MSc Thesis:

'An Investigation into Ground Source Heat Pump Technology, its UK Market and Best Practice in System Design'

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Declaration of Author's Rights:

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Abstract:

Ground Source Heat Pump (GSHP) technology has the potential to assist the UK government reduce CO_2 emissions associated with domestic space and water heating requirements. Only a very small number of these units are installed in the UK however. At levels far lower than in some other European nations. The running cost and CO_2 emissions reductions achievable by these systems will only be obtained if they are designed suitably to allow for efficient, reliable operation and competitive installation cost; therefore not damaging fragile customer confidence.

This thesis aims to address the current status of the UK GSHP industry. By constructing case studies of the market in Austria, Germany, Sweden and Switzerland valuable comparison with the situation in the United Kingdom was obtained. A deeper investigation into the significance of UK specific market barriers followed, including the construction of a matrix to compare statistics from the five nations. To gain a greater insight from those involved in the UK GSHP industry a questionnaire was designed and circulated. In order to assess design best practice of vertical GSHPs borehole length sizing programmes were obtained and reviewed with performance analysis of various scenarios then undertaken using the simulation tool TRNSYS.

From the market assessment it is shown that GSHP development in the UK is in the order of twenty years behind the other nations reviewed and receives lower levels of support from government and utilities. A significant inhibitor would appear to be the legacy of previous fossil fuel security in the UK. Feedback from the questionnaire suggested high capital costs were also a factor.

Performance of the sizing tools varied, with several incidences of undersized boreholes according to the TRNSYS results. It is recognised that fully understanding the causes of these discrepancies will require further study. The significant influence of ground conditions on sizing was highlighted while distribution temperature of the heating system was concluded to be a bigger influence on system efficiency than ground temperature depletion. Financial viability varied with the base conditions specified in the analysis. It is hoped that this research has outlined factors in market stimulation and design which will facilitate growth of the UK GSHP market.

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Introduction:

Heating accounts for forty-seven percent of the United Kingdoms' total carbon dioxide emissions, three quarters of which is attributed to the domestic sector [44]. Ground Source Heat Pumps (GSHPs) are a technology which can be utilised to offer low carbon heating and hot water provision in a domestic market currently dominated by the use of fossil fuels. As such these systems may have a role to play in meeting targets from the governments 2006 energy review 'The Energy Challenge' [42] to:

- Reduce carbon dioxide emissions 60% by 2050, with "real progress" by 2020.
- Ensure "every home is adequately and affordably heated" thus helping to reduce and eradicate fuel poverty by 2016.
- Reduce energy import reliance.

However by 2005 there were only in the order of five hundred units installed in the UK [32] a figure dwarfed by other European nations. It would appear that, from an energy perspective, government policy is more focused on renewable electricity generation and other means of reducing climate change impact from space and water heating such as combined heat and power systems and biomass combustion. With no specific government targets or stimulation measures for installed GSHP capacity set in the 2007 Energy White Paper. Through an investigation into the technology itself, its market and system design considerations this study aims to establish if ground source heat pump systems are worthy of greater consideration as a residential heating option and how best to maximise the potential of the technology.

The main body of the report is split into eight sections, covering three broad topics (shown in bold). The first two sections constitute the ***Literature Review***. Section one seeks to explain thermodynamically how a heat pump operates, its basic components and potential sources of low temperature heat. The term coefficient of performance (COP) is introduced and explained. From here issues such as how a unit is operated and integrated into a building heating system will be discussed alongside other related factors such as electrical requirements. An explanation of how a heat pump can reduce CO_2 emissions and cut running costs is also outlined. The aim of this section is to provide an outline of how the technology operates and current 'state of the art'.

Section two switches focus to systems which utilise the ground as a heat source. This covers all the factors which need be considered from ground thermal properties to piping materials. From here an outline of the myriad of different ground loop configurations available is given; from direct expansion and open loop groundwater configurations to more mainstream closed loop vertical and horizontal collectors. This section concludes with an outline of industrial, commercial and domestic opportunities for ground source heat pump systems. This information is valuable in the context of the design evaluation later in the study.

Section three and four consist of more focused data assimilation and analysis in order to conduct a ***Market Evaluation*** exercise. This attempts to explain the current status of the UK ground source heat pump market, focusing on domestic heating systems. In section three five market case studies are constructed. These seek to show the main trends, organisations and factors involved in the successful GSHP industries of Austria, Germany, Sweden and Switzerland and compare them with the less mature market found in the UK. These case studies contain many important lessons of what is required to promote the technology and build a strong heat pump market.

In an attempt to explain further exactly why the UK market is less developed than the other nations evaluated various perceived barriers are investigated in section four. These consist of the market factors highlighted in section three alongside reasons postulated in literature for lower levels of heat pump application in the UK. Each of these reasons is critiqued and a matrix constructed to compare key statistics from each nation relevant to each barrier. This should clarify the relative significance and impact of each.

In order to gain the opinion of those working in the UK GSHP industry on market barriers, opportunities and also design challenges a questionnaire was designed and sent to members of the UK Ground Source Heat Pump Association, Heat Pump Association and also system installers registered under the Low Carbon Building Programme. Feedback on the first two issues is presented in section four.

Sections five to eight consist of a ***Design Analysis*** exercise to establish what is considered best practice for vertical/borehole closed loop GSHP systems. Section five looks at relevant literature on the importance of accurate sizing and considerations which need to be taken into account in estimating a borehole length which can meet building demand. The various methods which can be utilised to produce a borehole length estimate are introduced as are technical developments in the field.

In section six various commercially available sizing programmes were obtained, either in full or demonstration version, and assessed. Firstly an attempt is made to clarify the underlying assumptions utilised in the programmes. This is built on by an analysis of the data required by each to produce a sizing and what information is obtained. An initial evaluation of usability is also conducted. This section also contains feedback on design methods utilised and major perceived challenges in the UK GSHP industry from the questionnaire circulated.

The main technical element of the study is outlined in sections seven and eight. These consist of two case studies broken down into various scenarios, for which results and analysis are delivered. The larger of the two is detailed in section seven; this consists of an evaluation of three sizing software packages GLHE-pro, GS2000 and EED, although only the limited demonstration version could be obtained for the latter. Performance of specified borehole lengths under different ground conditions, configurations and constructions are assessed. This is evaluated in terms of efficiency (COP), outline costs and long term temperature depletion in the ground using twenty year simulations produced with the programme TRNSYS. Section eight summarises a shorter case study focused on presenting a comparison of installation and running costs, and the main factors which make up these, between a ground source heat pump system and a gas condensing boiler.

Finally section nine will recap the main findings from each section of the study thus proving a better understanding of what benefits ground source heat pump technology can deliver in the UK and the way forward for ensuring they are achieved. An appendix is included to complement the main body of the report.

1. Heat Pump Technology Overview

1.1 Introduction:

1.1.1 Although this project is mainly focusing on Ground Source Heat Pumps (GSHP's) the underlying theory and components of heat pump systems are the same regardless of the heat source utilised. This section will therefore firstly outline the fundamental principles behind heat pump technology and build on this with a review of the key components of these systems (including refrigerants). Information on cooling applications, operation modes and ideal heat distribution systems will also be covered. Finally the potential for CO_2 savings will be clarified.

1.2 Thermodynamic Explanation:

1.2.1 The Clausius statement of the second law of thermodynamics states that it is impossible to operate a cyclic device in which the only effect is the transfer of heat from a cooler body (Tc) to a hotter body (Th). This still holds true but it has been found that the addition of an energy input can produce a net heat transfer from Tc → Th (figure one below).

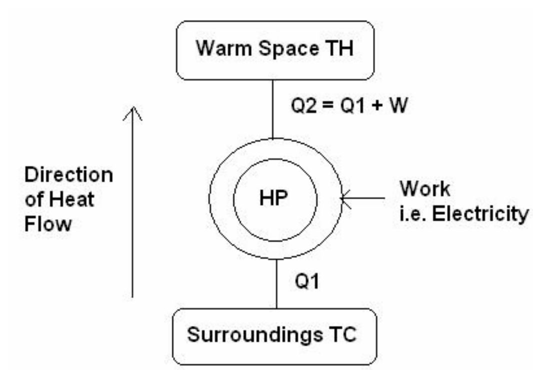


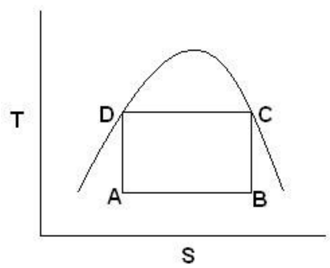
Fig 1. Basic Premise of a Heat Pump (reproduced from [1])

1.2.2 The first mention of exploiting this by means of a 'heat multiplier' is attributed to William Thomson (Lord Kelvin), in 1852 as part of his theory of the dissipation of energy, in which he outlined and designed a 'heat multiplier' to heat a room to a higher temperature than the ambient environment using less fuel than if burned in a furnace [3]. As such he had outlined the basic concept of a heat pump; a device which transfers heat from the surroundings to a warm space in order to maintain that space at a higher temperature than its surroundings.

1.2.3 Although there are several different thermodynamic cycles which can feasibly perform heat pumping, "the great majority of heat pump systems work on a vapour compression cycle" [7] and this is considered "state of the art" [5]. The principles of this will therefore be investigated in more detail. Other methods include absorption, adsorption, Vuilleumier, stirling cycles, single phase cycles (using air, CO_2, noble gases as a working fluid) and hybrid systems (of absorption and vapour compression cycles). The first two of these will be explained further in the Appendix section one.

1.2.4 Since heat transfer usually occurs from a hotter body to a cooler body (until they reach equilibrium) it can be seen that a heat pump is moving heat in a direction it would not normally travel. In this case it is helpful to remember that temperature is simply a term for heat energy. The heat energy, or Enthalpy[1] (H), of a body cannot be raised exempt for adding energy to it. A heat pump achieves this in the form of work for compression. This is in correlation with the first law of thermodynamics which states that it is always possible to convert any given quantity of mechanical energy into its equivalent heat energy.

1.2.5 **The Carnot Cycle:** Figure two below shows the ideal Carnot Cycle (2a) on a Temperature-Entropy (TS) diagram and equipment required to create it (2b).



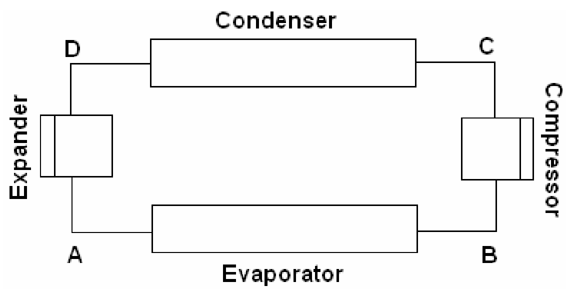


Fig 2a. & 2b. Carnot Cycle Explained (reproduced from [1])

This is a useful starting point for understanding the Vapour Compression Cycle. In 2a tracking the movement of a 'working fluid', which in this case is a refrigerant (in liquid/vapour form), form A→B and C→D 'isothermal' (i.e. constant temperature) reactions are taking place. These represent stages where heat is either extracted from a source (air, water, ground etc) or deposited in a sink (for a heat pump this could be a building). From B-C and D-A are 'Adiabatic' reactions where no heat is gained or lost although there is a temperature change. All stages in this process are assumed to be reversible.

1.2.6 In reality however this is not possible to achieve this ideal reversible cycle. Firstly difficulties are presented by trying to compress a two phase liquid and therefore evaporation will continue to the saturated vapour line. Secondly during the compression stage heat will be lost due to frictional losses. Furthermore the work output from the expander is relatively small compared to the work input during compression (due to a smaller specific volume) and therefore it is usually replaced by a simple throttle valve [1].

1.2.7 **The Vapour Compression Cycle:** This cycle is usually represented on a pressure-enthalpy diagram (figure three below) since it is composed of two constant pressure process and one constant enthalpy process.

[1] This is a thermodynamic property and consists of internal energy U + PV (pressure x volume).

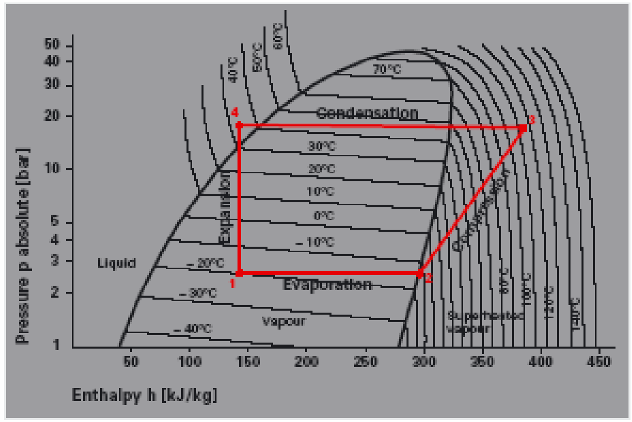


Fig 3. Vapour Compression Cycle on a Pressure/Enthalpy Diagram [5].

The Vapour Compression Cycle is basically a reversed Rankine cycle. The standard Rankine cycle is that used in a steam engine where some proportion of heat generated is utilised to drive an engine and perform work. This process shown above constitutes the working fluid moving in an anti-clockwise direction as opposed to the clockwise Rankine cycle.

1.2.8 The attraction of a heat pump system can be shown through calculation of its coefficient of performance (COP). This is a calculation of the systems steady state performance. For the diagram in figure three this is calculated as: -

Work utilised in compression = h3 – h2 = 390 – 300 = 90 kJ/kg
Heating effect from condenser = h3 – h4 = 390 – 140 = 250 kJ/kg

COP = Useful Heat (Th)/ Work Expended (Th-Tc) = 250 / 90 = 2.77

Therefore for every one kW of energy utilised 2.77kW of heat is generated. So where in a Rankine cycle it is expected that in utilising heat to drive an engine and produce work will have an efficiency of approximately 30% as expected reversing this process and using work to produce heat will conversely produce a reciprocal efficiency of 300%! It is therefore clear that a high COP value is desirable i.e. for a given amount of work as much heat as possible is delivered to the target area.

1.2.9 The heat pump itself is not ‘creating’ this extra heat but simply transporting it form a large low temperature ambient source, adding the heat produced from compression work and delivering a final amount to the desired hotter body i.e. building. This same principle can also be utilised to cool, and is the basis for refrigeration and air-conditioning systems. For cooling the refrigerant flow is reversed, i.e. the condenser acts as the evaporator and visa versa, heat is absorbed inside the building and deposited outside.

1.2.10 **Changes of State:** In order to understand this movement of heat in more depth a review of what happens during a phase change (change of state) occurs is important. A phase change is characterised by an abrupt sudden change in one or more thermodynamic properties, i.e. specific heat capacity[2], and a small change in thermodynamic variables such as temperature. Changes from solid to liquid and on to gas are known as first order phase changes. When these occur energy, in the form of heat, is absorbed or released depending on the direction of the change[3]. These reactions are termed endothermic if energy is absorbed and exothermic if energy is released. This amount of energy is fixed and typically significant [12].

1.2.11 In the cycle shown in figure three the heat is moved by the refrigerant. In heating mode energy is absorbed into the system within the evaporator coil (1→2), the refrigerant is changed from a low temperature/pressure liquid and vapour mix to a low temperature/pressure vapour through the addition of heat from the ambient source. In some cases this can cross the saturated vapour line (figure four) and become superheated, this will cause flow control devices to admit the correct volume of refrigerant to the coil. This vaporisation occurs since the external temperature level is higher than the boiling temperature of the working fluid, which is subject to pressure. If no superheating is involved this process is complete at the saturated vapour line (2). The vapour then flows to the compressor where it is transformed into a high temperature/pressure vapour and discharged to the indoor coil. During condensation the heat picked up during evaporation and added during compression is deposited to the indoor heating distribution system (water/air), which is initially at a lower temperature, and lost from the refrigerant (3→4). Warm high pressure liquid leaves the indoor coil (4) and undergoes a temperature/pressure drop by passing through the throttle valve (4→1) it drops below the temperature of ambient heat supplied and this drives the heat transfer during evaporation and hence the cycle repeats itself. Heat exchangers are used to facilitate heat transfer to the evaporator and from the condenser.

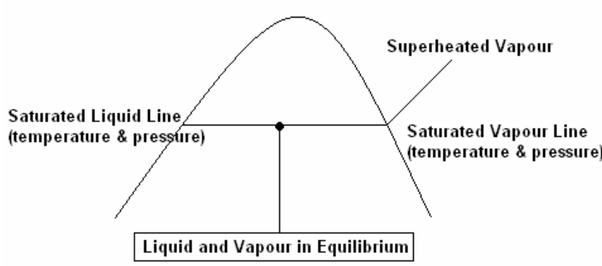


Fig 4. Liquid/Vapour and Mixed Zones

1.2.12 **Heat Generation by Compression:** It has already been mentioned that heat is given off during compression (1.2.9). The first law of thermodynamics relates to the fact energy cannot be created or destroyed, but simply transferred from one form to another. So in this case the energy input in the form of work (electricity) for compression is simply converted to heat energy. This is then added to the energy picked up from the surroundings.

[2] C, Measure of the heat energy required to raise the temperature of a given amount of a substance by 1 degree (Kelvin or Celsius)
[3] This Enthalpy change was previously termed latent heat

1.2.13 Since with pressure and volume all other thermodynamic properties are fixed, including temperature (T= f (p, v)) a useful analogy, using air, to explain how this energy transfer occurs is as follows. A given space, for example the size of a football, has X units of heat. The air within this volume is then compressed down to the size of a marble; however it still contains the same X units of heat. In this form however the heat energy is more concentrated and therefore the average heat per volume is far higher. In addition to the original X units of heat the additional Y units converted from work to heat during compression are added (total X+Y units of heat). If this volume of air is then placed in contact with a body with a lower per volume concentration of heat, i.e. cool water in a heat exchanger for the distribution system, the heat is lost to the water until they are at equilibrium. When expanded back to the size of a football the heat energy per unit volume of the air is less than the original X units and can therefore absorb heat from the surrounding area. To recreate the vapour compression cycle simply substitute air for refrigerant as the working fluid.

1.2.14 Utilising a liquid as the working fluid instead of air is preferable since it is “closer to the isothermal conditions of taking in and giving out heat of the ideal Carnot cycle” [3]. Air is a ‘bulky’ working medium and has higher power demands associated with larger frictional losses. Furthermore liquids have a greater “latent heat of vaporisation”[4] [3] than air and therefore heat pump units can be more compact. These are some of the main reasons behind the adoption of the vapour compression cycle for heat pumps as opposed to a reversed Joule cycle using air as the working fluid.

1.3 Low Temperature Heat Sources:

1.3.1 Throughout the thermodynamic explanation reference is made to absorbing heat from the ambient area, environment or surroundings (for a heating purpose). This will now be explained in more detail, “the technical and economic performance of a heat pump is closely related to the characteristics of the heat source” [7]. An ideal heat source will be: -

- High and stable during the heating season.
- Abundant.
- Not corrosive or polluted.
- Have favourable thermo-physical properties.
- Require low investment to exploit.
- Have a high specific heat per unit volume (so there is only a small temperature drop during extraction).

There is a variety of different sources from which a heat pump can draw heat during the evaporation process in the outer coil. The option selected will depend on local circumstances, the location of the building and its heat demand.

1.3.2 The most popular heat sources are air, water (i.e. lake, pond, ground) or the ground (soil, rock). Systems have been designed to take advantage of all types of different heat sources however such as exhaust air, sea water, waste water and effluent. Since heating demand will be highest however when

[4] Enthalpy Change

outside temperatures are low, how is it that heat is available from these sources?

1.3.3 There is a popular conception that 0℃, the temperature at which water freezes, is the limit of 'coldness' and therefore no heat can be extracted at this temperature or below whether it be from the earth, water or air. It is possible that we are conditioned to think in this way since human body temperature needs to be maintained at 37℃ and as we move away from this value we sense discomfort and 'coldness'. However it is only at -273℃ (absolute zero on the Kelvin temperature scale) that a substance is devoid of all temperature and energy. Therefore the environment can be seen to be a "surrounding cushion of useful heat that makes the operation of a heat pump possible" [3]. So even at 0℃ there are still 273 units of useful energy in the environment. This energy store in the environment is low grade however (as opposed to electricity for example which is high grade) and for this reason needs to go through the heat pump process before it can serve a useful purpose i.e. heating.

1.3.3 The level of temperature of the outdoor source will affect the heat pumps performance however. The lower the temperature (and therefore pressure) of the source the more work will be required by the compressor in order to raise it to the required level i.e. that set by the system thermostat. This drop in efficiency[5] is explained further since as the outside temperature drops the vapour density of the refrigerant also falls and suction pressure decreases. Therefore the compressor pumps less refrigerant which, by weight, is carrying X units of heat. Therefore the compressor needs to work harder, expending more work input, to meet the set heat demand [2]. Having a low compression ratio, which is linked to temperature differential, is desirable since "losses through the clearance volume and leakage through cylinder wall are kept low" [3] i.e. the lower the compression ratio the higher the efficiency or COP (discussed in 1.2.8) as shown by the output table below (figure five).

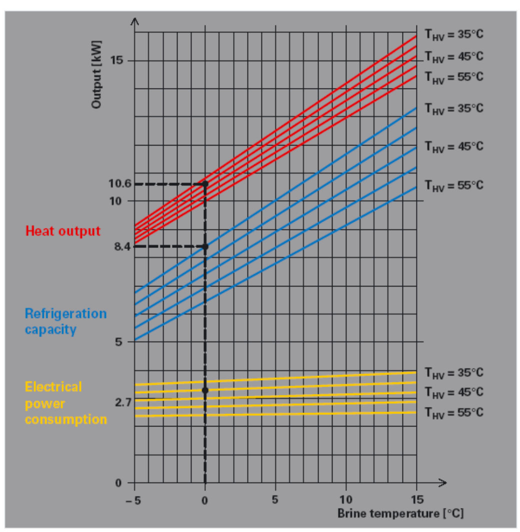


Fig 5. Heat Pump Output Diagram for Different Source and Sink Temperatures [5] (this shows the relationship between heating/cooling/electrical input and temperature)

[5] Which also effects heat pump capacity

On this principle, and as shown above, reducing the end point temperature of the building will also increase efficiency. This has consequences for heat distribution systems which will be discussed in more depth in section 1.8.

1.3.4 In terms of calculating heat pump performance we do not just consider COP but also its efficiency over time or Seasonal Performance Factor (SPF). This will take into account energy for circulation, variable loads and source temperatures over time and is a useful method of comparing the performance of a heat pump with more conventional heating systems.

1.3.5 Since this report is concentrating on GSHP technology more information will be provided on utilising the ground as a heat source in section two. It is however useful to understand that air and water sources are also utilised. Air is of course freely available and actually the "most common source for heat pumps" [11]. However in many cases Air Source Heat Pumps will have a lower SPF than those using water or the ground as a heat source, due to more variable temperature ranges (see figure six) which result in less operation time at the optimal design point, lower capacities at low temperature and additional energy requirements to defrost the evaporator coil in these conditions. This involves running the unit in reverse to provide heat to the outside coil. Air also has a lower thermal mass than the water/ground which hampers heat transfer.

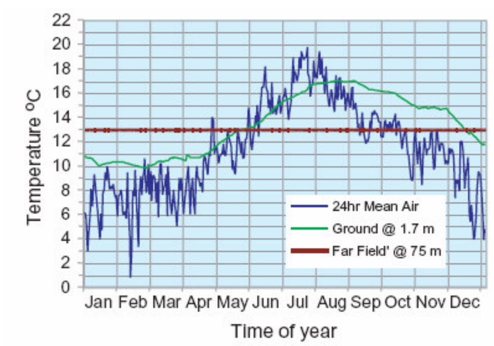


Fig 6. Temperature Variability between Ground and Air (Falmouth 1994), [11]

1.3.6 Water is a viable option for a heat source provided it is deep enough to prevent a temperature equalisation between top and bottom of the abstraction source. It is clear however that this will only be an option if a suitable water source if nearby. As previously mentioned sea-water can be utilised since at a depth of 25-50m there is a constant temperature of 5-8°C; this is mainly only considered for large systems however. In addition groundwater systems can be utilised which have an 'open loop' configuration if suitable aquifers[6] are present for extraction and re-injection, this will be explained further in section two.

1.3.7 In all these sources "the main thermal recharge for horizontal systems is provided for mainly by solar radiation to the earth's surface" [6]. The exception to this rule is when heat pumps utilise exhaust building air, waste water such as effluent or cooling water/waste heat from industrial process.

[6] An underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, silt, or clay) from which groundwater can be extracted

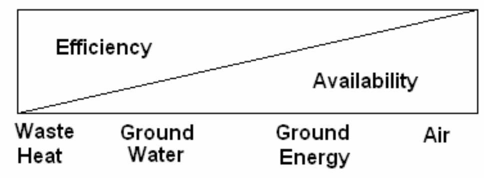


Fig 7. Efficiency and Availability of Heat Sources [5]

The table below shows the various different possible heat sources and the likely temperatures at which they can be found: -

Table 1. Commonly Used Heat Sources [7]

Source	Temperature Range (°C)
Ambient air	-10 - 15
Exhaust air	15 - 25
Ground water	4 - 10
Lake water	0 - 10
River water	0 - 10
Sea water	3 - 8
Rock	0 - 5
Ground	0 - 10
Waste water and effluent	>10

1.4 Heat Pump Components:

1.4.1 In this section the basic components of which any heat pump system will comprise are reviewed. The components selected are vital to the operation and efficiency of the unit as a whole.

1.4.2 **The Compressor:** This has already been mentioned on several occasions and is affectively "the heart of any heat pump" [5]. Improvements in compressor technology have resulted in improved heat pump performance as shown in the diagram below (figure eight):

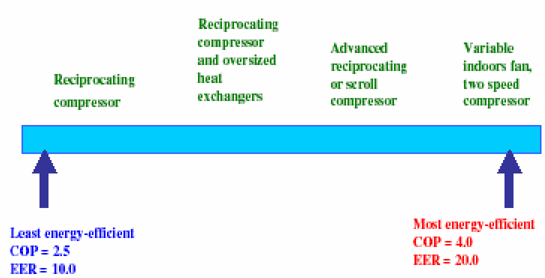


Fig 8. Efficiency for Different Types of Compressor (for an open earth-energy system with source temperature of 10ºC) [6]

1.4.3 Modern hermetically[7] sealed scroll compressors have brought improved system performance, longevity and quietness (6 dB (A) reduction) compared to the piston compressors previously utilised in heat pumps. The hermetic seal also means that maintenance is minimal. The compression process was briefly alluded to in 1.2.12/13. This will now be built upon using an explanation of how a scroll compressor operates. The compression process using a spiral compressor uses two lifting screws. The excentric drive of one of these spirals encloses two opposing crescent volumes of refrigerant. These are moved from the outside in and reduced in volume by a rotary movement. The layout of the compressor and prevention of oscillating masses minimise vibration and gas soundness between the individual volumes elements, this is ensured by a film of oil [5].

1.4.4 The compression ratio (mentioned in 1.3.3) can be defined as:

CR = absolute discharge pressure / absolute suction pressure

This ratio will vary for air conditioning/cooling and heating applications due to differing temperatures and suction pressures. Adequate lubrication is fundamental for good compressor performance and should mixing with refrigerant occur to a suitably high concentration this can result in failure.

1.4.5 **Reversing & Check Valve(s):** These change the direction of the refrigerant flow within the system. This can be actuated via a four way solenoid valve. This in required for heat pumps which offer both heating and cooling. For heating the inner coil acts as a condenser and the outer coil an evaporator, in cooling mode however the refrigerant flow is reversed and the roles of the inner and outer coils switch.

1.4.6 It is important that the flow of refrigerant is controlled and metered to the coil which will be absorbing heat (acting as the evaporator). The mass flow rate of the refrigerant (m kg/s) is a crucial factor in heating/cooling capacity as shown in the two equations below (with respect to figure three):

Refrigeration Capacity = m (h2-h1)   Heating Capacity = m (h3-h4)

Two flow control valves and two check valves, one set for each coil, is a common configuration. Check valves serve the function of ensuring that the refrigerant flows through the flow control device or bypasses it completely. These only open when pressure is applied in the correct direction.

1.4.7 **Accumulator:** This plays a key role in maximising the performance of the heat pump. Compressors are designed to compress vapours and not liquids (as mentioned in 1.2.6), excessive liquid returned to the compressor could for example could cause “the possible dissolution of the compressor lubrication oil” [1], washing out of bearings and cause loss of oil (slugging/oil pumping). The accumulator acts to trap the cool low pressure refrigerant and allow liquid to evaporate prior to entering the compressor i.e. it “acts as a reservoir to hold excess oil-refrigerant mixture and return it at a state that the compressor can handle” [2]. The accumulator is usually located after the reversing valve and before the compressor.

[7] Airtight

1.4.8 The accumulator can also be coupled to a heat exchanger to increase efficiency. An accumulator-heat exchanger has three key functions [2]:-

- Add ‘subcooling’ to high pressure liquid on its way to the evaporating coil. This is performed to reduce the loss in refrigeration/heating capacity since a proportion of the liquid refrigerant is evaporated to cool the remaining liquid to evaporation temperature (this is called flash gas).
- Provide a positive separation of low pressure liquid and vapour from the evaporating coil so only dry, nearly unsaturated, vapour reaches the compressor suction (low pressure liquid boiled off in shell).
- Assures positive oil return to the compressor at all times during operation.
- Lowers temperature differential and therefore compressor load, with a resultant performance factor increase of approximately 5% [5].

Saturated vapour moves to the upper part of the shell while cold liquid refrigerant will accumulate at the bottom.

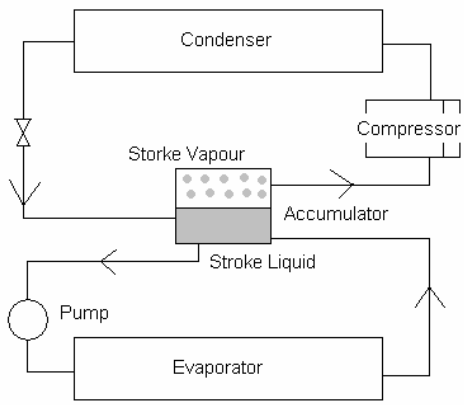


Fig 9. Heat Pump Cycle with Accumulator (reproduced from [1])

1.4.9 **Coils and Pipes:** In an air source heat pump indoor and outdoor coils act as the evaporator and condenser. These have a large surface area for heat exchange and are sized to balance system performance and maximum efficiency. If specified the coils will be engineered for both heating and cooling. For a water based system stainless steel plate heat exchanges are primarily used for the evaporator and condenser. These provide a turbulent flow pattern which results in better heat transfer characteristics. Piping is run in as direct a route as possible and is well insulated to ensure there is no capacity loss or ‘sweating’. The insulation must act as a vapour barrier and be suitable to withstand hot and cold temperatures.

