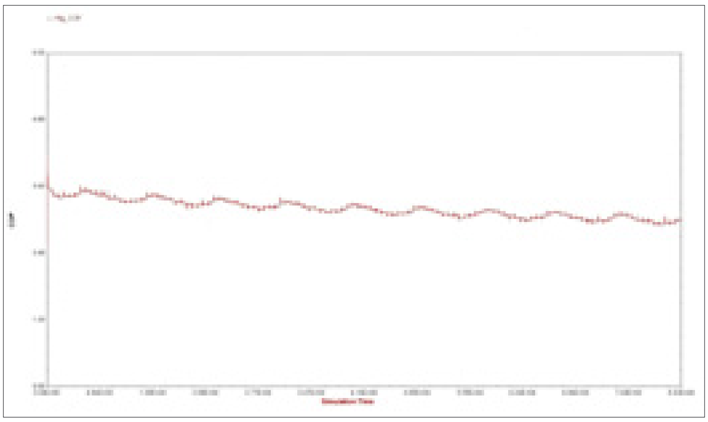
In addition to summer time heat rejection operation, a cooling tower can help to balance a cooling dominated load profile by operating during winter. Running the tower during the winter effectively imposes a 'false' heating load on the bore field, pre-cooling the earth surrounding the geothermal bores and thereby reducing temperature rise during summer.

For heating-dominated load profiles a similar balancing effect can be achieved using a bivalent system approach whereby solar thermal collectors impose a false cooling load during summer.

Overview of CLGHP analysis tools

Buro Happold currently uses the following CLGHP modeling tools:

- In-house spreadsheet in conjunction with GS2000
- GLHEpro
- Trnsys 16.



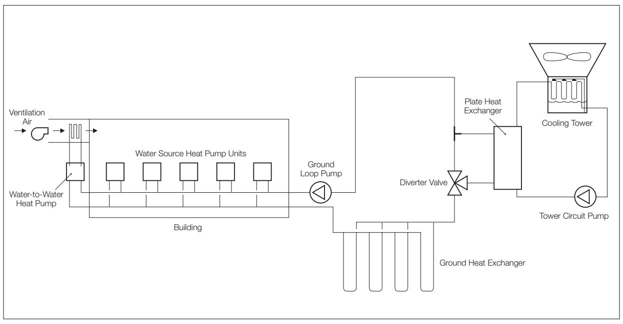


Figure 19 (left) Geothermal heat pump COP heating – 10 year simulation

Figure 20 (above) Bivalent CLGHP system with supplementary heat rejection

Massive Milanese scheme uses ground water cooling/heating

Buro Happold is providing M&E engineering design on the groundbreaking Garibaldi project in Milan. Steve Williamson explains how this scheme has become a prime example of a large scale commercial project responding to demands for low carbon buildings.

The Garibaldi development, Milan

With around 200,000m^2 of mixed use, predominantly office space, the Garibaldi project meets all the requirements of a world class commercial centre. Moreover, despite value-adding features such as highly-glazed facades, full air conditioning and a sound commercial approach, the project aims to achieve a gold LEED rating.

The buildings have a combined peak cooling demand of 18MW along with 12MW of heating demand, all of which will be provided by an open loop ground water heat pump system. Combined with Varasene, its sister project of a similar scale across the road, and by the same developer, it is believed that this is one of the largest ground water schemes in the world.

Alpine sourced ground water

Early design studies identified an ideal opportunity to make use of Milan's cool ground water fed from Alpine melt water en route to the Mediterranean. This was well received by the local authorities, who are most concerned with the increasing smog created by local gas emissions from inner city buildings.

The key to making the scheme viable is the proximity of the Martesana River that passes underground through the site. The combination of heat pumps and open well ground water discharging into the river actually costs less than a conventional chiller, boiler and cooling tower combination.

The project has been designed with 12 boreholes, each capable of providing 35l/s (litres/second) of ground water. The buildings are provided with reversible heat pumps to generate both heating and cooling.

Mechanical plant

The principle of ground water cooling is a simple, low energy alternative to conventional heating and cooling plant utilising boilers and cooling towers. The system takes advantage of constant temperature water (circa 12ºC) from deep boreholes, which is used to pre-cool air into air handling units, and to provide heat rejection for the chillers. The use of ground water for pre-cooling of ventilation air will be a direct energy saving, and using the ground water for heat rejection will improve the seasonal coefficient of performance (COP) of the heat pumps to around 6.5, thus giving further energy savings in both heating and cooling. A schematic of this system is indicated in *figure 1*.

The primary equipment deemed most suitable to take advantage of the ground water is a refrigerator/heat pump such as the 'frigorifero polivalente'.

A simple schematic is shown in *figure 2*. These heat pumps will simultaneously produce hot water (LTHW at 50°C) and chilled water (at 7°C), and are able to utilise the ground water for heat rejection.

As a result of the heating and cooling of the building, in winter the ground water will be cooled by the heat pumps from 15°C to approximately 7°C. In summer, it will be heated from 15°C to approximately 30°C. After passing through the heat pumps, this rejection water will then be pumped locally into the Martesena River. The quantity of water must be such that the temperature of the river is not increased by more than 3°C, measured from a point 5m upstream and 5m downstream from the area of discharge.

The system produces hot and chilled water with high efficiency, minimum noise and without local CO_2 emissions.

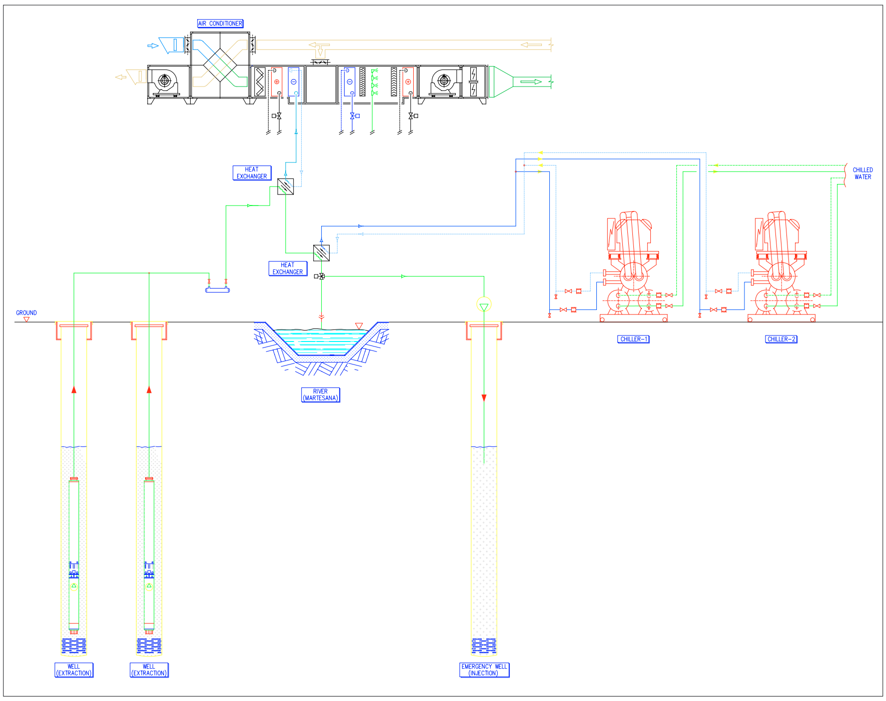


Figure 1 General ground water scheme

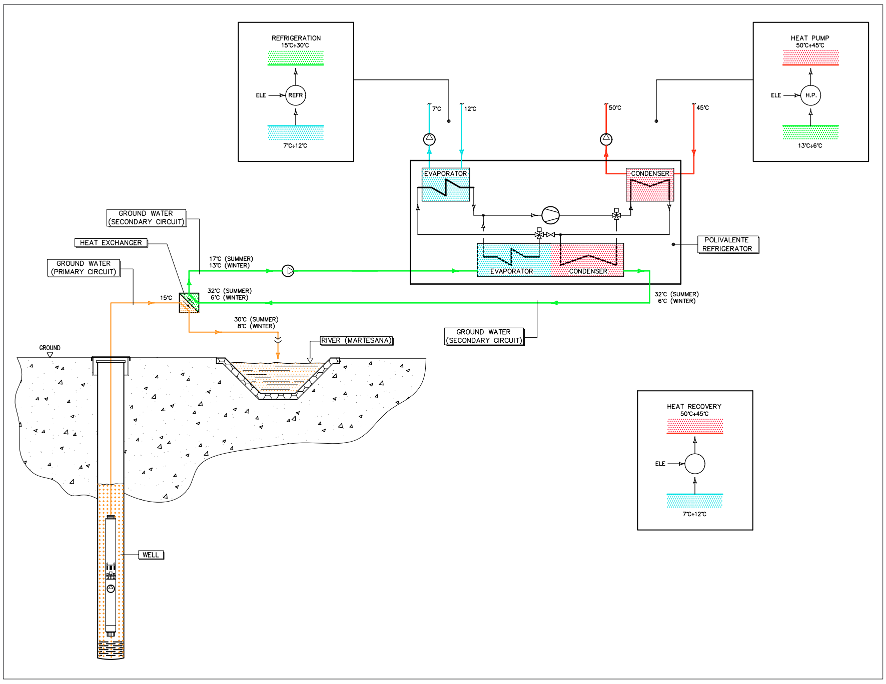


Figure 2 Frigorifero polivalente scheme

It has been agreed that the building will be designed with spatial allowance and facilities for conventional plant (boilers and cooling towers) to be installed in the future. Correctly sized pipes will be installed in the risers, allowing for easy future connection from roof cooling towers and boilers.

Ground water extraction

Ground water will be extracted from the 12 wells or boreholes located within the basement. The preliminary proposed positions of these are indicated in *figure 3*. Each well will have a nominal flow of 35l/s and will be served by two pumps (duty and standby) that supply a basement-wide distribution main, providing a maximum flow of 420l/s.

The ground water flow rate to the heat pump will vary between the minimum water flow required by the heat pumps and maximum demand in peak summer. Therefore, the ground water distribution main will be a variable volume pumping system, to guarantee the minimum pumping energy and cost.

Water pumped from the wells will be mechanically filtered prior to passing through heat exchangers. Two heat exchangers will be installed for each building (100% duty and 100% standby) and will be accessible for cleaning. When a heat exchanger is shut down for cleaning, the second heat exchanger will provide all the necessary duty for full load operation. In this system, ground water never goes directly into the heat pump condenser/evaporator, thus preventing potential problems with respect to dirt and deposits.

In *figures 4* and *5* the typical extraction well with all necessary components is shown. Each well will be accessible from the top to provide maintenance and control operations. Note that the position of each well has been estimated with a minimum separation distance of 70m.

Well extraction will also relieve ground water levels under the site, thus avoiding potential problems generated by the waterbed level increase recently registered in Milan. The waterbed level will be monitored by piezometers.

Ground water discharge

Ground water used by heat pumps will be discharged in the Martesana River located under Via Melchiorre Gioia. The Martesana River runs into the Redefossi River and then flows out of Milan to the south. The ground water is 'clean' and so may improve the water quality in these rivers which provide irrigation water for agriculture in the south Milan fields, where rice is grown.

The structural work associated with the ground water system will include a run-off pit which will enable the authorities to measure flows, and to gain water samples for laboratory analysis. Within this run-off pit, all pumped discharge pipes from each building will terminate, and accumulated discharge water can then flow by gravity into the river. A check valve will be installed to prevent a backflow of water from the river in flood conditions. This system will be designed to discharge at the maximum flow of 420l/s.

In all circumstances, according to Italian Law 152/99, the limit for the maximum increase in water temperature in the river is 3°C. Temperatures before and after the discharge point will be measured at a midpoint of the river, 5m before and 5m after the discharge point. This limit must be respected regardless of the rate of flow in the Martesana.

Emergency discharge

The Martesana River comes from the west of Milan and, before the Garibaldi area, there is a confluence with the Seveso River. Due to the natural flow of water from the Seveso River the flow rate cannot be controlled. Therefore, in the position near the Garibaldi area, the Martesana will never be dry (the estimated minimum flow is 1m^3/s). Therefore, flooding cannot be ruled out. To help improve the situation, the municipality is considering the creation of an artificial river (canal) to help attenuate flood water at such critical times. However, there is no official data available from the authorities indicating the potential scale of floods and their frequency during the year.

To ensure a robust solution for the Garibaldi site, an emergency system is proposed that will allow the system to work even if ground water cannot be discharged into the Martesana River.

Potential solutions include:

- Injection wells
- A large volume tank to attenuate flow
- Using water from the river as a heat sink instead of ground water during floods.

The best option in terms of reliability and feasibility is to utilise the injection wells system. In studying this system (assuming the nominal water flow of each well for injection in the ground is 35l/s like the extraction well), five injection wells are needed. Therefore, from the total 12 wells, six will be used for extraction and six for rejection. Hence, this system cannot discharge the maximum design ground water flow of 420l/s, but only half of it. However, it is most unlikely that the building plant will be required to operate at peak output (normal peak is high summer) during a Martesana flood (normally in winter or mid-season). The design must carefully consider the risk of ground water 'short circuit', to avoid extract water being discharged directly into an adjacent well used for abstraction.

It is also possible to take further mitigating steps if the required power is likely to be greater than the 50% available. This includes programming building management systems to reduce demand by switching off systems such as humidification/dehumidification, reducing external airflow and other measures.

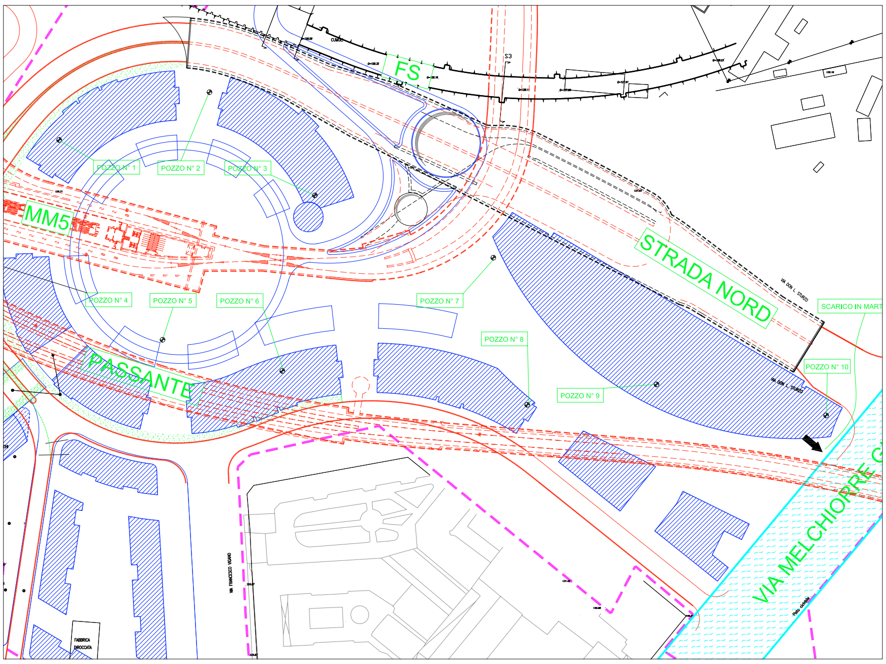


Figure 3 Extraction wells position

Other uses

Ground water may also be considered for other applications in the locality. The most important one is irrigation water for the campus (about 48,000m^2 of green park near the Garibaldi area). The water may be stored in a tank during the day and discharged on the campus overnight.

The proposed well positions are indicated in *figure 3*. The authority responsible for ground water extraction is the Provincia di Milano. Our local engineering partners, Ariatta, had initial meetings with the authority in September 2005, regarding management of the discharge in the river from the pollutants' point of view and managing the extraction of water from the ground.

Approval process

It is the approval process which is often cited as the most difficult hurdle for open loop ground water schemes, and Garibaldi was no different. The process is concerned with two aspects; approval for the ground water extraction and approval to discharge into the river.

The extraction approval required an initial request for permission to drill the wells. Once accepted, this aspect was given a time limit of one year.

To help to understand the effects of our proposed extraction on the local waterbed, it was necessary to undertake a mathematical simulation and desktop study. A laboratory analysis of ground water quality extracted from the first test wells (there were three across the site) was submitted, to ensure that the concentration of particulates was acceptable for discharge into a river (law 152/99). Finally, an impact study of the waterbed in the area (Garibaldi, Varesene, new building of Regione Lombardia) was also provided.

The approval process for the discharge in Martesana was more complex and created the biggest risk. There were many parties involved, and each had to be consulted individually and then together in a joint meeting, in order to agree a way forward.

The owner of the water in the Martesana River near the Garibaldi area is the Consorzio Villoresi. The party responsible for the structure under the road adjacent to the site, Via Melchiorre Gioia, that contains the river, is the Comune di Milano. They in turn let the management of the river to the Metropolitana Milanese (Servizio Idrico Integrato).

The initial agreement for discharge was granted by the Consorzio Villoresi. However, this also had to be ratified by another body, the 'Consorzio Navigli Lombardi', who would be taking over responsibility for the river from 1 January 2006.

The client is still not clear as to the fee for discharge into the river. However, they are protected by the local law, DGR 1/08/2003 7/13950, which should ensure that it is a nominal amount. The client has taken a view that the financial risk is low, but has asked us to design a building which can be easily retrofitted with cooling towers and boilers, should the future users be held to ransom.

The project is not yet cut and dried but all approvals are in place. The civil engineering has now begun, and the buildings were tendered in August 2007 with the ground water scheme intact.

Client: Hines

Architect: Pelli Clarke Pelli Architects, Adamson Associates, Tekne

Services: Building services, LEED environmental consultancy.

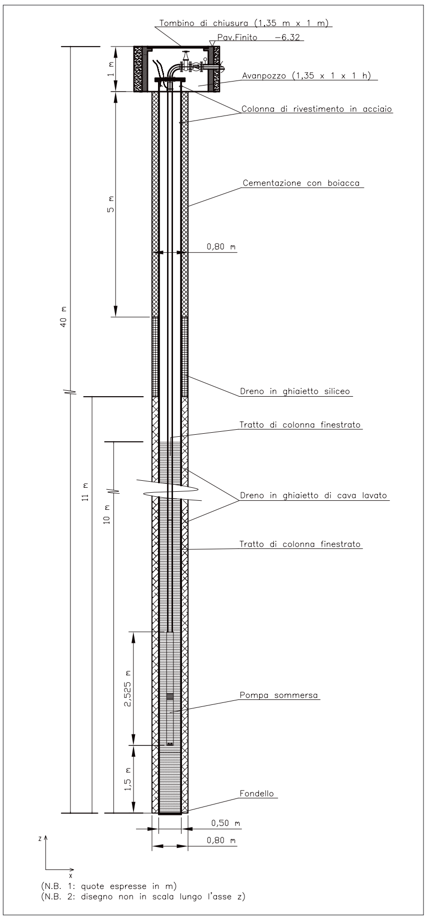


Figure 4 Typical extraction well

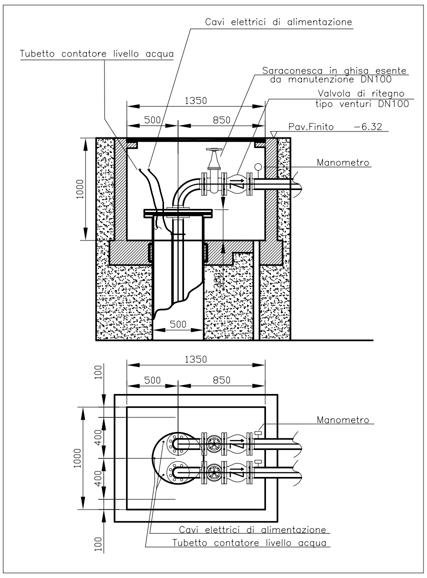


Figure 5 Typical extraction well detail

To bore or not to bore?

The refurbishment of the Royal Shakespeare Theatre in Stratford-upon-Avon is a great opportunity to create a high profile, low energy building. One of the key techniques will be ground coupling via a ground source heat pump. Mark Owen explains the design decision and its execution.

The refurbishment of the Royal Shakespeare Company's theatres provides an opportunity to investigate alternative energy sources such as closed loop ground sourced heat exchangers

As part of the transformation of the Royal Shakespeare Company's theatres in Stratford, the design team set itself a strict energy/carbon emissions strategy, with the intention of reducing overall carbon emissions from the redeveloped site by some 20%.

To achieve the target carbon emissions, a number of solutions for the energy saving, energy sourcing and generation were investigated:

- Combined heat and power (CHP)
- Site-wide energy loop
- Site-wide power network
- Improving the building fabric
- Heat recovery and improved control of the building services and environmental systems
- Ground source heat pumps (GSHPs).

During the Stage C design development, due to a combination of budget and site constraints, the possibility of utilising a CHP system and site-wide energy loop were discounted, along with the site-wide power option.

A study into the performance of the building fabric was undertaken. However, as a significant amount of the building's existing fabric is listed and, therefore, cannot be thermally upgraded, there were limited opportunities to enhance the overall performance.

To achieve the target carbon emissions reduction would require improving the performance of the building services systems, both in terms of efficiency and operation. This led to the focus on a ground source heat pump (GSHP) system as a low-cost, low carbon-emitting heating and cooling option, along with the introduction of improved control systems, monitoring and heat recovery systems.

Ground response test

A previous desk study, completed in August 2005, outlined the potential for a GSHP at the site. The study concluded that the local geology was thought to be well suited to the technology and the extra capital cost could be justified by the anticipated reduced operating costs and carbon emissions. Buro Happold advised that a Ground Response Test be carried out to ascertain the exact insitu thermal properties of the ground, prior to taking this approach further. The test was carried out in January 2006 and a single borehole was drilled to a depth of 125m in the corner of Theatre Gardens adjacent to the Swan Theatre. A summary of the results can be found in *figure 1*.

The most important parameter required for a GSHP system is the soil thermal conductivity. This reflects the rate of heat transfer to and from the ground, and forms the basis of calculating the system's performance. The actual test result of 1.69W/mK, while being slightly lower than the 1.9W/mK level indicated in the desk study, was still acceptable for use with a GSHP system. The soil thermal capacity and far field temperature results were also within the limits acceptable for the installation of a GSHP system.

Ground source heat pump system capacity

IES Thermal models of the Royal Shakespeare Theatre (RST) and Swan Theatre have established that the buildings will require the building services systems to cater for the following peak loads:

- Cooling: 350kW
- Heating: 1200kW

The test results from the borehole indicate that the size of well field to cater for the required peak heating load would exceed land that is currently in the ownership of the RSC.

Theatre Gardens to the south-west of the RST/Swan was identified as the preferred location for the well field or ground loop heat exchanger (GLHE). The area has the potential to cater for 65 to 70x125m-deep, closed loop vertical boreholes, each rated at around 5kW, spaced at between five and six metres (see *figure 2*). It will deliver a base load of around 350kW, in either heating or cooling mode. Although potentially catering for the entire cooling load (eliminating the need for chillers) it would clearly require additional plant for the peak heating load (*figure 3*).

IES dynamic analysis

Due to their operational profiles, theatre buildings traditionally encounter large peak loads for relatively small proportions of the day and then fall back to a base condition. Dynamic thermal models of the buildings established daily/monthly load profiles and these have been utilised to generate a more accurate assessment of the operation and integration of the GSHP system.

The estimated heating and cooling profiles for the 350kW GSHP system, in conjunction with the dynamic heating and cooling loads, are detailed in *figures 3* and *4* respectively.

The results concluded that, although a 350kW GSHP system may only be capable of providing approximately 30% of the peak heating load, it would be capable of delivering approximately 76% of the building's total yearly heating/cooling requirement and thus reduce the operation of the supplementary heating systems to 'peak lopping'. The GSHP is capable of providing the entire cooling load of the RST/Swan and the proposed GSHP system design enables heating or cooling at the same time, but with cooling taking precedence.

In early spring and late autumn, when there may be a requirement to both heat and cool the building at the same time, if the cooling load was small it could result in inefficient running of the system. However, the main cooling loads are associated with the air systems and it is, therefore, anticipated that during this period the free cooling potential of the external air will be utilised, reducing the cooling requirement.

Operational savings

The dynamic thermal models make it possible to assess the system's operational costs and the pay-back period for savings achieved, by utilising the 350kW GSHP system in conjunction with the top-up systems.

Parameter	Value	Range
Soil thermal conductivity (W/mK)	1.69	1.66 – 1.72
Soil thermal capacity (MJ/m³K)	2.19	1.95 – 2.58
Deep far field temperature (°C)	10.0	9.5 – 10.5
Groundwater effect	no	

Figure 1 A summary of the ground response test results

Figure 2 Theatre Gardens borehole plan

The operational costs assume that the GSHP system will provide the entire cooling requirement and the base heating load.

The analysis studied the dynamic loads and maximised the operation of the GSHP to achieve the best coefficient of performance (COP) for the overall system. Generally COPs of 3-4 can be achieved using traditional GSHP systems, in either heating or cooling mode. However, by providing simultaneous heating and cooling, COPs of up to 6-7 can be realised.

The analysis also included heat recovery systems serving the air handling systems. *Figure 5* highlights the estimated operational savings per year.

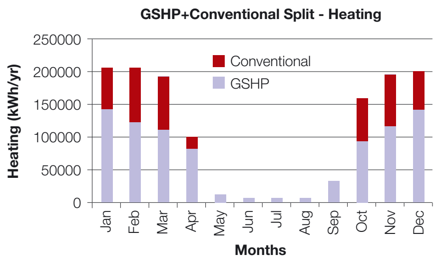


Figure 3 GSHP heating profile

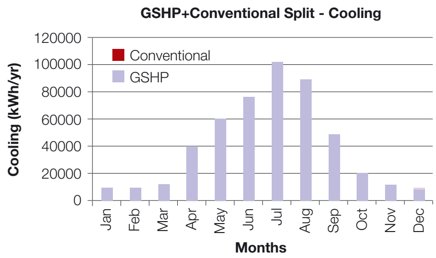


Figure 4 GSHP cooling profile

	Fuel costs per year	Savings per year
Scenario 1: Gas – £0.03/kWh Electric – £0.07/kWh		
Conventional (heating – gas, cooling – electric)[1]	£52,633	
GSHP (with peak gas and electric chillers)[2]	£32,584	£20,049
Scenario 2: Gas – £0.045/kWh Electric – £0.09/kWh		
Conventional (heating – gas, cooling – electric)[1]	£87,678	
GSHP (with peak gas and electric chillers)[2]	£46,572	£39,106

Figure 5 Estimated operational savings

Two scenarios are presented above for differing gas and electricity unit prices. Recently, the UK has experienced increasing utility prices so scenario 2 seeks to consider higher gas and electricity rates. Higher relative gas increases are likely as the supply from the North Sea diminishes. As the gap between gas and electricity prices reduces, the operational costs of the GSHP system will offer better value and improved pay-back.

Carbon dioxide emissions

The GSHP system is required to provide the significant portion of the target carbon emissions reduction. The current heating and cooling load for the existing RST/Swan, with no heat recovery and poor control systems, generates a total carbon dioxide emission of around 470,000kg/yr. This equates to 43% of the building's total emissions of around 1,090,000kg/yr.

The current target is to provide a 20% reduction in this figure of around 218,000kg/yr, resulting in revised total emissions of 872,000kg/yr.

	CO_2 Emissions (kg/yr)	Reduction (kg/yr)
Conventional (heating – gas, cooling – electric)	380,000	
GSHP (with peak gas heating)	220,000	160,000 or 42%

Figure 6 Carbon dioxide emissions

Figure 6 shows the calculated reduction in carbon dioxide emissions with the installation of a GSHP system, compared with a new conventional installation.[3]

Both the results include the operation of heat recovery systems and are based upon the new building's thermal models.

The electrical load for the new theatres will rise due to the inclusion of increased technical stage engineering requirements, such as power flying. Emissions of this increased load are somewhat unknown and will depend on factors such as show requirements. However, by assuming the current electrical loads as a base, it was possible to establish the expected carbon emissions of the new building and compare the GSHP system against a new conventional arrangement of gas boilers and electric chillers.

Conventional heating and cooling	
Existing electrical emissions	620,000kg/yr
Conventional gas heating with electric chillers	380,000kg/yr
Total	1,000,000kg/yr
GSHP/peak gas heating	
Existing electrical emissions	620,000kg/yr
GSHP/peak gas heating	220,000kg/yr
Total	840,000kg/yr

1 Based on an efficiency of 85% for the conventional heating system, and a coefficient of performance of 2.5 for the conventional cooling plant.

2 Based on the performance of a typical heat pump and GLHE system.

3 The calculations are based on a carbon displacement factor of 0.19 kg CO_2/kWh for gas, and 0.43 kg CO_2/kWh for electricity (CIBSE Guide F).

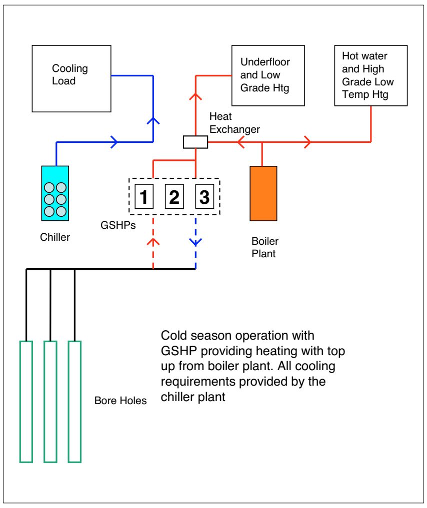


Figure 7 Cold Season operation

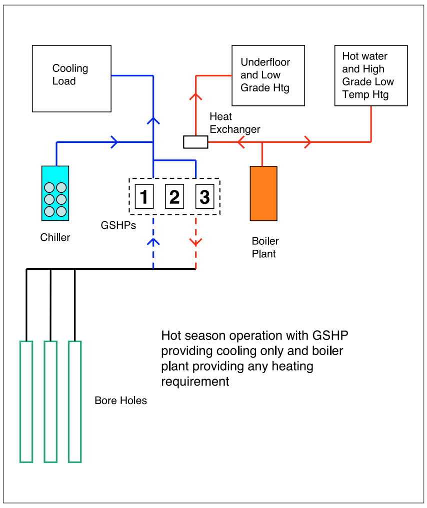


Figure 8 Hot Season operation

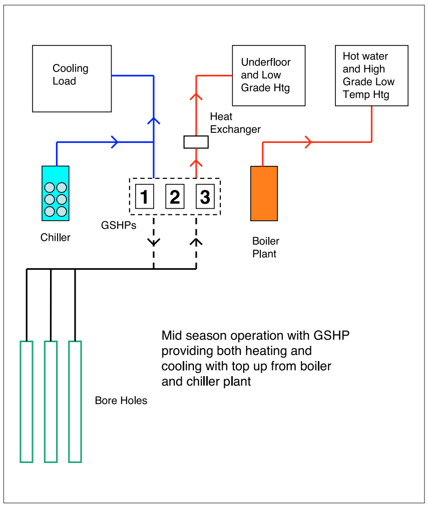


Figure 9 Mid Season operation

The comparison shows that although the new building will reduce emissions by some 90,000kg/yr (9%), compared with the existing building, the installation of GSHP results in an overall reduction in emissions of 250,000kg/yr (23%).

System design

A key element of the design is to maximise the efficiency of the heat pumps by allowing them to operate with the potential to simultaneously provide heating and cooling. They would use heat rejected during the cooling process as low-grade heating for the underfloor heating and the ventilation systems.

High-grade, low temperature heating will always be a requirement to cater for the generation of domestic hot water and to provide heating in retained areas of the building. Heating systems require higher temperature water, which will be generated by the gas-fired boilers.

While the analysis had established the potential for the GSHP system to cater for the entire cooling requirement, the design introduced the provision of a top up chiller. This recognised that a back-up system could be required in the case of GSHP equipment failure; the need to allow the borehole field to recharge itself on occasions, and future proofing against increased cooling requirements. The diagrams above (*figures 7-9*) indicate how the GSHP and top up systems will operate during various demand profiles throughout the year.

Project summary

In July 2007, the project took a significant step forward with the closure of the existing Royal Shakespeare Theatre. The Swan Theatre will continue to operate until August 2007. Full demolition of the RST auditorium will then begin, followed by its reconstruction along with the surrounding and support areas.

The re-opening of the RST and Swan Theatre spaces is scheduled for autumn 2010. Fortunately, the installation site of the GSHP systems does not lie on the critical construction path so it will be programmed during the intervening period.

Client: Royal Shakespeare Company

Architect: Bennetts Associates

Services: Building services engineering, structural engineering, infrastructure and development, geotechnical engineering, project management, fire engineering design and risk assessment, computation and simulation analysis.

Paper merchant pushes for water/water heat pump

In this case study of the Daintree Building in Dublin, Edith Blennerhassett looks at a ground source heat pump closed loop system used for heating only.

The Daintree Building is the concept of Paul Barnes who owns and operates a paper shop in Dublin. Not any old paper – Paul makes his own paper and imports unusual paper from all over the world.

The idea for this project stemmed from his vision to build a sustainable building in Dublin. Paul Barnes appointed Solearth Architects to develop the building design. Buro Happold was appointed as structural and building services consultant.

The primary heating energy for the building comes from the ground and for the domestic hot water from the sun

This four-storey building is structurally a single-storey reinforced concrete frame, topped by a three-storey timber frame. The concrete frame encloses ground floor commercial and retail space, while the timber structure encloses primarily residential space, with some retail and office space located on the first floor.

Underfloor heating was originally designed to be installed throughout the building, and the use of lower than normal flow and return temperatures facilitated the introduction of the ground source heat pump (GSHP). The heat pump installation is located in the basement plant room and was designed to be operated on low-rate electricity during night time hours.

Domestic hot water (DHW) to the building is being provided primarily from six solar water heating panels located at high level on the building. The panels are of the evacuated tube type that collect energy even in cloudy conditions, which are prevalent at all times of the year in Ireland. The solar panels are expected to provide all of the hot water requirements during the summer. The hot water generated by the solar panels is piped to the basement plantroom and stored in a cylinder, which is then used to supply pre-heated water to the main hot water storage vessel.

The primary energy source for heating is the GSHP and for DHW is the solar collector system. A gas-fired condensing boiler was installed to provide a back up/boost for the LTHW supply for space heating and for the DHW generation. The condensing boiler also feeds a small air handling unit (AHU) for the basement area. The hot water annual load was calculated as 2200kWh and the heating load for the basement AHU was 23,000kWh per annum.