1.4.10 **Control Units:** The “control circuit aims to operate the heat distribution system at the lowest temperature which will still meet required comfort conditions” [11]. This will maximise efficiency as previously mentioned in 1.3.3. Modern units have a similar standard of controllability as conventional heating systems i.e. weather compensated control, a selection of heating curves, timers and specific operating and fault messages.

1.4.8 Weather compensated control is the most efficient means of operation since it will ensure the heat pump never works harder than necessary through utilising a sensor for gauging the outside air temperature. This data can then be plotted on a curve of ambient air temperature and required output temperature. The compressor is then controlled in response to the water return temperature in the distribution system i.e. output will be lowered as the ambient temperature increases.

1.4.11 In large commercial systems a room temperature sensor, located centrally in the building, can be utilised in conjunction with an outside air temperature sensor. In most domestic heat pumps however is a simple on/off switch based on the distribution system return water temperature is used as a method of control. A heat pump however, when used in conjunction with a water based heat distribution system, will not have the same capacity for intermittent heating as conventional gas/oil systems. This is due to the fact the systems are designed for a stable temperature output and have relatively long lead in times.

1.5 Refrigerants:

1.5.1 As previously mentioned in 1.3.3 the efficiency (ŋ) of the heat pump is increased when the temperature lift is as small as possible. As, in most cases, the source temperature cannot be controlled the variable is the temperature at which heat should be delivered to the building. In deciding this, the temperature/pressure ratio of the compressor and the refrigerant utilised should be considered. For heat pumps the refrigerant must meet high temperatures without unduly high pressure [3].

1.5.2 The following factors should be considered when selecting the refrigerant to use as the working fluid [3]:

- Evaporator/Condenser Pressures – As previously mentioned the lower the compressor ratio the higher the efficiency. The pressure in the evaporator must be above atmospheric pressure.
- Ratio of Latent Heat (Enthalpy of Transformation) to Specific Volume – An ideal refrigerant will have a high enthalpy of transformation while vapour will have a low specific volume at the evaporator and thereby decrease compressor work and size.
- Ratio of Latent to Sensible Heat – ideally the maximum amount of liquid refrigerant should be converted to vapour at the temperature in the evaporator coil (see 1.4.4). Therefore a high ratio of latent to sensible heat (L/S ratio) is desirable. After condensation the L/S ratio will be far lower. The lower the volume of vapour at the suction temperature/pressure the small required capacity/speed of the compressor.

1.5.3 **CFC's:** Chlorofluorocarbons were developed in the early 1930's and at first were thought to be ideal refrigerants. Their chemical stability and low toxicity meant they were suitable for residential use and furthermore they were relatively inexpensive. The most common types of refrigerants previously used are [7]:

- CFC-12 – low/medium temperatures (max 80℃)
- CFC-114 – high temperatures (max 120℃)
- R-500 – Medium temperatures (max 80℃)
- R-502 – Low-Medium temperatures (max 55℃)

- HCFC – Virtually all reversible/low temperature HP's (max 55℃)

1.5.4 In 1974 however links were drawn between CFC's and ozone depletion (Domanski 1997 cited [13]) and it has since been proven that the chlorine content of CFC's (Chlorofluorocarbons) and their chemical stability means these substances have a high global warming and ozone depletion potential (GWP & ODP respectively). Since chlorine has a long life it is transported by winds into the stratosphere. Since there are no natural processes to remove it i.e. it is not dissolved by rain, the CFC compounds are broken down by strong UV radiation to release chlorine and bromine. One chlorine atom can act as the catalyst to destroy 100,000's of ozone molecules through the following reaction:

$$CL + O_3 \rightarrow CLO + O_2, CLO \rightarrow CL + O_2$$

$$\text{Net Result: } O_3 + O \rightarrow 2\,O_2$$

It is for this reason the CFC's such as R-11/12/13, R-113/14/15 and R-500/502 are now prohibited as refrigerants.

1.5.5 Any alternative working fluid will still require the same reliability and cost effectiveness as CFC's though. However "generally speaking the energy efficiency of a heat pump system depends more on the heat pump and system design than the working fluid" [7]. After CFC's were prohibited HCFC's (Hydrochlorofluorocarbons) were introduced. These also contain chlorine but have a far lower ODP and GWP, typically 2-3% and 12% of CFC 12 respectively, this is due to lower atmospheric stability[8] and the fact they are not so readily transported into the upper atmosphere. These (R-22, R-401/402/203) are considered transitional refrigerants however and can only be utilised in retrofit systems. Under the 1987 Montreal Protocol and 1995 Vienna Convention all CFC's and HCFC's are to be phased out by 2020 (2015 in the EU).

1.5.6 Long term options may be HFC's (hydrofluorocarbons) which are chlorine free. Examples of these are R-134a, R-152a, R-32 and R-507. Since these don't contribute to ozone depletion they are seen as an alternative to R-12, R-22 and R-502.

Table 2. Potential HFC's and their Properties [7]

HFC Refrigerant	Properties
HFC-134a	Similar thermo physical properties and achievable COP to CFC-12
HFC-152a	Component in blends. Flammable however so only used in small systems.
HFC-32	GWP close to zero. Can replace R-502 and HCFC-22.
HFC-125/143a	Similar properties to R-502 and HCFC-22. Three times GWP of HFC-134a.

1.5.6 **Blends:** "While some single component refrigerants present reduced performance possibilities, the solution appears to lie with synthetic mixtures" [13]. Also known as blends these could possible replace CFC's in the long

[8] Typically CFC-12 will have a lifespan of 102 years compared with HCFC-22 at 13.3 years [13].

term. These consist of two or more pure working fluids and can be either zeotropic, azeotropic or near azeotropic.

1.5.7 In a zeotropic mixture the concentrations of liquid and vapour phases are never equal. As these concentrations are constantly changing there is a temperature glide[9] during phase change. This glide should ideally be kept as small as possible to aid heat transfer and reduce losses through concentration differences. Looking at the graph below (figure nine) it can be seen that the bubble and dew lines of the ammonia and water mix never cross, except for as pure water and ammonia. Zeotropic mixes will have a non-linear temperature/enthalpy profile and therefore varying specific heat.

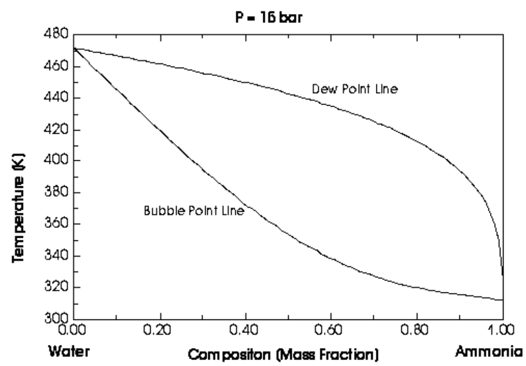


Fig 10. Zeotropic Ammonia/Water Mix [13]

1.5.8 Azeotropic blends however will evaporate and condense at a constant temperature and will therefore have a linear temperature/enthalpy profile. These are attractive since “almost all azeotropic refrigerants have a boiling point lower than either of the constituents” [13]. Near azeotropic blends will have only a slight difference between liquid and vapour concentrations for any given temperature and pressure (see figure eleven). At standard condenser pressure and temperatures however bubble and dew point vary by less than .1ºC. It is for this reason near azeotropic mixes will “usually work fairly well with existing equipment” [13].

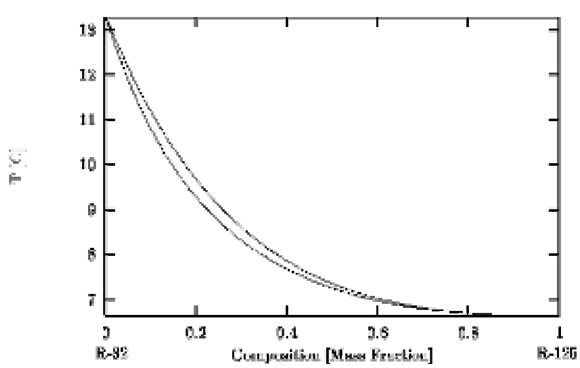


Fig 11. Pressure / Enthalpy Diagram of a Near Azeotropic Blend [13]

1.5.9 Early blends are transitional and could replace CFC-12, R-502 and HCFC-22/124. A new generation however, produced from HFC’s and Hydrocarbons (propane), are chlorine free and promising for replacing R-22 in

[9] Difference between dew and bubble temperatures.

heat pump applications. These are R-410A (mix of R-32 and R-125) and R407-C (mix of R-32, R-145 and R-134a). The former yields an improved COP performance compared to R-22 which was one of the most widely utilised refrigerants.

1.5.10 **Natural Working Fluids:** These are substances which naturally exist in the biosphere and have negligible environmental impacts. Ammonia has potential to be utilised in small systems with low fluid change, indirect distribution systems (i.e. using brine) and gas tight casings (for safety reasons). Hydrocarbons have favourable thermodynamic properties and material compatibility. Propane, propylene and butane are considered promising. As these are highly flammable a low fluid change is required. Hydrocarbons are already being used in domestic heat pumps in Europe.

1.5.11 Water is, of course, not flammable and non-toxic. There are already some closed cycle compression systems utilising this as a working fluid which can achieve temperatures of 80-150 °C, but since water has a low volumetric heat capacity (KJ/M^3) large compressors are required. There is also strong interest in utilising CO_2. It is also non-toxic and flammable and is compatible with normal lubricants and construction materials. Research has also shown competitive COPs can be achieved when compared with more established refrigerants.

1.6 Cooling:

1.6.1 Heat pumps are widely utilised world-wide for cooling applications in refrigerators and air conditioning systems. The initial concept for heating of simply utilising an air-conditioning system in reverse however does not bear comparison with modern heating specific heat pump systems and would be inefficient and expensive to run.

1.6.2 To offer optimum performance heat pumps for heating purposes will differ from standard cooling units since [2]:

- Additional surface area is required for the indoor coil to prevent excessively high condensing temperatures.
- For an air distribution system sufficient air flow will be required to ensure adequate condensing of the refrigerant.
- The compressor will need to be specifically designed to operate all year and under different pressures/conditions as a simple air conditioning system (if both heating/cooling needed).
- A defrost cycle will be required to ensure maximum operating efficiency (air systems only).
- Auxiliary heating may well be required in certain conditions.

1.6.3 Some heat pumps however can be specifically designed to offer cooling and heating services. In the USA these systems are widespread while in European markets, such as Germany, heating only units are more popular. Cooling can be performed by two methods, reversible operation and direct cooling. In the former the heat pump function is reversed while for the latter the brine/groundwater (i.e. in a GSHP) absorbs energy from the heating circuit and transfers it outside, in direct cooling the heat pump is actually turned off with the exception of the control unit and circulation pumps.

1.6.4 **Reversible Operation Cooling:** To be able to use a vapour compression heat pump for cooling requires the reversal of the compressor flow direction and the expansion valve. This will reverse the flow of the refrigerant in the system. To do this it is easiest to install a four way valve which will divert flow for the whole system and allow the compressor to maintain its original flow direction regardless of heating or cooling (this is shown in figure twelve).

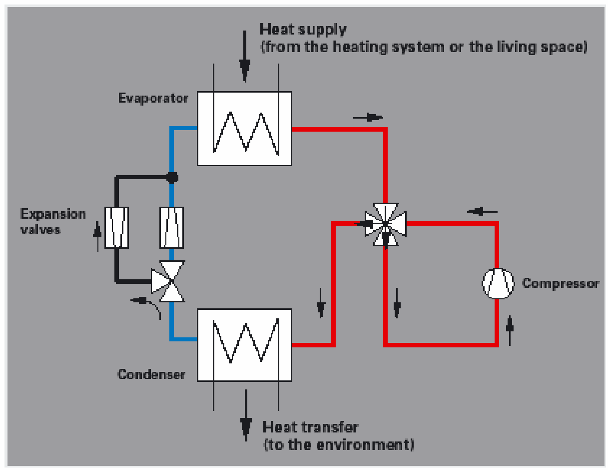


Fig 12. Function Diagram of a Reversible Heat Pump in Cooling Mode [5].

It should be noted that the cooling capacity of a reversible heat pump will not match its heating capacity. This is due to the fact that while the heat generated during compression is useful for heating it serves to lower the COP in cooling mode.

1.6.5 Reversible heat pumps operate best with an air heating/cooling distribution system. What happens if they are connected to a water based distribution system however? When heating is required it will be transferred to room via heat transfer surfaces (discussed further in 1.8) such as radiators or underfloor heating. However “radiators are particularly unsuitable for cooling a room” this is due to small summer temperature differences and a relatively small surface area to aid heat transfer from the room to the radiator. Furthermore heat rises and most radiators are situated at the bottom of a wall. The cooling effect of an underfloor system can be increased through the installation of an in-house ventilation system.

1.6.6 **Natural Cooling:** Air Source Heat Pumps (ASHP’s) are not suitable for natural cooling due to high air temperatures during summer. However in summer the ground/groundwater temperature will generally be lower than inside buildings this can be used for cooling. To use natural cooling additional equipment will be required (additional heat exchanger, three-way valve and circulation pump). The heat pump compressor is turned off and a circulation pump drives a secondary circuit. This removes the energy from the in house distribution system, i.e. underfloor, via a neat exchanger to the brine/water mix loop in the ground where the heat is lost. This is a very energy efficient form of cooling since the only power required is that needed to drive the circulation pumps (COP of 15-20 achievable).

1.6.7 For reversible operation/natural cooling it is important to monitor the dew point. This can be done by installing a dew point monitor to ensure the actual surface temperature of the cooling device stays above the dew point. This will prevent humidity from condensing on the surface.

1.7 Operational Modes:

1.7.1 When used for heating purposes heat pumps can be run in three different operating modes. These are:

- Mono-mode
- Mono-energetic
- Dual-mode (alternative/parallel/partially parallel)

and will now be explained in more detail.

1.7.2 **Mono-Mode:** In this case the heat pump acts as the "sole heat source" [5]. The heat distribution system is sized below the maximum heat pump flow temperature and it has therefore been decided at the design stage that demand will not be larger than the heat pump capacity. Typical applications could be detached houses or commercial buildings with two different users and therefore consumption profiles. This mode is suitable for low temperature heating systems generally up to 60ºC [14].

1.7.3 **Mono-Energetic Mode:** A second heat source is available but is only used in extreme conditions (-5 → -20ºC). This is usually in the form of an electric booster heater (i.e. immersion in hot water tank) and represents a "compromise between energy efficiency and investment outlay" [5]. "In this case the heat pump is sized for 20-60% of the maximum heat load and will meet 50-95% of the annual heating demand" [7]. This is predominantly for detached/semi detached houses with uniform heating demand and, preferably, underfloor heating systems.

1.7.4 **Dual Mode Systems:** The heat pump is combined with at least one other heat source (whether from solid./liquid/gas fuels). Either both heat sources are operated simultaneously (parallel) or, subject to sizing, alternative operation which means that the heat pump alone will cover the demand alone above a certain designated temperature.

- Parallel: Again a specific temperature is set, below this however the heat pump operates alongside the secondary unit and therefore provides a larger annual proportion of heating. This is suitable to be used in tandem with underfloor heating and radiators up to 60℃. In partially parallel mode operation is the same except the heat pump will be turned off if the flow temperature is deemed inadequate.
- Alternative: Above the designated temperature, for example 0℃, the heat pump will supply 100% of the heating demand. Once the temperature drops below this however it will switch off and the back up unit will take over. This is suitable for all heating systems up to 90℃ [14].

1.8 Distribution System:

1.8.1 The fact that an increase in temperature differential between the source and building will cause a drop in heat pump efficiency has already been stated. This relationship between source, output temperatures and COP is illustrated further in figure thirteen.

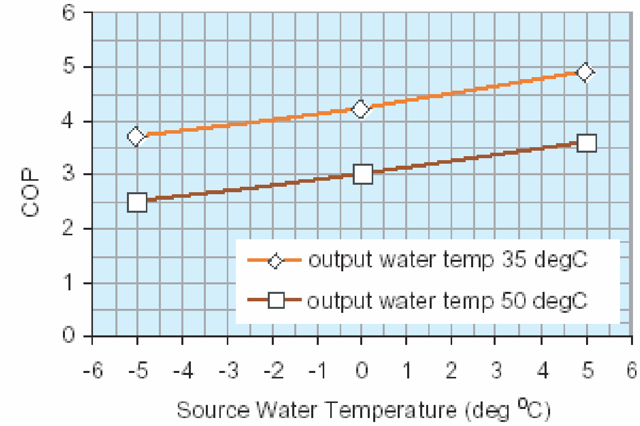


Fig 13. Source and Output Temperatures Influence on COP [11]

Since the source temperature is beyond influence (except in industrial applications) running at as low an output temperature will therefore help achieve high efficiency.

1.8.2 It is for this reason that coupling a heat pump with standard radiators is an unlikely solution (e.g. for retrofit) unless there is a significant increase in building insulation. Standard radiators are sized for a typical flow temperature of 80ºC. Running a heat pump with this temperature output, which is not currently possible, would dramatically decrease its COP. Therefore with a wet heat distribution system the radiator surface area will have to increase 30-40% to accommodate the lower heat pump output temperatures. It is for this reason that underfloor heating is very suitable for heat pump applications. Its large surface area allows a low output temperature and therefore high heat pump efficiency. Table three below outlines the delivery temperatures of various distribution systems.

Table 3. System Delivery Temperatures [reproduced from 11]

Distribution System	Delivery Temperature Required (ºC)
Underfloor	30-45
Low-Temperature Radiators	45-55
Conventional Radiators	60-90
Air	30-50

1.8.3 The thermal capacity of the distribution system is important. If it is too low the heat pump may be subjected to long off periods at times of low load (kW). Often a restart delay is fitted to reduce compressor wear and rapid on/off cycling. In this case it is valuable to ensure some disconnectable thermal capacity to compensate for any restart delay. This can be provided in the form of a 'buffer' hot water tank (volume 60-150 litres) [11].

1.8.4 **Buffer Tank:** A buffer tank will separate the volume flows inside the heat pump and distribution circuit. As the heat pump output cannot always match demand requirements (see 1.4.9) the additional buffer tank can even out the heat pumps operation and reduce cycling. So even if the distribution circuit temperature is reduced at the thermostat the heat pump can continue as before. This offers several benefits [5]:

- Power off periods are bridged.
- Constant volume through the heat pump.
- No flow noise in the heat distribution system.

A rough estimate of the tank capacity required can be estimated from the following equation:

$$VHP = Qa \times 60\text{-}80 \text{ (litres)}$$

V HP = Tank volume
Qa = Output requirement of building (kW)
If no power off periods expected (or backup plant available):

$$V\ HP = Qa \times 20\text{-}25 \text{ (litres) [5].}$$

1.8.5 **Domestic Water Heating:** Hot water unlike heating is a year round load and is typically delivered from the tap at 35-45ºC. The thermal power output of a heat pump is generally insufficient to provide direct heating to the level required to achieve this and, for this reason, a direct storage system will be required. This can also be provided by means of a tank heated via a primary coil or jacket. However since most, domestic, heat pumps will have a maximum output temperature of around 55ºC. This will result in a storage temperature of approximately 50ºC and therefore an auxiliary electric system will be needed to boost temperature above the 60ºC required to avoid legionella bacteria.

1.8.6 If a heat pump has a cooling function a 'desuperheater' can be fitted for partial hot water heating; a modification popular in the USA. This involves a heat exchanger, between the compressor and reversing valve of the heat pump, to exchange heat between hot refrigerant gasses and a water heating tank. This thermal power output is generally low but it can act as a boost. Since the desuperheater is only operational when the heat pump is on it cannot be used as a stand alone system. This is mainly used with a high cooling load building since this heat exchange will increase COP through utilising unwanted compression heat.

1.9 CO2 Savings and Miscellaneous Benefits:

1.9.1 Although heat pumps cannot be considered a 100% renewable heating technology (unless the compression work is generated from a renewable source i.e. wind turbine), they are certainly a highly efficient means of heating which utilises a significant proportion of renewable energy. The renewable fraction is of course determined by the COP, using a value of four for example means that for every 1kW of electricity utilised 3kW, or 75%, of heat is obtained from either the air/water/ground which is recharged from solar energy. Modern electrical heat pumps can achieve COP's from 3.5→5.5 [5].

1.9.2 **Emissions Reduction:** By contrasting a heat pump of this efficiency with standard fossil fuel heating systems it can be seen how emissions reductions are achieved. A simple analogy is contrasting with a 1kW electric bar fire which will operate at 100% efficiency and give out 1kW of heat, using a heat pump however the initial 1kW of electricity (work) can yield heat at seasonal efficiencies of 250% (air) to 300-500%[10] (ground/water) i.e. 2.5→5kW of heat [11].

1.9.3 The renewable component extracted from the heat pump displaces the need for the additional heat to be obtained from fossil fuels, which for electric heating is generated at approximately 30-35% efficiency. It is well documented of course that burning of fossil fuels releases carbon dioxide (the primary green house gas (GHG)) as well as air pollutants such a NOx, SOx and particulates. A recent study of ground source heat pumps cited CO_2 emissions reductions from 15-77% [6]. Also since heat pumps are so widely replicable it is postulated that “there is unlikely to be a potentially larger mitigating affect on GHG emissions and resulting global warming impact of buildings from any other current market-available technology” [6].

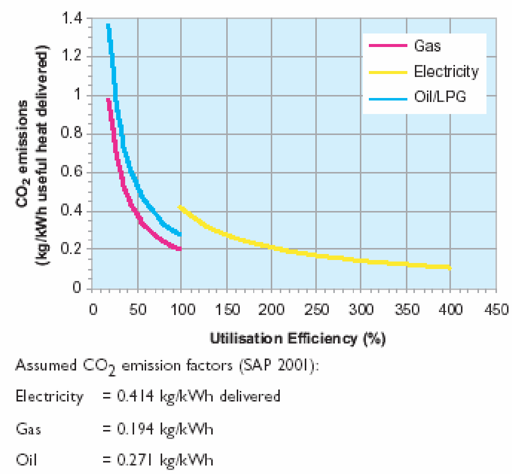


Fig 14. Carbon Dioxide Emissions for Different Fuel Use Efficiencies [11]

1.9.4 Although the example shown in 1.9.2 is perfectly valid the majority of households will not rely on an electric bar fire for their heating, figure fourteen (above) allows comparison of using electricity at different efficiencies with oil and gas systems. Using the emissions factors shown[11] a heat pump using electricity at 400% utilisation efficiency (COP of 4) will produce approximately .1 kg CO_2 for every 1 kWh of useful heat delivered. Using a gas boiler however with a typical seasonal efficiency of 85% and the emissions factor stated would produce .23 kg CO_2 for the same quantity of heat [11]. As can be shown by the blue curve Oil/LPG will release even higher emissions.

1.9.5 **Cost Savings:** Since the renewable component, from the air/water/ground, is free by the same logic shown above it can be seen that heat pumps will yield competitive running costs than standard heating technologies. By comparing the delivered price of each of the alternative fuels by their seasonal efficiency factor (SPF) costs can be compared. This is shown for a ground source heat pump in figure fifteen below. As heat pumps

[10] Depending on whether the system is direct or indirect, to be explained further in section two
[11] It should be noted however that at peak demand electric emissions factors could be higher (up to .8kgCO_2/kWh) as less efficient means of generation are utilised [11].

use electricity it is important that any preferential tariffs (i.e. for off-peak use) are utilised, some utilities[12] now offer specific heat pump tariffs.

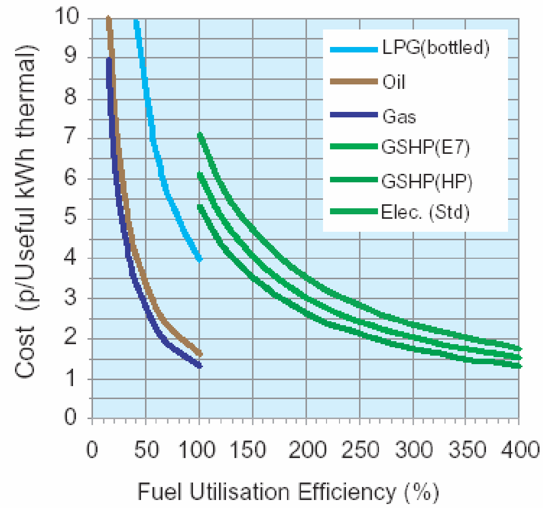


Figure 6: Domestic fuel costs versus fuel utilisation efficiency*

** Fuel prices taken from SAP 2001 (Table 12 and Appendix F)*

Standing charges are not included

GSHP(E7) is a 7-hour off-peak tariff, GSHP(HP) is a special heat pump tariff

Fig 15. Cost Comparison Example Using GSHP's [11]

1.9.6 **Miscellaneous Benefits:** There are also several other advantages to utilising heat pump technology. These are [11]: -

- Long system life expectancy, typically 25 years.
- No combustive or explosive gases in the building.
- No need for annual safety inspection.
- No local pollution.
- No flue/ventilation requirements.
- Low maintenance requirements. The weakest part of the system will be circulation pumps, compressors however can last from 15 years or 25 for a Scroll compressor.

1.10 Electrical Requirements:

1.10.1 Heat pumps are driven by an electric motor and this will draw an inductive load and therefore require high electric currents on start up. This can cause disturbance to the electricity distribution network (especially where it is weak and single phase), which will result in lights flickering, premature main fuse failure and voltage surges which can damage electronic equipment [11]. The electricity supply regulations (1988) specify set limits to voltage variation caused by switching a load (i.e. the heat pump) on and off. This variation will depend on the electrical impedance[13] of the network at that point and also the size of the load (heat pump).

[12] Such as Scottish and Southern Energy
[13] Combination of resistance and reactance Z = R + jX.

1.10.2 Heat pumps can be modified in certain ways in order to limit voltage variance [11]:

- Soft start mechanisms fitted to spread the load on start up.
- Specially designed low torque compressors.
- Auxiliary systems to limit required heat pump capacity.
- Three phase supply and motor (where possible).

1.11 Section Conclusion:

1.11.1 This introductory overview should have explained the generic theory behind heat pumps and how they operate. Furthermore the main components which make up these systems have been covered as have how they can be utilised, i.e. for heating/cooling, and in terms of operational modes. Finally the benefits of utilising a heat pump system have been outlined.

2. Ground Source Heat Pumps (GSHP's)

2.1 Introduction:

2.1.1 This section will describe Ground Source Heat Pump technology in more detail building on the general heat pump information presented in section one. Firstly the varying characteristics of the earth as a heat source will be outlined; this will be followed by the different methods of abstracting this heat in terms of direct/indirect/open systems and the types of loop configuration. Finally potential applications for GSHP's are discussed.

2.2 The Earth as a Heat Source:

2.2.1 The use of low temperature heat sources was discussed in 1.3; the case of using the ground for this purpose will now be presented in more detail. Half of the solar radiation received by the earth is absorbed at its surface and for this reason the ground temperature will show seasonal variations down to a depth of approximately 15m (see figure sixteen below). There is more pronounced variation in the first two meters although this does lag changes at the surface[14]. Below this level however the temperature is fairly constant and will roughly equate to the mean annual air temperature of the region[15], this is due to the fact the earth has a high thermal mass / inertia of soil and is able to store the heat absorbed. After heat is extracted it is regenerated by solar irradiation, precipitation and on a smaller scale thermal gradient in the ground. "Energy flowing from deeper layers upwards represents only .063→.1 W/m² and can be disregarded" however [5]. As depth increases further there is a slow but steady increase in temperature of 2.6ºC per 100m, the mean temperature at 100m is usually between 7-15ºC in the UK [4]. This is of course subject to variation dependant on the local geology/soil conditions and therefore two identical heat pumps may differ in performance according to location.

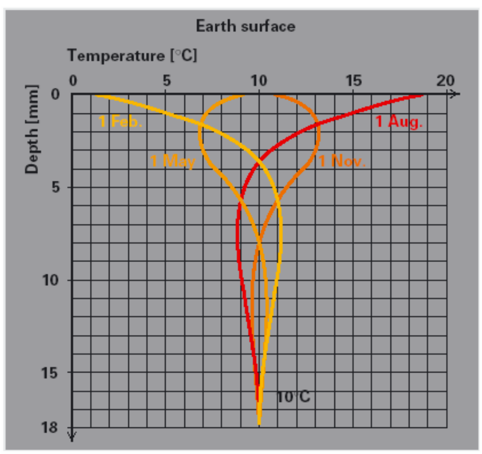


Fig 16. Example of a Typical Ground Temperature Profile [5]

2.2.2 **Ground Characteristics:** The definition of geothermal is subject to variation, in some cases it is considered to be heat below 15-20m in the ground while in others simply all energy stored as heat beneath the earth's surface. Regardless of definition this relatively constant store can be utilised

[14] By one month at 1.5m [4]
[15] 8-11ºC [4] or 10-14ºC [11] in the UK

by a heat pump for heating and cooling applications since in winter the ground temperature will be above the average air temperature while in the summer it is likely to be below it. The capacity of the GSHP for heating/cooling will depend on not just the size of the system but also the thermal properties of the ground (examples of these are shown in figure seventeen below).

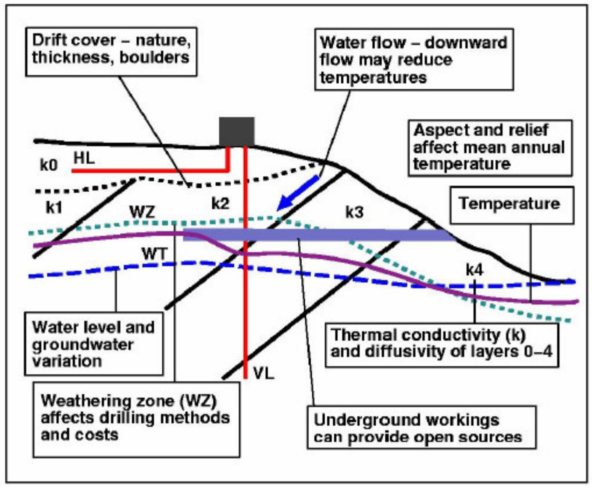


Fig 17. Varying Factors Affecting GSHP Installation and Performance [4]

These factors will also have a strong influence on the capital costs associated with installing the ground heat exchanger, which can account for 30-50% of total capital costs [4], and it is for this reason that a geo-technical report is strongly advised before installing a GSHP system.

2.2.3 In section 1.3 it was explained that the "temperature difference between the earth and the fluid in the ground heat exchanger drives the transfer of heat" [4], i.e. for heating the earth has a higher temperature than the solution in the ground loop, which when heated has a higher temperature than the condensed refrigerant. The rate of this transfer is in turn determined by the thermal properties of the ground.