Grant funding

An application for grant funding was made to Sustainable Energy Ireland under its House of Tomorrow scheme to part pay for the heat pump and other energy saving initiatives based on the seven apartments. Using the calculation spreadsheet provided as part of the House of Tomorrow package the use of the GSHP showed an energy reduction, compared with gas-fired boiler plant of 71%. However, it also showed an increase in carbon emissions of approximately 13% due to the high carbon dioxide factor in Ireland for power generation. (These calculations are based on a coefficient of performance (COP) of 3, as stipulated in the SEI calculations).

However, the client intended to procure electricity from a renewable supplier, such as Airtricity, to remove/reduce the carbon content of the electricity. The proposal, therefore, resulted in significant CO_2 savings, in addition to kWh savings. A grant of €35,000 was provided towards the total GSHP capital cost of €50,000.

The heat pump for the building is a water to water heat pump rated at 30kW (based on 0°C out of the ground and 50°C running which would represent a COP of 4. The output could be as much as 45kW, with a 7°C out temperature from the ground and a running temperature of 40-50°C). The heat pump was designed to take the full space heating load, which was calculated at 31,000kWh per annum on an overall area of 1346m^2. The heat pump is linked to three 150m deep and 150mm diameter boreholes spaced a minimum of 15m apart. This is used as a rule of thumb by heat pump suppliers in the absence of ground information – one 150m deep borehole for every 10kW of output.

The heat pump unit is a Fighter 1310 model supplied and installed by a company called Unipipe. The refrigerant is R407c. The heat pump is used in this instance for heating only.

Within each borehole is a closed loop collector of polyethylene (Upanor 'energy system') pipework filled with a water and anti-freeze medium (glycol). These loops are pumped and collected at a single manifold adjacent to the heat pump unit. The pipework was installed within the boreholes as the boreholes were being formed. The borehole is not backfilled with bentonite or any other medium; it is only lined through the alluvial layer. The borehole is capped with a neoprene cap to prevent direct entry of ground water into the water course. The average cost of the boreholes is currently €25 per metre with a further €70 being required for the neoprene cap.

The collector flow temperature is between 0°C and -4°C during the heating season, with return temperature of between 7°C and 3°C. The heat pump is designed to deliver water at 45°C to the underfloor heating and radiator circuits.

The controls system was designed to allow the gas-fired boiler to feed onto the header only when the heat pump could not deliver the minimum temperature of 45°C. A buffer vessel was installed in the line to limit cycling. The controls are based on floating condensing technology but are essentially compensated controls.

Altered designs

The heat pump was performance specified and a number of changes were made to the installation whilst on site without reference to us as designers. In particular, the outlet connection from the buffer vessel was limited to half an inch which had a throttling effect on the heat pump, and the boiler was fed onto the system beyond the buffer vessel rather than at the header position. These changes and the set up of the associated controls combined to result in higher water return temperatures than desirable, and the heat pump cutting out on its high temperature return thermostat.

The result is more continuous running of the back up boiler than envisaged in the original design.

In addition, for cost and construction reasons, underfloor heating was provided to the basement and ground floor only: the higher levels, including the apartments, are heated by radiators. This change led to the flow temperature to the system being increased above that required for underfloor heating in order to keep the size of the radiators within the small apartments to acceptable levels. This reduced the usage and COP achievable from the heat pump.

We are currently reviewing the installation, with a view to altering the buffer vessel and back up boiler connections to set the system running as designed.

Client: Daintree Paper

Architect: Solearth ecological architecture

Services: Structural engineering, building services engineering.

Complementary technologies

The most environmentally responsible means of applying ground source heat pumps is when the motive energy can be renewably supplied on-site. Jason Gardner explains how his team have achieved this ideal combination on a project in Sheffield – integrating ground source heat pumps to deliver a carbon neutral building.

The Advanced Manufacturing Research Centre (AMRC) at Sheffield University is an environmentally innovative facility that will be one of the UK's first carbon neutral building of its type; it is capable of generating its entire annual energy consumption. At the heart of the AMRC's energy strategy are ground source heat pumps and on-site renewable electricity generation, shown above. Moreover, this is designed to be a financially viable, repeatable solution. With Carbon Trust funding, there is a five year payback period for the energy efficiency measures and electricity generation.

Reclaimed mine land forms the bulk of the AMRC site. The 4,200m^2 facility will provide a mixture of flexible workshops, laboratories and offices to support the University of Sheffield's work in the field of innovative manufacturing techniques for the aviation industry.

All heating and cooling energy is provided by wind generated electricity to ensure the carbon neutral target is met. Ground source heat pumps, linked to a closed loop network and boreholes, provide the building's heating, cooling and hot water loads.

Occupants will have a high quality internal environment. Workshops and laboratories are closely temperature controlled, primarily to maintain equipment calibration. In contrast, the offices will offer a comfortable, naturally ventilated environment.

The AMRC's on site generation complements the ground sourced heat pumps

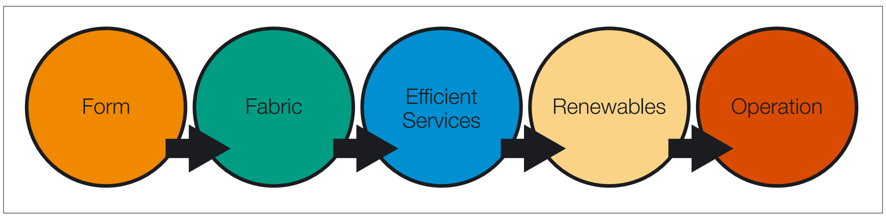
Design process

During the earliest stage of the project Buro Happold applied a 'carbon mitigation' design strategy to the design process (refer to diagram below). This involved focusing on reducing energy consumption, initially through good building form and fabric design. Only once the energy saving contribution of the building's form and fabric had been fully exploited did the design team move onto developing the use of energy efficient services in detail, of which ground source heat pumps formed a key element. Applying this ordered design process enabled Buro Happold to minimise the scale of the heat pump installation, thereby maximising its positive contributions by reducing the energy consumption and system costs.

A vital part of the carbon mitigation design process was to ensure that the technologies applied to the project complemented one another. Hence when considering the fourth stage of the carbon mitigation design process, the introduction of renewable technologies, a key element was to ensure that the renewable technology was compatible with the heat pumps. The wind turbine, which generates 1,000,000 kWh of electricity per annum, ideally complements the ground source heat pump installation by supplying all the system's power needs in conjunction with entire building electrical demand. It should be noted that during periods of low demand, excess electricity is exported to the national grid, so enabling the building's carbon neutral status to be realised.

Ground sourced system

A ground source heat pump system provides the entire cooling load for the AMRC building. The heating load for the offices, laboratories and ancillary spaces is also provided by the pumps. The heating and cooling requirements are supplied by four reverse cycle heat pumps, each providing 45 kW of heating and 38 kW of cooling. Care was taken to make the heating and cooling loads of similar value so as to achieve the highest efficiencies from the heat pumps and also to ensure that the overall installation was as economically feasible as possible.



Carbon mitigation design process

The entire ground loop system is located beneath the site car parking area adjacent to the building. The car park is provided with a permeable surface to prevent the soil surface drying out, as this would decrease the ground loop heat transfer capability in this region. To achieve the required performance a total of 20 boreholes have been sunk at a depth of 100m each (see *figure 2*).

Heat pump hydraulic circuits are arranged to achieve free cooling from the ground loop whenever possible. The cooling mode of the heat pumps is only activated when this free cooling capacity is exceeded. In cooling mode, any heat from the heat pumps, normally classed as waste, firstly 'looks' for either a domestic hot water (DHW) or heating circuit load, before being rejected back to the ground circuit. This significantly increases the efficiency of the system during any periods when simultaneous heating and cooling are required.

Cooling energy is transferred to the distribution system via a plate heat exchanger. A buffer vessel maintained at the required distribution temperatures ensures that chilled water is always available.

The heat pumps are arranged with a lead unit that provides higher temperature water to a domestic hot water cylinder. A distinct and separate 'hot gas' circuit through the heat pumps provides additional heat recovery from each unit when they are in operation. The heat pumps contain an extra integral heat exchanger to recover all available heat from the refrigerant gas before it enters the expansion side of the system. The harder the heat pump units work, the higher the amount of secondary heat is available for recovery. Flow in this heating circuit is varied, to achieve the higher low temperature hot water (LTHW) temperatures required to heat the DHW cylinder.

Cooling is coupled with efficient displacement ventilation systems that raise the flow and return temperatures

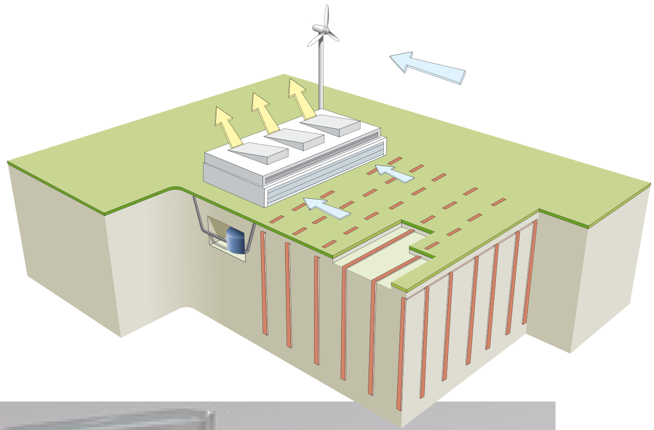


Figure 2 The 20 boreholes 100m deep are beneath the car park

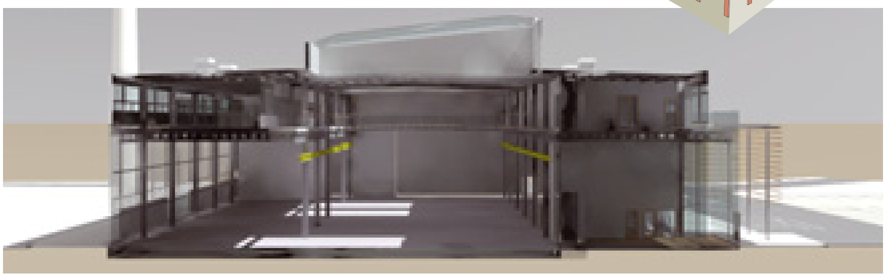


Figure 3 Building and building services design was tuned to maximise the usefulness of ground sourced heat with lower heating flow and return temperatures and higher chilled water temperatures than usual

and reduce the demand for chilled water (see *figure 3*). Displacement ventilation supply air temperatures are in the region of 19°C instead of the 12-14°C that would be required from a traditional mixing ventilation system. Increasing the supply air temperature significantly reduces the amount of cooling that is required, especially considering the fact that latent cooling is not required. Increased water flow and return temperatures of 11-15°C, instead of the more conventional 6-12°C, have been used to further reduce the energy requirements to generate chilled water.

Heating distribution is via wet underfloor heating circuits throughout. This allows low flow and return temperatures of 40°C and 30°C to be used for the LTHW circuit. These temperatures are well matched to the most efficient achievable output temperatures of the heat pumps.

On-going monitoring

The final stage of the carbon mitigation design process, 'Operation', embraces the need to ensure that the building services operate as the designer intended. Only by continually monitoring the energy and usage characteristics can the low carbon credentials of a building be fully proven, and potentially improved upon.

The factory of the future has been designed as a prototype, but the concept is applicable to many energy-hungry facilities. It will undergo extensive post-occupancy analysis and has been provided with targets and a means of monitoring performance.

The heat pump installation has been provided with sufficient monitoring equipment to enable the seasonal co-efficient of performance (COP) to be measured. To achieve this, the heat pumps heating and cooling generation will be metered separately along with the power consumption of the heat pumps in both modes.

This project is due for completion in December 2007, and the subsequent monitoring will reinforce the value of the AMRC as a learning facility that will help teach the construction industry the way to achieve carbon neutral industrial buildings.

Client: University of Sheffield

Architect: Bond Bryan

Services: Building services engineering, structural engineering, ground engineering, civil engineering, BREEAM consultation and assessment, acoustics, fire engineering design and risk assessment.

Ground source heating and cooling study

James Dickinson from the Sustainability and Alternative Technologies (SAT) group looks at the application of ground source heat pumps in this case study of the Stockport Academy.

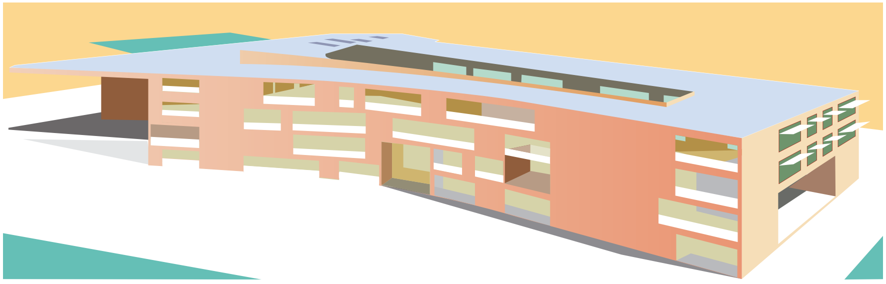


Figure 1 3D Model of the Stockport Academy building

The new Academy is to be built on the same site as an existing high school in Stockport. The relevant proposals for the building were summarised as follows:

- Provide a sealed building due to acoustic restrictions on the site arising from its close proximity to Manchester airport.
- Mechanical ventilation with heat recovery to be provided to all occupied areas.
- Ground source heating and cooling to provide the required cooling for all the ICT areas, cooling to air handling units and low grade heat to air handling units and underfloor heating systems.

A 3D representation of the building is shown in *figure 1*.

Design method

To optimise the GSHP, in terms of capital and operational costs along with carbon dioxide reduction, a detailed simulation of the system was completed.

Building thermal model

The thermal performance of the building was evaluated using the software package IES. This generated the hourly heating and cooling loads for an average test year. The resulting load and energy profiles are shown in *figures 2* and *3*.

It was evident from this review that the heating and cooling loads and annual respective energy requirements were very different. Closed loop GSHPs can be sized to meet a building's dissimilar heating and cooling loads. However, it is possible to make considerable savings if steps can be taken to equate both these system parameters.

Heat is abstracted from the ground in the heating mode and rejected to the ground in the cooling mode. Net heat abstraction over the year means that the potential to 'recharge' the borehole field over the year is reduced. The cumulative length of the ground loop must be increased to ensure continued long term performance.

GSHP sizing

Due to this imbalance it was decided to consider a bivalent[1] system. In this instance, relatively infrequent peak loads could be covered by conventional lower cost technology. There were two main cost benefits to this; firstly the borehole field size could be optimised and secondly, less expensive plant could be used for infrequent loads. The capital costs could be minimised but significant operational benefits would still be realised.

Following interpretation of the simulation it was decided that a 300kW GSHP offered the best solution. This size has the added benefit of eliminating the need for conventional cooling plant. The heating and cooling requirement is essentially out of phase, with cooling demand (aside from IT server rooms) in the summer and heating in the winter. The GSHP system will include four heat pumps, each being able to modulate between heating and cooling, so in mid season the system will be able to cover both heating and cooling loads. High efficiency gas fired boiler plant is sized to cover residual heating loads in the building.

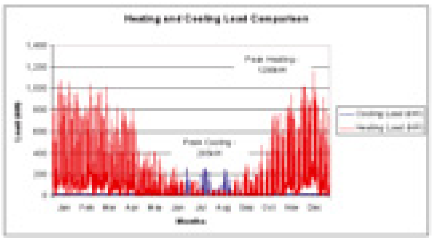


Figure 2 Heating and cooling load comparison

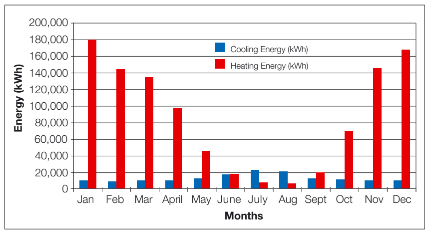


Figure 3 Heating and cooling energy comparison (kW)

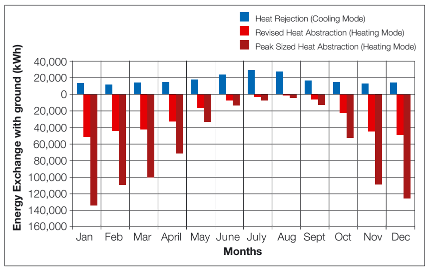


Figure 4 Ground energy exchange comparison (kWh)

Figure 4 shows the resulting ground energy exchange comparison with a peak heating sized GSHP system. The revised total heat abstraction and heat rejection from the ground is now much closer.

[1] *Bivalent – Where two sources contribute to the overall heating and/or cooling demand, as opposed to monovalent where one type of equipment is used for the entire heating load, and similarly for the cooling load.*

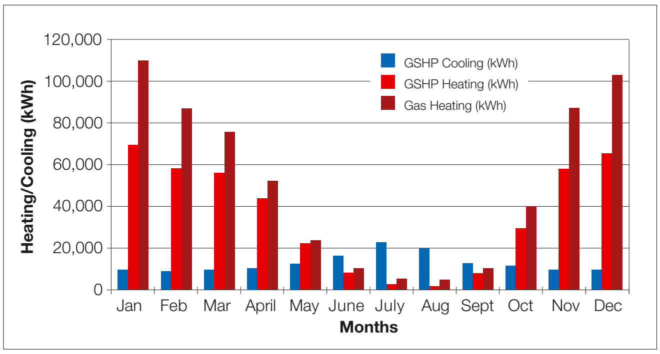


Figure 5 Stockport Academy final energy mix

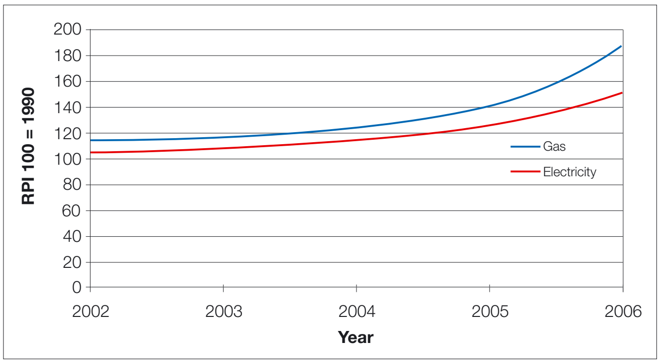


Figure 6 Retail price index utility price trends (DTI)[2]

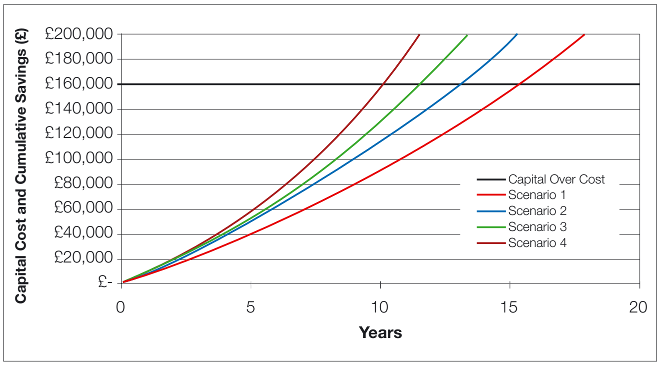


Figure 7 Payback scenario analysis

The total heat abstraction is still marginally higher, but this could change with the future effect of global warming causing higher cooling demands and hence heat rejection.

The final calculated energy mix for the heating and cooling in the building is presented in *figure 5*. Note that the building heating energy provided by the GSHP is slightly higher than the heat abstraction from the ground – this is because of the added electrical energy from the heat pump. In the cooling mode the building cooling energy is lower than the heat rejection as the electrical energy is transferred in the opposite direction. This can be further understood with reference to the thermodynamic Carnot cycle.

Using GSHP simulation software Buro Happold estimated the cumulative length of both the peak sized GSHP system and the bivalent option. The peak sized system was estimated to need 210x100m deep boreholes whilst the alternative requires approximately 45 boreholes of a similar depth. As the borehole field is the most expensive aspect of the GSHP installation it is clear that the bivalent option would be less capital intensive and would be more cost effective.

Operational savings and payback

The GSHP simulation predicted the electricity used by the heat pump plant so comparisons could be made with more conventional plant. For this analysis the following assumptions were made:

- Seasonal Gas Boiler System Efficiency: 80%
- Conventional Electric Chiller Plant Seasonal Co-efficient of Performance (SCOP): 2.5.

The payback was based on additional capital expenditure of approximately £160,000 therefore taking into account the extra cost for the GSHP but also the consequent elimination of conventional chiller plant and reduction in gas boiler capacity.

To assess the economic feasibility of the GSHP the system was modelled using sensitivity analysis of future utility prices. *Figure 6* shows how energy prices and specifically gas prices relative to electricity prices have increased over the last few years.

Forecasting for future electricity and gas prices is extremely complex and it can be difficult to predict the long term payback for more efficient, but higher cost, plant. However, four scenarios were constructed to reflect different changes in the energy market that are supported by the recent trends reported by the DTI. The third was chosen as the most likely based on reasoned analysis of energy imports and increases in the cost of the different utilities.

[2] *Department of Trade and Industry, Quarterly Energy Prices www.dti.gov.uk/energy/statistics/publications/prices/tables*

Figure 7 (on previous page) shows the resultant payback predictions.

A summary of the estimated payback and annual savings for each Scenario in year 10 are:

- Scenario 1: 15.2yrs/£11,300
- Scenario 2: 12.93yrs/£14,100
- Scenario 3: 11.5yrs/£17,900 (Predicted)
- Scenario 4: 10.2yrs/£24,500

This analysis also highlighted the added resilience the GSHP system gives to future fossil fuel prices.

Building services

To maximise the GSHP efficiency heating, low temperature hot water will be delivered via an underfloor heating circuit and chilled beams at 45ºC.
A gas fired boiler will deliver heat to all the AHUs, radiators and radiant panels. Cooling will also be delivered via the chilled beam circuit and cooling coils in the AHUs. The cooling system has been sized to allow for higher than usual cooling flow temperatures of 14ºC.

The GSHP will serve the cooling circuit as a priority but, via a sliding header arrangement, the heat pumps will be able to modulate between the heating and cooling loads. That the GSHP will act as the primary heating provider when the cooling demand is low to maximise the benefits of its operation. The gas fired boilers will provide back up during peak loads via an injection circuit. During periods where there is spare GSHP capacity, heat will be diverted to preheat the domestic hot water for the building.

A simplified schematic of the arrangement is shown in *figure 8*.

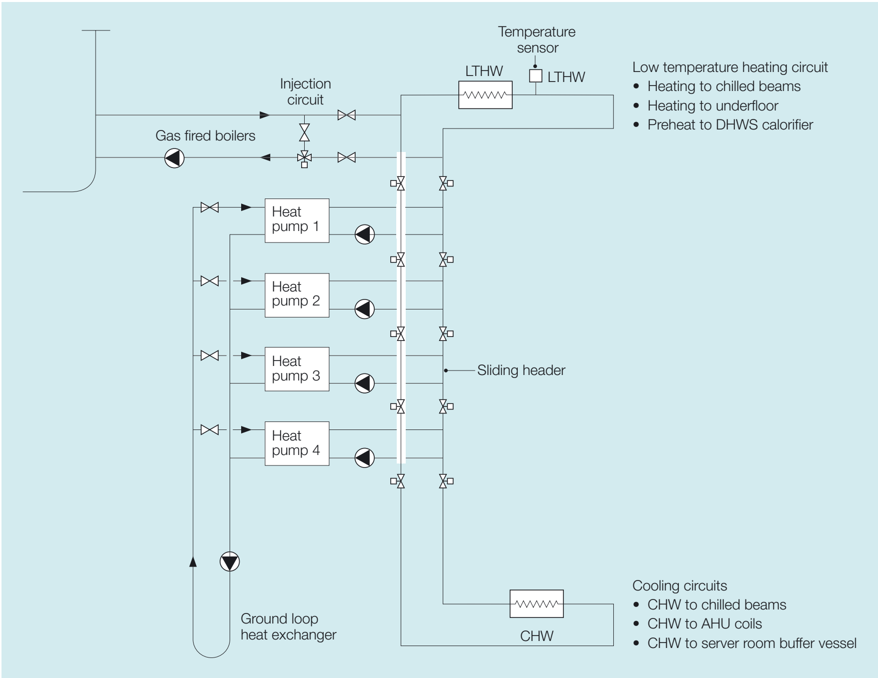


Figure 8 Simplified GSHP Building Services Schematic

Conclusions

The bivalent GSHP system designed for the new Stockport Academy will significantly reduce the operational costs of the heating and cooling provision and reduce the total effective carbon dioxide emissions from operating the building.

The estimated annual carbon dioxide savings are 67mtCO_2 (11.5% of the building total). The GSHP provides 30.6% of the building's total energy requirement (23% of which is renewable). The carbon dioxide reduction is an essential part of the strategy to ensure the building meets 2006 Part L Building Regulations.

The analysis and the consequent installation of a GSHP at Stockport Academy shows the potential for the application of this technology in educational buildings. The initial consideration should include a review of the respective heating and cooling loads to optimise the operational benefits with respect to the capital costs. When occupation is low during the cooling season (summer) the overall heating energy required for the building is generally much higher than the cooling energy.

In new academies or other schools where the cooling requirement is significant due to restrictions in providing natural ventilation, there is a particular benefit in sizing the GSHP to meet the cooling load. This enables the elimination of extra conventional cooling plant while reducing the net heat abstraction from the ground. Particular attention should also be given to future utility prices as this can make a significant impact on the economic case.

Client: ULT Projects Ltd

Architect: Aedas

Services: Building services, building structures, SAT, CoSA.

Double slinky in County Kerry

Transferring the technology of commercial scale developments to a domestic scale of project can pay dividends. There are, however, a number of pitfalls to avoid, as Brian Doran explains in this ground source heating case study.

There is some satisfaction in being able to practice what you preach – a chance to utilise new technologies within one's own dwelling. The renovation/rebuilding of my house in rural Ireland provided the opportunity to examine and install a ground source heat pump and solar domestic hot water heating for me and my family.

This case study summarises the ups and downs of an installation, which eventually delivered a successfully operating 8kW water/water heat pump (HP) serving space heating via a horizontal ground loop array. The design justification was not skewed by any artificial factors such as grant aid, which was not available at the time in Ireland. The choices were justified on the straightforward capital cost and simple payback periods.

However, the process did highlight the considerable resistance to out-of-the-ordinary techniques in a marketplace unfamiliar with heat pump technology and energy-conscious construction. The heartening news is that in the intervening months there has been a sea change in terms of the situation in Ireland and it would now be much easier to progress this project.

Because this project was part existing building and part new build, the scenario of a very low energy building at or approaching Code for Sustainable Homes Level 6 (zero carbon) was not viable, even ignoring our budget constraints.

Scenario	System	Dwelling emissions		Assumed System Efficiency
		$kgCO_2$/year	% saving compared with scenario 1	
1	Direct electric heating	2556	–	99%
2	Gas fired heating	1306	-49%	80%
3	Oil fired heating	1719	-33%	80%
4	Air source heat pump (space heating only)	1661	-35%	COP: 2.2
5	Ground source heat pump (space heating only)	1332	-48%	COP: 4
6	Ground source heat pump (space heating). Solar water heating	1053	-59%	HP COP: 4 Solar contribution: 30%
7	Ground source (space and water heating)	1265	-51%	COP: 2
8	Biomass	235	-91%	80%

Notes
Emissions are based on the following data:

Typical dwelling requirements		
Space heating demand	3500	kWh/year (delivered)
Water heating demand	2000	kWh/year (delivered)

Carbon emissions		
Gas	0.19	$kgCO_2$/kWh
Oil	0.25	$kgCO_2$/kWh
Electricity (Average for UK grid)	0.46	$kgCO_2$/kWh
Biomass (harvesting/transportation)	0.03	$kgCO_2$/kWh

Figure 1 Approximation of dwelling emissions

Why use a heat pump?

For us, the key design choices regarding energy strategy and heat source were:

a) How low we could go, in terms of energy conservation
b) Minimising carbon emissions from the energy consumed – and looking at available alternative technologies
c) Aspiration for a hassle free operation – low maintenance, simple energy purchase and delivery
d) Enthusiasm to learn a little more about domestic scale installation of alternative technologies, with a hands-on approach and post occupancy monitoring.

After energy saving measures were incorporated, the above criteria gave us an obvious steer to an HP solution serving underfloor heating. However, there was a choice to make regarding the use of air source or ground source heat pumps. Though generally not classified as a renewable technology, the former does offer a simple, cost-effective solution, assisted by the mild Kerry climate.

Hot water

The other issue considered was whether to utilise the HP for delivering the domestic hot water demands or limiting it to space heating, operating only in winter. We looked at using the HP to deliver the high temperature primary water (>60°C) and alternatively as simply a pre-heat to the domestic water load, thereby maximising the system's Coefficient of Performance (COP). There are a number of manufacturers who claim their high temperature (>60°C) domestic heat pump packages achieve a COP of >3. They publish test analysis to substantiate this, but proven examples with monitoring tend to be scarce. It is clear however that the thermodynamics dictate that the temperature difference of a HP system should be minimised in order to optimise COP.

As can be seen in *figure 1*, the overall system COP (space and hot water heating) needs to be in excess of 2 to make it comparable with the emissions from gas-fired heating.

The additional cost of a domestic water and space heating HP package also gives credence to the argument to utilise separate alternative technologies to serve the differing system needs (ie solar thermal for the higher temperature needs and heat pump for the low temperature heating circuit).

Space heating is therefore delivered from the ground source heat pump, with the domestic hot water heated primarily from a flat plate solar collector (operating as a thermo-syphon) to a thermal store with supplementary heating by direct electric means.

The procurement of the heat pump system was on a DIY package basis from Kensa Engineering, which included the 8kW HP with integral circulating pumps (£3,500 +VAT), and pre-measured and formed 'slinky' ground source tube loop network (£550).

View of garden containing septic tank percolation area and slinky trenches (around the perimeter)

Even with domestic installations, some debate takes place regarding the sizing of the ground array. Although there are instances where insufficient ground loops have caused freezing and ground heave, the relatively small cost of the external works (in a non-confined site) mean that it should be easy to install a generously sized ground array with the possibility of an additional loop(s). The ground loops serving the 8kW HP consisted of two 40m long trenches (300mm wide x 2m deep) for the pipework formed from 40mm diameter HDPE pipe. Both loops are installed in parallel around 6m apart and rely on being of identical pressure drop to balance flow and minimise pumping costs. There was little concern regarding the sizing of the ground loops, even though they were not particularly deep, given the southerly aspect of the site and mild climatic conditions.

Lessons learned

Hopefully the following hard-earned advice offers some pointers for future domestic scale schemes:

1 Never underestimate the limitations that can be imposed on a project due to the skill base within the construction industry. To be fair, it is understandable that contractors do not wish to move outside the comfort zone of previous experience and standard solutions. But this can affect even simple design concepts such as insulation thicknesses. We had to compromise on the cavity wall design, with a 150mm cavity, which the local contractor found too onerous to construct.

2 The 'lead-in' period for the site's electricity supply may be protracted due to the larger than 'normal domestic' load of the heat pump. In our case, the 8kW HP required a 25amp single phase power supply (typically 65amp starting current).

3 Never believe a JCB driver when he tells you that he'll be there to dig trenches!

4 Make sure every inch of the ground works are supervised at all times. At one stage on our project, a 20m section of trench was backfilled, unsupervised.

5 The cost of the ground works installation isn't great and pales into insignificance compared with the cost of ground remedial works when it's not done right the first time.

6 Make sure all ground loops are pressure and flow tested, both before backfilling and as soon as the trenches are backfilled. To our detriment, we found out that a kink in the ground pipe is much worse than a fracture.

7 Make sure your plumber carries out a flow test and checks for air locks before filling the system with anti-freeze. This avoids the need to repeatedly drain the system (or pollute the ground) if an obstruction in the pipe is discovered.

8 Due to the points above, consider installing at least one extra slinky. We did not have the foresight to do this and discovered an obstruction in one of the slinkies. This was attributed to either an air lock, debris or a kink in one ground pipe.

9 When the usual available pumps were not able to remove the offending obstruction, we resorted to a drainage pressure jet company to assist. This may be a fairly high-risk strategy as the pressure delivered to the pipe should be in excess of its design rating. In our case, however, we had little to lose – safely exhuming the offending slinky would be next to impossible without further risk of damage and we had resigned ourselves to simply replacing a complete section of the below ground installation. As it happened, the pressure jet equipment easily tracked down the problem by fracturing the pipe at the point of weakness (the kink caused during backfilling) and forcing water to the surface. This was clearly not a scientific approach. The remedial works led to a major additional cost – approximately three times the cost of ground loop installation. In addition, there could be significant health and safety issues with re-excavation of the trenches.

10 Never assume there is only one kink in a faulty installation.

11 Never underestimate the force needed to remove an air lock in a pipe (not just in the slinkies).

12 When installing a heat pump, don't forget to spend a little more and install an electricity meter in its power supply.

View of trench with slinky installed

13 Don't be put off by these avoidable construction errors and take heart in the fact that the technology is robust (and now working perfectly). Since completion at the end of 2006, we have been through heating a full season and the system performs extremely well and efficiently.

Finding the way through labyrinths and earth tubes

Using the earth as a method of thermally preconditioning the supply of air is a simple, cost effective way of employing huge thermal masses. Mike Entwisle outlines the advantages of this technique and discusses some recent examples.

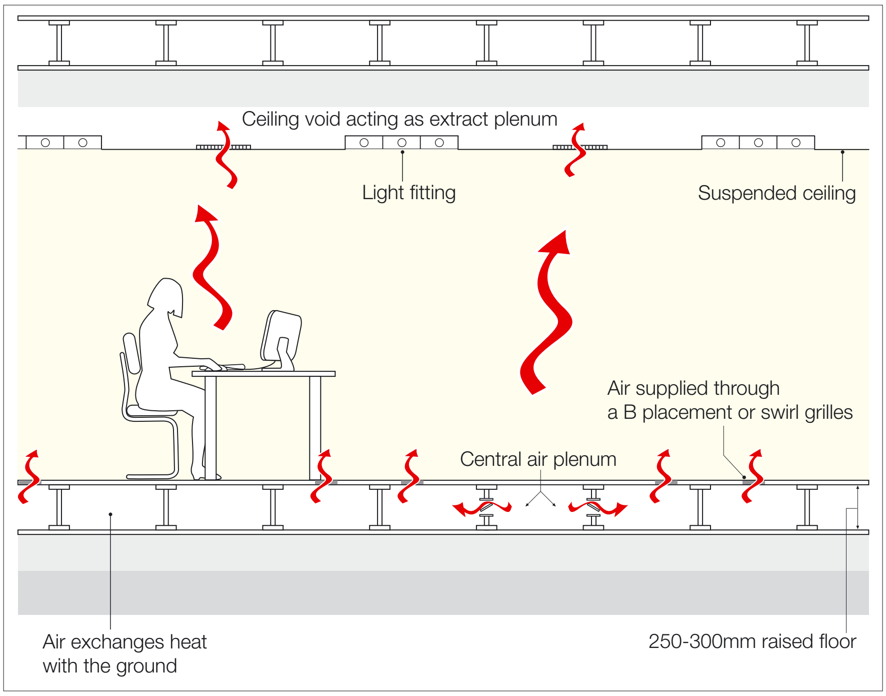


Figure 1 1980s floor void ventilation system

History

One renewable energy source that has been exploited for many years is the stability of the ground temperature. This is demonstrated in many extreme climates by the use of ground sheltered buildings, and indeed in China cave dwellings have existed for centuries, which take advantage of this lack of thermal variation.