2.2.4 System performance is significantly affected by the material in which the ground heat exchanger (also referred to as a loop) is laid. Factors which will determine performance are [4]:

- Subsurface temperature.
- Thickness and nature of superficial deposits i.e. soil.
- Rock properties i.e. stratigraphy (formation) and lithology (type). These will determine strength and conductivity.
- Hydrological issues, depth to groundwater, seasonal variations in groundwater, flow direction etc.

"In general groundwater flow improves heat exchange" [4], when significant flow is present, at 4-10°C [11], heat exchange occurs through a dual mechanism of conduction in the aquifer material and convection in the groundwater itself. Ground source heat pumps which are located on a site of low permeability rock, and hence low water flow, will not benefit from convective heat transfer.

2.2.5 Thermal conductivity and diffusivity are two parameters which need to be clarified in order to estimate the likely subsurface temperatures and heat transfer characteristics. The heat transfer to the ground collector (loop) will not only be determined by the area for exchange but also these two factors.

2.2.6 **Thermal conductivity (K):** This is a measure of the quantity of heat transmitted per unit area, per unit temperature gradient and in unit time, under steady state conditions. Multiplying this factor by the thermal gradient will give the heat flow within the ground. When considering thermal conductivity in rocks factors such as porosity, composition and the nature of any saturating liquids will determine its value. Generally, the larger the extent of porosity the lower the thermal conductivity will be; unless the rock is saturated as stated in 2.2.4. Thermal conductivity can vary by a factor of two for rocks most commonly found near the surface and even more significantly for the range of sediments found in this area. Generally rocks have higher K values than soils. Variability in the latter is explained due to mixing of mineral and organic particles and their associated thermal characteristics[16]. Furthermore in dry soils air is trapped, and since this has a low K value (see table four), saturation will raise the conductivity of soils; "Low conductivity soil may require as much as 50% more collector loop than highly conductive soil" [11].

2.2.7 **Thermal Diffusivity (α):** Is a measure of ground thermal conduction in relation to thermal capacity. This links thermal conductivity, specific heat (Cp) and density (ρ). Density multiplied by specific heat is termed volumetric heat capacity. The relationship is shown in the following formula (SI unit = metres squared per second):

$$\alpha = k / \rho C_p \quad m^2/s$$

A high thermal diffusivity value is desirable since this means the material will quickly adjust temperature to that of the surrounding environment since heat is conducted rapidly relative to thermal mass. Specific heat capacity (c) describes how much heat is required to change unit mass of the material by unit temperature i.e. how much energy can be dissipated/absorbed before a change in temperature. Water has a high specific heat capacity (4190 J/Kg-1) which explains how saturation will increase the overall value for the rock/soil.

Table 4. Thermal Conductivity of Typical Rocks and Sediments [4]

Material	Typical Thermal Conductivity (K) Wm-1K-1
Low porosity sedimentary rocks (<30%) i.e. shale, sandstone, siltstone	2.2-2.6
Quartz sandstone (5% & 30% porosity)	6.5, 2.25
Igneous plutonic rocks i.e. granite, gabbro	3.0
Schist, Serpentine	2.9
Quartzite	5.5
Sand (gravel), saturated sand	0.77, 2.5
Silt	1.67
Clay, saturated	1.11, 1.67
Loam	.91
For Comparison:	Water = 0.6, Air = 0.0252

[16] Higher mineral content equals better conductivity

Table 5. Thermal Diffusivity of Typical Rocks and Sediments [4]

Material	Typical Thermal Diffusivity (m^2 day-1)
Basalt	.059
Granite	.086
Gneiss	.106
Quartzite	.255
Clay	.082
Limestone	.091
Sandstone	.143

2.2.8 **Thermal Recharge:** With groundwater coupled GSHP the hydrologic cycle[17] circulates liquid and therefore heat via pressure difference. This heat can be attributed to the atmosphere and geothermal heat flow in proportions relative to the depth of the aquifer. For this reason there is generally a stable temperature present in the aquifer which does not exhibit major seasonal changes, "any deficit created by heat/fluid extraction is replenished by the (lateral) groundwater flow" [25]. For all horizontal systems in heating only mode, the main thermal recharge is provided by solar radiation falling on the earth's surface. It is therefore vital to ensure the surface above the ground heat exchanger is not covered.

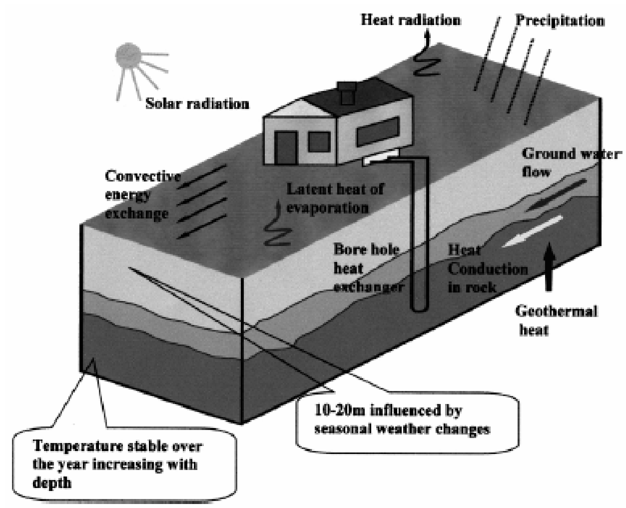


Fig 18. Factors Affecting Thermal Recharge [37]

2.2.9 However with a borehole heat exchanger which only provides heating, i.e. and is not therefore replenishing heat to the ground in summer cooling mode, heat replenishment takes place due to the lower temperatures around the heat exchanger. These lead to heat inflow from the surrounding ground i.e. it becomes a heat sink. This is a far slower process of replenishment that in a saturated or surface system. To ensure reliable operation of the system accurate design is required. For example utilising set extraction rates in low conductivity material could lead to system collapse due to insufficient heat replenishment and freezing around the exchanger. During summer, when the system is not utilised, thermal recovery will begin "strong at first and then decreasing asymptotically" [25], there can also be year on year reductions in thermal recovery. It is for this reason that borehole length is longer for heating only systems that those which offer heating and cooling. This is an active

[17] Infiltration of Precipitation

research area within the industry with differing predictions as to long term effects. To ascertain thermal properties of the ground thermal response testing has been developed to ensure correct borehole sizing. Modelling programmes are also actively used for this purpose.

2.2.10 An alternative to natural recharge is to utilise forced recharge. For example should a building be equipped with solar collectors and a GSHP, during conditions where excess heat is present which is not required for water heating it can be injected into the heat exchanger and thermally replenish the surrounding ground [35].

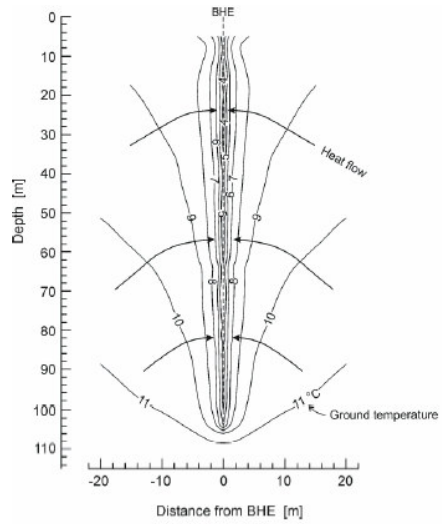


Fig 19. Temperature Recharge Isolines around a Vertical Borehole [25]

2.3 Direct and Indirect Systems:

2.3.1 There are many possible means by which to tap the large supply of low grade heat in the ground. It is firstly important to clarify the difference between direct and indirect systems. In an indirect system the circulating fluid, to which heat is transferred to/from the ground, will be a water/antifreeze mix. The antifreeze could be brine (water saturated or nearly saturated with salt[18]) or compounds such as Ethylene Glycol or Propylene Glycol. It is important however to understand that the antifreeze selected may increase in viscosity as temperatures drop, this is the case with glycols, this will increase pump energy demand and reduce the heat transfer rate and overall efficiency. In general it is best practice to ensure the circulating fluid has a freezing point at least 5ºC below the mean temperature of the heat pump[19]. With indirect systems the ground loop is made from plastic, usually high density polyethylene or polybutylene, which has a long life[20]. Energy is transferred from the ground loop to the refrigerant by the means of a heat exchanger.

2.3.2 An alternative configuration is to circulate the refrigerant through the ground loop in order to pick up the low grade heat. This is called a direct expansion (DX) system. This offers several advantages over an indirect system which raise efficiency, such as [11]:

- Increased thermal contact with the ground.
- No requirement for a circulation pump.
- The elimination of a heat exchanger between ground coil liquid and refrigerant.
- Shorter ground coil required.

Conversely however more refrigerant will be required and there is a larger probability it will leak. Should a toxic refrigerant like HCFC-22 reach groundwater it could represent a serious problem. Copper is utilised as the

[18] At 23.32% saturation freezing point is -21ºC [15]
[19] Average of the inlet and outlet temperatures
[20] Circa 50 yrs [17]

piping material for direct systems. A direct system is more viable the smaller the heat pump capacity.

2.4 Ground Heat Exchangers:

2.4.1 The direct and indirect systems above are both classified as closed systems i.e. the heat carrier (water/antifreeze) is separated from the earth within the piping and continuously circulated. However although a closed loop configuration is the most popular not all ground loops are closed.

2.4.2 **Open Loop Systems:** In some cases these are known as water source heat pumps. In an open loop system groundwater/lake water is used as the heat carrier and it is brought directly to the heat pump evaporator i.e. there is no barrier between the heat carrier and soil, rock etc Sufficient permeability is required for this kind of system. Open loop systems consist primarily of extraction/reinjection wells and surface water systems. The water is drawn from a source i.e. the primary aquifer, passed by the heat exchanger and then discharged/re-injected into a separate aquifer, well or surface water system (river/lake). Open loop systems tend to be utilised on a large scale. The largest heat pump constructed utilises this configuration to provide 10MW heating/cooling to a hotel and office complex [6].

2.4.3 Water quality is a key consideration with open loop systems[21]. The heat exchanger, since it is exposed to the groundwater, can be subject to fouling, corrosion and blockage. This will obviously raise maintenance requirements. It is also important to ensure there is a suitable water flow past the heat exchanger "typically between 1.5 and 3.0 gallons per minute per system cooling/heating ton (.027→.054 L/s-kW)" [6]. Such significant water requirements may contravene local water regulations, "in the UK there is stringent environmental legislation for the extraction and discharge of groundwater" [17].

2.4.4 With ideal geology and hydrology there are many advantages to an open loop system. Firstly drilling requirements can be lower than those for a closed loop system and thermodynamic performance can also be improved since the groundwater will deliver heat at the ground temperature removing any losses through heat exchange to a circulating fluid. There are also disadvantages however, apart from those already mentioned such as impairment of the heat exchanger, water regulations and the need for suitable water flow; open systems are "typically subject to the highest pumping power requirements" of any GSHP system [6] which can make costs excessive (especially if the pump is not sized correctly). There is also a possibility of undesirable hydraulic connections and temperature changes in the aquifer and pollution through leaks in the system. Finally these systems can not be widely applicable since they require the presence of suitable geology and hydrology (i.e. aquifers, surface water systems etc). Disused mines however can be an ideal site for an open system.

[21] A low iron content is preferable

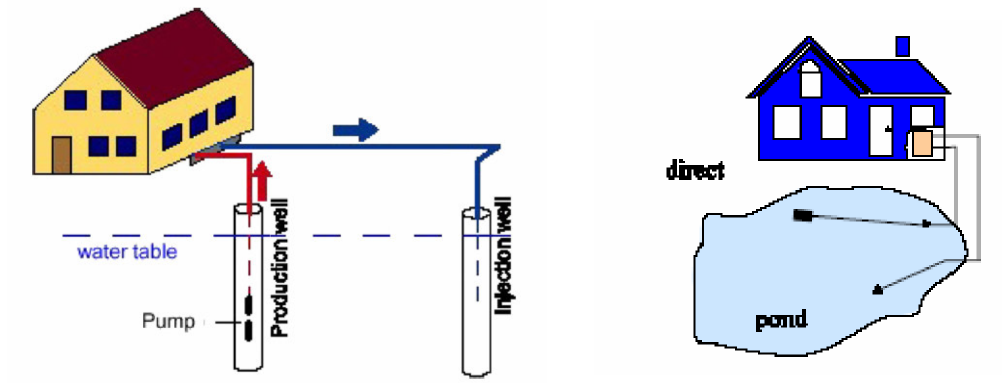


Fig 20 a & b. Open Loop System Using Wells [6] and a Pond [27]

2.4.5 **Horizontal and Vertical Closed Loops:** “The choice of horizontal or vertical system depends on the land area available, local ground conditions and excavation temperatures” [11]. If land area is at a premium or the soil is too shallow for trenching a vertical borehole may be required for the ground loop in order to maximise heat gain for the space available. Fitting a vertical collector will be more expensive, due to high drilling costs, but will yield an increased thermal efficiency, require less pipe material and pumping energy while also being less likely to suffer damage. For horizontal collectors a large surface area is required, preferably free of rocks and large boulders. Generally the deeper the loop the more stable the ground temperatures and therefore higher the system efficiency; this however must be balanced against higher installation costs.

2.4.6 In a horizontal system the pipes are buried beneath the ground at a depth between 1.2 and 2m. It is important to ensure that each pipe run is not so long an excessive pressure drop is incurred and pumping power increased. Furthermore all pipe runs should be of the same length; this will ensure that the collector field (ground loops) have the same pressure drops, flow conditions and consequently collect heat evenly over the ground. Approximately 35-60m of length is required for each kW of heating i.e. a heat extraction of 15→30 W/m [37].

2.4.7 Horizontal systems can be laid in either series or parallel as shown in figure twenty one, these dense patterns offer maximum heat extraction for the space available. A distance of approximately 3m should be kept between pipe runs however to avoid thermal interference.

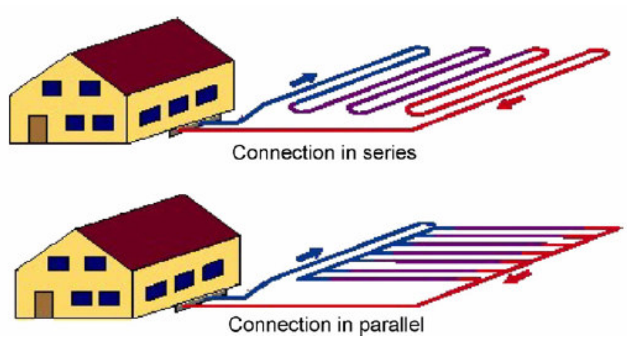


Fig 21. Series and Parallel Ground Loop Configurations [6]

In North America, where land is more widely available and cheaper, finding space for a trench system is more likely than in the UK where land prices are higher. However in the U.S.A. and Canada borehole loops are still popular since constant temperatures in the ground are deeper due to strong ambient air temperature variation between summer and winter. Within each trench a number of pipes (at least .3m apart) with circulating fluid are attached to the steep walls (see figure twenty two below).

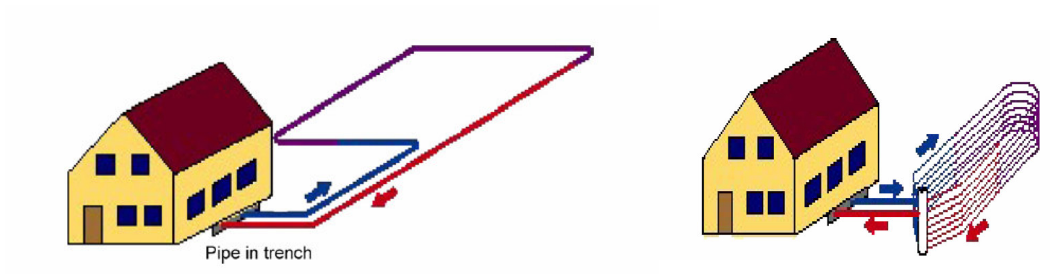


Fig 22. Trench Collector Systems [6]

To ensure good thermal contact with the ground horizontal loops are laid on a bed of sand. They are also covered with a top layer of approximately 150mm sand for protection before being backfilled with the excavated top soil.

2.4.8 In a vertical system boreholes can vary in depth ranging from 15→150+m depending on the capacity required. If a DX system is used the maximum suitable borehole depth is 30m. Width will vary depending on the number of pipes fitted; generally from 10-60cm diameter. There can also be more than one borehole so long as they are kept approximately 3-5m apart to avoid thermal interference. In most cases two pipes are installed, in parallel, per borehole[22]. In addition the pipes should be connected in such a way to ensure that equal flow in both is achieved. Under standard hydrological conditions[23] an average vertical borehole system will yield 50W/m pipe length [5]. The annular space between the pipes and borehole wall is backfilled with grout material; this will stop the vertical migration of groundwater, support the pipes and ensure a good thermal contact. To ensure the best possible performance enhanced conductivity grout has been developed, this results in "a significant reduction in ground thermal resistance" and therefore increases the system efficiency.

2.4.9 The advantages of a vertical system are that total pipe requirements will be less, as will pumping energy demand. Furthermore as previously mentioned ground area required is smaller and the deeper into the ground the collector goes the less the seasonal variation (see 2.2.1). Drilling costs are typically higher though than the trenching needed for a horizontal system. Furthermore there is a greater potential for disturbance of the natural temperature regime at greater depths; temperature increase or decrease depending on heating/cooling load. A temperature drop could occur over an extended period of use due to the fact energy is not replenished as quickly as

[22] Except in Switzerland where the default is four
[23] Assuming no groundwater present

when at the surface or if the boreholes are not adequately spaced there is potential for long term heat build up.

2.4.10 The pipes fitted into a vertical borehole will either be in a U-pipe or Concentric/Coaxial configuration. U-pipes consist of a pair of straight pipes connected with a 180° turn at the bottom. Due to the fact piping material is relatively low cost up to three pairs of these pipes can be fitted into a single borehole. A concentric configuration basically can simply consist of one pipe inside the other or alternatively many fitted around a larger central pipe.

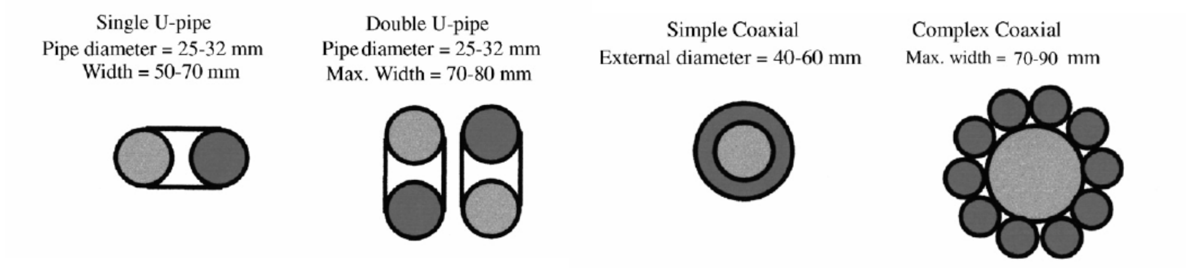


Fig 23a. Vertical Heat Exchanger Pipe Configurations [37]

2.4.11 **'Slinky' Loops:** Also known as spiral loops, this is a different piping arrangement which can be used with either horizontal or vertical systems. Typically a slinky loop will require more pipe per kW heat (43-87m, i.e. 12-25 W/m of heat extraction [6]) but conversely less trench space (by 20% [17]) thus saving on installation costs due to the fact ground excavation is more expensive than the pipe material. A horizontal slinky loop will require the trench to be approximately 2m wide. This type of piping requires a higher pumping energy demand than a standard horizontal system and is best suited to areas where natural recharge to the ground is not essential.

Fig 23b. Slinky Pipes in a Trench [16]

2.4.12 **Piping Material and Pump Considerations:** Piping material is an important consideration as it will affect:

- System lifetime.
- Maintenance.
- Pumping energy.
- Capital costs.
- COP.

As already mentioned so long as the system is indirect (2.3) the piping is likely to be high density polyethylene or polybutylene. This has the advantage of being a flexible material and also can be joined through heat fusion.

2.4.13 The pipe diameter also has to be sized correctly. Should it be too small pumping requirements will increase while if it is too large turbulent flow will not be created which will be detrimental to heat transfer processes. Pipe diameters are usually in the region of 20-40mm. In a DX system copper pipes will be used with a 12-15mm diameter; depending on the soil conditions these may have a plastic coating. The pump generally has a low electrical load but, for the same reasons described above, needs to have sufficient power to ensure turbulent flow. A general rule of thumb for pump power requirements is 50W per kW installed capacity [11].

2.5 GSHP Applications:

2.5.1 Having outlined the technology the sensible next step is to assess how it is applied. Ground Source Heat pumps are suitable for use on a variety of scales in industrial, commercial and domestic applications. However it is thought there will be constraining factors for GSHP use in the first two sectors, these will be explained further. Although "96% of heat pumps sold in the UK are for non-domestic buildings" [9], these are mainly cooling and air conditioning systems and not ground loop heating systems.

2.5.2 **Industrial Applications:** Heat pumps are used in industry in a number of different applications [7]:

- Space heating.
- Heat/Cooling of process streams.
- Steam production.
- Drying/dehumidification.
- Evaporation.
- Distillation.
- Water heating for washing/sanitation/cleaning.

Although heat pump use is currently limited it is thought that it will increase as climate change legislation becomes stricter. In general industrial uses are more variable than domestic or commercial applications (in terms of drive energy, size, operating conditions etc) and as such they tend to be specially designed to fit the required purpose.

2.5.3 However in most of these applications there is no reason to use a GSHP. This is firstly because the temperature lift would be too high, as already mentioned the higher the output temperature the lower the COP. For example if an industrial process required hot water at 120ºC, the temperature lift using ground heat at 10 ºC would require excessive compressor work. The second reason is that most industrial processes will have readily available waste streams at a far higher temperature than the ground i.e. cooling water, exhaust gases etc.

2.5.4 **Commercial Applications:** There is potential for GSHP's to be used for space heating and cooling in offices and retail spaces. Sports centres are also a promising option for the technology especially if they have swimming pools which require a constant heating/dehumidification load or if cooling is required elsewhere in the building. Limitations on an extended use of GSHP's however could be [10]:

- Most commercial premises are leasehold and owners would have to be willing to allow drilling/disruption close to the building.
- Land in shopping and office areas is of high value and there is unlikely to be large areas available for collection systems. Also once collectors are laid land value drops further due to limited further uses.

- Buildings tend to be bigger and as such will require large collection systems.
- In business payback is often an investment criterion and higher capital costs may rule out a GSHP system.

2.5.5 **Domestic Systems:** It is thought that the technical potential for GSHP systems is predominantly in housing even "though the existing market is overwhelmingly in commercial buildings" [34]. "GSHP's can be used to provide space and domestic water heating and, if required, space cooling to a wide range of building types and sizes" [11]. Domestic systems can be either fitted at the time of building or retrofit. Due to the fact laying the ground loop and fitting the correct distribution system i.e. underfloor heating, is far cheaper during the building stage the most promise for GSHP technology is the new build market. Also since heat pumps are best suited to well insulated buildings (thus minimising temperature lift required and keeping heat demand stable) any retrofit should be combined with additional insulation measures. As far as the domestic market is concerned the greatest potential appears to lie with smaller (i.e. 5-7 kW demand) new build houses. A typical detached low energy house can be comfortably heated using a 6kW heat pump [5]. Especially attractive are properties located in rural areas with larger land availability and no mains gas supply. There is currently a paradox as regards heat pump use in that "it is clear that the technical potential is in housing" [34][24] although as previously mentioned the majority of heat pumps in operation at the current time are for commercial purposes.

2.6 Section Conclusion:

2.6.1 This section has described how the earth can be used as a heat source and the key geological and hydrological factors to consider when planning a GSHP system. From this point the different methods of extracting heat have been described. From direct and indirect systems, open heat pumps using groundwater as the heat carrier and the different types of ground loop collectors designed. Finally a brief overview of potential uses for GSHP technology has been given. From this it would appear that the domestic heating market is the prime growth area in the UK.

[24] This quote is attributed to all heat pumps and not simply GSHP i.e. the majority of HP systems are commercial air based cooling systems

3. Market Outline

3.1 Introduction:

3.1.1 This section will attempt to highlight the current Market status of GSHP technology. Through firstly looking at the world and European situation, at a relatively high level, the varying maturity of markets in different nations will be demonstrated. Following on from this, case studies of Austria, Germany, Sweden and Switzerland, the foremost nations in terms of GSHP penetration within Europe, will be presented. Finally these will be contrasted with the current UK Market situation, which is less developed. This will serve as a platform to a more in-depth look at UK GSHP market barriers in section four.

3.1.2 Even though this is a review of GSHP technology in certain cases it is also useful to gauge and present information on the heat pump market in general, since in many cases this will have knock-on effect for ground coupled technology infiltration. It should also be noted that there may be some discrepancies in figures relating to GSHP numbers, capacity etc these are explained by the fact these represent the market status in different years while it is also impossible to log every system installed.

3.2 World and European Overview:

3.2.1 In general the implementation of GSHP technology is fast growing with annual global increases in excess of 10% for the last ten years. Furthermore over 30 different countries are experiencing similar impressive growth rates. In May 2005 it was gauged that world installed capacity amounted to 15,384 MWth. However despite this positive trend "at a country level, there are great differences. In addition to some pioneering countries, there are several countries and regions in which there are only a few or even no GHP's[25] in operation" [25]. There are many underlying factors which explain this and these will be made clear during the following case studies.

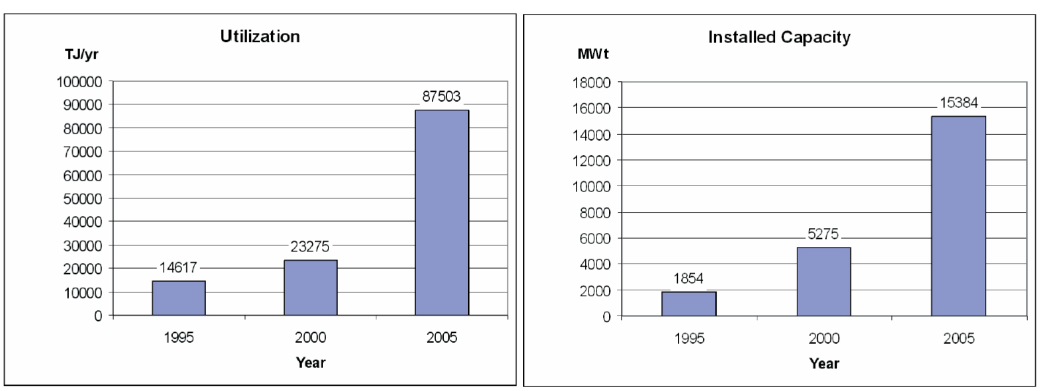


Fig 24 a & b. Growth in GSHP Utilisation and Installed Capacity 1995-2005 as Reported at the World Geothermal Congress 2005, Antalya, Turkey [25]

[25] Heat Pumps using the ground as a heat source

3.2.2 A breakdown of the above figures for the thirty-four nations who submitted data can be found in the appendix. This clearly shows the widespread difference in the utilisation of this technology in different nations. Consequently however it also demonstrates the wide geographical spread of the resource and replicability of the technology under a myriad of different conditions.

3.2.3 At this rate of exploitation heat pumps represent the largest exploitation of direct geothermal resources. This usage equates to approximately 24,000 GWh of energy annually. From an environmental perspective the attraction of this becomes clear in terms of a 5.6 million TOE[26] saving per year. This rate of fossil fuel displacement reduces annual CO_2 emissions by 17.2 million tonnes and therefore contributes towards alleviating climate change.

3.2.4 **Top Ranking Nations in terms of GSHP Utilisation:** The following tables rank various worldwide nations in terms of geothermal heat pump utilisation. The highest installed capacity of heat pumps worldwide can be found in the USA (7200 MWth, 22,214 TJ/yr), however this is clearly a large country both in terms of area and population. Heat pump infiltration (in terms of capacity and energy) will therefore be rated in different nations according to their area and population.

Table 6. GSHP Market Ranking (reproduced from [25])

Category / Rank	Installed Capacity (MWth)	Energy Use (TJ/yr)	Capacity per Area (MWth/Km²)	Capacity per Capita (MWth/Capita)	Energy per Area (TJ/yr/Km²)	Energy per Capita (GJ/yr/Capita)
1	USA	Sweden	Switzerland	Sweden	Denmark	Sweden
2	Sweden	USA	Sweden	Norway	Sweden	Denmark
3	China	China	Denmark	Switzerland	Switzerland	Norway
4	Switzerland	Denmark	Netherlands	Denmark	Austria	Netherlands
5	Norway	Norway	Austria	Finland	Netherlands	Switzerland

3.2.5 From viewing table six several trends become apparent. Firstly, there is a dominant presence of European Markets as the top performers when it comes to infiltration per capita and area. It can be seen that Switzerland, Sweden and Austria perform particularly highly in this respect and it is for this reason they have been selected for a more in-depth case study analysis. Germany can be added to this since although not represented in the ranking, due to its large area and population relative to the other European nations, table it still has a high number of units installed and thermal capacity.

3.2.6 The USA and China of course will not fare so well when performance is reviewed in terms of population or area due to the vast number of citizens and land area. However they should not be ignored as significant players in the world GSHP market. Canada can also be added to this category (531MWth capacity and 2160 TJ/yr energy use). As previously mentioned the large availability of land in these countries makes GSHP technology attractive. Outside of these nations and Europe the only other countries reported to be utilising GSHP technology are Japan, South Korea and Australia. These are

[26] Tonnes of Oil Equivalent

all at very low rates however. Japan has an active heat pump market but this is more focused on reversible air to air systems due to the widespread need for air conditioning and dehumidification.

3.2.7 When comparing installed capacity and energy usage it can be seen that in terms of the top ranked nations they don't exactly match. Taking the cases of Sweden and the USA this can be clarified further. At 2840 MWth Sweden's installed capacity is only just over half of the USA's and yet the energy provision from this is actually higher, 36,000 TJ/yr as opposed to 22,214 TJ/yr. This can be explained due to the different climates in the two countries and the specifics of the units installed. Climatic demands mean Swedish, and European GSHPs in general, are usually are designed to satisfy a heating load while American systems will usually offer both heating and cooling services but are sized for the latter. The Swedish units are also largely monovalent systems which account for the whole heating demand. This, combined with harsh and long winters found in Sweden results in these units accounting for a far number of heating hours per year, from 2000-6000 per annum [27], than those used in the United States.

3.2.8 **General European Market Info:** As shown in table six the GSHP market in central and western European market is significant. This has occurred due to in the order of twenty years research, development and practical experience. This has established [27]:

- Well established sustainable credentials.
- Sound design.
- Good installation criteria.