Water based ground source systems harness this stability by passing a fluid through pipes that are in contact with the ground, or use ground water from deep sources. However, air based systems are generally relatively low tech and to date have received little attention. They require shallow interventions in the ground and as such are suitable for most sites. They can often be implemented relatively cheaply with little mechanical equipment required. Whilst the Greater London Authority's renewables guide does not recognise such a system as counting towards the 10% contribution, there can be no doubt that the energy recovered from the ground is a true renewable source and can indeed be considerable. However, the behaviour of air based systems is not as well understood as that of buried loops, and in particular the effect of the system itself on the temperatures of the relatively shallow buried air paths.

Serendipitous cooling

I first became aware of the magnitude of the energy available from this method when I studied an office building in Peterborough in the mid-1990s (see *figure 1*). This was mechanically ventilated using a raised floor plenum, and provided good internal conditions as the thermal mass was accessed through the floor plenum.

The floor void ventilation system of the office building in Peterborough was not zoned, and the client was finding it impossible to provide comfortable conditions on all floors simultaneously during summer; when the upper floors were comfortable, the ground floor temperature was too low, and if the controls were configured to avoid overheating on the ground floor, the upper floors were too warm. This provoked consideration of the degree of heat transfer into the uninsulated ground floor slab. I took a detailed set of measurements and found that on warm days (temperatures of around 25°C peak), the air was exiting the floor grilles at up to 5°C below the external temperature. On extremely warm days, the conduction into the ground provided even more cooling – none of which was available to the upper floors and gave a considerable difference in performance between the ground and upper floors!

Earlier uses of this technology include The Royal Victoria Hospital in Belfast, which proved to be a landmark in ventilation of hospital buildings (see *figures 2* and *3*). Air was supplied from a series of subterranean plant rooms, in which the air was filtered and/or cooled using wet sprays (in the days before Legionnaires Disease was an issue!), and heated before passing through buried brick corridors on the way to the wards. While the ground connection would have been wasteful of heat energy (unlikely to be of concern at the time), it would have provided some useful additional cooling in summer, thus maintaining the comfort of patients.

Wolverhampton Civic Hall's ventilation system, constructed in the 1930s, also uses myriad buried ducts as a way of getting from A to B which reap the benefits of cooling in the summer.

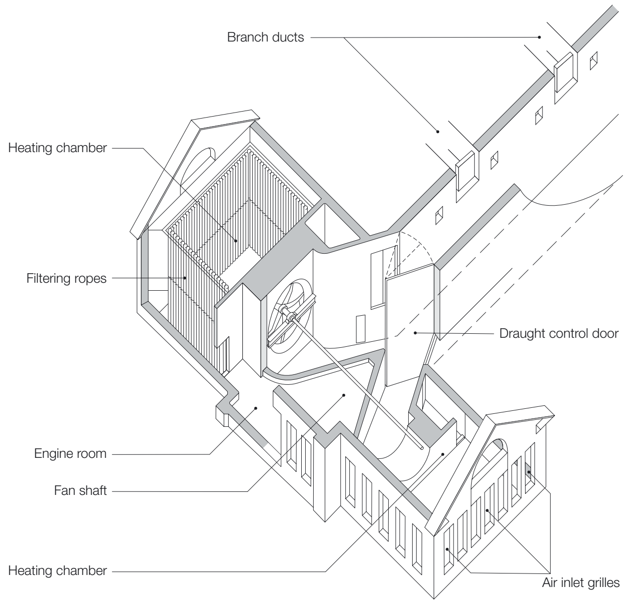
Principles

As with all ground coupling, the basic principle is that the ground temperature is much more stable than the ambient conditions. Passing cold or warm air over a surface at a certain temperature will bring the air temperature closer to the ground temperature. Very little additional equipment or ground intervention is needed, particularly if the building is to be mechanically ventilated anyway.

The heat transfer achieved depends on the surface area available, the velocity (which to a large extent determines the heat transfer coefficient), the time spent in contact with the ground and the external temperature. These are often competing with each other, but the critical issue in any system is to ensure that the airflow in the ground contact zone is turbulent. For a typical floor plenum 300mm deep, this occurs at a velocity of as little as 0.2 ms^{-1}, reducing proportionately in larger ducts and increasing in smaller pipes. Once in the turbulent zone, heat transfer coefficient will continue to increase as the air moves faster. However, it can still obey the law of diminishing returns, with high velocities increasing pressure losses, resulting in noisier fans and more electrical energy usage.

Analysis of the airside heat transfer can be performed relatively simply, but assessment of how the temperature of the ground varies with depth and time is more difficult, and requires detailed thermal modelling in four dimensions. However, as a general rule, the deeper the ducts the better, although it's not worth going below 2-3m deep!

The heat and coolth recovered from the ground can not only reduce heating use in the building, but can effectively enable thermally lightweight buildings to have summertime performance similar to those with large amounts of thermal mass. This can provide a high degree of resilience against changes in use, such as increased IT loads, occupancies, and longer hours of use. Most critically for the future, it is able to deal with the effects of climate change.



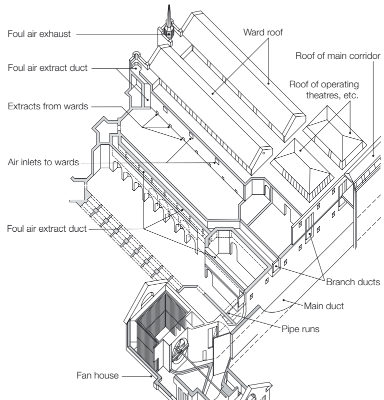
Royal Victoria Hospital, Belfast
Cutaway section of engine house and head of main duct

To illustrate the energy available, on a hot summer's day the external temperature could easily be 30°C in the south of the UK, with a ground temperature of maybe 15°C. Heat transfer coefficients of 8 $Wm^{-2}K^{-1}$ are easily achievable, giving a cooling potential of 120 Wm^{-2}! Our experience is that this can usefully serve buildings of two to three storeys. Indeed, Buro Happold has recently reached completion on a three storey school served entirely by a labyrinth.

There are many possible configurations of air based systems, but the following are the most common:

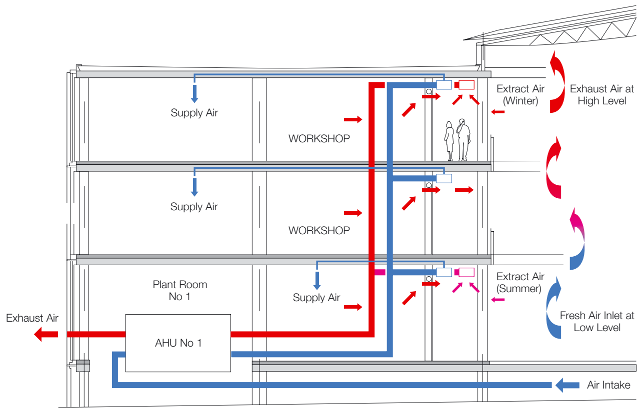
Earth tubes

With earth tubes, pipes are buried in the ground. This is a cheap technology that can be easily utilised beneath the footprint of the building or in its surroundings. Burial depths of 2m are preferred, but 1m of cover can provide a good degree of stability.



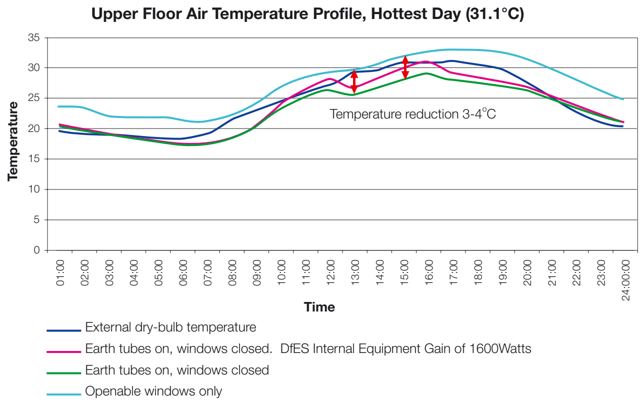
Royal Victoria Hospital, Belfast
Cutaway of the complete ventilation system

Figures 2 and 3 Diagrams of the early ground coupling ventilation system at the Royal Victoria Hospital, Belfast



Dyson – schematic

Figure 4 Ventilation schematic for the proposed Dyson Academy with intake air draw – through culverts



Steiner Academy – graph of performance

Figure 5 Graph showing earth tube performance at Hereford Steiner Academy

Concrete and clay pipes are preferred, as they have a thermal conductivity similar to the materials in which they are buried and (in the case of clay) a low embodied energy. These ducts can be used as the inlet to a system or even on the supply to a room. However, care must be taken not to heat air in winter before passing it through the buried ducts as heat will be lost into the ground.

One of our earliest systems of this type was at Bristol City Academy. Like many schools, the building was fundamentally designed to be mostly naturally ventilated, with classrooms of the appropriate depth and construction. However, shortly before going to tender, the DfES's new Acoustic regulations, Building Bulletin 93, came into force and after much discussion we were advised that they applied to our scheme. On closer examination, it emerged that much of the school was located in an area of the site with ambient noise levels that would make compliance with the strict regulations impossible for a naturally ventilated scheme. Having already been through the planning process, we were reluctant to introduce changes that would radically alter the external appearance of the building, so rooftop mounted plant and ventilation stacks were not practical.

Therefore, mechanical ventilation was introduced; the supply air plant is located in external pods and connected to the rooms through a series of clay pipes, buried with around 1.5m of cover. Air is then supplied to the classrooms through a perimeter trench heater, ensuring that draughts are avoided during winter. The rooms still have openable windows but in many cases they do not need to be used in summer, as the earth tube system maintains temperatures at least 4°C cooler than outside on a hot summer's day.

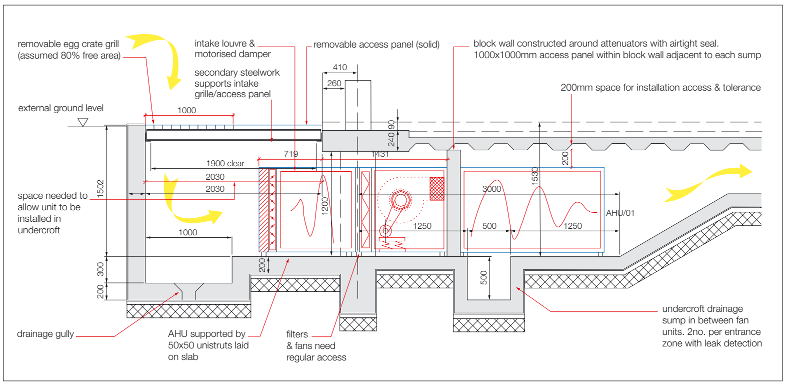
Since then, earth tube technology has been applied to other buildings from project inception, including the 3 Ways Special School in Bath, St Mary Magdalene Academy in Islington, the Dyson Skills Academy in Bath and they have also been proposed for the Hereford Steiner Academy. Further explanation of the last two is beneficial here:

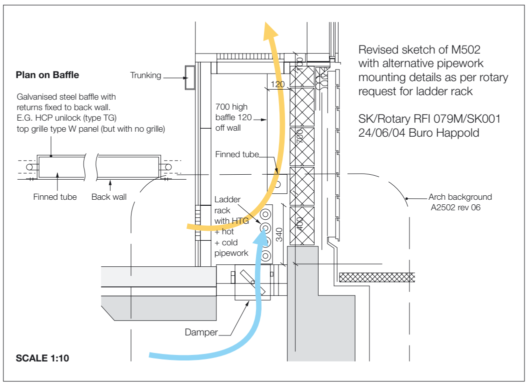
The Dyson Academy (see *figure 4*) is a hybrid scheme where the buried air ducts perform as a series of earth tubes, but are much larger, and similar to labyrinth sections. The site is very constrained, and is located in a visibly sensitive area of the World Heritage City of Bath. In addition, a busy and polluted road runs down one side of the building.

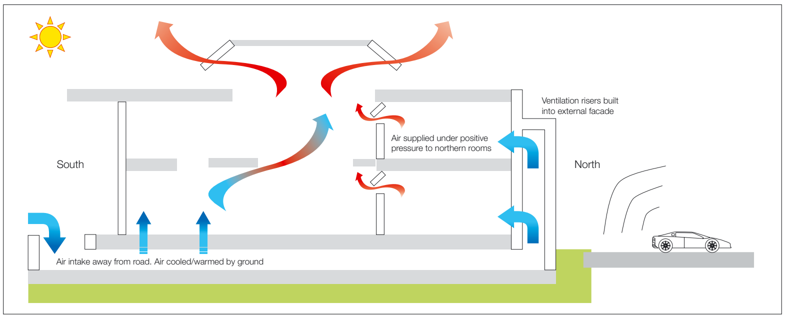
Therefore, a mechanical ventilation solution is achieved with plant inside the building rather than at roof level. The north side of the building is flanked by the River Avon and allows the flow of clean air into the building. The intake ducts run to the plant room as large culvert sections, with the pre-cooling and pre-heating that they provide being augmented by the use of river water for further cooling and heating when necessary.

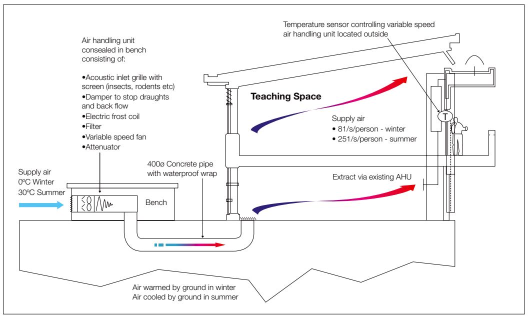
Lastly, the air is supplied to the spaces through the 'Concretcool' system which uses ducts cast into the structure to increase thermal mass contact still further. Sadly, this scheme is unlikely to be built in this form as the site has since become available, but we are keen to exploit these principles and techniques on its new site.

The brief for the Hereford Steiner Academy was for a low energy and sustainable building that would assist with the Steiner education methods and philosophy. After lengthy debate, an exceptionally well-insulated building envelope was adopted, with the use of a timber frame. This of course, gave little opportunity for the inclusion of thermal mass, which would have provided resilience against the ever warming climate.









From top, left to right:

Figure 6 West London Academy – section through subterranean air handling plant

Figure 7 West London Academy – sketch section through air supply from undercroft

Figure 8 West London Academy – schematic section

Figure 9 Teaching space – alternative ventilation strategy for BB93

We therefore introduced earth tube ventilation into the classrooms, utilising passive techniques in winter, boosted by low pressure fans in summer when lower wind and thermally driven pressures coincide with increased ventilation requirements. The analysis in *figure 5* shows that whilst the winter heat gain in this case is relatively small, the thermal stability that this afforded the building in summer was remarkable, ensuring that peak summertime temperatures were again 3-4°C below the external.

Labyrinths and undercrofts

The schemes above have all used the simple and cheap technology of earth tubes. However, a more powerful technique that can harness the entire footprint of a building is the use of labyrinths and undercrofts. These can be located under the building, or even extend beyond it, and can be deep enough to allow access for maintenance. The most well known labyrinth scheme is probably that at the Earth Centre, where the walls even have an irregular shape to increase the turbulence and also the surface area available for heat transfer. However, there are a number of other schemes that have been less high profile. West London Academy, shown in *figures 6-9*, and one of the first waves of DfES City Academies, is located very close to the A40 Westway dual carriageway on the outskirts of London. In addition to the traffic noise, part of the site also sits in an area where the air quality is deemed to be unacceptable for ventilation use. Given that the location of the building on the site was constrained to a ribbon close to this road, the challenge was to provide a solution that met the acoustic and air quality requirements, whilst drawing air from the far side of the building and including a degree of passive behaviour.

As a solution, we placed a shallow undercroft below the majority of the building footprint, which acted as a supply air plenum to the rooms closest to the road. In winter, the air is tempered by passing through the undercroft and is further warmed by passing it over radiators on entering the room. Once the heating had been commissioned fully the building produced an exceptionally stable internal environment, with the undercroft plenum tempering summer and winter temperatures by up to 6-8°C and internal peak summertime temperatures in hot weather being 5-6°C below the external peak – a remarkable performance for any building without mechanical cooling.

Seasonal variations were accommodated by varying the fans from a winter trickle to high summertime rates, (a ratio of around 10:1), night ventilation in summer, and careful sequencing of optimum start for heating and ventilation in winter.

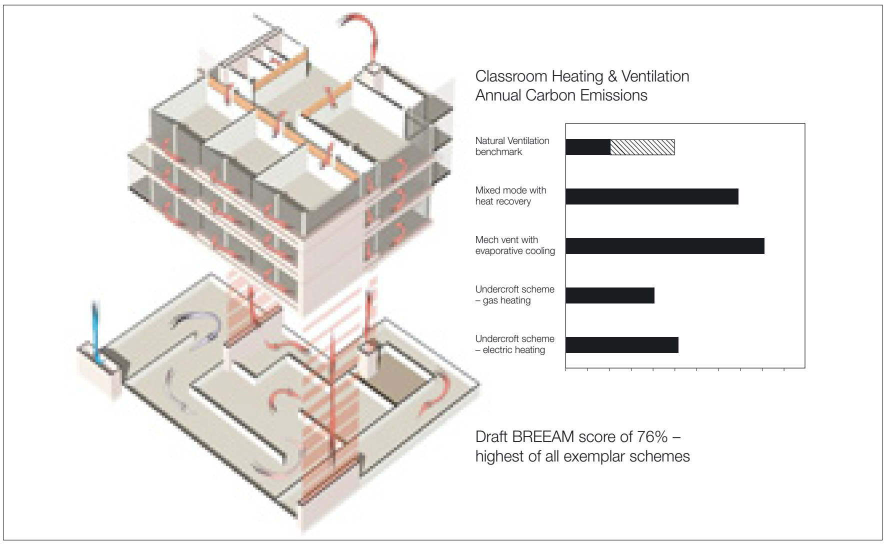


Figure 10 DfES exemplar scheme – now completed at Paddington Academy

Having succeeded in this large scheme, the principles were developed for an exemplar design for the DfES, working alongside Feilden Clegg Bradley Architects, and shown in *figure 10*. A relatively noisy site and compact building plan enabled the introduction of a labyrinth beneath the building footprint. Intake air is circulated in a 2m deep labyrinth below the building, configured to maximise heat transfer at minimum fan energy. This is then tempered by air handling units before passing through insulated ducts to the perimeter of each classroom. The air provides the ventilation, heating and passive cooling to the classrooms, which themselves have exposed thermal mass. The air then passes through passive attenuators to a central space, where it is extracted for partial recirculation (in winter) or discharged to outside (in summer). This recirculation also ensures reasonably high supply temperatures in winter, avoiding draughts. This ingenious scheme has now been constructed as the Paddington Academy, which has been completed this summer. It is expected to deliver exceptional internal conditions in a hostile environment with low energy use and simple management. A rigorous programme of post-occupancy monitoring and evaluation will be carried out to ensure that its performance is optimised, and learn more about the behaviour of these systems.

Health and safety

Concerns are raised from time to time about the cleaning and maintenance of undercrofts and earth tubes. The latter can be dealt with in a similar way to drains, with access necessary at both ends, and preferably a pit at one end. CCTV techniques can be used to check for defects, and spray methods can be used to clean the ducts. To ensure that condensation is managed efficiently, the ducts need to be laid to a slight fall. Labyrinths are best dealt with by making them tall enough so that they are accessible. If this is not possible, regular access points into shallower voids should be provided. In any of these situations, it is crucial to ensure that dirt and vermin ingress is avoided by sealing any inadvertent entries to the duct.

One issue with the current undercroft schemes is that while they recover heat during the winter, and coolth in the summer, there is a period in between when the air is likely to be cooled down by passing across the ground and then need to be reheated before entering the building. In future schemes we will allow the intake air to be taken either from the ground source or directly from outside. This will enable the optimum balance of conditions, and reduce energy use further.

The thermal storage effect of large underground ducts can be increased further by placing gabions within them, which provide an increased surface area. Furthermore, the roughness creates a more turbulent flow.

These ideas are amongst those which will develop in the next generation in low energy labyrinth schemes.

So, in summary:

Why do it?

1 To recover heat or coolth from the ground, and to reduce energy consumption.
2 To provide future proofing against climate change without needing mechanical cooling.
3 The energy recovered is renewable.
4 If a building is mechanically ventilated, the additional cost of an undercroft or earth tubes can be relatively minor.
5 The solutions do not generally involve significant technology, and are simple.

What to watch out for:

1 Controls take some time to settle down, and post-occupancy evaluation, control modification and maintenance modification regimes are critical.
2 Make sure your air flow is turbulent, but not so fast as to generate large pressure drops.
3 Ensure that clients and occupants are aware of the nature of the system so that they can be 'on board' and supportive as it settles down, particularly in the first few months of use.
4 Allow for adequate cleaning and access facilities.
5 Beware the mid season condition when the ground might cool the air down when in fact, it needs to be warm!

Dynamic modelling benefits of Jennie Lee labyrinths

When considering using labyrinths or undercrofts to condition supply air, an accurate assessment of the effect and feasibility of the strategy with a computational model is vital. Daniel Knott explains the process and the benefits the Open University's Jennie Lee project.

The Jennie Lee project is a faculty building on the Open University campus at Milton Keynes with a project value of €19m. The inspiration to provide a building with low energy consumption and excellent green credentials was integral to the client and the local planning authority.

The original aim to provide on-site renewables was severely limited due to a restricted site. Therefore a system for preconditioning the fresh air supply via a series of thermal labyrinths, positioned in the building undercroft, was investigated and adopted.

The labyrinths are designed to precondition external air used for the fresh air supply in the atrium and surrounding inner offices. The outside air is drawn through an underground system by the ventilation plant. Partly using the earth as a heat source and sink and partly using its own thermal mass, the labyrinth preheats the air in the heating season and cools the supply in the summer months. The technique is suitable for new mechanically ventilated buildings with appropriate ground conditions. The main benefit is the reduced peak demand for cooling and heating plant, which helps to reduce the size and cost of the HVAC system.

Buro Happold's London CoSA (Computational Simulation and Analysis) team was asked to model the cooling effect provided by the labyrinths for the air supplied to the atrium and internal office spaces using a high external ambient temperature. From our initial work the investigation developed into a wider study of the modelling capabilities of the IES Dynamic Thermal Model in predicting the temperature drops

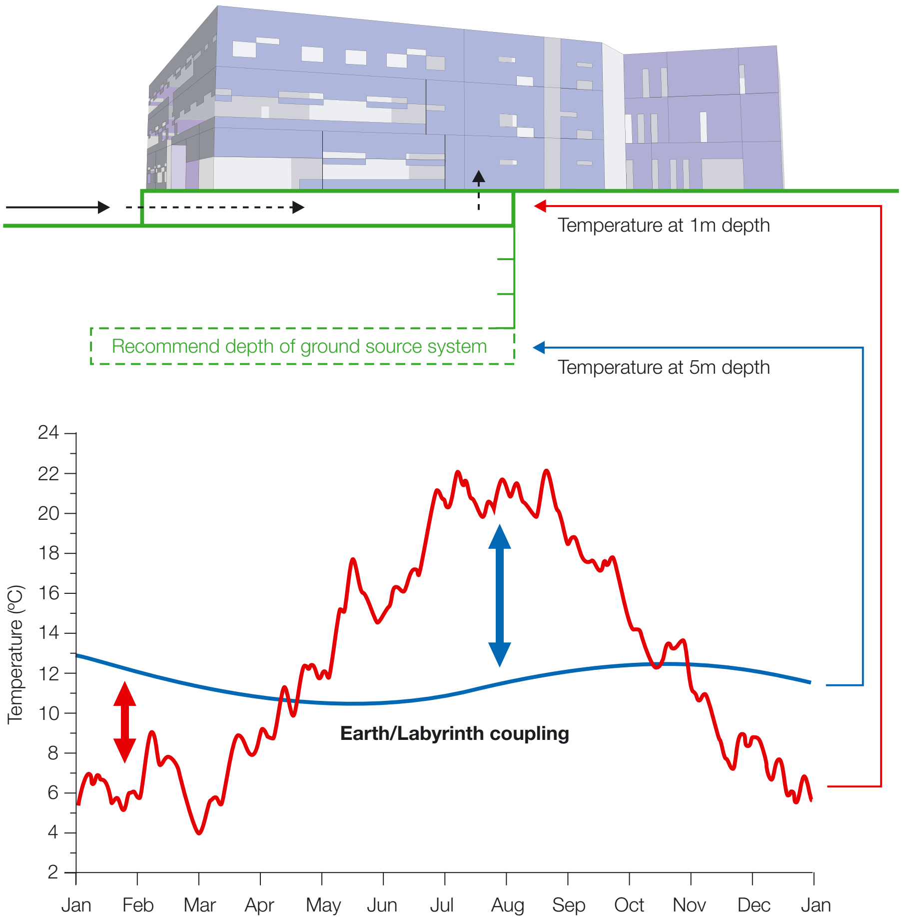


Figure 1 Temperature difference is reduced in both summer and winter for 1m comparative to 5m depth

achieved by an earth-coupled system via a dynamic temperature boundary condition (see *figures 1* and *2*).

Challenges

The site had strict boundary requirements, which restricted the position, depth and orientation of the labyrinth. The only sub-surface access was from the south, as the north side was close to a retaining wall, the east side had underground drainage and a trench occupied the west orientation.

Favourable factors for the use of ground conditioning include average ground temperatures of less than 12°C and soft, moist earth. Sacrificing these preferential conditions would lead to smaller temperature gradients between the labyrinth walls and the incoming air, resulting in a reduced cooling or heating effect.

Earth tubes or pipes are typically placed at a depth of 5m and sufficient land area should be available for the output requirements. The recommended distance between pipes is 1m.

However, the project finances dictated that the labyrinth could not be fully submersed at a suitable depth below the building. It was instead contained within channels in the foundations. In addition, due to the cost of excavation, the design team was forced to further reduce the amount of earth around each of the ducts, by connecting the three separate labyrinths. Both measures would decrease the desired characteristics of the labyrinth due to the lower adjacency areas exposed to the earth.

The distance between the intake and the internal zones suggested that a labyrinthine system of walls and passages would increase the effective length of the undercroft and encourage fluid mixing, leading to an increased cooling or heating effect. Unfortunately the introduction of internal walls will increase the pressure drop and consequently significantly increase the energy consumption of the dedicated extract fan.

Benchmarking

One of the main concerns in this project was to address the lack of ground temperature benchmarks. The determination of a thermal condition for labyrinth walls was essential to predict the thermal environment of the labyrinth and consequently the cooling and heating effects used to justify Part L compliance.

Although there is an equation for calculating ground temperatures (Mihalakakou 1992, 1997), in this project the labyrinth and the adjacent earth were also dependent on the thermal characteristics of the building above. For this reason we believed that modelling the thermal mass of the earth, labyrinth and adjoining building was justified.

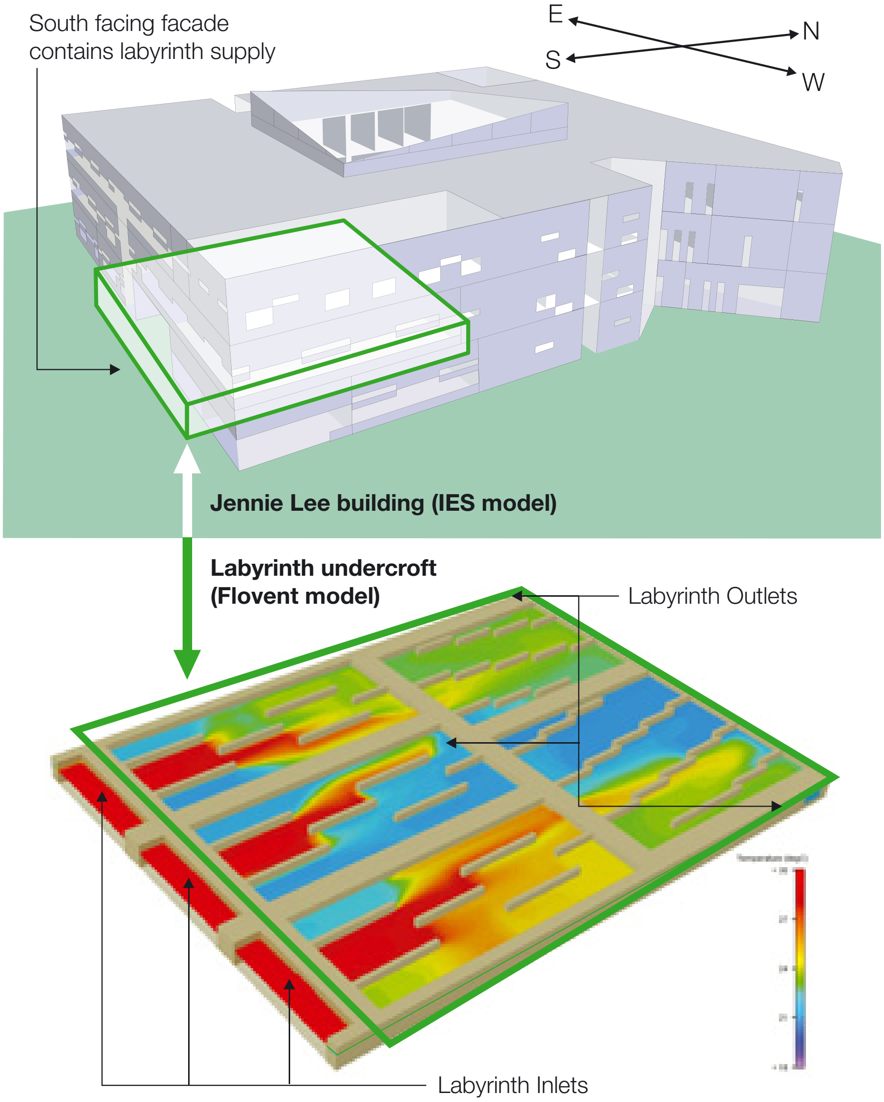


Figure 2 Computerised fluid dynamics model of the Jennie Lee faculty building labyrinth

The operation of earth tubes and labyrinths are still not easily predictable, and they vary in success from project to project. This is understandable as the passive system relies on many variables which are in continuous flux and change from site to site. The density of the earth, water table levels and sources of heat above and below ground, all effect the heat sink characteristics of the labyrinth.

If a basic fixed temperature assumption is used for the earth at a certain depth then the results will differ vastly to a variable earth temperature which takes into account the diurnal changes, seasonal variations, and the soil characteristic previously mentioned. At depths of below 10m the earth temperature is steady enough for such basic assumptions, but with a labyrinth or undercroft constructed at a depth considerably above this, we should consider a variable adjacent earth temperature to be more accurate. In this case, the location of the labyrinth within the building foundation indicated that a variable condition would provide the most accurate results.

Contradictions on the thermal 'benchmarking' of earth are prevalent. For example, the website www.actionrenewables.org states that "In the UK, several metres below the surface, the ground maintains a constant temperature of 11-13°C", while Kensa Engineering argue that "the ground temperature is around 10°C, the same as the inside of a fridge but there are obvious exceptions such as Bath and Southampton."

One of the conclusions of the analysis for the Jennie Lee Building was that temperature benchmarks for the use in computation models should be published by CIBSE or a similar organisation. The popularity of ground source heat pumps and labyrinths is now highlighting the need for some common conditions to base analysis on. This is increasingly important, as the passive cooling and heating achieved by any ground source energy system is considered in the Part L assessment.

Modelling and verification

A Dynamic Thermal Model (DTM) was created in the IES Virtual Environment software. It was used to calculate the thermal characteristics of the Jennie Lee Building, the undercroft and the surrounding earth down to a 10m depth. The intention was to create a large earth thermal mass which reacted dynamically with the weather creating varying boundary conditions for the building foundations and labyrinth system.

The IES DTM was assessed against empirical data and was found to have a high correlation for all depths. For the Jennie Lee Building, the temperatures in the adjacent earth zones at a 1m depth were used as the dynamic boundary condition for the labyrinth walls. Due to the proximity of the ground surface and the ground floor to the building, the temperature profile varied significantly and closely followed the external ambient.

Conclusions

One of the conclusions from both the empirical data and results attained from the IES model simulation is that the earth temperature stabilises around 12°C at a depth of 10m, as shown in *figure 3*. The observed temperature fluctuations and season shifts follow the external ambient temperature, with a significant time lag due to the ground's large thermal mass. The analysis also highlighted the need for a bypass system for periods in the autumn season when the thermal mass of the earth causes large lagging effects in ground temperature. When the temperature of the labyrinth supply is higher than the external ambient, low level vents in the atrium corridors are opened to supply fresh air directly into the atrium and adjoining zones.

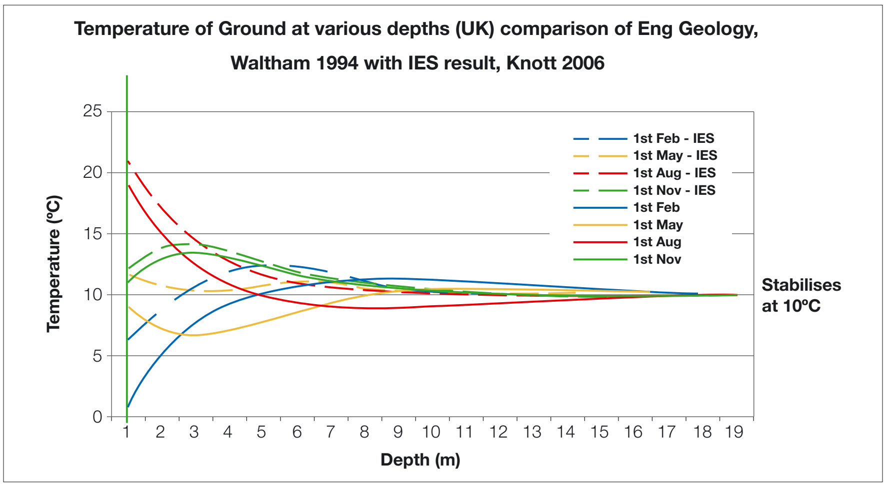


Figure 3 A ground temperature study showing stabilisation at 10°C

Due to the proximity of the labyrinth to the ground floor slab, the double effect of warmer than ambient ground temperatures and heat recovery prove beneficial in creating large energy savings in the heating season. This relationship is reduced by introducing a layer of thermal insulation on the ceiling of the labyrinth and serves to limit the undercroft/building coupling. This is a balancing act but the insulation is needed so that the earth heat sink effects in the cooling season are not compromised by heat recovery.