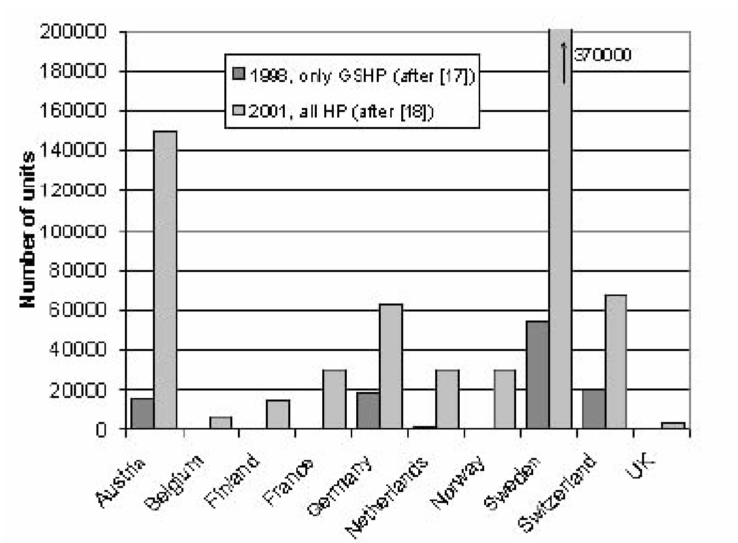


Fig 25. All Heat Pump and Ground Source Proportion; European Comparison [27]

3.2.9 The graph above, although slightly out of date, highlights the relative differences by nation in terms of GSHP usage and what proportion of all heat pumps this accounts for. From this it is shown that generally nations with a high number of heat pump units will fare better in terms of utilising GSHPs. There is definitely room for further expansion however since "the market penetration of GSHPs is still modest throughout Europe, with the exemption of

Sweden and Switzerland" [27] however market development is now also "obvious in Austria and Germany" [30]. It should also be mentioned however that this graph takes into account commercial and industrial installations i.e. the air conditioning heat pump market. When viewing heat pumps for residential heating only the ground fraction becomes far more significant. It is also worth noting at this stage the almost non-existent GSHP market penetration of the UK. To grow this market, and that of other nations not utilising GSHP's, many issues must be considered relating to climate, technical feasibility, reliability, awareness, service provision, economic factors and environmental benefits. To summarise:

"Success in the market is not an accident – it is a result of research, excellent products, skilled installers, the support of utilities and a political goal" [24].

3.3 Ground Source Heat Pumps in Austria - A Case Study:

3.3.1 **Key Stats [27]:**

Capacity: 275 MWth

GSHP Energy Usage: 370 GWh/yr

Approximate Numbers Installed: 23,000

3.3.2 While figure twenty five would suggest dominance of air sourced heat pumps in Austria, in the housing market this is not the case with approximately 95% of all heat pumps utilising the ground as a heat source (the residual 5% being air sourced), the majority of these being below 15 kWth in size. The Austrian Research Centre Survey has reported seasonal performance factors (SPF's) obtained from these units ranging from 2.1 to 4. As a nation Austria has a high proportion of district heating systems, either fossil fuel or biomass fired, and in many cases heat pumps are seen as 'the' alternative for residences too remote to be connected.

3.3.3 **Market Development:** The growth of heat pumps and renewable technologies in general can be traced back to the oil crisis of the 1970's. After the first crisis in 1973 Austria realised its reliance on imported fuels, however little changed in way of energy infrastructure. After the second oil crisis of 1978 however the Austrian government commissioned an energy review with a lasting legacy. The main results of this was targeting change within the space conditioning sector through methods such as increased insulation, district heating, solar and heat pump technology. This resulted in a boom in heat pumps sales from 1980, as shown in figure twenty-six.

3.3.4 The early heat pump market consisted of two main products. Either a monovalent groundwater[27] source heat pump system (mainly found in new builds of the time) or a bivalent ASHP system (usually associated with retro-

27 In some areas of Austria water sanctuaries have been designated meaning government authorisation is required for water source heat pumps and borehole heat exchangers

fits). The boom was based upon government tax reductions for this technology and higher oil prices by a factor of 2.5. However the market could not cope with this rapid rate of growth and many systems were unreliable. As supply could not meet demand the door was opened to less established companies with plumbing or air-conditioning backgrounds to step in. The main cause of system failure was poor design either in integration with the existing heat distribution system, “due to a lack of information and experience, the system integration of heat pumps was carried out much in the same way as integrating oil boilers” [36], or from over sizing.

3.3.5 This caused a reduction in the market until 1990. A trend exacerbated by the removal of heat pump subsidies in 1985, due to a drop in oil prices, which made many bivalent systems uneconomic. Although the market reduced during the 1980’s those companies still operating had learnt from these early failures and improved service and reliability, “only serious companies with reliable products and trained installer survived” [24]. By the mid eighties the first heat pumps using the ground as a heat source were installed with DX ground loops a popular configuration (see 2.3.2), most of these systems were monovalent and for the new build market. Since the late 1990’s most new systems have utilised low temperature, 30-35ºC, underfloor heat distribution systems.

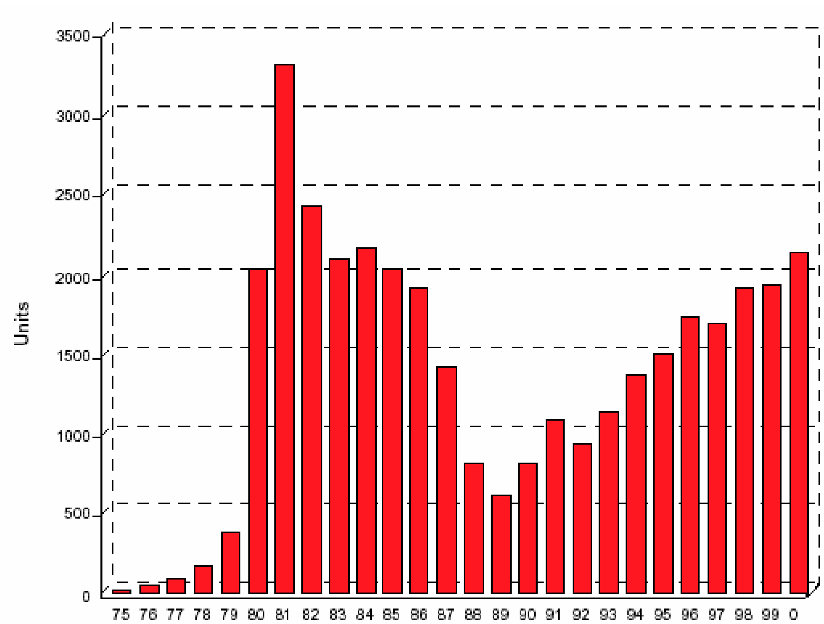


Fig 26. Heat Pump Market Development in Austria [24]

3.3.6 **Utility Involvement:** Since deregulation Austrian electricity utilities have been very active in the heat pump market. This change from a supplier/distributor of electricity to a ‘seller’ has resulted in the most forward thinking organisations offering support to heat pumps as electricity using devices and therefore a means of entry into the ‘wet’ heating market. Offering a heat contracting service the utility will often own, service and operate the heat pump while the customer just pays for the heat utilised[28]. In many cases this has made installation of relatively more expensive large capacity vertical borehole systems possible. The successful example of Austrian utilities seems to be based on the concept of creating "a climate of confidence for the customers, and to support them by supplying reliable systems" [21], many also offer special heat pump tariffs.

3.3.7 The electricity company OKA is a positive example of the key role utilities can play in developing the heat pump market by viewing heat pumps as a new segment of the electricity market. As a result of its activities since the late 1970's the region of Upper Austria, where it operates, now contains 50% of all Austrian ground source heat pump systems and every second new home in the region uses a heat pump system. OKA has forged strong partnerships with competent installers and manufacturers in order to offer a reliable service. Heat pumps in this region are also attractive financially due to an interest free loan offer from the utility to partner a federal state grant.

3.3.8 There has never been reason for OKA to offer special heat pump tariffs due to the fact they have ensured supported customers with reliable and efficient systems. After-sales service is made a priority and the monitoring programme put in place has shown steadily increasing efficiency over the last fifteen years.

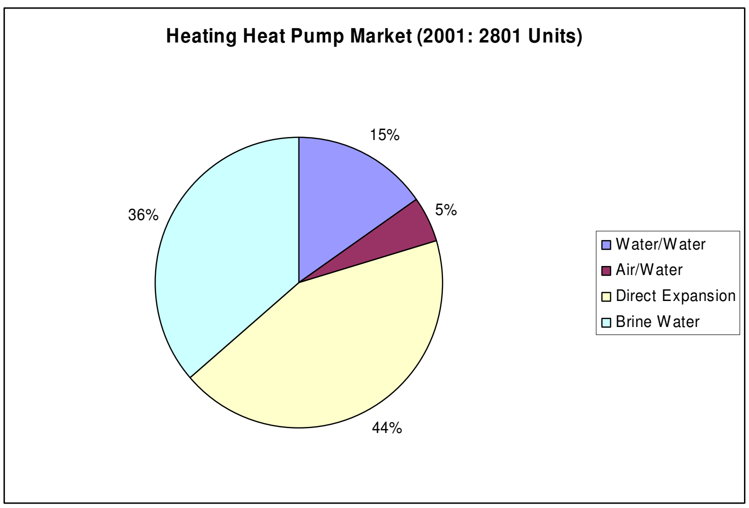


Fig 27. Breakdown of the Austrian Heating Heat Pump Market in 2001, reproduced from [36]

3.3.9 **Subsidies:** In Austria each of the nine federal areas offers different support. The value of this differs if the heat pump is for heating or hot water, with the latter receiving less. There is also varying levels of support according to the heat source. In these cases ground and water sources receive a larger amount due to the higher COP's achievable. While in some areas the level of funding which can be obtained depends on having a D-A-CH[29] quality label and certified installers. A typical level of support for a ground source space heating heat pump would be in the region of 2000€.

[28] Similar to the Energy Services Company (ESCo) concept
[29] Joint quality assurance scheme with Germany and Switzerland (see 3.3.14)

3.3.10 **Awareness Raising:** In an effort to widen the customer base as far as possible heat pump technology is proactively marketed with targeted mail, printed information, trade fairs and radio/television advertising. Public awareness differs from region to region; this is explained since “utilities are the main promoters of heat pumps” [36] and these operate is defined regions with some more active than others.

3.3.11 Experienced installers, with good reputations, support heat pump awareness raising through good quality installations within local areas where performance and service spreads by word of mouth. The installer carries the main responsibility of ensuring system quality and is the first point of call in dealing with any problems.

3.3.12 **Manufacturers:** These have played a key role in developing the heat pump market through the provision of quality products (better flat plate heat exchangers, compressors, advanced cycle controls etc) and also demonstrating the value of heat pumps to customers. Active co-operation has been present between manufacturers, even though they are in direct competition, to establish heat pumps in the market.

3.3.13 The LGW[30] trade association was formed in 1990 to [24]:

- Promote heat pumps (targeted at politicians and developers).
- Solve legal issues.
- Influence regulations.
- Education and training.
- Research and development.
- Publicise environmental benefits.

This has clearly corresponded with an upturn in the market. The main Austrian manufacturers of heat pump systems are Junkers, Buderus, Elco, Hagleitner, Ochsner, Vaillant and Veismann.

3.3.14 **Ensuring Quality:** Linking with the Swiss and German heat pump associations LGW has formed the D-A-CH heat pump quality label, this specifies achievable coefficient of performances, set servicing standards (24hr call out service), spare part availability for ten years and gives a three year system guarantee. To ensure quality in the whole heat pump system i.e. sink, source, heat pump and integration with the distribution system, a certification programme for installers has also been started.

3.3.15 Austria is also a world leader in terms of linking GSHP and solar technologies. An example of this is at the ESG Oskpark in Linz where a horizontal ground loop system has been combined with 35m² of solar panels. These collectors are utilised for ground thermal recharge (as mentioned in 2.2.10) when the temperature is not suitable for use within the buildings. This has exhibited an SPF of 3.3 with 55% of the energy attributed to the earth and 19% from the sun (the remaining 26% is from fossil fuels) [30].

[30] Leistungsgemeinschaft Wärmepumpe

3.4 Ground Source Heat Pumps in Germany – A Case Study:

3.4.1 **Key Stats [27]:**

Capacity: 640 MWth

GSHP Energy Usage: 930 GWh/yr

Approximate Numbers Installed: 46,400

3.4.2 Approximately two thirds of heat pumps sold in Germany utilise the ground as a heat source (as shown in figure twenty-eight). This has risen significantly from only 30% in the late 1980's. At a domestic level the majority of ground source heat pumps are monovalent heating systems. Due to the prevailing climate while cooling is sometimes needed dehumidification is not as necessary and therefore the former can be offered with a wet distribution system via 'chilled ceilings' or passive/natural cooling (see 1.6.6).

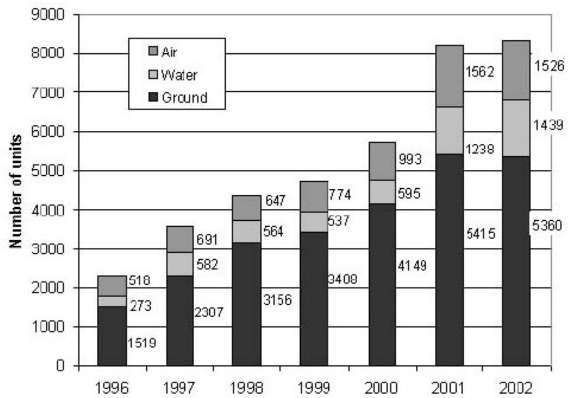


Fig 28. Heat Pump Sales in Germany 1996- 2002 by Heat Source [27]

3.4.3 **Market Development:** The development of the heat pump market in Germany bears many similarities to Austria. From viewing figure twenty-nine it can be seen that there is a sales explosion in 1980 and then a gradual reduction to 1990. After this there is a slow but gradual recovery. Again the same explanation is hypothesised. After the second oil crisis heat pumps were pushed onto the market without the industrial or professional competence for manufacture and installation. Fluctuating oil prices were also influential.

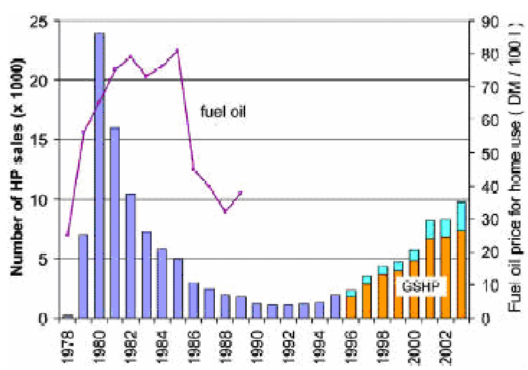


Fig 29. Heat Pump Sales in Germany 1978-2003 (air and ground source distinction from 1996 onwards) [35]

3.4.4 The majority of these early systems were air sourced and incorporated with existing/new systems utilising peak demand boilers (e.g. bivalent). Again issues relating to poor quality and system integration caused the market to crash. This created an image of heat pumps as ‘unreliable’ technology [30].

3.4.5 **Utility Involvement:** Like in Austria utilities play a strong role in the heat pump market offering reduced tariffs, grants (of different amounts depending if for individual/district heating systems and heating/HW or both) and engaging in “strategic and operative heat pump marketing activities” [21]. As part of the ‘Essen Energy Programme’, the utility RWE has achieved virtually a doubling of heat pump installations every year.

3.4.6 **Subsidies and Government Support:** Government support has been offered since 1997 and is available for heat pump projects at a varying rate per kW of heating capacity which reduces for larger systems i.e. if above 15kW. There are certain conditions placed on applications however such as using H-CFC refrigerants and achieving set seasonal performance factors (which increase year on year). There is also strong government support for heat pump research and a dedicated heat pump information centre.

3.4.7 Government support is also provided in the form of Local Authorities providing information on local geology, legislation and design factors. For example the Nordrhein-Westfalen area has been completely mapped and a CD-ROM of subsurface geology provided to those interested in installing borehole heat exchangers.

3.4.8 **Awareness Raising:** The heat pump association informs politicians and the media regarding the latest developments in heat pump technology while also supporting those in the trade who wish to undertake advertising activities.

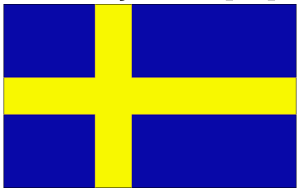
3.4.9 **Manufacturers:** The federal heat pump association was formed in 1993 and has over 300 members, including 95% of manufacturers and approximately half of suppliers. The main goal is to increase the use of heat pumps in the new build sector from 2% to 20%. Selected German manufacturers are ERW Wärmepumpen, Dimplex, Steibel Eltron and Viessmann.

3.4.10 **Ensuring Quality:** In Germany the GSHP has left the research, development and demonstration stages well behind and the present emphasis is on further optimisation and securing quality. New initiatives in this area to protect the fledgling industry include technical guidelines, certification for contractors and quality awards.

3.4.11 Design, installation and building connection of heat pumps is covered by the technical guideline VDI 4640. As previously mentioned the German Heat Pump Association has joined with counterparts in Austria and Switzerland to form the D-A-CH quality label (see 3.3.14).

3.5 Ground Source Heat Pumps in Sweden – A Case Study:

3.5.1 **Key Stats [27]:**



Capacity: 2,300 MWth

GSHP Energy Usage: 9,200 GWh/yr

Approximate Numbers Installed: 230,000

3.5.2 Sixty five percent of all domestic heat pump sales in Sweden are brine/water systems; this is followed by exhaust air-water (25%), air-water (6%) and air-air (4%). These figures can be explained since similarly to Austria and Germany there is a historical scepticism over air-air heat pumps while ground source heat pumps are considered "well tried and reliable" [36] and "the most popular type of heating device for small residential buildings with hydronic systems in Sweden" [27]. The majority of these systems are borehole based with an average vertical depth of 125m. Many of these are operated bivalently (alongside back up electric systems) covering 60% of the peak load, this gives 2,500-4000 full load hours per annum [27].

3.5.3 Only a relatively low number of ground source systems are of a direct expansion (DX) configuration (see 2.3.2). In addition there are not many groundwater source heat pumps, this is mainly due to low temperatures and concerns regarding water quality and supply availability [36]. Although the average size of installed Swedish GSHP's is 10kW there are also many large (600-900kW) systems which support district heating networks. Furthermore GSHPs in Sweden are able to offer competitive emissions reduction due to the high contribution of hydropower in the nation's electricity generation portfolio.

3.5.4 In the residential sector there is little interest in cooling, however on a commercial and industrial scale this is under consideration. Examples of these are a ground coupled district cooling system utilising a groundwater aquifer and borehole cooling systems used for telecommunications cooling.

3.5.5 **Market Development:** Heat pump systems first became popular in the early 1980's, and by 1985 over 50,000 units had been sold. From the middle of the decade onwards sales were stunted slightly due to lower energy prices and some quality issues, however development of the heat pump market in Sweden has demonstrated stable and sustainable growth. The exception to this being a spike in sales during 1990 (see figure thirty-six), this can be attributed to an upcoming VAT charge on heat pumps and energy starting in 1991.

3.5.6 As shown in table six Sweden is undoubtedly the European leader in GSHP technology. One of the main reasons behind this can be attributed to unlocking the potential within the existing housing stock "more than 75% of all heat pumps sold are retrofitted into buildings" [36]. This has proven a considerable stumbling block in other European nations.

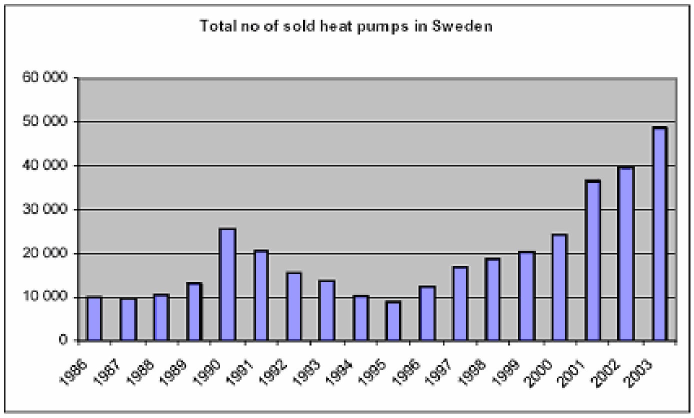


Fig 30. Heat Pump Sales in Sweden 1986-2004 [36]

3.5.7 The heat pump market is now so well developed the technology is being considered for utilisation on almost a complete village/town sale. In Stromstad, 200km north of Gothenburg, 3000 homes (about half the population) are supplied by 140 GSHP systems utilising 400 borehole heat exchangers. The main reason behind this concentrated number of installations was that the rocky subsoil prohibited using a district heating system based on biomass or fossil fuels [20].

3.5.8 **Government Support:** At present there are no direct subsidies to install heat pumps, although R&D is still supported. Therefore it can be assumed that the market has reached a stage of maturity where installation/running costs are deemed competitive with other fossil fuel technologies. Financial incentives were on offer however from the mid eighties to nineties.

3.5.9 Swedish building regulations state that the maximum distribution temperature of hydronic (wet) systems is 55ºC; this of course greatly advances the use of GSHP technology with low distribution temperatures. At present 70% of all wet systems are underfloor which is again ideal for heat pump technology (see 1.8.2). A government permit is required prior to a GSHP installation, especially for water sourced systems.

3.5.10 **Awareness Raising:** Marketing of heat pumps is carried out by the manufacturers (both Swedish and foreign) and installers with no active involvement from utilities[31]. Marketing activities are conducted via adverts, television commercials and presentations.

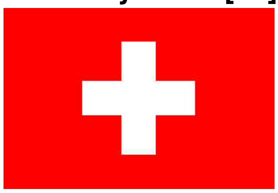
3.5.11 **Manufacturers:** To reflect the high number of installations Sweden has two national heat pump associations, SVEP and SEV. These jointly act on issues such as promotion, lobbying and ensuring quality. As in Austria, resellers (either plumbing or installation companies) are the main point of contact for the customer and shoulder many of the responsibilities in ensuring the system works to specification. SVEP has twenty-five manufacturer and installer members such as NIBE, Thermia, TESAB and foreign manufacturers such as Panasonic and Mitsubishi.

[31] Utilities do not play an active role in the Swedish GSHP market at all

3.5.12 **Ensuring Quality:** An ECO-labelling scheme for heat pumps called 'Svenan' has been developed. Equipment and procedures for in-situ testing of the thermal properties of the ground were first developed in Sweden; these allow better simulation and design accuracy for GSHP systems.

3.6 Ground Source Heat Pumps in Switzerland – A Case Study:

3.6.1 **Key Stats [27]:**



Capacity: 525 MWth

GSHP Energy Usage: 780 GWh/yr

Approximate Numbers Installed: 30,000

3.6.2 Forty percent of all heat pump systems utilise the ground as a heat source; of these 5% use horizontal loops, 65% boreholes (100-400m depth[32]) and 30% use groundwater as a heat source. These are yielding reported seasonal performance factors in excess of 3.5. ASHP systems are also popular in Switzerland and account for the majority of the remaining heat pump market. This is mainly due to lower installation costs although achievable SPF's are lower.

3.6.3 Climatic conditions on the Swiss plateau are very suitable for GSHP systems. There is long steady heating periods (air temperature at 0ºC) with a ground temperature of 10-12ºC at a relatively shallow depth. These steady ground temperatures result in favourable SPFs. Technologies in this area are also developing fast with use of multiple borehole ground heat exchangers, energy piles and combinations with other renewable sources being utilised.

3.6.4 **Market Development:** A strong emphasis on heat pump use from Government and Utilities alike has resulted in a "steadily growing residential market" [21]. In some regions one third of all new houses utilise a heat pump system and there are set targets for numbers of installations. Growth rates are annually increasing at a rate of 15% [27], with the biggest increases for systems under 20kW. The commercial market is still low and fluctuating however.

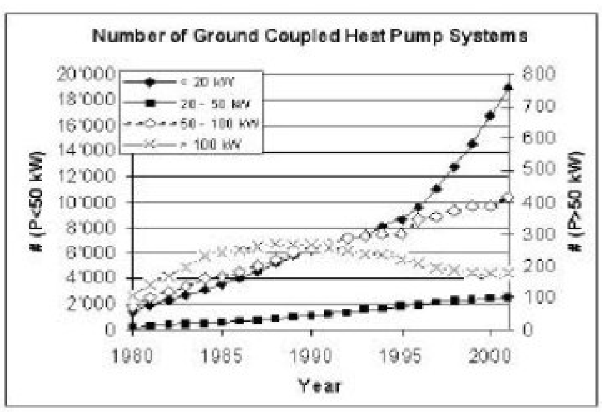


Fig 31. GSHP Market Growth 1980-2002 by System Size [27]

[32] Average 150-200m

3.6.5 As shown in figure thirty one above the Swiss market does not show the 'boom and bust' characteristics of Austria and Germany with all system sizes showing steady growth with the exception of >100 kW commercial size systems where growth reached a peak in the late 1980's and then reduced. This trend is underlined in figure thirty two which highlights the steady increases in borehole geothermal energy extraction. The main explanation for the increase in growth within the small domestic sector is the concentrated activated of utility companies as explained in 3.6.7.

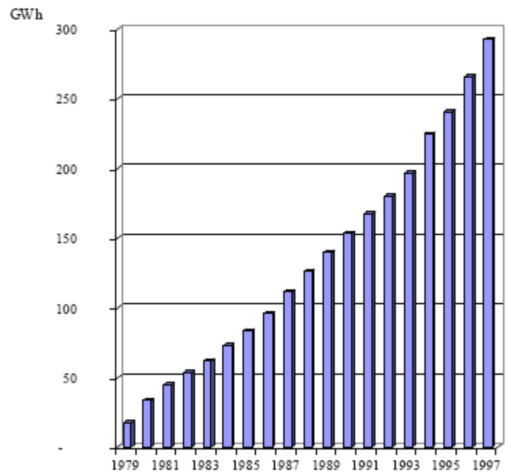


Fig 32. Geothermal Energy Extraction from Borehole Heat Exchangers in Switzerland 1979-1997 [30]

3.6.6 There is still a large potential to increase the market share of heat pumps and ground source heat pumps in Switzerland however. This is borne out by figure thirty three which shows the relatively small proportion of heat pumps in the low grade heat market. The retrofit market is largely untapped while 20-50 kW size systems are still at a relatively low level as is infiltration of large scale heat pump district heating schemes.

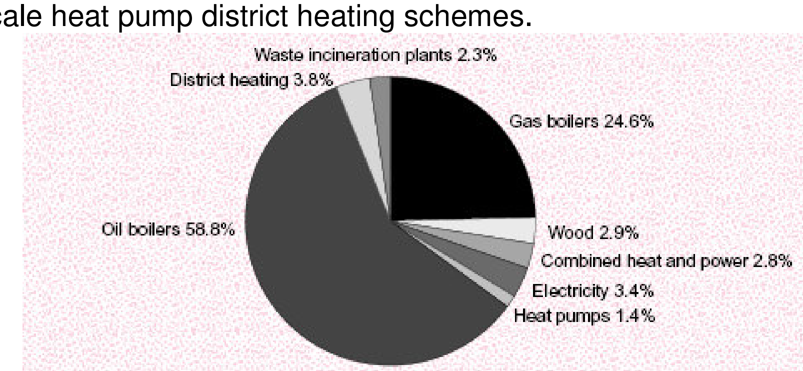


Fig 33. Low Grade Heat Production Sources in Switzerland [23]

3.6.7 **Utility Involvement:** Several Swiss utilities have played a key role inn developing the heat pump market. St. Gallen-Appenzell Power Company Ltd. (SAK) started their involvement in the heat pump market in 1993 with three key goals [23]:

- Information provision.
- Customer service package.
- Increasing the cost effectiveness of heat pump systems.

3.6.8 In order to initiate the market SAK actively sought out potential users such as architects, engineers and designers to highlight the advantages of heat pumps. To make the package more attractive to the home owner investment risk is reduced through SAK designing the system, obtaining the relevant permits, performing installation and offering service support. Subsidies of the order of 145€/kW capacity and reduced tariffs are offered. In some cases SAK has retained rights to switch off the units at peak times as part of a demand side management (DSM) scheme. Overall this strategy was targeted to infiltrate the space heating market for new build homes single/small multi-family homes.

3.6.9 The primary indicator that this approach has been successful is that the market share of heat pumps in the target group is almost 50% in certain SAK regions; "The comprehensive service package, from the consultancy phase to monitoring efficiency, was a determining factor in the success of this direct marketing campaign" [23]. Since SAK has customer confidence it is in an ideal position to introduce heat pumps. One third of these are brine to water heat pumps.

3.6.10 The North East Switzerland Power Company (NOK) is also involved in the heat pump market through offering grants and running information campaigns. They, like SAK, are also trialling DSM techniques where heat pumps are switched off for an hour twice daily during peak periods.

3.6.11 The Electric Utility of Freiberg (EEF) in West Switzerland created the heat pump organisation SAPAC in 1985 with the key aim of production and promotion of heat pumps. SAPAC offers many free services including demand assessment, planning and sizing for heat pumps, cost approximation and obtaining drilling permits. One disadvantage of the strong presence of Utilities in the heat pump market is the difference in services found within the various areas. This can cause confusion with potential customers not understanding why they cannot have the same package available elsewhere.

3.6.12 **Subsidies and Government Support:** Renewable technologies, and therefore heat pumps, were promoted through the Energy 2000 programme in Switzerland, which was the core of energy policy in the 1990's. The main focus of Energy 2000 was to increase jobs and lower CO_2 emissions. The promotion of superior energy efficiency in buildings as part of the programme has also aided heat pumps. Economically, installation costs are favourable with oil systems and running costs are lower than alternative fossil fuel systems. In addition Government is actively supporting research and development into geothermal energy.

3.6.13 Heat pump activity should be further stimulated by the introduction of a CO2 tax on heating fuels which is due to be introduced in 2008. The rate of this tax is related to emissions "it will initially be set at SFr12 (€7.5) per tonne of CO2 and rise or fall depending on how emission levels move against baselines to be set annually" [38]. In some cases however the channels to receive approval for a GSHP system have been "time consuming and costly" [23]. In addition if groundwater is utilised as heat source there is a charge for each cubic metre delivered to the heat pump; this obviously damages cost effectiveness.

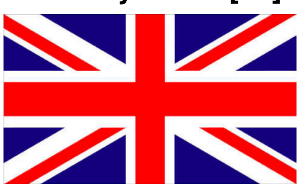
3.6.14 **Awareness Raising:** In Switzerland heat pump promotion activities have taken place since 1991. These have been initiated by the Government but receive strong utility support. As already mentioned electric utilities undertake promotional programmes within the regions in which they operate and hence “heat pumps are being promoted in a new and future orientated way” [23].

3.6.15 **Manufacturers:** The Swiss Heat Pump Association (FWS) runs events, provides information and publications. In addition there is WPZ the national heat pump test and training centre, and AWP the heat pump manufacturers association, members include Steinmann, Novalen and Hoval among others.

3.6.16 **Ensuring Quality:** As previous mentioned in the Austria and Germany case studies Switzerland is a partner in the D-A-CH quality label formed in 1998.

3.7 Comparisons with the UK Heat Pump Market:

3.7.1 **Key Facts [39]:**



Capacity: 10.2 MWth

GSHP Energy Usage: 12.6 GWh/yr

Approximate Numbers Installed: 530

3.7.2 **Market Development:** As the figures presented in 3.7.1 suggest “the adoption of heat pumps for heating buildings has been inexorably slow” [27] in the UK when compared with the other countries outlined in this section. From 1852, when Lord Kelvin put forward the concept of the heat multiplier, until the late 1980’s there was only a handful of heat pump heating technology applications [3]:

- System built by J.G.N Haldone 1930.
- Domestic system installed by John. A. Sumner in 1946.
- Twelve prototype domestic GSHP systems commissioned by Lord Nuffield in 1948.
- A highly publicised failure of a water source system for London’s Festival Hall in 1952[33].

3.7.3 Between 1970 and 1994 it is estimated that just twelve GSHP systems were installed in the UK. This is significantly different from the gradually developing markets of Sweden/Switzerland and erratic but prominent development in Germany and Austria during this time. By 1992 there were 3,000 heat pumps in single family homes, forty percent of these however were mainly air-water systems utilised to heat swimming pools; while in 2001 it was

[33] Where design errors didn’t take account of sound proofing insulation and causal gains.

projected that there could be in the region of 110 GSHP installations in the UK [19]. If the figures presented in 3.7.1 are accurate this would indicate a 500% increase in GSHP systems between 2001 and 2005. So while this rapid growth, depicted in figure thirty-four, is encouraging it is still far behind the European markets presented in 3.3-3.6.

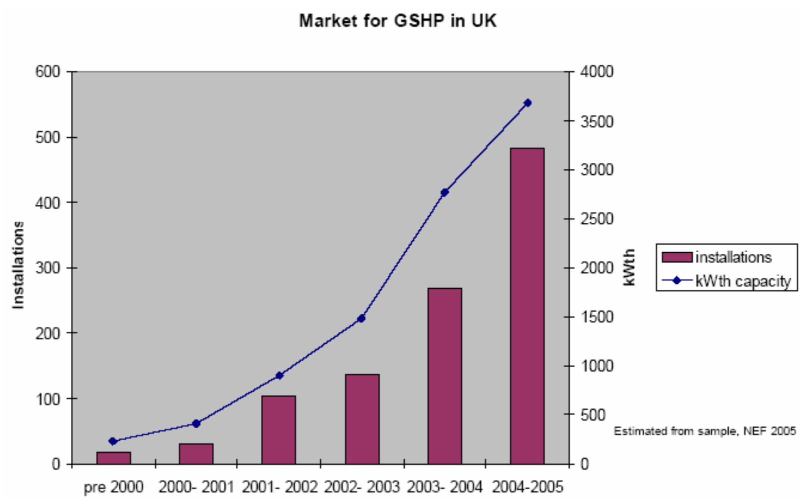


Fig 34. Estimated GSHP Market Growth in the UK 2000-2005 [32]

3.7.4 It is promising that “markets are developing and at a pace that should allow the industry’s capabilities and structures to grow in step with demand” [34]. Should the market develop in this way the boom and bust trends of early heat pump development in Austria and Germany can be avoided and thus fragile customer confidence maintained.

3.7.5 One of the main reasons for this slow take up could be simply that it has taken time to find a suitable solution to match the UK housing stock and unique issues found within the country. It has been hypothesised that the development of the UK market has in effect been a “distillation of both American and (mainland) European practices of design methods, installation methods, equipment and heat pump technology which can be used in the UK environment” [19]. As will be shown in section four there are many background factors which distinguish the UK from the mature heat pump markets already outlined.

3.7.6 The most prolific area of heat pump application in the UK remains air conditioning systems in commercial buildings, accounting for 25% of systems used in offices, hotels and the retail sector; however “less than one percent of heat pumps” are “being used as a prime heat source” [29]. As regards public perception though a link has not been developed between these installations and the use of GSHP systems within the home and therefore “heating optimised dedicated heat pumps for domestic space heating and domestic water heating are almost unknown in the UK” [28]. Hence “the domestic sector remains dominated by gas fired conventional wet central heating systems” [18]. Since 20% of total energy consumption for space and water heating is in the domestic sector bridging the domestic market is key to successful widespread implementation of GSHP technology.

3.7.7 There is also a strong focus within the UK in targeting properties not connected to the mains gas distribution network for heat pump systems. It is estimated that there are 4.42 million houses in this sector, each with an 18MWh/yr heating demand [10], 1.3 million of these utilise electric heating systems. Therefore should the electric heating systems in these 1.3 million houses alone require replacement every 20 years a 65,000 per year potential heat pump market is opened. New build houses in the UK number approximately 400,000 per year with 80,000 off the gas network [34]; these are also prime targets for GSHP system installations. These figures highlight the potential for GSHP market expansion which exists in the UK.

3.7.8 The reason for the popularity of the new build market in terms of heat pumps is based on the lower installation costs for the ground loop/borehole, less disruption (since building works are ongoing anyway) and the greater ease of installation for which a low temperature distribution system can be fitted (i.e. underfloor heating). In addition it is easier to ensure the high insulation standards needed required for heat pumps systems at this stage.

3.7.9 However it may be short sighted to dismiss retro-fit opportunities altogether, these should be reviewed on a case by case basis since the cost effectiveness of a GSHP will depend on the efficiency and performance of the previous heating system. In some cases running cost savings can be hard to estimate however due to the fact that they will be dictated by ever changing electricity/gas/LPG tariffs. Finding a way to penetrate the retrofit market, as has been done in Sweden, will truly open the door to widespread acceptance and applicability of GSHP systems. This is demonstrated by table seven, which shows that while the technical potential of GSHP systems is very substantial[34] the actual predicted share is only a fraction of this.

Table 7. Potential GSHP Markets (adapted from [10]).

Potential	Residential Market (no. homes*)		
Year	2010	2015	2020
Technical	4,244,000	4,306,000	4,361,000
Market	1,061,000	1,079,000	1,089,000
Predicted	28,000[35]	156,000	406,000

*based on a demand of 18 MWh/yr per home

3.7.10 It is thought that there is also "considerable technical potential for open loop heat pump systems in the UK" [19], this is due to the presence of groundwater under a large proportion of the UK and a relatively high and accessible water table. This technology however faces additional constraints to even ground based heat pump systems due to the need for the relevant approvals (i.e. from the Environment Agency or SEPA[36]), proof of the resource and well testing as discussed in 2.4.2. Conservatories are also thought to represent an area of potential growth, and a route to market

[34] 18.45% of the 23 million housing stock (2002 levels)

[35] It should be noted however that at current growth rates the prediction for 2010 made in table seven looks unlikely to be met

[36] Scottish Environmental Protection Agency

infiltration, in the UK due to the need for cooling in summer and heating in winter.

3.7.11 The "small size of the current domestic heat pump market suggests it will favour an expansion of market penetration for existing heat pump types rather than new application areas" [18], this should result in electrically driven vapour compression heat pumps being the most prominent type of system as in the mature European markets already covered. "It has been estimated in the UK that an achievable sales target would be 15,000 heat pump systems per year" [29]; with GSHP systems accounting for a significant proportion of these systems.

3.7.12 **Utility Involvement:** In the early 1990's 40 domestic 1.4 & 2.5kW DX systems were installed in Scotland by Scottish Hydro-Electric[37], this pioneering development however was not built upon. Powergen has recently launched the 'Heat Plant' scheme which aims to install 1,000 'Calorex' GSHP systems into the social housing sector to satisfy its Energy Efficiency Commitment (EEC) targets. These schemes however are not comparable to the large scale activities undertaken in Switzerland and Austria where real partnerships are formed with manufacturers and installers. Also the Utility activities in these countries are business based, and treated as such with targeted installations and customer groups, not simply an effort to meet legislation.

3.7.13 **Subsidies and Government Support:** "It will always be fiscal, or legislative measures that will dominate the rate at which new products penetrate a given market" [19] and considering this it seems there are a number of initiatives either available or upcoming which could aid the GSHP market in the UK.

3.7.14 Firstly heat pumps are now included as suitable technology under the Energy Efficiency Commitment, Low Carbon Buildings Programme (Phase 2)[38], and Scottish Community and Householder Renewables Initiative (SCHRI) funding schemes. In addition there are various pieces of legislation relating to new build commercial and domestic buildings which could stimulate GSHP installations. The Energy Performance in Buildings Directive (EPBD) places a higher emphasis on building energy efficiency and also requires consideration to be paid to various renewable technologies (including heat pumps) on new buildings over 1000m^2. Various local government organisations are formulating planning restrictions, for example:

- The London Borough of Merton stipulates that new build commercial buildings source 10% of their energy needs from renewable sources.
- The London Borough of Croydon, which states that 10% of the energy demand from new developments should be met from renewable sources.

[37] Also known as Scottish and Southern Energy

[38] This has replaced the Clear Skies scheme which also funded heat pumps. Grants are available for non-reversible closed loop systems, utilising a borehole or trenches. A grant of up to £1,200 is available for domestic systems, and of up to 50% for installations made under the Community stream (to a maximum of £30,000)

Known as the 'Merton Rule', similar approaches have now been developed in a multitude of regions, County Councils, City and Metropolitan Councils and other London Boroughs.

3.7.15 New building regulations also set high standards and tough challenges for the construction industry as regards energy performance. The 2006 regulations (Part L) relate to the conservation of fuel and power and [31]:

- Limiting heat gains and losses through using thermal elements and building fabric.
- Providing and commissioning energy efficient fixed building services.
- Provide good performance in terms of associated CO_2 emissions.

Building houses in this manner will suit heat pumps and other LZC[39] technologies.

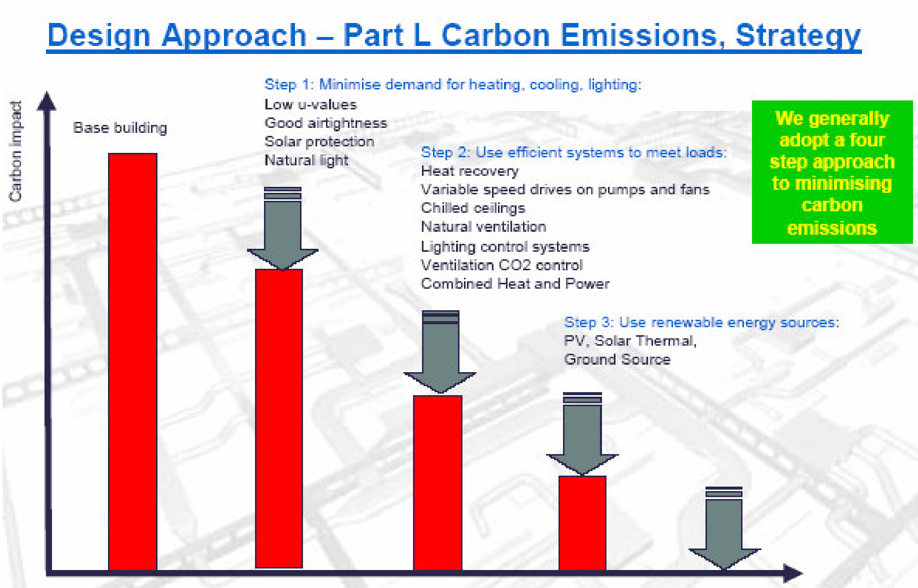


Fig 35. Step by Step Approach to Limiting Carbon Emissions as Stated in the Building Regulations 2006 (Part L) [31]

3.7.16 The majority of heat pump R&D in the UK however is currently aimed at cooling technologies; "the greatest proportion of R&D activity in the UK focuses on improving sorption cycles" [19] rather than optimisation of current heating technologies. It is clear there is still room for improvement in terms of further research into optimisation of the electric vapour compression heat pump to suit the UK market and deliver optimum performance.

3.7.17 As has been stated in the Royal Commission on Environmental Pollution's year 2000 energy review report 'Energy: The Changing Climate', GSHP's have a strong role to play in meeting energy efficiency, renewable energy and affordable warmth[40] targets set by the government [32]. It is hypothesised that a geothermal heat pump connected to the UK grid could lead to overall CO_2 emissions reductions of 40-60% dependant on the

[39] Low or zero carbon technologies
[40] Such as the abolition of fuel poverty by 2016

previous system in place. Widespread infiltration could therefore go someway towards contributing to the Governments target of a 60% reduction in CO_2 emissions[41] by 2050. Also with the "decreasing carbon intensity of power generation in the UK" [32] i.e. through a higher infiltration of renewables or more nuclear capacity, these savings will become more pronounced.

3.7.18 Although there are numerous targets for renewable electricity generation in the UK, such as 10% by 2010 for the UK and Scotland's ambitious target of 40% by 2020, there has as yet been no development of a renewable heat target. This is despite the fact the domestic sector accounts for approximately a third of all primary energy use and CO_2 emissions. A renewable heat target would place more emphasis of technologies such as GSHPs and aid market development while also contributing to improve security of supply.

3.7.19 **Awareness Raising:** It is clear that at present GSHP technology, and its environmental/cost saving potential, is not widely recognised by the general public (as also mentioned in 3.7.6), and as such there is a real need for demonstration and promotional efforts on behalf of the UK government and local authorities. In addition "there is little, if any, direct marketing effort from manufacturers or installers to end users" [36]. This is a marked distinction with, for example, Austria where close relationships and familiarity have been built up with the general public.

3.7.20 To date there is also no uniformity in installations of GSHP systems in the UK. Sizes have varied from 4-200 kW with boreholes, direct expansion, slinky and single pipe trench collector systems installed. Further variation is added with the different distribution systems utilised such as radiators and underfloor wet systems and various air based distribution systems. This lack of a large number of uniform, installations is perhaps detrimental to proving system performance in the public eye and raising awareness and acceptance.

3.7.21 **Ensuring Quality:** Heat pumps are typically exempt from many of the restrictions and standards stipulated in building regulations as regards heating systems since they do not utilise combustion. The standard BS EN 255, which covers manufacture of air conditioners, liquid chilling packages and heat pumps with electrically driven compressors is utilised however. In the UK source/load testing temperatures are 5ºC/45ºC instead of 0ºC/45ºC used in Europe though, due to the generally warmer maritime climate [28].

3.7.22 To ensure a quality service to customers a support and training network for suppliers/installers to develop "a skilled design and installation workforce" [34] would be beneficial; this has proved successful in the European markets already discussed. At present there is no independent test centre in the UK for heat pumps, developing such a facility would allow optimisation of GSHP technology for the UK market. An accreditation system similar to those found in Europe (i.e. the D-A-CH label) would give customers added reassurance and help to allay fears as regards investing in a 'new' technology.

[41] On 1990 levels

3.7.23 **Manufacturers:** The UK Heat Pump Network was formed in 1999 to offer support, provide a platform for networking and bring together expertise within UK manufacturers and installers. It has been stated however that "there is considerable scope for developing a more competitive network of developers and installers" [10]. A sub-committee has also been established to investigate domestic ground source heat pumps. In 1999 the UK joined the IEA[42] Heat Pump programme.

3.7.24 In addition there is the Heat Pump Association (HPA) for manufacturers of heat pumps and associated components which is part of the Federation of Environmental Trade Associations (FETA). The HPA works on technical/market research, legislation issues and promotional activities.

3.7.25 The national Ground Source Heat Pump Association (GSHPA) was formed in 2006 with the aims of [32]:

- Raising standards.
- Promoting the industry and market.
- Developing technology.
- Providing information.

The presence of such an organisation will support the development required to meet the growing demand shown in figure thirty four.

3.7.26 Market expansion however will "require considerable investment by the industry to expand its capacity" [19] this will be required to ensure the same problems of poor quality installation which occurred in Germany and Austria, when supply could not match demand, do not occur in the UK; encouragingly, "the UK is beginning to see developments in terms of the supporting infrastructure that will be required before these systems can be widely applied" [19].

3.7.27 In summation "delivery of attractively priced systems, using appropriate heat pumps for the UK market, across a wide range of geological conditions has to be the focus for would be suppliers and installers in the UK" [19]. There are several prominent manufactures represented in the British market (from the UK, Europe and Japan) examples being Calorex Heat Pumps Ltd, Clivet UK Ltd, Dimplex, Kensa Engineering, Worcester-Bosch and Viessmann UK Ltd. Under the Clear Skies funding scheme, since replaced by the Low Carbon Buildings Programme, 23 manufacturers and 66 installers were accredited.

3.8 Section Conclusion:

3.8.1 This section has firstly highlighted the large potential ground source heat pumps have to become established as a widespread option for space heating provision. At present the rate to which this has occurred differs radically from nation to nation; although overall growth rates are encouraging.

[42] International Energy Agency

3.8.2 Through looking at the heat pump and GSHP markets in four of the leading European GSHP countries it can be seen that they share many similar traits in terms of how the market has been developed i.e. the key role of utilities in Austrian, German and Swiss market development. While each country however still has its own vagaries as regards how the market developed and the key players within it; Sweden for example is alone in widespread retrofitting of GSHP systems.

3.8.3 Comparing the current UK situation with the markets in these nations has shown there is still considerable scope for improvement in order to strengthen the position of heat pumps as a viable heating option. Positive steps are being taken however in terms of legislation, establishing trade associations, significant growth rates and some tentative involvement from utilities. It has been hypothesised that “the UK was not slow in recognising that heat pumps could benefit the growing demand for energy efficient systems in all sectors” [18], so how can the relatively modest market infiltration of GSHP’s be explained? This will be considered in section four.

4. UK Market Barriers

4.1 Introduction:

4.1.1 There have been many reasons postulated to explain the lower levels of ground source heat pump utilisation in the UK compared to other European nations. In this section these reasons will first be presented in more detail and then contrasted with the situation in Austria, Germany, Sweden and Switzerland by means of a matrix.

4.1.2 This section will also comprise feedback from a market research questionnaire circulated to gauge the opinion of those in the GSHP industry on potential UK specific market barriers and the means by which to encourage growth.

4.2 Potential Market Barriers for GSHP's in the UK:

4.2.1 Each of the barriers highlighted during research will be presented alongside the reasons postulated for it inhibiting GSHP development.

4.2.2 **Electricity Supply:** The vast majority of all UK domestic properties are supplied with a single phase 230V 50Hz electricity supply. With a single phase supply the size of load which can be connected is limited and high start-up currents can cause disruptive loads across the network (although solutions have been put forward to counter this, see 1.10.2).

4.2.3 A single phase supply will therefore limit compressor size to 2-3 kWe which in turn will affect the size and capacity of heat pump systems which can be installed. In addition the electric motor used in a vapour compression heat pump will operate better and with a longer lifespan using three phase power.

4.2.4 Since "almost all EU homes have a three phase power supply" [28] it can also be difficult to obtain European closed loop water-water heat pumps which are manufactured to offer >4 kWth capacity and operate on single phase power [19]. EU proposals are also being drafted to reduce start-up currents to 60A. If these are adopted in the UK it could be detrimental to the use of the scroll compressors now considered 'state of the art' in GSHP technology.

4.2.5 **Housing Related Issues:** While building science has improved greatly in the last thirty years, offering a wide range of energy saving measures, methods and technologies, this has not resulted in a representative change in the efficiency of the UK housing stock. The large majority of housing in the UK is / was built with what would be considered, by the standards of other European nations, a very low level of insulation[43]. "Comparisons with other European countries confirm the view that British homes are the least efficient with comfort levels the lowest in Northern Europe" (Schipper 1987 cited [75]);

[43] "The levels of insulation expected in the UK are much the same as those required in Sweden thirty five years ago" [75]

which has resulted in a higher and more variable heat demand. This of course is less suitable for GSHP systems who work best with a steady and generally low heat demand.

4.2.6 In addition this is compounded by the limitations on heat pump capacity imposed by the electricity supply (see 4.2.2), especially in rural locations where the electricity network is 'weak'. This is particularly detrimental to heat pump development since rural areas are typically off the gas grid and have large areas of available space to install a ground loop.

4.2.7 This poor thermal performance is not a problem which can be fixed overnight since new buildings, built to higher regulations, are only a relatively small percentage of the total (approx 23million) housing stock. In fact "86% of the 1996 housing stock will still be standing in 2050" [40] with demolition rates relatively low as shown in figure thirty six below. The 1990 Housing Act has played a key role in keeping demolition low through changing the compensation package to owners from the land value alone to the cost of land and building [75].

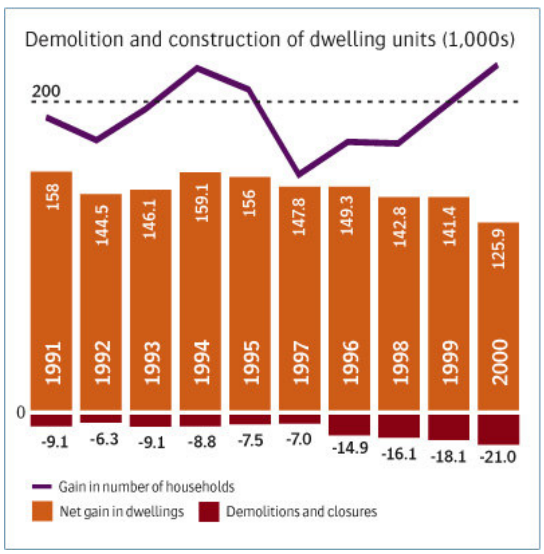


Fig 36. Construction and Demolition Rates 1996-2000 [40]

4.2.8 In addition there are many types of housing in the UK such as solid walled and non-traditional post war constructions which are not suitable for low cost insulation improvements. Furthermore Local Authorities have previously been reluctant to invest in improving thermal performance since under 'Right to Buy' legislation, introduced in 1980, this would make the property more attractive for acquisition by the tenant and therefore an unattractive investment. In the 1991 English House condition Survey it was shown that of Local Authority housing; 81% had unfilled cavity walls, 79% single glazing and 57% of lofts had less than 100mm of insulation [75]. While legislation (such as the Energy Performance in Buildings Directive, Home Energy Conservation Act and Energy Efficiency Commitment) and aligned UK targets (on carbon emissions and fuel poverty etc) will stimulate an improvement in existing stock this is clearly a massive undertaking and will therefore present a major barrier for ground source heat pumps in the retrofit market for years to come.

4.2.9 Legislation to stimulate the construction industry, such as the reduction in planning restrictions and removal of tax on development profit, has “transformed the commercial potential of property speculation” [75] and attracted purely profit seeking actors. This has cultivated a view of development in purely financial terms which has resulted in quick, least cost construction for maximum profit with little regard for end use value.

4.2.10 The prevalence of the natural gas domestic boiler (discussed in 4.2.13) will also act as a hindrance to the use of GSHPs indirectly through its interaction with buildings. Firstly the domestic boiler is relatively small and easy to install. A ground source heat pump system however is not. The disturbance associated with retro-fitting a system i.e. ground excavation for the loop, fitting the distribution system, noise, lorry deliveries etc may well put off even the most ardent GSHP advocate when considering the relative ease with which a boiler system could be installed.

4.2.11 Widespread utilisation of condensing boilers is also detrimental to GSHP infiltration since these utilise high temperature ‘wet’ distribution systems (i.e. 80ºC & 70ºC flow and return temperatures) with heat exchange areas not suitable for utilisation of a heat pump system (see 1.8.2). Therefore to retro-fit a system to fit oversized radiators will cause significant disturbance and add to the project costs. The ideal solution is to fit underfloor heating but financially this is not a serious option for a domestic retrofit property; this is one of the main reasons the target GSHP market is principally new build where a suitable distribution system can be fitted with less disturbance and at a lower cost.

4.2.12 **Prevalence of Fossil Fuels:** The UK has a long history of being self sufficient in fossil fuels being described as ”an island of coal, sitting on a bubble of gas, surrounded by a sea of oil” [35]. It could be that these once vast reserves have cultivated a rather blinkered attitude, both from government and the general public, towards alternative energy sources and means of generation. This has resulted in the construction, and subsequent reliance, on well developed gas and electricity networks. Due to the challenge presented by climate change and dwindling reserves[44] a revaluation of our utilisation of fossil fuels is required.

4.2.13 The United Kingdom has a widespread mains gas distribution grid which serves approximately 75% of UK housing and most urban areas. Natural gas is typically the cheapest heating fuel in the UK and cheaper per kWh than alternatives such as oil, LPG[45], coal or electric heating which is mainly utilised in areas off the gas grid. The presence of gas utilised in conjunction with a high efficiency (condensing) boiler can provide a cost-effective and controllable heating option; which is therefore appealing to the general public.

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[44] The UK became a net gas importer in 2004 and a net importer of oil and refined products in 2005
[45] Liquefied Petroleum Gas

4.2.14 If heat pumps are to compete with fossil fuel systems and penetrate the retrofit market in gas network areas payback periods will need to improve. This can only occur with increases in system performance i.e. COP and SPF through further research and development or a rise in gas prices.

4.2.15 **UK Geology:** As shown by figure thirty seven 100% of the UK should have suitable ground temperatures for a GSHP system. This is not the sole geological criteria however. Should a borehole be required to house the heat exchanger the in-situ geology will be of prime importance in determining the thermal conductivity of the ground, and therefore length of exchanger required, and also installation (drilling) costs.

4.2.16 In the UK there is an “extensive range of geology that exists within such a small regional area” and “almost all known geological sequences exist within the UK” [19]. This variability will bring uncertainty and can mean that installing GSHP systems in a uniform, and cost effective, manner may not be possible in different areas of the country since drilling, trenching costs and thermal properties will differ. This raises the need for thermal conductivity testing to determine the anticipated geology, sizing, drilling methods etc or greater input from local authorities such as that mentioned in Germany (see 3.4.7). The problem with the former is that it is expensive and therefore unlikely to be cost effective for a domestic installation.

4.2.17 Variability also exists due to the fact that a large proportion (>75%) of the United Kingdom has a shallow water table. This will generally improve heat pump performance however, as discussed in 2.2.4, through increasing the grounds thermal conductivity.

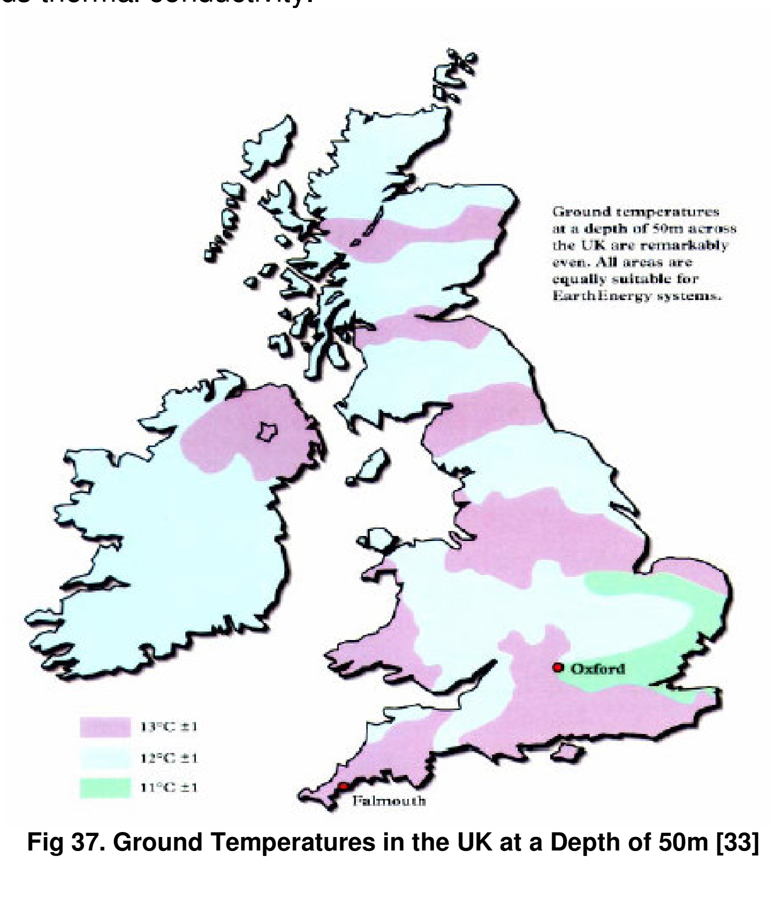


Fig 37. Ground Temperatures in the UK at a Depth of 50m [33]

4.2.18 **Awareness & Acceptance:** It is clear that as regards GSHP systems in the UK there is a “lack of understanding and confidence around their use amongst both potential users and investors” [10]. If the general public as a whole is not aware of the environmental and cost reduction benefits of installing such a system they will not be an attractive proposition. Therefore the market will be restricted to those who are environmentally conscious and keen advocates of the technology and even then there will be a lingering suspicion until system performance has been proven by installed systems.

4.2.19 When considering the nations highlighted by the case studies in section three it is not just the GSHP market which is less well developed in the UK. Utilisation of all renewable technologies is higher in these countries. This greater variability brings greater acceptance of non fossil fuel technologies and can therefore be seen as a stimulant to the use and acceptance of heat pumps. For example in 2005 only 4.1% of the UK’s electricity was generated from renewable resources and although this is growing it is not significant enough to term renewable technologies mainstream. The trend regarding renewable heat is even less encouraging at 1% of total heat use, as shown by table eight below in some cases this could actually be reducing.

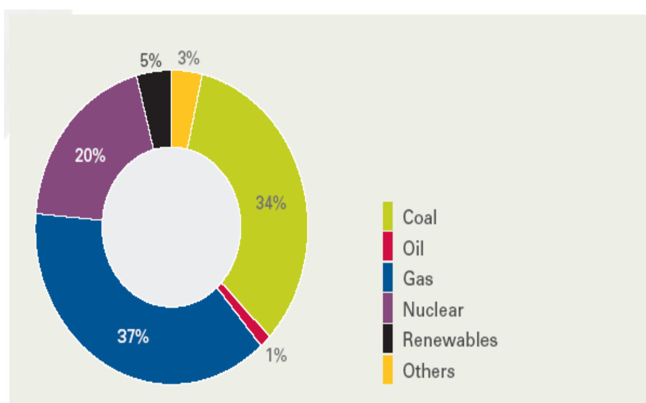


Fig 38. Renewable Contribution to Electricity Generation in the UK 2005 [42]

Table 8. Renewable Heat Utilisation in the UK [43]

Source	Penetration 1997 (ktoe)	Penetration 2004 (ktoe)	Av. Annual Growth (%)
Biomass	858	703	-3%
Solar Thermal	9	25	16%
Geothermal including Heat Pumps	1	3	22%

4.2.20 These low current levels of renewable exploitation represent a potential opportunity for expansion but while the market mainly involves those who wish to utilise renewable technologies due to their own ethics, in some cases it could be that different technologies are actually in competition. This is highlighted by figure thirty nine below which shows all the different technologies considered as part of a study of housings role in meeting the governments' target of a 60% reduction in CO_2 emissions by 2050.