The amount of heat removed from the supply air was greater than 2°C for all external ambient temperatures above 24°C. This minimum temperature drop of 2°C was used in the Part L assessment for criterion one and three and therefore represented a conservative estimate of the reduced carbon footprint of the Jennie Lee Building.

Design guidance

The original target was for the labyrinth to be fully passive for the majority of the year. Wind and stack effects are expected to drive the air through the labyrinth with the fan providing draw only when the flow rate is not sufficient. In practice, the control of the fan and large pressure drops in the labyrinth will force the fan to run for a higher percentage of the year.

There are several issues that arise during construction that the constructors should be aware of. These include water collection in the labyrinth due to rain water, the subsequent problems of cleaning ready for use, and the need for compacted earth around the labyrinth. The execution of the labyrinth construction is often overlooked and the observation and testing of undercrofts once installed is needed to further our understanding of the success of projects.

Operational risks of condensation, fan noise and earth temperature should also be monitored.

Client: Open University

Architect: Feilden Clegg Bradley

Services: Structural engineering, building services engineering.

A question of coupling

On the air side there are two main types of system commonly used to pre-condition supply air – earth-to-air heat exchangers (earth tubes) and thermal labyrinths. However, each option has markedly differing degrees of earth coupling and operational characteristics. David Warwick runs through the key points and differences.

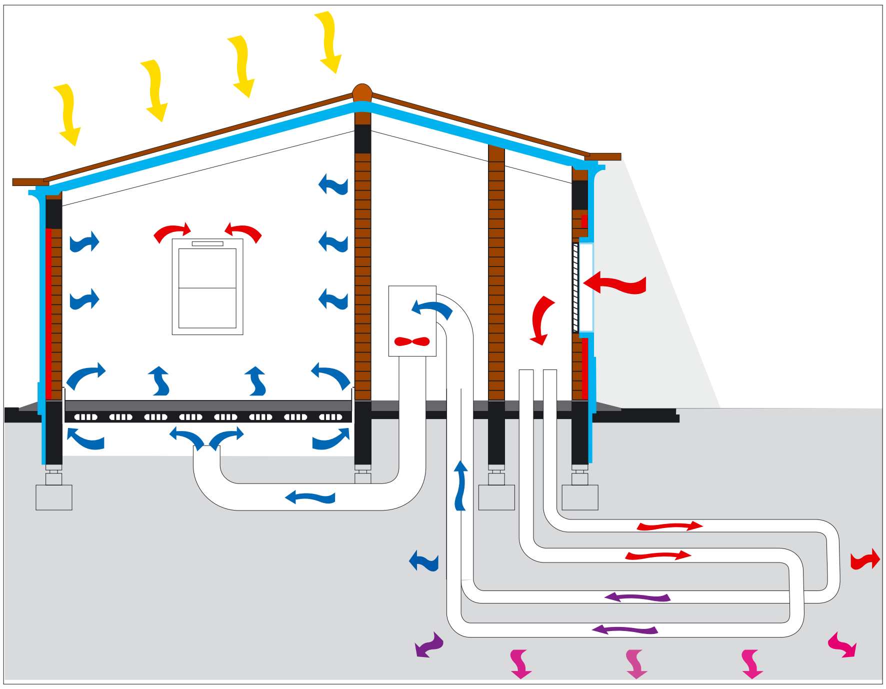


Figure 1 An earth-to-air heat exchanger can be equally well applied to domestic or commercial premises. Diagram courtesy of INIVE

Earth-to-air heat exchangers (ETAHE)

An earth-to-air heat exchanger draws ventilation supply air through buried ducts or tubes, as shown in *figure 1*. As the temperature of the ground below 3m is practically constant, it substantially reduces ambient air temperature fluctuations. It therefore provides space conditioning throughout the year, with the incoming air being heated in the winter and cooled in the summer by means of earth coupling.

System options

Systems can be driven by natural stack ventilation, but usually require mechanical means. In some cases air is circulated via air handling units, allowing filtering and supplementary heating/cooling. A simple controller can be used to monitor inlet and outlet temperatures, as well as indoor air temperatures. Ground coupling ducts or tubes can be of plastic, concrete or clay – the material choice is of little consequence thermally due to the high thermal resistance of the ground.

ETAHE are suited to mechanically ventilated buildings with a moderate cooling demand, located in climates with a large temperature differential between summer and winter, and between day and night. Location of the ducts in sand or gravel below the water level, with moving ground water, gives the best performance. However, the presence of ground water involves extensive sealing precautions.

Size and output

The optimum pipe length is a function of pipe diameter and air velocity. Small pipe diameters of between 200 and 300mm are thermally more efficient – they should be buried at a minimum depth of 2m and separated by 1-2m to allow heat dissipation. Optimum air velocity is typically 2m/s.

Under constant load, the cooling capacity of the ground may become exhausted and, therefore, generally it is not possible to meet high loads. With high loads, two separate duct systems could be considered – one for use in the morning and one for use in the afternoon. A bypass can be used to improve the performance of the system during periods when the ambient air temperature can meet the cooling requirements. In unoccupied periods when the ambient air temperature falls below the surface temperature in the ducts, night cooling can be used to pre-cool the system.

The ground temperature is based on 'undisturbed' conditions. When the ducts are installed beneath the building, or even within a built up area, this will be affected substantially. The effect that the duct has on the ground temperature also needs to be considered. Optimisation of the design requires a complete thermal simulation of the system.

In principle, these are low-cost systems – the excavation is the major part of the installation cost. Maintenance is minimal, but regular inspection and cleaning of the ducts is recommended.

Summary

ETAHEs can be used on new buildings or refurbishments to provide free cooling in the summer and pre-heating of air in the winter. They have high capital costs, but over the life of the system will yield substantial savings.

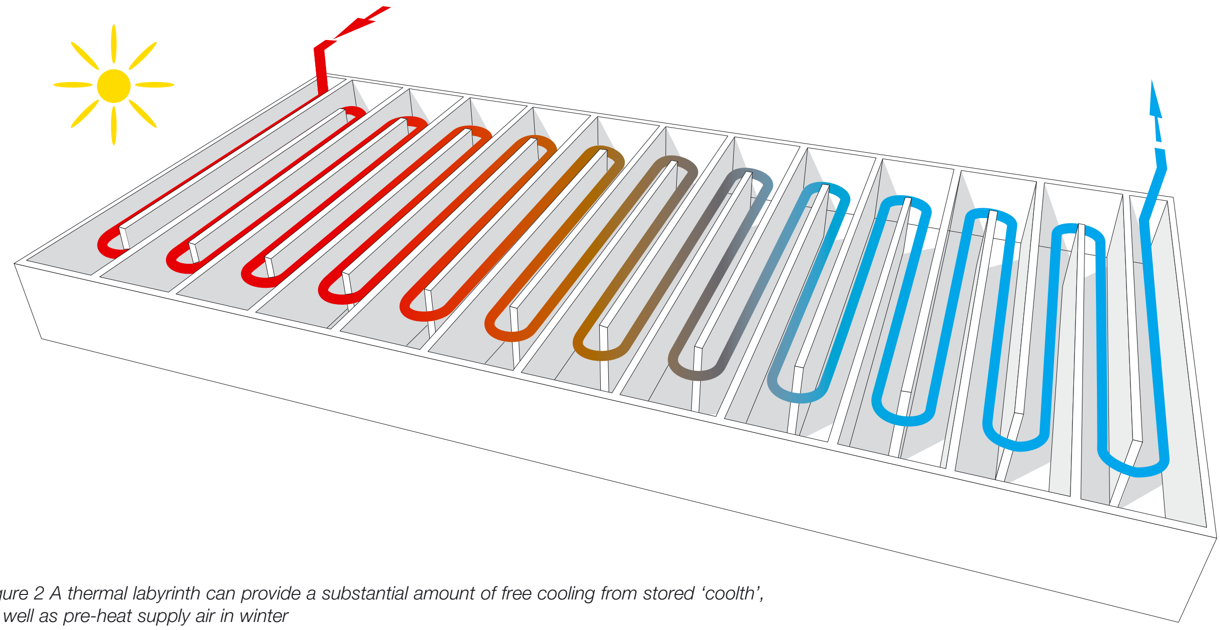


Figure 2 A thermal labyrinth can provide a substantial amount of free cooling from stored 'coolth', as well as pre-heat supply air in winter

Thermal labyrinths

A thermal labyrinth (see *figure 2*) decouples thermal mass from the occupied space, usually by creating a high thermal mass concrete undercroft with a large surface area. Decoupling the mass means it can be cooled lower than if it was in the occupied space. This stored 'coolth' can be used to condition the space for a number of days in hot periods.

Options

The labyrinth layout needs to balance optimum thermal storage with the air resistance of the system. Creating air turbulence, by increasing the roughness and incorporating bends, improves heat transfer. However, incorporating more bends may increase the air resistance beyond the point where the system can be part of a passive or naturally ventilated scheme.

Thermal labyrinths are suited to new, mechanically-ventilated buildings with cooling demand, located in climates with a large temperature difference between day and night.

Size and output

As labyrinths are often constructed directly beneath a building, only the sides and floor of the labyrinth are in contact with the earth and the top of the labyrinth is directly coupled with the building. The labyrinth needs to be well insulated from the building to prevent heat transfer.

The earth contact of the labyrinth does give the benefit of steady ground temperatures. However, the undisturbed ground temperature cannot be used due to the effect of the building and the operation of the labyrinth. Optimisation of the design requires a complete thermal simulation of the system.

A bypass can also be used to improve the performance of the system. When the ambient air temperature can meet the cooling requirements of the building, the labyrinth can be bypassed to retain maximum cooling for use during peak conditions. During the unoccupied period when the ambient air temperature is low, night cooling is used to 'charge' the labyrinth.

Running costs

Regular inspection and cleaning of the labyrinth are recommended, although thermal labyrinths are generally maintenance free. The major cost is when fan power is required to supply air through the labyrinth.

Summary

Thermal labyrinths can be integrated into the building structure to provide free cooling in the summer and pre-heating of air in the winter. They have high capital costs, but over the life of the building they will yield substantial savings by reducing peak demand for cooling and heating.

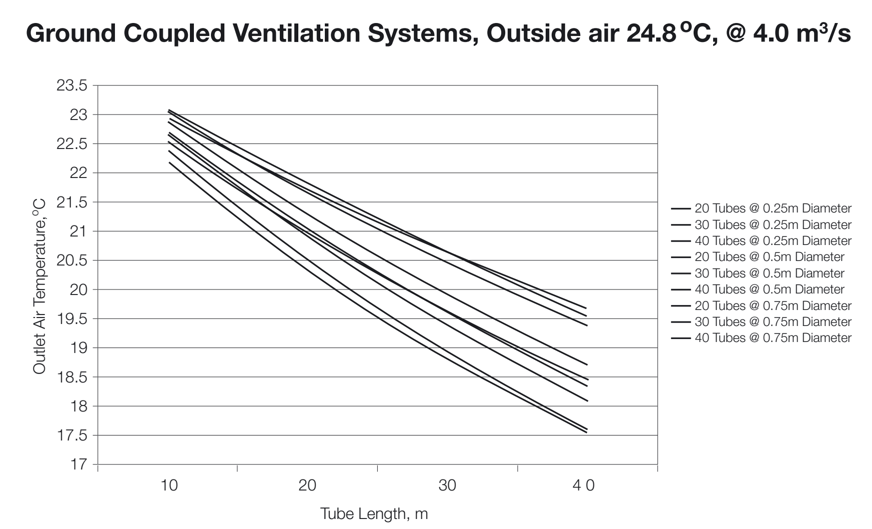
Double couple at Robert Burns Museum

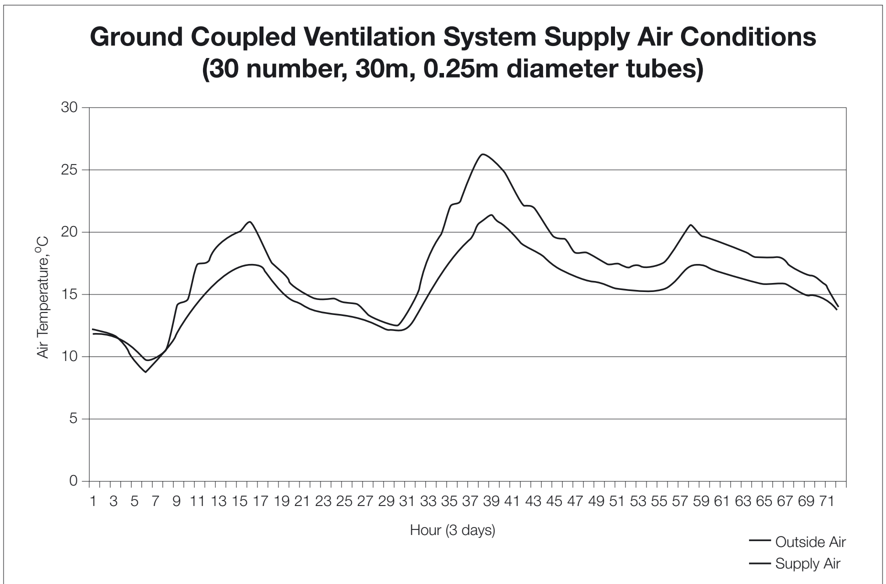
The redevelopment of the Robert Burns Museum offered an opportunity to use two earth coupling systems – a ground source heat pump (closed loop) and earth tubes. Scott Baird explains the advantages of earth coupling HVAC systems on the water circuits and air-side.

Sustainable building design should aim to provide a balanced solution, offering optimum working/living conditions alongside reduced environmental impact, both now and in the future. When you take the complete building lifecycle into consideration, there are many factors involved; from the location of the building, its design, subsequent operation and maintenance, to the construction materials and practices used, and how any future changes of use are addressed.

But energy consumption is an overriding concern for building services engineers. This mostly relates to the efficiency of the building in use, with the main measure being the carbon emissions for the building.

Previously the only way to sell this to clients was to demonstrate the economic efficiency of the design (whether this included renewable/alternative technologies or purely energy efficiency measures) in the hope they would invest the capital for the future and long-term delivery of the project. However, new regulations have changed this and there is ever-increasing consumer and political pressure for the construction industry to become more sustainable.





Figures 1 and 2 Computer modelling helped optimise the size and length of the earth tubes

At Buro Happold for many years we have been challenging ourselves to review and, where applicable, integrate energy efficient practice and renewables/alternative technology into as many projects as possible.

We still need to question how far we are taking our research as engineers. Are we fully understanding the long-term local and global impacts, or are we simply providing a solution to one issue without fully understanding the other impacts this may have?

For instance at the Robert Burns Museum we have looked at the viability of various technologies and system approaches. After a considerable amount of analysis we developed two sustainable systems for the project ground source heat pumps (GSHP) and earth tubes.

Earth coupling

Museums are generally energy intensive due to the very onerous environmental conditions required for artefacts and exhibits. With this in mind, we evaluated the existing Burns collection to identify any opportunities to house these within smaller volumes.

As the Robert Burns collection was largely manuscripts of his poetry and songs, there was potential to house the majority of it within museum display cases. Display cases are designed with a silicon drawer mounted below the exhibit. The silicon gel will absorb or release any humidity build up within the display case to retain a relatively steady state humidity level. As the cases are not fully sealed, the temperature within the case is controlled from the air within the main exhibition space.

The conditions required within the main volume of the exhibition areas were then able to be relaxed, which would provide long-term energy savings for the client, while allowing a more sustainable servicing approach to be adopted for the exhibition areas.

From a low energy sustainable design approach, it was thought that the best method would be to passively ventilate the building. This is not standard practice within a museum as they usually have controlled facades with little or no glazing and can be relatively deep plan in configuration. There was, however, an opportunity to investigate the possibility of labyrinth ventilation or earth tubes. Through a period of investigation a number of stumbling blocks appeared for the labyrinth ventilation, including possible gas issues, substructure depths and so on.