Uptake of LZC technology under the 40percent house scenario, 2050

	Ownership
Gas Boilers	10%
Electric Heating	10%
Community Heating (using CHP and biomass)	22%
Stirling Micro-CHP	21%
Fuel Cell Micro-CHP	20%
Heat Pumps	9%
Biomass (wood boiler rather than stove)	5%
Photovoltaics	30%
Solar Water Heating	60%
Wind	5%
Total number of LZC installed	53.6 m
Electricity generated by LZC (TWh pa)	100.9 TWh
Heat generated by LZC (TWh pa)	260.9 TWh

Fig 39. Renewable Contribution to Fulfilling a 40% reduction in Housing CO2 emissions [40]

4.2.21 The following research, conducted by the Department of Trade and Industry, further highlights why public awareness could be a stumbling block to establishing a prosperous ground source heat pump market. Figure forty below shows the responses to a survey regarding the main reasons for saving energy in the home. As shown by the results the environment is not a principal concern with more emphasis on comfort and cost savings.

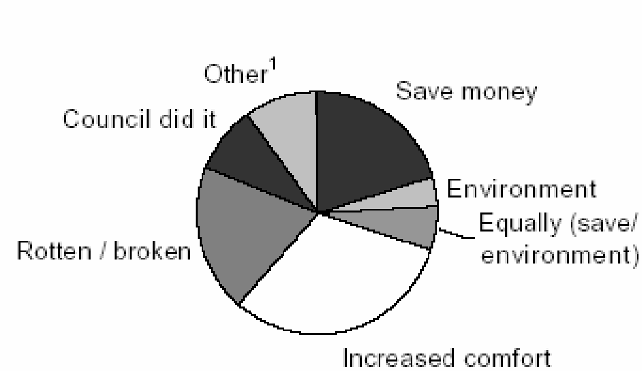


Fig 40. DTI Survey Results on the Main Reasons for Saving Energy in the Home [47]

4.2.22 Perhaps these results are partially explained by the following, table nine, which shows the responses to the question regarding which of the categories given, has the most impact on climate change. Energy use in the home scores lowest at 20%; this perhaps shows that a large proportion of the general public see climate change as something they cannot influence. And therefore are less likely to invest in a GSHP system for environmental reasons if energy use in the home is not seen as a significant contributor to climate change.

Table 9. Responses on Primary Climate Change Causes [47]

Climate Change Cause	% Response
Destruction of Forests	74
Emissions from Power Stations	65
Emissions from Transport	56
Use of Gas, Electricity by Industry	28
Use of Gas, Electricity in the Home	20

4.2.23 In addition during the 2005 general election the green party did not win a single parliamentary seat and polled just 1.07% of the vote. This is in stark contrast to Germany for example where the green party has had a strong influence on politics and was in fact part of a coalition government between 1998 and 2005.

4.2.24 Research conducted by the government's Environment Committee in 1993 [75] focused on the social factors which affect infiltration of energy efficiency measure and technologies. Three main factors were highlighted:

- Lack of Knowledge and Information - the general public at large were generally unaware of their energy consumption and associated carbon dioxide emissions.
- Capital Priority - individuals and businesses want short term returns on investment.
- Energy Prices do not Fully Reflect Environmental Costs – since the cost of energy does not reflect the impact it has on the environment the incentive to save is reduced.

Addressing these factors would undoubtedly provide a stimulus to renewable technologies in general including ground source heat pumps.

4.2.25 **UK Climate:** The UK is subject to a more moderate 'maritime' climate than that found in Scandinavia and Central Europe and hence has mild and moist conditions during winter rather than the more severe low temperatures found in the latter two. This could perhaps go some ways to explaining the issue of poorly insulated housing discussed in 4.2.5. The mild climate can also be a hindrance to heat pump use in that at night/during the day it is acceptable to turn off the heating. In the morning or on return from work however this means that the building needs to be heated quickly, and therefore a demand peak occurs; this fast responsiveness is far better suited to a boiler than heat pump which will have a lower installed power. This is exacerbated if underfloor heating is used due to its slower response.

4.2.26 Conversely summers are also not so hot which reduces the need for cooling systems. If there is a high cooling requirement heat pump systems will be more prevalent within that country i.e. such is the case in Japan and the USA. Even though mostly of an air source/distribution variety a high number of heat pump systems could raise awareness, and therefore acceptance, of using the technology for heating purposes. The four nations presented in the case studies had higher number of all types of heat pumps, not just ground source systems; this suggests that acceptance of the heat pump as a valid technology is essential to market development.

4.2.27 **Costs:** The relatively high installation costs, compared to other more conventional heating systems and therefore long pay back period on running costs savings are “at present a major barrier to the widespread adoption of this technology” [10]. Running cost savings will be aided by an increase in fossil fuel prices however. The high population density of many parts of the United Kingdom has resulted in high land prices and relatively low areas of surrounding land available for properties. Less land available will result in the need to utilise a boreholes rather than horizontal heat exchangers and therefore higher GSHP installation costs.

4.2.28 At present UK costs for complete GSHP systems are approximately £800-1300 per kW of heating capacity, with the variation mainly dependant on the site geology/availability of space. These “tend to be higher than those overseas” [35]. This could simply be linked to the fact that the market is less well developed and therefore not subject to competition between manufacturers and installers or economies of scale. If this is the case these costs should lower as the market develops.

4.2.29 Since the main competitor to widespread use of the electric vapour compression heat pump is the gas fired domestic boiler the relative prices between gas and electricity are fundamental in determining comparative running costs. Table ten highlights relative prices between the two from 1997 to 2005. Relative to gas the price of electricity is higher, which will negatively affect heat pump cost savings. However, as shown in table ten, the difference between the two appears to be narrowing which should increase the attractiveness of heat pump systems.

Table 10. UK Domestic Gas and Electricity Prices [46]

Year	Gas (p/kWh)	Electricity (p/kWh)	Ratio
1997	1.8	7.6	1:4.22
1998	1.7	7.3	1:4.29
1999	1.7	7.2	1:4.24
2000	1.7	7.1	1:4.18
2001	1.7	7.0	1:4.12
2002	1.8	7.0	1:3.89
2003	1.9	7.1	1:3.74
2004	2.0	7.5	1:3.75
2005	2.2	8.2	1:3.73

4.2.30 **Utility Involvement:** It has been clearly demonstrated in the case studies of Austria, Germany and Switzerland that utilities have played key role in developing the heat pump market through promotion, active marketing, forming networks with installers and offering financial incentives. Although there has been some involvement from utilities with Heat Pumps in the UK (from Powergen and Scottish & Southern Energy) it has been on a far smaller scale with very little publicity and active marketing to end users.

4.2.31 Heat Pumps are not being seen as a core element of the business, such as is the case with OKA in Austria and SAK in Switzerland, and British activity seems more aimed at generating positive publicity and satisfying legislative requirements than as a genuine business activity with potential to access new markets. In Austria, Germany and Switzerland utilities, as well known organisations, have played a key role in providing credibility to heat pump systems and by backing the technology have helped to erase customer scepticism.

4.2.32 **Quality of Systems and Installation:** In the 1970's Air Source Heat Pumps were sold as energy efficiency products, "on the whole these installations did not live up to expectations and have left a legacy of half remembered suspicion" [35]. It could be that this has tainted the use and reputation of GSHP systems before they can become established. It should be noted however that similar situation occurred in Austria and this has not impeded long term market infiltration of GSHP systems.

4.2.33 Installing a GSHP system is more complicated than a standard condensing boiler, in addition to any specialist drilling which may be required; issues such as calculating pressure drops, flows and system sizing are of prime importance. Therefore good installations will "require the expertise of an engineer and contractor qualified in the installation of ground source heat pumps" which at present "represents a significant barrier to market penetration" [20]. Although the knowledge base is growing, installers with the relevant skills are not present in enough numbers to support a large scale increase in demand without allowing those less qualified to enter the market (as happened in Austria and Germany with negative consequences).

4.2.34 At present the absence of a well regulated, accredited supply and installation structure is not aiding customer confidence. This could be exacerbated by concerns regarding continuing maintenance and service availability of systems. These can sometimes be justified in situations where a small company, trying to grow and operate on a UK scale, is performing nationwide installations without the necessary support infrastructure. Furthermore although UK manufacturers are producing ground source heat pump systems it could be argued that they will lack the twenty years of experience and technical development of European counterparts.

4.2.35 Therefore it can be surmised that "market penetration is restricted by the small size and fragmented nature of the industry" [35]. This is not necessarily completely negative since it may promote slow and steady rather than boom and bust growth. However only with growing customer demand, which is linked to awareness, can the market grow and support a larger manufacturing and installation base.

4.2.36 **Role of Government:** The initial developments within the heat pump markets of Austria, Germany, Sweden and Switzerland occurred as a result of the second oil crisis in the late 1970's. Prompted to reduce the reliance on important fuels the governments of these nations sought alternative energy sources and as such stimulated heat pump demand through generous subsidies. Perhaps due to the relative security of domestic fossil fuel reserves at the time the UK (see 4.2.12) did not follow this path. In addition the earliest response to climate change concerns also did not include energy efficiency and alternative energy sources but instead pursuing the 'dash for gas' (and its associated lower CO_2 emissions in combined cycle electricity generation) of the 1990's.

4.2.37 There is now a growing number of renewable energy based targets in the UK. There is a strong focus in these however in electricity generation with only carbon targets covering renewable heating. A renewable heat target, in the same vein as the 10% renewable electricity by 2010, could go a long way to furthering the case of heat pumps and as shown by figure forty one could also significantly lower CO_2 emissions. Also, as highlighted by the European case studies, subsidies have played a vital role in market development. Heat pumps are eligible for funding under several schemes (see 3.7.14) but none of these are dedicated heat pump programmes, instead they support a wide range of technologies.

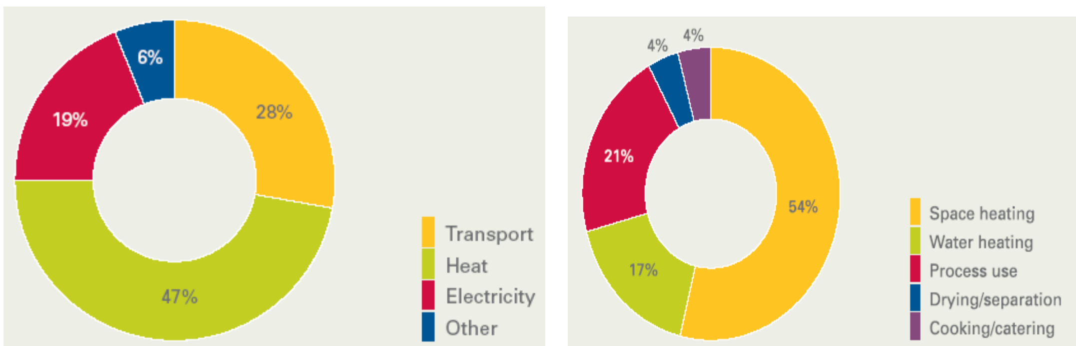


Fig 41 a & b. Proportion of CO_2 Emissions from each Sector (a) and Breakdown of End Uses of Heat (b) [44]

4.2.38 The Government has also played a key role in housing development and as such is culpable for the low levels of insulation within the housing stock. Although actions are being put in place to rectify this with tighter building regulations, energy efficiency programmes and the zero carbon homes programme (which stipulates that all new homes should be zero carbon from 2016) standards are still well behind those set in other European nations.

4.2.39 It is also clear that the level of support offered to heat pumps, whether in the form of regional grants such as found in Austria or assistance with borehole geology information in Germany, is not present from Local Authorities in the UK. An active involvement from local government in supporting GSHP installations and utilising the technology within social housing could go a long way towards increasing awareness and demonstrating performance.

4.2.40 The introduction of a carbon tax in Switzerland in 2008 will further raise the appeal of heat pumps; this option however is not on the political agenda of the UK according to the 2007 'Energy White Paper'. Heat pumps in Sweden were greatly boosted by the regulation stating a maximum distribution temperature for wet heating systems of 55°C. These kind of regulations show the strong role government needs to play for renewable technologies to become mainstream. In this respect it can be seen the UK government has taken a more 'hands off' approach to heat pumps when compared to other nations; instead concentrating its efforts in other areas and relying on the market as a means of development.

4.2.41 **State of the Art in Technology:** Due to the low awareness of heat pump technology and prevailing reliance on the gas fired boiler it could be that the technology will need to improve before it can be seen as a viable widespread heating option. This means that more R&D will have to be focused on electric vapour compression heat pumps for heating to improve attainable COP values and make running costs more competitive with natural gas.

4.2.42 The ability to still achieve good efficiencies at higher distribution temperatures would also open the door to the possibility of easier retrofitting of heat pumps through utilising standard high temperature radiator systems. Improvements are being made in this area with the Swiss company SATAG thermotechnik and Viessmann teaming up to produce a ‘turbo’ heat pump which can produce output temperatures of 65ºC +. This may be achievable but at present the high focus on heat pump R&D funding for cooling applications is not aiding system improvement. In addition there is no independent test centre in the UK as mentioned in 3.7.22.

4.3 No Barrier Argument:

4.3.1 It could be suggested that there is no overwhelming barrier, or combinations of circumstances, which explains the reasons for lower utilisation rates of GSHPs in the UK and that the market will eventually grow and establish itself as accepted technology like in Austria, Germany etc This is based on the fact that each nation has its own unique set of circumstances, policies etc and will grow in its own way.

4.3.2 For this to be true the explanation is simply that the UK started involvement in the heat pump market later. While other nations were experiencing high sales numbers in the early 1980’s the UK market only exhibited clear growth since 2000. And while manufacturers and installers were forming trade associations in the early 1990s the UK GSHP Association only started in 2006. The same can be said for the provision of subsidies etc Assuming this argument is to believe that the current impressive growth stats in the UK will continue; matching global trends, and negate the various barriers highlighted in 4.2 until a natural market level is reached.

4.4 Overcoming Barriers – Market Growth Strategies:

4.4.1 The various stages of establishing a successful GSHP market, such as that of Sweden, are shown in figure forty two. The UK is currently sitting somewhere in-between stages four and five.

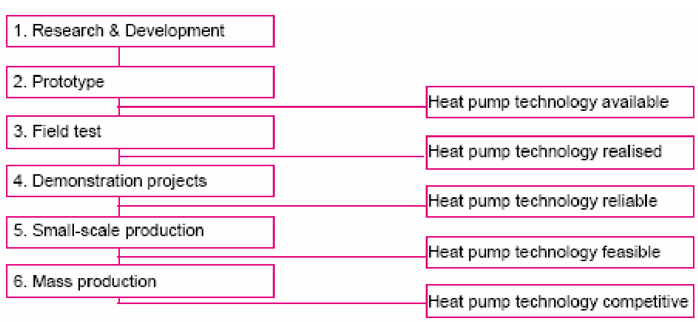


Fig 42. Stages in Creating a Successful GSHP Market [21]

4.4.2 The wide variety of technical, financial, organisational and environmental barriers to an established ground source heat pump market, in the United Kingdom, were presented in section 4.2. In order to counter these various instruments can be utilised. The first step to encouraging market growth should be to prepare a clear strategy to remove the barriers present in a particular market situation.

4.4.3 "The boundary conditions of technical and economic feasibility of an increased number of applications are improved by the marketing efforts of manufacturers, utilities and the government" [21] and hence the responsibility for this could fall to any of those organisations or a combination i.e. heat pump association. The interaction between these various different parties in the establishment of the GSHP market is shown in figure forty three.

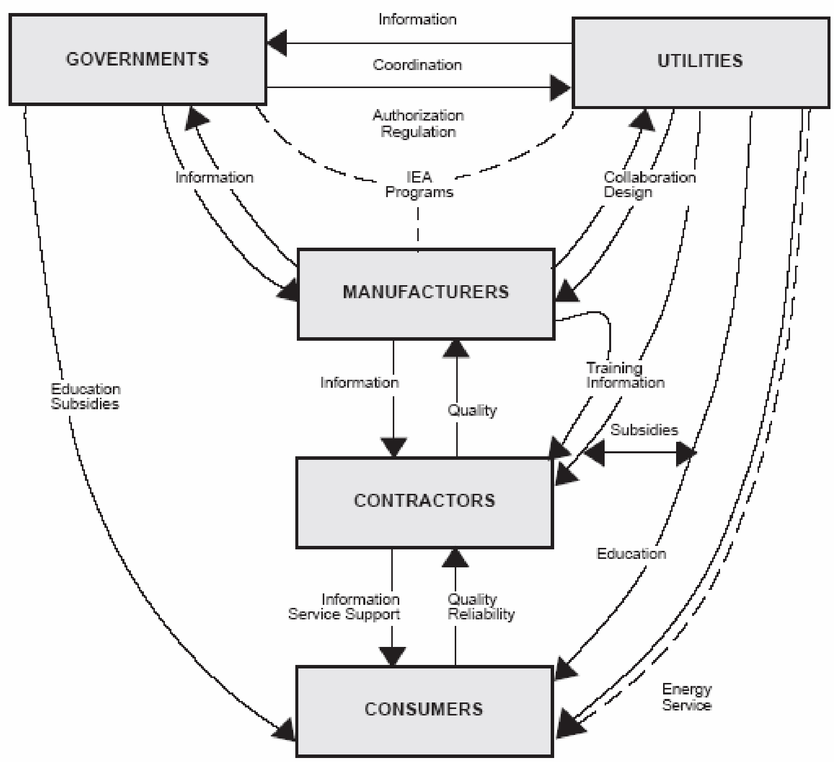


Fig 43. Interaction of Different Parties in Developing a Heat Pump Market [24]

4.4.4 Governments can play an important role in removing technical barriers through funding R&D; addressing issues relating to efficiency, safety and reliability. This instrument is mainly utilised when the market is at an early stage. Once a prosperous manufacturing industry is in place research and development can be funded internally. The government can also play a key role in providing regulation which will stimulate the market and then enforcing it. In the sphere of heat pumps this obviously relates to the fields of renewable energy, carbon emissions reduction/energy efficiency and housing.

4.4.5 The concept of awareness and confidence is a recurring theme throughout section 4.2. Promotion and the provision of information can play a key role as instruments to increase familiarity and customer confidence.

Ideally marketing of this kind should be conducted in conjunction with actual demonstration projects and financial incentives however.

4.4.6 The need for active marketing varies with the maturity of the market i.e. more onus is required the less ‘mature’ the market. As mentioned previously government and utilities have a key role to play in providing credibility to GSHP systems. In this respect demonstration projects can be used “to confirm the feasibility of heat pump concepts and simultaneously increase the awareness of potential users” [21]. Trade Associations can also increase customer confidence and service quality through training and accreditation schemes.

4.4.7 “Since higher investment costs still form one of the main barriers to further dissemination of heat pump technology, many instruments focus on financial aspects” [21]. As outlined in the case studies financial incentives (i.e. grants, tax reductions, special tariffs etc) can be utilised to create a market. Careful consideration needs to be given to when these are withdrawn however; for example markets in Austria were affected when they were removed.

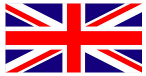
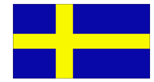
4.4.8 Another tactic to ease the barrier surrounding installation costs is the formation of utility founded Energy Services Companies (ESCOs), sometimes in co-operation with local authorities, who can install, provide and service the heat pump in return for a fixed ‘heat contract’ with the customer. This has been particularly affective in Austria and Switzerland.

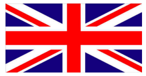
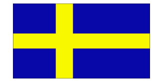
4.4.9 Market infiltration will be further accelerated by sound co-operation between various parties with the same goal i.e. increasing the GSHP market. These could mean research bodies, local authorities, manufacturers, installers and drilling contractors. This has been particularly evident in Sweden and Switzerland. The formation of trade associations has been a key factor in the development of all the mature ground source heat pump markets.

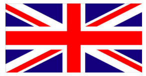
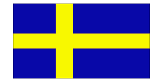
4.5 Barriers Comparison Matrix:

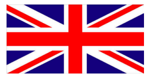
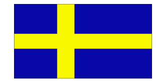
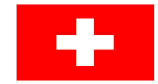
4.5.1 A selection of the UK barriers presented in section 4.2 has been contrasted with the underlying conditions within Austria, Germany, Sweden and Switzerland by means of a selection of statistics, figures and quotes. This is designed to highlight the different base conditions from which a heat pump market must grow.

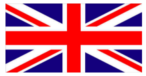
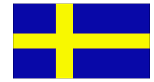
4.5.2 Although not comprehensive it should provide a valuable reference when considering the actual impact of the barriers presented in section 4.2. How influential is each specific circumstance? Can some be ruled out altogether as inhibitors to the ground source heat pump market? The matrix is presented in the following table and will then be evaluated in section 4.6.

Nation Barrier					
Electricity Supply, 4.2.2 **(Distribution)**	230V 50 Hz Single Phase	230 V 50 Hz Three Phase	230 V 50 Hz Three Phase	230 V 50 Hz Three Phase	230 V 50 Hz Three Phase
Housing Issues 4.2.5	"In terms of energy efficiency, the built environment has historically been a poor performer, a state of affairs brought about by a distinct lack of energy awareness in building clients, designers and occupants" [49]. 2006 Regulations – 146 kWh/m^2/yr 29% of primary energy used domestically [50]	Part of 'Passivhaus' building network of nations, standards of this construction 85% lower than UK 2002 regulations. New buildings less than 100 kWh/m^2/yr 27% primary energy used domestically [51]	Part of 'Passivhaus' building network of nations, standards of this construction 85% lower than UK 2002 regulations. Standards approx 100 kWh/m^2/yr 34% of primary energy used domestically [52]	Energy related Building Standards in 1983 superior to those in UK 2002. Dwellings pre-fabricated and transported to site for construction. Therefore they must be able to equally suit Lapland as southern Sweden. 1990 standards 108 kWh/m^2/yr 21% of primary energy used domestically [53]	Part of 'Passivhaus' building network of nations, standards of this construction 85% lower than UK 2002 regulations. 2001 standards less than 100 kWh/M^2/yr 27% of primary energy used domestically
Domestic Fossil Fuels Production **(as a proxy of historical reliance on fossil fuels)** **4.2.12**	The UK is the "largest producer of oil and gas in the EU" and also a "significant producer of coal" [50]. Domestic Production: Solid Fuels - 15.6 Mtoe Oil - 96.9 Mtoe Gas - 86.4 Mtoe Energy Import Dependency – 52%	"Austria remains an importer of energy, particularly fossil fuels" [51]. Domestic Production: Solid Fuels - 0.1 Mtoe Oil - 1.0 Mtoe Gas - 1.7 Mtoe Energy Import Dependency – 70.8%	Germany is the second largest coal producer in the EU. Domestic Production: Solid Fuels – 58.3 Mtoe Oil - 5.7 Mtoe Gas – 14.7 Mtoe Energy Import Dependency – 61.3%	There is a "relatively low presence of fossil fuels in the energy mix" of Sweden [54], with low use of gas and solid fuels. Domestic Production: Solid Fuels - 0.4 Mtoe Oil & Gas - N/A Import Dependency – 36.5% (due to large exploitation of nuclear and renewables)	Energy Import Dependency – 67% Domestic Production: Solid Fuels, Oil and Gas - Unknown

Nation / Barrier					
Utilisation of Renewables **(as a proxy of awareness & acceptance of new technologies)** **4.2.18**	Renewables account for 2% of primary energy supply and 2% of domestic production.	Renewables account for 21% of primary energy supply and 71% of domestic production. Electricity generation is mainly based on renewables such as biomass and hydro.	Renewables account for 4% of primary energy supply and 10% of domestic production. Germany has the highest installed wind capacity in the world.	Renewables account for 26% of primary energy supply and 41% of domestic production. Results of 1980 referendum on nuclear policy paved way for easier transition for alternative technologies.	Renewables account for 15% of primary energy supply and 34% of domestic production.
Climate **(from representative locations)** **4.2.25**	Average Temperature ℃: Jan - min 2, max 5 July- min 12, max 20 Discomfort from heat and humidity – N/A Birmingham [54].	Average Temperature ℃: Jan - min -4, max 1 July- min 15, max 25 Discomfort from heat and humidity – July & Aug 'moderate' Vienna [54].	Average Temperature ℃: Jan - min -2, max 3 July- min 15, max 25 Discomfort from heat and humidity – July & Aug 'moderate' Frankfurt [54].	Average Temperature ℃: Jan - min -5, max -1 July- min 14, max 22 Discomfort from heat and humidity – N/A Stockholm [54].	Average Temperature ℃: Jan - min -3, max 2 July- min 14, max 25 Discomfort from heat and humidity – July & Aug 'moderate' Zurich [54].
Utility Involvement **4.2.30**	Negligible involvement with GSHP industry. Two schemes have been instigated. Scottish Hydro Electric installed 40 DX systems in the early 1990's and Powergen have launched a 1000 unit scheme aimed at Social Housing.	Austrian utilities have a strong presence in the heat pump market, although involvement differs according to region. In Upper Austria the utility OKA has set a positive example through offering a good quality 'heat contracting' service and strong links with installers.	Utilities offer reduced tariffs, grants and are involved in heat pump marketing activities.	Utilities are not involved in the Swedish GSHP market.	Utilities play a very strong role in the heat pump market. In addition to offering subsidies, grants and undertaking marketing / awareness raising activities Swiss utilities have gone a step further by offering design services and obtaining drilling permits.

Nation Barrier					
Government Support 4.2.36	Subsidies are available under several schemes; these however support a wide variety of different technologies and not just heat pumps. Targets based on carbon dioxide emissions reduction are in place but there is a strong focus on targeted increase of renewable electricity generation as opposed to heat. Limited assistance from local authorities.	Strong government support for heat pumps including regional subsidies.	Direct heat pump subsidies are available at different rates per kW of capacity. Local Authorities also support installation with in-kind data and assistance.	"Low carbon energy is a high priority in government policy" [53]. Although there is a strong support of R&D into heat pumps there are no schemes offering subsidies since the market is considered to be mature. The regulations stating a max distribution temperature of 55°C for wet systems is favourable to GSHP.	Carbon tax to be introduced in 2008. The Government has conducted heat pump awareness raising initiatives since the early 1990's.
Market Networks 4.2.32	The GSHP Association has 53 members, of these 15 are manufacturers/resellers and 20 installers. There are no utility members however. Formed 2006. In addition there is also a general heat pump network, formed 1999. No certification/training/quality labels at present.	The LGW association was formed in 1990. Training and certification schemes for installers are in place. Part of D-A-CH quality label. Installers have close links with utilities.	The heat pump association has over 500 members including 95% of manufacturers and over half of installers. There are also 34 Utility members. Part of D-A-CH quality label. Formed 1993.	The two heat pump associations SVEP and SEV have over 700 members. A quality label is in place. Formed 1990.	The FWS heat pump association is complemented by the AWP heat pump manufacturers association. Part of D-A-CH quality label. Formed in 1993.

Nation Barrier					
Variation in Geology 4.2.15 **(to highlight variability in installation)**	See appendix section 3.1 for Geological Map Significant variation in rock types present	See appendix section 3.2 for Geological Map Variation in rock types present but with a lower number of different types than found in the UK	See appendix section 3.3 for Geological Map Large areas of uniform geology, less variation than UK	Geological Map not Available	See appendix section 3.4 for Geological Map Large areas of uniform geology, less variation than UK
Start of GSHP Market Growth 4.3	Annual GSHP market growth shown from the year 2000 onwards.	Groundwater systems were first installed circa 1980. In mid 1980's the first heat pumps using the ground as a heat source were utilised. These were direct expansion systems.	Initial heat pump market growth was circa 1980. Most of these systems were air source however. When the market started to grow again in the mid 90's the majority of the systems were ground sourced.	Sweden has exhibited strong and steady growth in the heat pump market since the early 1980's, with the majority of systems being ground sourced.	Steady growth in ground sourced (borehole) systems since 1979.
Domestic Gas & Electricity Prices and Ratio 4.2.27	At 2006 prices (excluding tax): Electricity= .088 Euro/kWh Gas= .028 Euro/kWh Gas – Electric Price Ratio = 1:3.1	At 2006 prices (excluding tax): Electricity= .085 Euro/kWh Gas= .038 Euro/kWh Gas – Electric Price Ratio = 1:2.2	At 2006 prices (excluding tax): Electricity= .138 Euro/kWh Gas= .043 Euro/kWh Gas – Electric Price Ratio = 1:3.2	At 2006 prices (excluding tax): Electricity= .084 Euro/kWh Gas= .052 Euro/kWh Gas – Electric Price Ratio = 1:1.6	Data not available

Nation / Barrier					
Gas Supply Network 4.2.12	The domestic gas supply network is available to approximately 75% of households.	27.4% of households utilised gas as a heating fuel in 1999.	48% of households have a gas fired heating system.	Gas only accounts for 1.5% of primary energy use and the majority of this is for industry. There is only one supply pipeline in Sweden (from Denmark) and hence only a small network around Gothenburg and sporadic use for district heating systems.	40% of households have a domestic gas supply.

4.6 Barriers Matrix Evaluation:

4.6.1 Of the various base conditions which were suggested to be impeding GSHP market development in the UK there is no doubt that some appear more influential than others. The historical high abundance and utilisation of fossil fuels in the UK has created a legacy of inefficient housing stock and preconceived conceptions as regards what is a ‘conventional/acceptable’ means of domestic heating i.e. fossil fuel based. This could explain the relatively lower number of renewable energy technologies present compared to large potential. In addition the UK has more widespread gas distribution network than the other countries mentioned; this, in tandem with cheaper prices, has made it hard for alternative heating technologies to become established in these areas. Since the vapour compression cycle needs a work input in the form of electricity the greater inequality of gas and electricity prices highlighted in the UK does not aid GSHP cost effectiveness either.

4.6.2 Some of these barriers can be removed with relative ease. Market networks will grow in step with market development. This has already been seen with the establishment of organisations, such as the Ground Source Heat Pump Association in 2006, as sales started to reach a level to support a larger number of market actors. Government and utility support can also be increased / modified as there is no shortage of lessons which could be learned from the four European nations reviewed.

4.6.3 Other barriers may well be removed in time but will present a massive undertaking. Due to national government and European legislation initiating programmes to raise levels of insulation in the housing stock, complemented by higher quality new build, energy efficiency in housing is increasing. However since there is a relatively small stock turnover and large number of properties unsuitable for improvement measures or with 'unaware' residents it will take a long time to reach parity with the four other countries discussed. In addition switching to three phase domestic power supplies would require large scale reconfiguration of the electricity distribution network; easier adoption of heat pump technology is not reason enough to undertake this.

4.6.4 There are other factors however over which we have no control. The UK climate does not experience the higher summer temperatures of Austria, Switzerland and Germany and while this may have resulted in a lower adoption of air sourced heat pump technology for cooling it is the author's opinion that this has not been a major influence on the discrepancies in GSHP market between these nations and the UK. Especially since the majority of ground sourced heat pump systems in Europe are heating only, unlike in the United States where heat and cool systems are more widespread. In addition while the geological maps of the UK do indicate a high degree of variability, especially compared to Germany and Switzerland, this cannot be changed and would not appear to be a prominent factor in heat pump procurement. Especially since borehole based heat exchanger systems are the more popular configuration found in Europe.

4.6.5 The fact that the UK heat pump market has developed far later (in the region of 15-20 years) that the other nations mentioned[46] cannot be ignored when considering the lower number of installations present. Estimates show the UK market is currently growing rapidly and with the correct support this should continue. With this in mind it may well be that the relative impact of these potential inhibitors will not be discovered until the market reaches a level of stability. If this is at a far lower level than the other nations it may be that these base conditions are constraining the market.

4.6.6 At present though it is hard to judge, especially since some of these perceived UK specific conditions are present in the other four nations. Sweden for example has little utility involvement with heat pumps and cooling requirements similar to that of the UK; while Germany also has a relatively

[46] Most likely due to a higher security of fossil fuel supplies affecting the government response to the second oil crisis

high degree of fossil fuel security (in the form of large coal supplies). So while overall it would seem that the UK currently has less favourable conditions to the establishment of ground source heat pump technology the affect these will have in the long term and relative strength of each factors still requires clarification.

4.7 Market Assessment Questionnaire Results & Discussion:

4.7.1 As part of this research it was thought beneficial top obtain the viewpoint of those involved in the British ground source heat pump industry as regards the various barriers outlined in section 4.2, or indeed highlight any that may have been missed, and also gauge opinion on possible solutions. Some of these originate from the 'Market Growth Strategies' discussed in section 4.4 while others are from the successful activities of the case study nations Austria, Germany, Sweden and Switzerland. In order to get a broad industry perspective 123 individuals or organisations from the 'UK Ground Source Heat Pump Association', 'UK heat Pump Association' and registered installers of heat pumps under the 'Low Carbon Buildings Programme' were e-mailed. This covered organisations such as heat pump manufacturers, system installers, consultancies, resellers and specialist drilling / underfloor heating contractors; or various combinations of the above. In all twenty replies were received, a response rate of 16%, these were from a variety of different bodies (see figure forty four below).

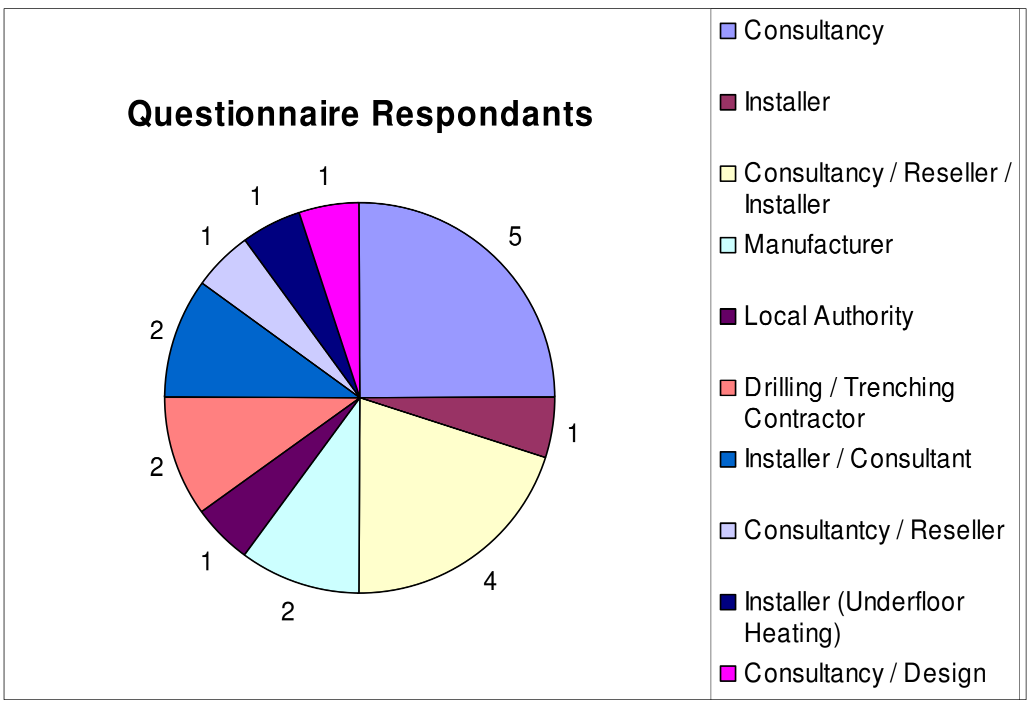


Fig 44. Organisations Who Replied to the GSHP Questionnaire

4.7.2 A blank copy of the questionnaire can be found in the appendix section six as can tables of respondent's answers. The questionnaire is split into three sections. Questions one and two relate to market barriers, three and four on possible solutions and five to seven regarding design practice (results will be covered in 6.7). It is acknowledged that due to the relatively small number of responses no wide ranging conclusions can be made of the opinions of the UK ground source heat pump industry as a whole. It is hoped however that the response detailed will give a useful insight into what the main issues are perceived to be and how they could be tackled.

4.7.3 **Perceived UK Market Barriers:** In question one the respondents were asked to select up to three of nine possible explanations of what they perceived to be key factors in the relatively immature UK ground source heat pump market.

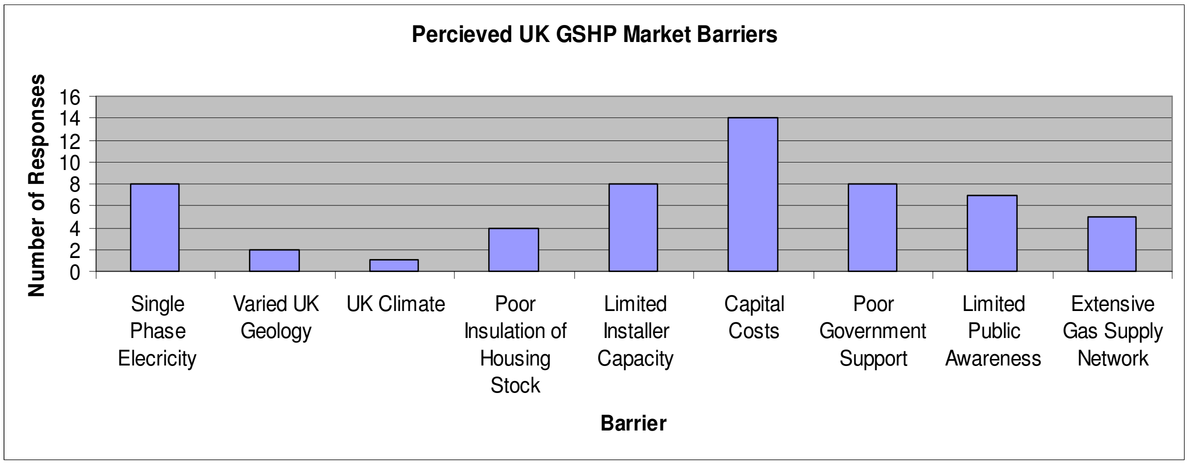


Fig 45. Responses to Questionnaire Question One

4.7.4 The clearest message from this feedback is that the high capital cost of systems, especially compared with fossil fuel heating, are considered to be inhibiting market growth. Issues of single phase electricity, limited installer capacity to fit systems and low public awareness are also acknowledged to be influential. It is perhaps surprising that the UK's legacy of energy inefficient housing and high fossil fuel availability[47] do not appear high on the agenda. Perhaps this can be explained since these factors cannot be overcome, at least not in the short term, and therefore the focus falls on the issues that are inhibiting growth within the defined niche of what is thought to be the potential GSHP market i.e. new build houses off the gas grid. This is opposed to looking at the more ambitious target of infiltrating the retrofit market, as has been achieved in Sweden. UK climate and geology (the latter only being chosen by drilling / trenching contractors) were not in the main seen to be major constraining influences.

4.7.5 Question to invited respondents to offer their opinion on any other barriers they felt relevant. In addition to the issue of a limited capacity of installers to fit systems it was also specifically mentioned that it is hard to obtain organisations to undertake drilling and trenching operations. Furthermore the issue of a lack of experience of many of those operating in the market was raised, this of course can lead to poorly fitted systems and dissatisfied customers in some cases.

[47] Leading to a large gas network, low gas prices and preconceived ideas as regards 'conventional' heating methods (see 4.2.12)

4.7.6 Lack of available space to install horizontal ground loops was also cited as a limiting factor. This results in the need to utilise boreholes and links with the opinion that high capital costs are holding back market expansion. Other issues mentioned:

- Building Regulations not stringent enough.
- The grant application process being too long / complex.

The above two can be linked to ‘poor government support.’

- Provision of misinformation on heat pump systems.
- A lack of awareness and technical knowledge amongst professionals (not just the general public).

4.7.7 **Potential Solutions to Increase GSHP Installations:** Question three was structured in the same manner as question one where three or less check boxes, each detailing a method of increasing the UK market, must be selected from a possible nine. The results are shown below.

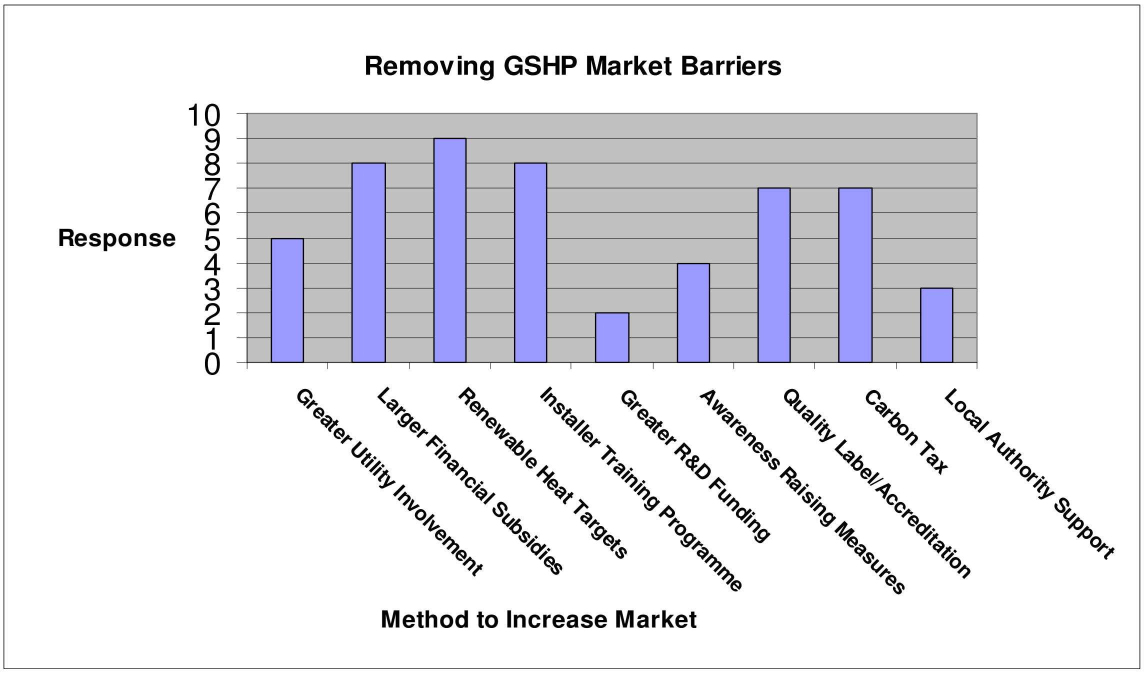


Fig 46. Responses to Questionnaire Question Two

4.7.8 Unlike the responses to question one there is not one answer which received a significantly higher backing than others. Not surprisingly due to the high number of respondents who considered high capital costs a primary inhibitor methods to make GSHP’s more financially attractive scored highly. Whether this was in the form of financial subsidies to offset investment costs or a carbon tax (as will be introduced in Switzerland) to increase the running costs of fossil fuel systems and hence increase potential savings from a GSHP system.

4.7.9 Renewable heat targets were supported as a means by which government could strengthen its support for the technology. In order to tackle

the issues regarding installer capacity and quality of work training programmes and quality label / accreditation schemes were endorsed. It is interesting however that these ideas were not widely supported by the respondents who actually install systems.
4.7.10 Increased Local Authority support and utility involvement, prevalent in the case study nations of section three, received less backing. Rather surprisingly despite seven respondents stating low public awareness as being a significant inhibitor only four suggested that implementing awareness raising measures would be a positive step. Increasing research and development funding to improve the products on the market only received the backing of two individuals, neither of which were manufacturers.

4.7.11 Once again further suggestions as to possible methods to increase the number of GSHP installations in the UK were solicited. In this instance there was nonconformity in responses. The wide ranging suggestions given included:

- Development of greater competition.

This of course will primarily occur with market growth itself and hence presents a 'chicken and egg' argument.

- Development of a robust supply chain for system parts.
- Heat Pump specific electricity tariffs / increasing domestic fuel costs.
- Sales training in order to stop misinformation.
- Provision of a three phase supply (this is unlikely, see 4.6.3).
- A scheme similar to SEDBUK for boilers to gauge system efficiency, instead of using a default COP value of 3.2.
- More stringent building regulations (Part L) including energy targets for new and retrofit homes.
- Planning schemes such as PPS22, which outlines the government's policies for renewable energy, that local authorities should consult when preparing local development documents and making planning decisions.

4.8 Section Conclusion:

4.8.1 Section four should have demonstrated that there is a wide range of reasons postulated for the relatively low levels of ground source heat pump utilisation found in the United Kingdom. While all of these may play a role to a certain degree it appears that they vary in overall influence; with the UK's history of large fossil fuel reserves particularly pertinent. Utilising the matrix as a means of comparison has helped to determine which can be deemed more influential through analysing the alternative (or otherwise) situation present in each of the case study nations. It should not be ignored however that the UK ventured into the heat pump market far later than the other countries mentioned and this will to an extent explain the discrepancy in numbers installed.

4.8.2 The different methods which have been utilised to overcome these barriers have also been highlighted (4.4) and in conjunction with the case studies in section three show that a wide range of measures can be utilised to stimulate the market and alter the conditions in which it will grow. At present the end result of many of the limiting factors mentioned in 4.2 is the prospective market for GSHP's being seen as new build properties off the gas grid, which as shown in table seven is only a fraction of technical potential. And even this is not being realised due to issues regarding awareness and finance. To fully embrace this technology it is clear that changes will need to be made and more proactive methods undertaken.

4.8.3 Conducting the market questionnaire has proved a useful exercise. It highlighted a clear belief that market growth is being inhibited through high capital costs. Insight was also received on the relative influence of each of the barriers outlined in section 4.2. Backing for each of the solutions outlined was more uniform however. This may highlight an opinion that no one measure will serve to radically transform the GSHP market and elevate installations to the levels seen in Sweden or Switzerland. The answer to achieving this is through steady improvement and alterations in a number of different areas. In this respect the survey exercise highlight some further solutions not initially considered.

5. Ground Heat Exchanger Design Considerations:

5.1 Introduction:

5.1.1 This section will firstly outline why correctly sizing the length of ground collector is fundamental in ensuring optimal ground source heat pump performance. The implications of over and under sizing will be covered. Following this the many different factors which a designer/installer must consider in selecting the correct length are outlined alongside explanations of why they must be considered. Finally the various methods available to improve design accuracy in respect to ground loop length are introduced.

5.2 The Importance of Correct Ground Heat Exchanger Sizing:

5.2.1 "Sizing the ground heat exchanger is one of the most important tasks in the design of a geothermal heat pump system" [68] and is critical to achieve good performance. It is therefore essential that calculations are done accurately to ensure that it is not under or oversized. If the loop is undersized it will result in:

- Poor efficiency.
- Decreased comfort levels.
- Nuisance heat pump lockouts and safety control activation.

Heat pump designs need to balance long term issues such as heat build up or depletion while also catering for short term peak loads (during which temperatures can increase between 5-10℃ in 1-2 hours).

5.2.2 With an undersized ground heat exchanger there is considerable risk of it not being able to meet the building heat load. This will result in the utilisation of auxiliary heating, i.e. direct electric systems, thus reducing system efficiency, running cost savings and increasing carbon dioxide emissions. If a system has an undersized ground loop a higher level of antifreeze pumping will be required in order to transfer the quantity of heat required to the heat pump and satisfy building loads. Furthermore as the ground temperature drops (see next paragraph) the antifreeze will become more viscous and hence increase pumping requirements further.

5.2.3 Under sizing will also result in more significant heat extraction from the ground and a longer recovery time until it reaches original conditions (see 2.2.8). For a heating only heat pump, used over several years, if complete recovery is not obtained between heating seasons ground temperatures will gradually decrease year on year. This could result in the required entering fluid temperature being below that acceptable to the heat pump system and cause system failure. Increased working fluid viscosity at low temperatures will also result in laminar flow of the working fluid and therefore impaired heat transfer. This is a more pertinent issue for vertical heat exchangers since thermal recharge is harder to obtain at greater depths.

5.2.4 A bigger ground heat exchanger will result in increased system capacity. However the ideal solution is to size the heat pump to meet peak power[48] and extract no more heat/energy from the ground than can be collected on an annual basis. This highlights the advantage of heat pump systems that offer both heating and cooling operations, such as those common in North America, since heat is returned to the ground during summer cooling and therefore aids thermal recovery of the ground.

5.2.5 If the ground loop is over sized the installation cost of a GSHP will increase and may make overall project costs unacceptable. Accurate sizing is important from an economic perspective since GSHP installation/capital costs are higher than conventional heating systems and since "costs associated with the ground coil are typically 30% to 50% of total system costs, over sizing will be uneconomic" [11] furthermore "due to the relatively linear cost relationship in loop installation over sizing carries a much higher penalty than is the case with conventional equipment" [67].

5.2.6 An unnecessarily large ground heat exchanger could, if the designer is using rules of thumb, result in selection of an oversized heat pump. This would increase the amount of time at which the heat pump is operating at part load. This can result in frequent cycling[49] which will shorten the system lifespan and result in lower performance efficiency. In bivalent applications incorrectly sized loops will mean that pre-defined switching temperatures between the heat pump and auxiliary systems may no longer be applicable and hence the auxiliary system is no longer the optimal size. This section should have outlined that the "performance of the heat pump depends on the performance of the ground loop and visa versa" [11] and it is therefore important they are designed in tandem.

5.3 Design Factors:

5.3.1 In designing a GSHP system there are many factors which need to be taken into account in order to estimate the length of the ground loop required. Firstly it is essential that the building loads are known, "the most important step in the design of a GSHP installation is accurate calculation of the building heat loss, its related energy consumption profile and the domestic hot water requirements"[50] [11]. This should include the 'design' loads i.e. peak demand, which for heating will be the coldest winter period[51]. Heat gain should also be considered and the system 'balance point' determined[52]. Since net heating and cooling of the ground depends on the heat load of the building, design should be based on loads for a whole year and not just peak heat/cooling demands. Therefore the total annual heating energy requirement and a monthly profile are also needed. Calculating the loads will require knowledge

[48] For a monovalent system

[49] Where the heat generated during the minimum run time of the heat pump cannot be absorbed by the buildings heat distribution system, results in the system switching on and off too regularly

[50] If the heat pump is to supply DHW

[51] Especially if the heat pump is to be operated monovalently

[52] Where the structure heat loss line intersects heat pump capacity [3]

of the desired indoor conditions (i.e. room temperatures), distribution temperature needed to achieve these and prevailing climate.

5.3.2 When using a borehole heat exchanger for a GSHP system the length required to satisfy a given building load is largely dependant on the thermal properties of the ground (see section 2.2). Accurate design cannot be accomplished without information of the soil/rock properties on site i.e. thermal conductivity, diffusivity, volumetric heat capacity etc. The moisture content/saturation of the ground will further affect design considerations through altering thermal conductivity (see 2.2.4).

5.3.3 "Climatic conditions significantly affect the performance of heat pump systems" [69] through determining the temperature of heat source and the extent of thermal recovery after heat extraction has taken place. This is important since the specific thermal power (in Watts/metre) a loop can extract is dependant on the temperature difference between the circulating fluid and far-field ground temperature i.e. that undisturbed by the heat exchange influence of the ground coil[53].

5.3.4 The ground loop itself is comprised of many different elements and these will all affect the performance of the system and actual size of loop/borehole required. The following should all be specified:

- Pipe material, diameter, wall thickness.
- Loop configuration i.e. horizontal, slinky or vertical. If a vertical system is used how many boreholes and in what pattern? Single, straight line, L-shape or grid?
- Spacing between boreholes and horizontal ground loop pipes/slinkys (see 2.4.7 and 2.4.8). "Special attention should be paid to minimising interference between neighbouring borehole heat exchangers" [70].
- If a borehole is used with a u-tube (or double u-tube) pipe (see 2.2.10) the separation distance between them should be known. In some cases separators are utilised to ensure a set distance.
- The thermal properties of the backfill i.e. grout. Backfill is located in a critical heat transfer region; therefore poor thermal conductivity will impede heat transfer and result in longer loop/borehole length requirements. It is for this reason thermally enhanced grout (bentonite, silica sand, cement, superplastisizer and water) is a popular option.
- Heat transfer fluid (antifreeze/brine) utilised.

Different combinations of all these factors will influence the length of heat exchanger required in order to meet the conditions specified in 5.3.1.

5.3.5 Operating characteristics of the heat pump itself need to be known. What are the minimum and maximum entering temperatures[54]? What flow rate of refrigerant inside the unit is required? The latter will in turn affect pumping requirements and auxiliary energy consumption. Pumping is required in order to circulate the heat transfer fluid through the ground and heat pump.

[53] Typical heating only vertical collector systems are designed assuming a mean ground loop fluid to far field temperature difference of ten degrees Kelvin.

[54] The performance of the heat pump is a function of its capacity and the entering water temperature

Pumping energy requirements are a factor of flow, head, control, loop configuration and pressure drops. Excessive pumping energy will limit expected running cost savings and lower the seasonal efficiency of the system. Furthermore the function of the heat pump must be known, is the system to provide heating only or both heating and cooling? If the latter is the case the relative ratio between them must be considered.

5.3.6 The performance of the overall heat pump system is a function of the antifreeze temperature from the ground coil (a factor of ground temperature, pump speed and the design of the coil) and the distribution temperature as mentioned in section (1.8.2). The amount of energy that a ground heat exchanger, of a set size, will deliver is derived from the hours of use at particular temperature differences (and therefore fluxes) over a given time period i.e. one month/year.

5.3.7 With so many factors to consider in design and optimising the performance of a ground source heat pump system it is clear to see why engineers and specialised installers are required to design and fit systems. This explains the focus placed on installer training and certification schemes, to ensure quality, found in the countries with mature heat pump markets discussed in section three. And also the feedback from the UK questionnaire which seems to collaborate the assumption that the limited number of experienced / trained installers (specifically drilling / trenching contractors) is a significant UK market barrier at present (see 4.2.32 and 4.7.5) and offers backing to training and certification schemes.

5.4 Design Methods & Tools:

5.4.1 There is an element of risk which needs to be taken into account when designing a heat pump system. If the engineer works ‘close to the edge’ in order to save unnecessary costs and provides only the minimum length of ground heat exchanger to meet predicted building loads, i.e. has no safety margin, this will inevitably lead to undersized systems in some cases. Due to the uncertainty and possibility of errors in calculation regarding many of the determining factors mentioned in 5.3. It is therefore unsurprising that “studies of projects reveal far more cases of generously sized heat exchangers than undersized ones” [68].

5.4.2 Conservative designs incorporating a high factor of safety, to counter uncertainty in design considerations, will lead to increased installation costs. The end result of this is that while the heat pump should experience no problems meeting demand it will not be as cost-effective an investment. In many cases this cautious design approach also extends to the number of pumps utilised.

5.4.3 Various methods have been developed in order to remove some of the uncertainty associated with designing a GSHP system and strike a healthy balance between overly risky and cautious practice. A test bore can reveal the ground properties at the surface for horizontal systems and also give the depth and transition from soft to hard conditions. This information is vital for drilling contractors and cost estimation for vertical systems.

5.4.4 A thermal conductivity test (see figure forty seven below) consists of a fully drilled borehole fitted with a u-tube and backfilled. This is then connected to a defined artificial load and the resultant temperature fluctuations of the circulating fluid are measured. Data on the energy use of the pump and inlet/outlet water temperature and flow rate can then be used to determine the thermal properties of the soil. It should be noted though that while on-site tests are accurate they are also expensive to conduct. Furthermore this method is only relevant for multiple borehole applications, where the test bore is utilised to design the following. In most cases these factors will limit the application of thermal conductivity testing to larger scale commercial projects.

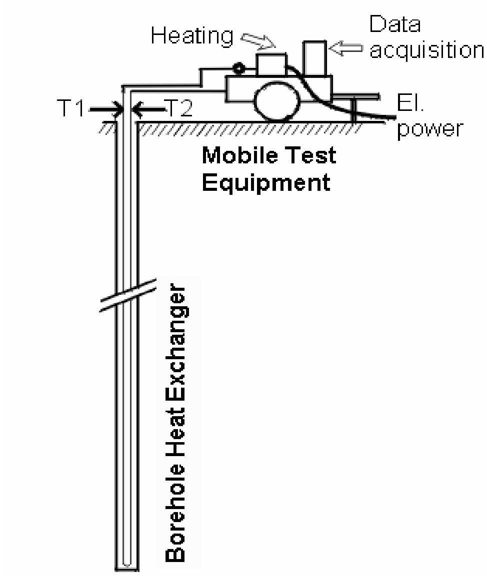


Fig 47. Schematic of a Thermal Response Test [70]

5.4.5 “The recent development of design tools for the engineer will assist in the design and installation of more cost effective, reliable and efficient systems in the future” [67]. The core of any sizing package is to model the heat transfer between the heat transfer fluid (brine/antifreeze) and surrounding ground (soil/rock etc) and hence to “select a heat exchanger length that limits the water temperature exiting the loop (and entering the heat pump) to some user specified minimum or maximum value” [68]. For a system used primarily for heating the minimum temperature limit may well be dependant on the freezing point of the working fluid. In order to perform these calculations quickly design programmes use various simplifying assumptions. These assumptions of course must be valid otherwise the programme will give unreliable results.

5.4.6 There are a multitude of different software packages available on the market. These vary in terms of calculation method/assumptions utilised and the inputs required to perform sizing. The majority of these packages have been developed in the U.S.A and hence several have specifics related to this market i.e. in terms of the units utilised, heat pump systems incorporated and ground temperature data available. Most will offer the opportunity to utilise 'user defined' data however. There is currently no software package developed specially for the UK market.

5.5 Section Conclusion:

5.5.1 This section has shown that over or under sizing the ground heat exchanger will result in either impairment of system performance, increased capital costs or both. Finding the ideal length is complicated by the need to take into account a multitude of different factors; many of which are tinged with uncertainty.

5.5.2 Before the advent of modern computer packages "design with tedious calculations was rarely done in practice" [72] and many systems were installed using generalised 'rules of thumb' in combination with data from the manufacturer of the heat pump. This may explain the multitude of conservatively designed systems mentioned in 5.4.2. These were mainly utilised since performing the calculations required to estimate a ground source heat pump's performance with different loop lengths over a prolonged period by hand was both time consuming and prone to error.

5.5.3 In combination with thermal response testing design software should ensure vertical heat exchangers are sized correctly and GSHP's offer good performance and value for money. Some of these software packages will be outlined in more detail in section six.

6. Sizing Software Overview

6.1 Introduction:

6.1.1 This section aims to give an overview of the different programmes which are available to aid the user in sizing ground source heat pump systems. Firstly the general calculation methods behind programmes will be introduced. From this point the three principal programmes which will be analysed further in section seven's case study will be covered alongside some information on other similar software available.

6.1.2 Most of these programmes focus on vertical borehole heat exchanger systems only and do not conduct calculations for horizontal systems (although some do both). This is because the issue of heat build up/depletion is more of a factor with a vertical configuration as is the additional installation cost penalty for over-sizing. Finally to switch the focus back to a UK perspective results from the questionnaire exercise as regards design feedback will be discussed.

6.1.3 Design software "is a suitable compromise between rules of thumb and tables on one hand and time consuming numerical simulation on the other" [72]. Early programmes utilised for this task such as TF Step[55] and INOUT[56] required a base level of engineering knowledge to use. The advantages of the various design packages mentioned in this section are the fact they make a relatively complex and time consuming calculation achievable by the layman (for example a novice system installer) or someone with limited engineering knowledge, relatively quickly.

6.2 Calculation Methods:

6.2.1 The ability to predict short term behaviour of ground loop heat exchangers is critical to accurate design and predicted performance analysis of ground source heat pumps systems. Different programmes vary in both calculation approach and accuracy of findings in tackling this problem. Some purely domestic programmes rely on empirical[57] values for ground temperature and are therefore time consuming for larger borehole field calculations i.e. commercial applications. The software mentioned in this section, unless stated otherwise, is suitable for both domestic and commercial sizing.

6.2.2 **Cylinder & Line Source Methods:** In 1947 Carslaw and Jaeger developed an equation for heat transfer from a cylinder based in the earth. This was later used by Ingersoll and Zabel for sizing purposes. Related research by Ingersoll (1948) centred on modelling of cyclic pulses of heat (a measure the quantity of heat transfer between two mediums over a specified time i.e. hour or day) from a certain source was build upon by Kavanaugh in

[55] A programme which calculates the fluid temperatures for a single or multiple borehole system at an arbitrary time, the heat extraction rate is given by twelve or less steps each with arbitrary lengths. The 12 steps are repeated cyclically after the period of time, normally one year

[56] Calculates the inlet and outlet temperatures when the mean fluid temperature is given

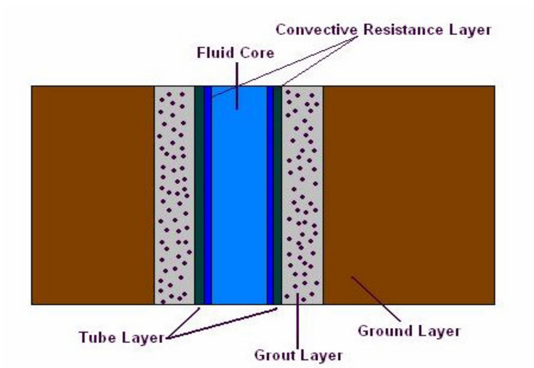
[57] Produced by means of an experiment or observation

1984 to produce the cylindrical source solution for heat transfer to borehole heat exchangers. This approximates the time varying nature of heat addition and extraction from the ground to and from the heat exchanger during cooling and heating operation. This leads to a "steady state solution and effective thermal resistance" [70]. This method allows for calculation of thermal interaction between boreholes and estimation of long term heat build up and depletion. For the Carslaw / Jaeger and Ingersoll equations see appendix section four.