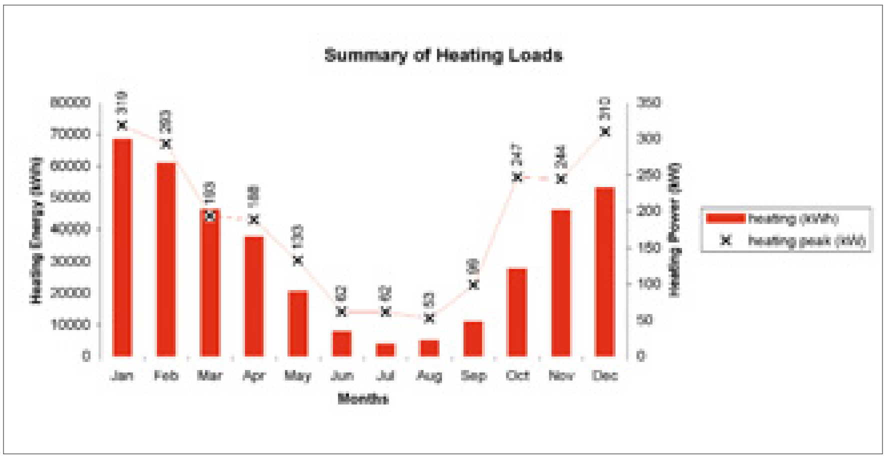


Figure 3 Monthly heating load characteristics

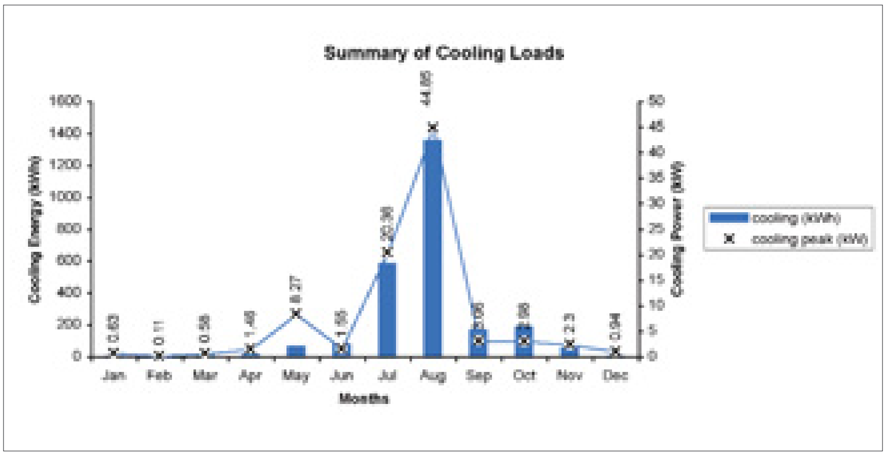


Figure 4 Monthly cooling load characteristics

Earth tubes were considered a better option. The principle of earth tubes is to bury a pipe made from materials with good thermal transfer properties at a depth of 2m or so where the ground temperatures are constant all year. As the air is drawn through the earth tube it is either pre-heated or pre-cooled, depending on the season.

The strategy uses an earth tube network to provide partially passive, low energy ventilation. For the exhibition spaces the air supply systems will be the primary source of heating or cooling through heating/cooling coils within the air path of the earth tubes. This will also minimise the need for any wet services in the exhibition areas where artefacts are located.

Ventilation within the exhibition areas is achieved through natural ventilation using the buoyancy of the air rising to high level extracts within the exhibition areas. This in turn pulls the air through the earth tubes to make up for the air that has been extracted. In periods of low external pressure, low-speed fans induce the air through the earth tubes into the exhibition areas. Other areas of the building, with the exception of the toilets and kitchen, are naturally ventilated. The earth tube ventilation system supplies the vast majority of ventilation.

The comfort-controlled exhibition spaces are serviced via ten ventilation earth tubes and low-speed supply fans. The earth tubes run in soft ground where air can easily absorb heat or cool due to surface contact with the soil. The tubes run from the integrated architectural landscaping feature to the sunken external plantroom where air is treated and supplied to the building.

Supply fans in the sunken plantroom are mounted in line with filters, cooling coils and LTHW heating coils.

Fans only operate when there is insufficient wind pressure or natural buoyancy to allow the air to be passively pulled through the earth tubes.

To improve the efficiency of the earth tubes it was also recognised that air turbulence within the earth tube would allow maximum thermal transfer to take place between the solid surfaces of the earth tube and the air passing through. Turbulence was generated by introducing bends in the earth tube paths before they entered the sunken plantroom.

After the air is treated within the sunken plantroom, it is transferred through supply branches to insulated floor voids. Supply duct branches terminate in the floor void, creating a positive pressure. Supply diffusers will be mounted in the floor of the comfort controlled exhibition spaces, allowing the air to be displaced into the room. A solar thermal wall made from fire clay brick has been provided in the exhibition area to improve the thermal mass and provide further stability to the rate of change within the museum environment.

From the modelling carried out it was considered that for a 25m length buried at 2m, a 4°C temperature difference could be achieved. This would allow the pre-heat or pre-cool to reduce the coil sizes and loads so that the extremes and plant sizes could be vastly reduced.

Smaller diameter tubes were investigated, as these would provide a more efficient transfer of energy due to the greater air to solid surface contact. However, having smaller diameter earth tubes also means that more of them are needed to provide the same volume of air, and the spatial requirements would increase due to the spacing between earth tubes. In the end, based on the available areas, we were able to use ten 500mm-diameter (internal) earth tubes, leaving a 2m spacing between tubes.

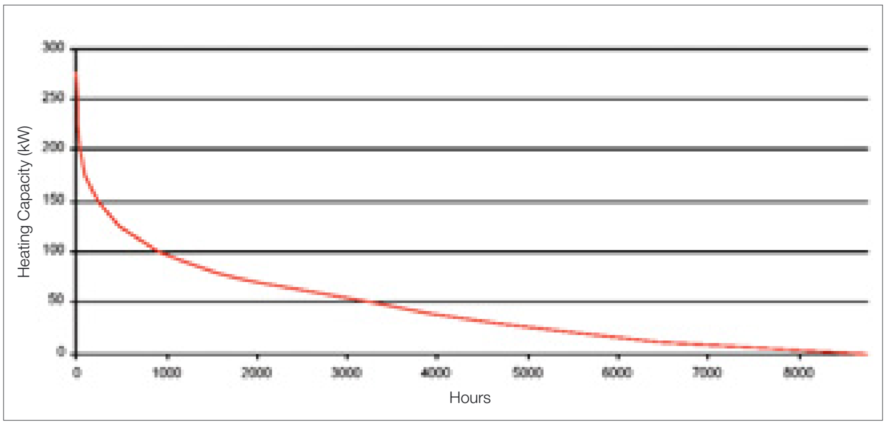


Figure 5 Museum heating duration curve

Geothermal energy

Initial feasibility calculations showed the possibility of applying a vertical closed loop ground source heat pump (GSHP) to provide heating and cooling for the new Burns Museum. We examined both the adoption of GSHPs to meet part of the heat load (in conjunction with supplementary heating), and a GSHP sized to meet the entire load.

A short review of the geology and building heating and cooling loads was followed by a simulation of a number of GSHP systems. A review of the possible size of the ground loop heat exchanger, external area required and the operational savings, both in terms of running costs and carbon dioxide, was provided from the model.

To analyse the geology down to 100m, the depth typified by the installation of a vertical GSHP system, it is usually possible to use data from the British Geological Survey (BGS). Unfortunately there are no suitable deep borehole logs in the vicinity of the site.

Using a combination of local geological maps and literature we assumed that the prevalent bedrock is sandstone with bands of Westphalian coal measures.

Whilst coal has a relatively poor thermal conductivity, sandstone has a higher value more suited to higher performance installations.

However, as there is some doubt regarding the exact geological sequence and relative depths of the respective strata, it was considered that a thermal conductivity test by a specialist GSHP contractor was needed to confirm the suitability of the site for a closed loop GSHP. This reduces the cost risk in the procurement of the system and, if the ground conditions are deemed suitable, enables the system to be optimised using insitu data.

Heating and cooling review

A dynamic thermal model was completed for the building using the building simulation software, IES. A summary of the monthly heating loads are shown in *figure 3*, whilst the cooling loads are shown in *figure 4*.

It can be seen that the heating loads, both in terms of peak (kW) and energy (kWh), are far greater than the cooling loads. Using the example weather year for Glasgow, the peak heating load of 319kW occurs in January, whilst the total annual heating energy simulated is 386,934kWh.

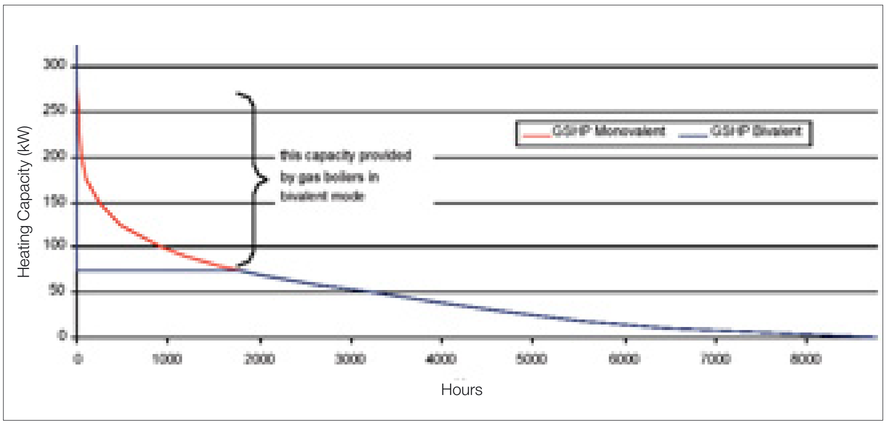


Figure 6 GSHP heat duration curve – monovalent versus bivalent

The peak cooling load of ~45kW occurs in August and the annual cooling energy required is 2,550kWh. As a consequence, the GSHP design will ultimately be led by the heating requirements in the new building.

The building heating profile can be further analysed by plotting the heat duration curve, which is shown in *figure 5*. This highlights the infrequency of some of the higher heating loads; particularly above 75kW. Although 75kW is less than 25% of the total peak load, over 83% of the total heating requirements over the year can be provided with this capacity.

GSHPs are generally more expensive per kW installed than conventional systems. From this basis, and because the higher heat loads can be infrequent, it is sometimes more cost-effective to reduce the capacity of the GSHP and to use cheaper plant to provide supplementary heat at colder times of the year. This is often called bivalent heating, as opposed to monovalent where the heat is provided from one source only. This way, the capital costs can be minimised whilst the majority of the operational benefits can still be realised.

Figure 6 shows the heat duration curves for a monovalent and an example bivalent mode, where the GSHP provides 75kW of the heating load and the remainder of the load is provided with gas-fired boilers. This gives an example of how the proportion of the heating can be split in the two modes.

GSHP analysis

Generally larger GSHP systems are more suited to balanced heating and cooling loads, so heat abstraction from the ground loop heat exchanger (GLHE) in the heating mode can be replenished during the summer months, ie through heat rejection in the cooling mode. However, GLHEs can be optimised to allow for heating only or heating dominated applications, by ensuring that both the cumulative length is adequate and the spacing between the boreholes is adequate to minimise thermal interference and ensure thermal capacity in the long-term. The sizing of the GLHE is very important, as this is the greatest proportion of the total cost of the GSHP.

This study firstly simulates the effect on the cumulative length of the GLHE in monovalent mode with two different borehole spacings, and then two bivalent systems with two different borehole spacings. The different simulations are summarised in *table 1* (see page 43).

To enable the simulation, the following assumptions have been made:

- Ground thermal conductivity of 2.3W/mK
- GLHE return temperature never falls below -2ºC in the heating mode to ensure continued system performance
- Flow rate of ~0.15m^3/hour/kW extracted to be maintained at all times
- Each borehole is 100m deep, which may change depending on the bedrock and the consequence drilling conditions.

Each simulation will be run for 20 years to ensure long-term performance of the system.

Results

Ground loop heat exchanger length

This is the cumulative length of the boreholes required for each proposed GSHP system. The results of the simulation for the different modes are shown in *figure 7*.

Figure 7 shows the benefit in this case of maximising the borehole spacing due to the heat dominated load. The shortest cumulative borehole length is 4,350m for the 75kW bivalent system with 8m spacings. Assuming a nominal length of 100m for each borehole in the GLHE, this equates to 44 boreholes. The monovalent GSHP system has been calculated to be only 1,700m longer or, assuming a nominal borehole length, requiring only 17 further boreholes. There is very little difference between the 125kW bivalent and 325kW monovalent system.

Configuration	Borehole spacing	Heating capacity	Cooling capacity	Supplementary heating capacity
Monovalent				
Compact GLHE	6m	325kW	45kW	0kW
Low density GLHE	8m	325kW	45kW	0kW
Bivalent				
Compact GLHE	6m	75kW	45kW	250kW
Low density GLHE	8m	75kW	45kW	250kW
Compact GLHE	6m	125kW	45kW	200kW
Low density GLHE	8m	125kW	45kW	200kW

Table 1 Simulation parameter summary

External space requirements

The external space required for the three suggested systems is summarised in *figure 8*.

This highlights the extra area required for the monovalent systems, but also between different borehole spacings. Although fewer boreholes are required for the respective 8m spacing systems, extra external area is still required.

Operational savings

In each case, the simulations also enable the electricity needed to run the GSHPs to be calculated. For this set of calculations the following assumptions have been made:

- Electricity unit price: 8p/kWh
- Gas unit price: 2.5p/kWh
- System efficiency gas fired heating: 85%
- System coefficient of performance conventional electric chiller: 3.

The calculations can be compared to a conventional gas-fired heating and electric chiller cooling plant, as shown in *figure 9*. In the case of each bivalent GSHP system, conventional plant, efficiencies and utility prices are used to provide supplementary heat.
No supplementary cooling is required as even the smaller bivalent GSHP can cover the entire cooling load throughout the year, as this does not coincide significantly with heating loads elsewhere in the building.

As expected, the savings are very similar for both borehole spacings for each system so an average reduction in sterling and in percentage terms is shown in each case. The savings between the different systems are less marginal, with the monovalent system offering the greatest potential for operational savings at 27% and £3,105 per annum.

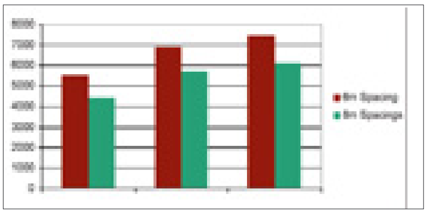


Figure 7 Ground loop heat exchanger length comparison

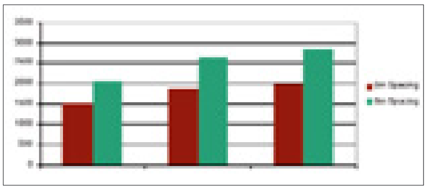


Figure 8 External area: comparison

Carbon dioxide savings

Figure 10 shows the simulated carbon dioxide emissions that will be realised with each GSHP system and also the conventional plant total. There is again very little difference between the estimated reduction in emissions for different borehole spacings for each system so an average is shown in each case. All the GSHP systems show a possible reduction of over 40% versus a conventional system, with the monovalent option offering the largest saving at 48% or approximately 42 tons CO_2 per annum.

Conclusions

In conclusion, the adoption of a GSHP at the Burns Museum offers the potential to reduce both the operational costs and carbon dioxide emissions of the space heating and cooling element of the building. All the systems modelled offered significant carbon dioxide reductions of over 40% versus conventional plant.

In addition, there are significant estimated operational savings of over 20% in each case. The earth tubes will significantly reduce the ventilation load, both in terms of fan energy and heating/cooling input. It is likely that 60% of the cooling costs will be removed, as the pre-cooling provided from the earth tubes at peak external temperatures will reduce the air temperature to a suitable level for the exhibition area.

The building space conditioning is dominated by the heating requirement. A large borehole spacing has significant benefits in terms of the number of boreholes needed, even if this does mean a larger external area for the borehole field.

The simulations highlighted that the reduced capacity of the bivalent GSHP approaches did not match an equal relative reduction in the size of the ground loop heat exchanger and the resultant space needed.

The heating profile remains relatively high, even during unoccupied periods, due to the sensitivity of some of the exhibits. Therefore, there is reduced benefit in applying a bivalent GSHP at the site, due to the high frequency of heating loads at approximately 30% of the peak capacity. This would improve if the heating requirement during unoccupied periods were to reduce significantly. This limited potential is also exaggerated by the imbalance between heating and cooling loads over the year.

The GLHE is the most expensive element of almost all GSHP installations so this aspect will undoubtedly reduce the cost effectiveness of the bivalent approach. In addition, the bivalent approach will add complexity to the system and supplementary heating plant will still be needed.

To confirm the optimal approach it is advised that both the bivalent 75kW and monovalent 325kW GSHP systems are costed, including estimations for any supplementary plant that will still be needed. The results of this may confirm that the monovalent approach is the most cost-effective way to adopt a GSHP for the new building. After the insitu thermal conductivity test is carried out to confirm the thermal properties at the site, an informed judgement can be made.

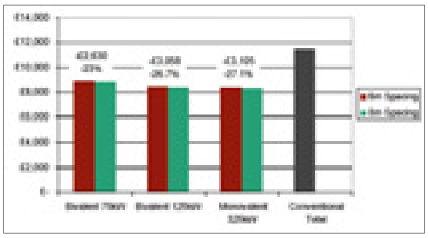


Figure 9 Estimated annual operational savings per annum

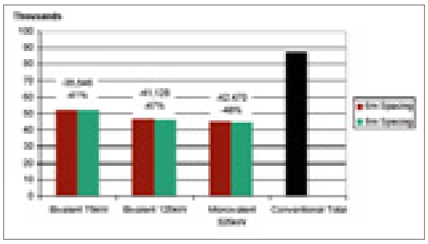


Figure 10 Estimated carbon dioxide savings per annum

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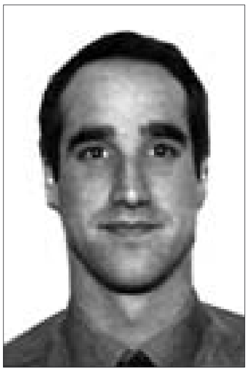

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