6.2.3 This algorithm assumes that a cylinder of soil exists between the pipe (horizontal systems) or borehole's grout (vertical systems) and a far field radius of effected ground. The far field radius is the distance at which the ground temperature can not be affected by heat exchanger activity. The thermal resistance inherent to the pipe material and grout is taken into account within the programme; thermal capacitance of these factors, the ability of a material to store and absorb heat over time, is ignored however. Daily and monthly time steps are then assessed using the method.

6.2.4 An alternative approach is the one dimensional line source heat transfer equation. This treats the heat source as a line in an infinite medium, neglecting the end effects of the heat exchanger piping. The borehole can be modelled in this one dimensional manner since the length of the pipe is far greater than its diameter. The amount of heat extracted or rejected by the heat exchanger is treated as a constant for each time step i.e. modelled as a constant pulse[58]. This is possible since as "the temperature variation inside the borehole is usually slow and minor" [76] heat transfer in this region can be considered a steady state process. The line source analysis is conducted for a single pipe and the results are then reproduced is a multi-borehole system is utilised.

6.2.5 The following two diagrams outline the key factors to consider when assessing the thermal performance of a borehole heat exchanger. The thermal properties of each layer i.e. ground, fill, pipe material and working fluid will all need to be accounted for in any sizing programme. As will their respective sizes.



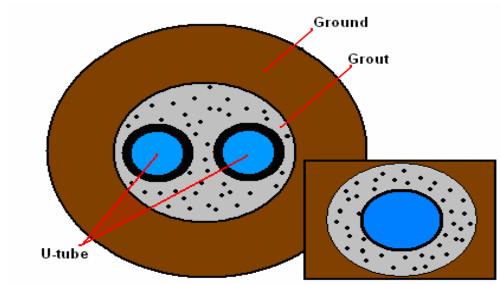


Fig 48a. Heat Transfer Model Implications & Fig 48b. 'Birds Eye View' of Borehole (reproduced from [77]), to simplify further the u-tube can be modelled as a single cylinder with twice the area (see inset)

[58] An equal and opposite pulse is then subtracted by the programme to cancel the original for the remainder of the simulation.

6.2.6 **G-Functions:** Algorithms have been derived for the estimation of required ground heat exchanger length, to satisfy a given heat load, from modelling exercises and parameter studies[59]. This has produced an analytical solution to assess heat flow with different functions for particular borehole patterns and geometry. These are called g-functions[60] and are dependant on the defined spacing of boreholes (if more than one), depth of the borehole and space between the top of the heat exchanger and ground surface. A sizing programme is able to store these g-functions in a data file where they can be accessed rapidly and thus allow quick retrieval of results.

6.2.7 Eskilson (1987) developed the long time step response function. Eskilson's approach to determining the temperature distribution around a borehole consisted of a hybrid model of both analytical and numerical solutions. The g-function represents the response of a set borehole configuration to a heat pulse and hence the impact of any step change in heat extraction or injection can be determined. As g-functions are non dimensional temperature response factors this allows the temperature fluctuation at the borehole wall to be calculated in response to changes in heat input over a specified time period. Eskilson's approach can also be found in the appendix section four.

6.2.8 Eskilson's research has since been built on by various parties to develop shorter time step g-functions which can be used by sizing software packages to predict the nature of the borehole/ground relationship over shorter time periods. In multiple borehole fields g-functions are produced for fixed spacing 0.1 apart. "The thermal interaction between boreholes is stronger as the number of boreholes in the field is increased and as the time of operation increases" [77].

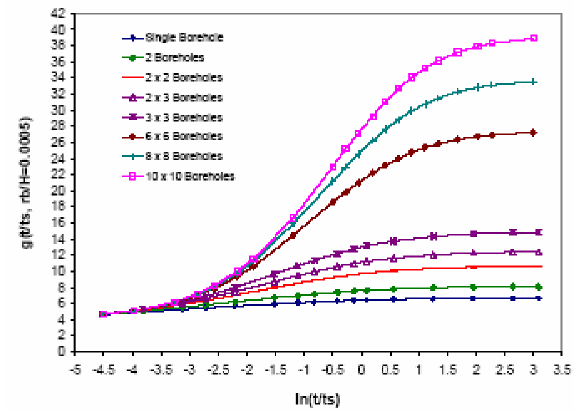


Fig 49. G-functions for various Multiple Borehole Configurations compared to a Temperature Response Curve for a Single Borehole [77]

6.3 GLHE-pro:

6.3.1 **General Information:** The programme was developed by Jeffrey D. Spitler of Oklahoma State University and is available from the International Ground Source Heat Pump Association (cost $525). The software is for the sizing of vertical systems only.

[59] Using the numerical simulation model SBM

[60] also known as response functions

6.3.2 **Calculation Method:** The g-functions utilised in GLHE-pro are pre-computed using a finite difference model and hence the user is limited to pre-computed configurations. “The response to a peak pulse is estimated with a simple analytical approximation to the line source model” [79], the equation for which can be found in the equation section four.

6.3.3 **Inputs:** GLHE-pro has 307 pre-computed borehole configurations, each with a respective g-function, in which the depth of the borehole can be assessed. In GLHE-pro the user must provide:

- Monthly heat and cooling loads[61].
- Monthly peak loads (optional), with number of peak hours i.e. three. GLHE-pro can size taking account of both monthly and peak loads simultaneously.
- Specifics of Heat Pump System (entering water temperature, inputs and outputs i.e. performance map). There is a built in catalogue of existing U.S. heat pump system models from seven manufacturers.
- Thermal properties of the ground (thermal conductivity, volumetric heat capacity and undisturbed ground temperature). There is a library of standard characteristics available for different ground types and a map of undisturbed ground temperature for different areas in the USA.
- Configuration of Heat Exchanger i.e. single borehole, line, L-shape or grid (with spacing if applicable).
- Heat Exchanger Construction (borehole diameter, u-tube diameter/material, grout thermal properties). This is used in combination with flow rate to determine thermal resistance.
- Working fluid (volumetric heat capacity and density) and its flow rate. There is a library of standard characteristics available for different fluid types.

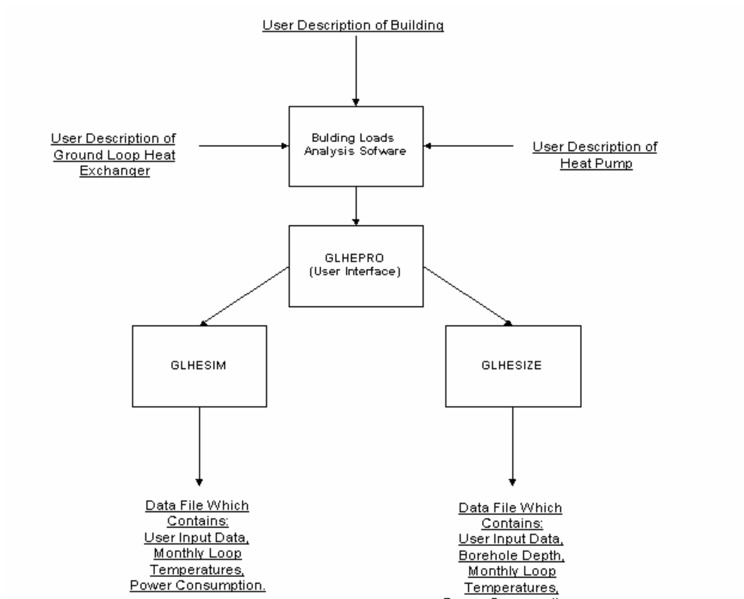


Fig 50. Flow Chart of GLHE-pro for Windows (from programme itself)

[61] Obtained from manual calculation (e.g. SAP) or separate energy analysis programme (e.g. ESP-r or TRNSYS)

6.3.4 **Outputs:** When the data has been entered the sizing calculation can be performed for a time period of 1 to 300 months (25 years) to give the minimal depth required to meet specified minimum and maximum temperatures of the heat transfer fluid entering the heat pump[62]. The results output file consists of the recommended borehole(s) length and maximum/minimum average ground temperature. If peak data has been entered maximum and minimum temperatures under peak conditions will also be included. An output file can also be obtained from a simulation, for a specified depth, with heat rejection rate (W/m), power (kWh), maximum and minimum entering water temperatures for each month of the simulation.

6.3.5 **Initial Evaluation:** The programme is user friendly with the ability to change between metric and English units. There were no errors or crashes and while a warning appears if data is outside recommended limits, this does not stop the user from running the simulation. The user can select the length of time to run the simulation for and results are obtained almost immediately.

6.4 GS2000:

6.4.1 **General Information:** GS2000 was developed by the CANMET Energy Technology Centre (CETC)[63] and Caneta Research Incorporated. The programme was first released in 1995 and is available free of charge.

6.4.2 **Calculation method:** GS2000 uses the line/cylinder source concept (see 6.2.2).

6.4.3 **Inputs:** Twelve different configurations can be modelled, seven horizontal and five vertical. The last of which is a grid type in which the number of boreholes can be manually inserted. Data must be inputted on the heat exchanger i.e. borehole diameter, distance between them (if more than one), and depth of the top of the borehole under the ground's surface. At this point fill material is selected from one of fourteen options available.

6.4.4 The pipe material is selected from a standard library giving material, pressure rating, wall thickness and size etc, user defined data can also be entered but in some cases this will not be accepted by the programme. Ground temperature properties can be chosen from either pre-entered information for numerous locations throughout Canada and the U.S.A or 'User Defined' data can be added.

6.4.5 Heat pump characteristics are also a requirement. To outline these the following inputs are required:

- Minimum entering fluid temperature.
- Maximum entering fluid temperature.
- Heat pump heating capacity (kW) and respective coefficient of performance.

[62] These must be stated

[63] Canada's principle federal government S&T organization with a mandate to develop and demonstrate energy efficient, alternative and renewable energy technologies and processes

- Heat pump cooling capacity (kW) and respective energy efficiency ratio (EER).
- Antifreeze / brine flow rate through loop.

6.4.6 Antifreeze is chosen from a standard library of seven fluids, each of which can be varied in concentration from 10→50%. Ground thermal properties are also contained in a standard library containing rock, soil, silt, loam types at different degrees of moisture content (dry, damp, saturated) and therefore thermal conductivity and diffusivity; once again however this data can specified by the user if required. The monthly heating / cooling loads can only be entered once all the remaining criteria had been completed. The system will size either using monthly loads or peak demand (which will result in a longer borehole length), but not both simultaneously.

6.4.7 **Outputs:** Either a single year or multi-year analysis can be run. The exact length of the simulation cannot be specified however. The results of the sizing simply give the recommend depth / length of the heat exchanger.

6.4.8 **Initial Evaluation:** On the positive side the programme will allow sizing of vertical and horizontal systems. Also it has a useful facet in that once entered 'user defined' data is stored so the same properties can be utilised again if required. There is also a 'residential loads' function which can be used to generate a profile of the required energy use for a property if the user has degree day, design heating and indoor temperature values. The programme has been validated against monitored data from actual installations.

6.4.9 One drawback with GS2000 in terms of usability is the pre-set limits specified i.e. for flow rates, distance between boreholes etc which must be adhered to for the programme to run even if this is not the scenario that is to be sized. The sizing estimate cannot be conducted until all parameters are entered to the satisfaction of the programme. There is also a propensity for the programme to close unexpectedly if an 'error' is found with data inputted. This is prone to happen when entering 'user defined' data as opposed selecting from the standard libraries; which would be a necessity for sizing UK heat pump systems.

6.5 Earth Energy Designer (EED):

6.5.1 **General Information:** EED was first released in 1995 with promising early validation when compared with actual installations. Version 2.0 of EED has been developed as a joint project by:

- Dr. Thomas Blomberg, Building Technology Group, Massachusetts Institute of Technology, USA
- Prof. Johan Claesson, Dept. of Building Physics, Chalmers University of Technology, Sweden
- Dr. Per Eskilson, Dept. of Mathematical Physics, Lund University, Sweden
- Dr. Göran Hellström, Dept. of Mathematical Physics, Lund University, Sweden
- Dr. Burkhard Sanner, Justus-Leibig University, Germany

The software is available for $540.

6.5.2 **Calculation Method:** G-functions (see 6.2.7).

6.5.3 **Inputs:** Ground properties such as thermal conductivity, volumetric heat capacity, surface temperature and geothermal heat flux must be entered. A table of recommended values for different ground types is given however, as are temperatures and heat flux's for selected locations in Germany, Italy, Sweden and Switzerland.

6.5.4 Only vertical systems can be simulated. The pipe arrangements which can be considered are:

- Coaxial (one tube inside another).
- Single, double or triple u-pipe(s) per borehole. For these 'shank' spacing is also required i.e. distance between the centre of the up and down tubes.

U-pipe properties are also contained in a standard library with information on diameter, thickness and thermal conductivity for a range of different types.

6.5.5 The borehole pattern may be chosen from a database of more than 300 basic configurations from lines, L-shapes, U-shapes and rectangles. If a multiple borehole model is being utilised the spacing between each should be specified. The thermal resistance of the borehole is calculated through taking account of borehole geometry, grouting material (for which thermal conductivity must be known) and pipe material properties. Heat carrier (antifreeze / brine) thermal properties are also suggested in a library of seven fluids at different concentrations.

6.5.6 In EED calculation of brine temperatures is estimated for defined monthly heating and cooling loads. The building heating / cooling load can either be entered as an annual figure or preferably monthly breakdown, with expected performance factor. There is also an option to specify peak heat / cool power and associated number of hours for each month for simultaneous sizing based on peak and average values. The seasonal performance factor of the heat pump is also requested.

6.5.7 **Outputs:** The simulation period is selected (up to 25 years) as well as the starting month. The output file from an EED simulation includes:

- Design data entered.
- Required length of borehole(s).
- Average monthly specific heat extraction rate (W/m)
- End of month mean fluid temperatures for years 1, 2, 5, 10 and 20[64].
- Minimum and maximum mean fluid temperature with month of occurrence for final year of simulation.

6.5.8 **Initial Evaluation:** The programme is easy to use and has a comprehensive level of in-built data to reference. The data fields are not restricted i.e. only information within a set range can be entered, which means any set of circumstances can be sized. In the demonstration version the ground's thermal properties cannot be altered which will restrict its application

[64] For a 20 year simulation

in section seven's case study. Results are generated almost instantly. Figure fifty-one below verifies the opinion that "EED gives a rather good prediction of temperatures found in reality" [71]

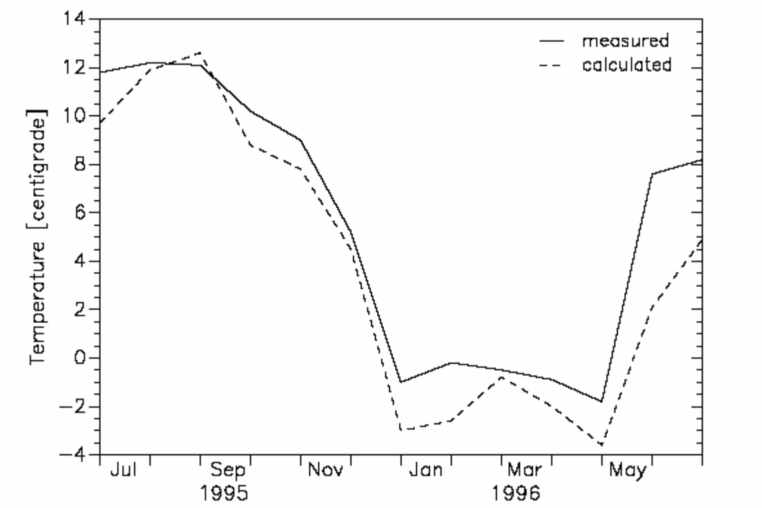


Fig 51. Measured and EED Calculated Brine Temperatures for UEG Plant, Wetzlar [71]

6.6 Other Software Packages:

6.6.1 **GCHPcalc**: This programme has been developed by Kavanaugh and Rafferty at the University of Alabama, purchase cost $300. It will only size vertical heat exchangers. The programme requires the user to have a grasp of the fundamentals of heat pump technology in order to utilise it fully.

6.6.2 GCHPcalc utilises Kavanaugh's cylindrical source method. Variation in load (and the switching on/off of the heat pump) is represented by four (four hour, daily, monthly and annual) cyclic pulses of heat, representing the load of the building.

6.6.3 The programme considers the building in terms of design thermal comfort zones. There is also an option for entering hot water requirements if these are required to be met by the heat pump system. Heat losses and gains then need to be entered for the time periods 8am - 12pm, 12pm - 4pm, 4pm – 8pm, 8pm – 8am as well as the equivalent full load heating and cooling hours. The programme specifies the minimum allowable entering water temperature allowable to the heat pump for heating (maximum for cooling)

6.6.4 The following key factors must be entered:

- Design inlet heat pump heat / cool temperatures and flow.
- Undisturbed ground temperature.
- Thermal conductivity and diffusivity of ground. A list of standard values is available as is the option to produce average results for multi-layer ground profiles. A table of typical values for soil and rock types is included.
- Thermal conductivity of fill/grout; values for typical materials offered.

- Tube qualities i.e. diameter, flow regime (laminar, transient turbulent etc), spacing within pipe (for u-pipe).
- Borehole diameter.
- Number of boreholes, distance between them and arrangement (grid only).
- Data on the pump which is intended to be utilised (head, efficiency).

6.6.5 Heat pumps can only be selected from a standard list of fifteen North American systems. Although files of specific data can be imported an additional programme GCHPfile is required to do this; this does not seem to be available with the demonstration version utilised. The programme output gives required bore lengths for minimal or a high rate of groundwater movement alongside a summery of the design data inputted. Units are only English with no option to switch to SI.

6.6.6 GCHPcalc will not be considered as part of the modelling within section seven since the demonstration limits are not defined (simply stated as 'key design parameters cannot be altered') and there is no means to import the data on the heat pump to be simulated. In addition as units are only English time consuming conversion is required.

6.6.7 **Earth Coupled Analysis (ECA):** This programme was developed by Elite Software and can be utilised to size vertical and horizontal ground source heat pump ground heat exchangers. Cost $395. The calculation methodology utilised is that specified by ASHRAE[65] in their design manual for closed loop ground coupled heat pump systems.

6.6.8 The heat load is required along with the 'dead band'[66], outdoor and indoor design temperatures. Ten standard soil types with set thermal characteristics (conductivity, diffusivity, density and specific heat) can be selected or user specified. Antifreeze properties such as concentration, viscosity and density must be added. Pipe characteristics (i.e. material, diameter) can be selected from a standard listing of seven types or inputted manually.

6.6.9 As with GCHPcalc there is a set list of North American manufacturers (seven in all) and the various models they produce to select from, although alternative models can be considered if the data is available. Weather data can be user specified (for Jan and July) or selected for a pre-set list of conditions found in American cities.

6.6.10 The programme's output is a calculation of the required pipe loop length necessary for heating and cooling a building with the heat pump, soil, and weather conditions specified. Pressure drops are also reported. An option can be exercised to input costs for drilling, pumps, antifreeze etc and therefore generate a complete 'bill of materials' for the project. Demonstration limits allow sizing with a heat load up to 17000 Btu/hr which would only allow

[65] American Society of Heating, Refrigerating and Air Conditioning Engineers

[66] Defined temperature range where no heating / cooling will take place i.e. heat pump inactive

for a maximum heating load of 4.97 kW; this is lower than the load associated with the case study in section seven and therefore it cannot be utilised as part of the experiment. Only English units can be utilised.

6.6.11 **CLGS:** This ground heat exchanger design program can be utilised for residential applications only. It has been developed by IGSHPA[67] executive director Dr. Jim Bose. It handles both horizontal and vertical systems, and provides initial values for entering minimum and maximum water temperatures. Cost $500.

6.6.12 The user must input the building loads, design area, heat exchanger configuration, pipe size / type, and heat pump capacities. CLGS outputs are sizing of the ground heat exchanger, heating, cooling and water heating costs, peak heat and cooling demands, loop pipe lengths, and pressure drops. CLGS also provides a comparison of operating costs of gas, LPG, electric heating / cooling systems and GHP systems. Unfortunately a copy of the programme could not be obtained for the analysis.

6.6.13 **Other Programmes:** Ground Loop Design (GLD) from Thermal Dynamics Incorporated and the Swiss system PILESIM developed by Daniel Pahud (which simulates heat exchanger piles as well as vertical borehole heat exchangers).

6.7 Feedback from Questionnaire Design Questions:

6.7.1 The questionnaire (see appendix section six for blank copy) discussed in section 4.7, as regards market barriers and solutions, also aimed to collect data on design practice and the use of software tools. Question five urged the respondent to answer the question 'How does your organisation go about designing GSHP systems?'; three options were presented in a 'drop-down menu.' The not applicable option was presented for organisations such as manufacturers who would not actually install the system themselves. Responses were as follows:

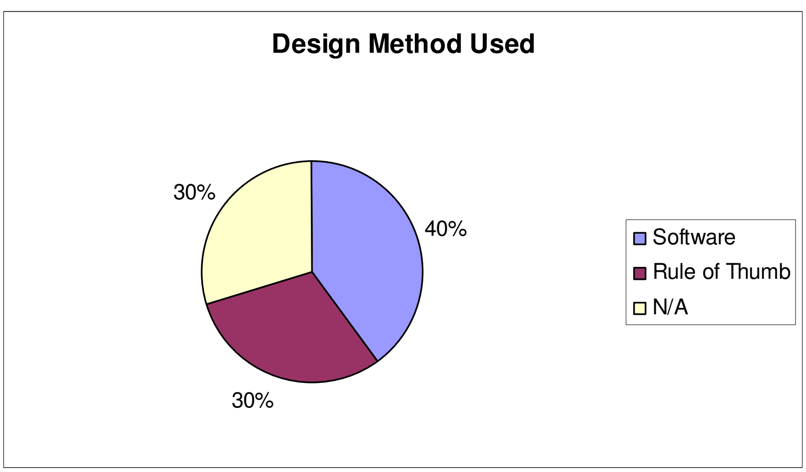


Fig 52. Response to Questionnaire Question Five

[67] International Ground Source Heat Pump Association

6.7.2 Although the numbers are too small to make any real conclusions as regards design method used these figures seem to suggest that both the use of software and rules of thumb are prevalent design methods in the UK for ground source heat pump systems.

6.7.3 If design software was selected as the method for design the respondent was prompted to state which package in question six. The option to choose between EED, GLHE-pro or type another of their choice was given. GS2000 was not selected as it is thought this package is not widely used in the UK.

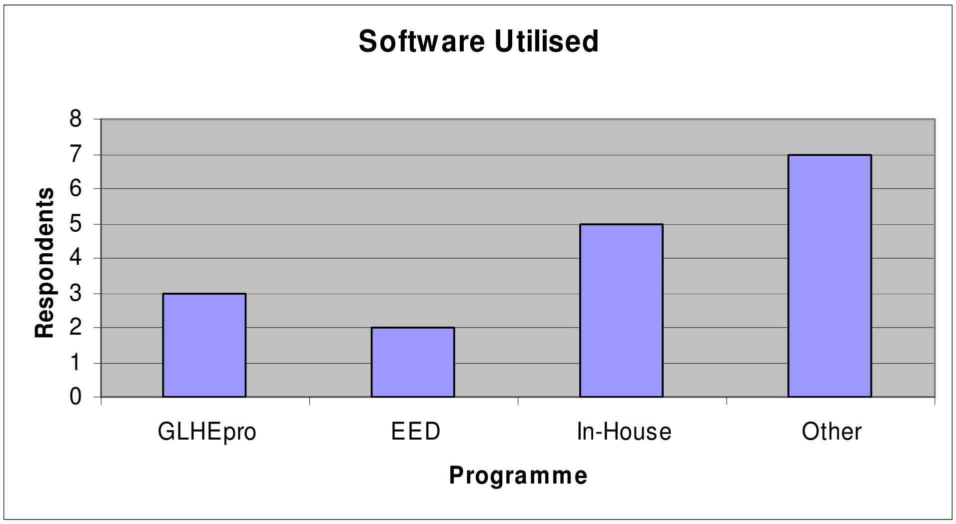


Fig 53. Answers to Questionnaire Question Six

6.7.4 The higher number of in-house and variety of 'other' programmes used shows that there is little uniformity in the software by which installers are sizing ground loops. Other systems utilised were:

- HevaComp[68].
- AutoCAD[69].
- Geothermal International GAIA.
- GLD.
- Pilesim.

No respondent reported using GS2000. The application of information from manufacturer's information, to guide rules of thumb, in design practice was reported from several individuals.

6.7.5 Question seven asked the respondent to identify what they thought to be the main challenge in designing GSHP systems. By far the most popular answer in this category was obtaining the heat load of the building and conducting heat loss calculations. Difficulties with obtaining accurate drawings to perform these were also mentioned. This is interesting in that all of the sizing programmes require the building heat loads, mostly in terms of a monthly breakdown, in order to conduct the sizing.

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[68] This is a building simulation tool

[69] This is in fact not a sizing programme but a engineering drawing tool

6.7.6 This would seem to highlight there is a need for training in methods of obtaining building heat demand; whether this is by means of the standard Assessment Procedure (SAP), National Home Energy Rating (NHER), Building Research Establishment Environmental Assessment Method (BREEAM) or the use of software packages such as TRNSYS or ESP-r. Obtaining an accurate representation of building heat demand is crucial for accurate design, whether by means of a software package or rule of thumb. Based on this feedback therefore it could well be that utilisation of these methods could form the core of any installer training programme and will be as useful as the development of a UK specific sizing programme.

6.7.7 It was perhaps of interest that only two respondents stated that obtaining the thermal properties of the ground was an issue. It could therefore be a useful research exercise to assess how this information is being gathered in the UK at the present time.

6.8 Section Conclusion:

6.8.1 This section has highlighted that there is a plethora of different systems available to assist the installer/designer in selecting a suitably sized ground heat exchanger for a GSHP system. In order to do this the software must be able to assess the heat transfer relationship between the working fluid and surrounding ground; a complicated combination of short term relatively small scale convection transfer and a more significant slower conduction process in varying materials. The packages highlighted vary in terms of calculation method, although some i.e. EED and GLHE-pro utilise the same, but most have similar inputs as regards parameters which need to be known. While ‘user friendliness’ varies between programmes, all are able to produce results almost instantly. Prices are also typically similar, ranging from $300-500.

6.8.2 It should have become clear however that there are no systems which have been developed in the UK and therefore have relevant data on ground temperatures and available heat pump systems. This means that the user is required to enter ‘user defined’ data specific to a UK situation. This is not always possible or troublesome with some programmes.

6.8.3 The questionnaire results regarding design practice seemed to highlight that there is no uniform method of sizing GSHP systems. Both rules of thumb and software are utilised, and when the latter is used a variety of different programmes both commercial and in-house are utilised. There did seem to a consensus that it is difficult to accurately estimate building heat demand however.

6.8.4 Section seven will present a case study to analyse the performance of three of these software packages (GLHE-pro, GS2000 and EED) and implications of their results in more depth.

7. GSHP Sizing Software Case Study

7.1 Introduction:

7.1.1 The focus of this case study is examining ground source heat pump exchanger sizing software, design practice and the long term implications of their recommendations for heating in a domestic building; an area with considerable potential for expanded growth of the technology in the UK. Cooling will not be considered since it is not a widespread requirement for domestic housing in the UK climate, furthermore introducing cooling into the model would reduce the possibility of investigating long term heat depletion in the ground[70]. Only vertical heat exchanger systems will be modelled. This is due to the fact they are more prone to inducing long term variation in ground temperature and accurate sizing is of more importance due to the higher associated installation costs of a borehole.

7.1.2 The packages considered in the study are GS2000, EED and GLHE-pro. For the reasons stated in the previous section these were the only packages that could be evaluated. It was only possible to obtain a demonstration version of EED, with fixed ground properties, and therefore it plays only a small part in the study.

7.2 Key Objectives:

7.2.1 The principle objectives of this case study are highlighted below:

1. To review and compare the output of the sizing packages. This will be undertaken with different base ground conditions and heat exchanger configurations (single and double borehole systems).
2. To evaluate the influence of ground conditions of GSHP performance, in terms their impact on long term efficiency (in terms of COP) and heat depletion of the ground.
3. To assess the impact of different heat exchanger configurations on long term efficiency (through COP values) and heat depletion in the ground.
4. To gain a greater understanding of the key factors to consider in heat pump design and performance over a prolonged time period.
5. To evaluate the level of knowledge required to design GSHP systems using various software programmes and the possibility of errors occurring.
6. To evaluate the capital and running costs of GSHP systems.

7.2.2 Considering the first objective, i.e. the variation in recommendations of the software, allows for an evaluation of how the different calculation algorithms (g-function and cylinder/line source) produce results. The recommendations can also be compared over a systems lifetime, in this case twenty years, to see the long term implications of design specification. Furthermore the length of the borehole has an associated installation cost. Therefore the financial impact of different recommendations can be evaluated.

[70] Due to heat rejection to the ground during summer cooling

7.2.3 To recap sections 2.2.8 and 5.2.3 heat depletion in the ground is a key consideration with heating only heat pumps since the principle method of heat transfer is conduction and not convection. Therefore depending on the method of extraction or injection the temperature in the neighbouring vicinity may rise or fall over the lifetime of the system, “a design goal must therefore be to control the temperature within acceptable limits over the life of the system” [78]. A significant drop in temperature will decrease system efficiency and should this cause the inlet temperature to the heat pump to fall below an acceptable value result in system failure.

7.2.4 System efficiency is measured in terms of the coefficient of performance (see 1.2.9). Through looking at variation in COP over a period of time (i.e. Seasonal Performance Factor) the implications of heat build up on efficiency and hence running costs can be assessed.

7.3 Previous Related Research:

7.3.1 A 1996 comparison study conducted in order to “increase design confidence in available ground heat exchanger sizing methods” [68] generated length estimations for a residential dwelling from different sizing programmes and validated them against TRNSYS (see 7.4) results. This produced a 30% mean value for variation between outputs. This experiment was repeated again in 1999 and the follow up study highlighted that variation had reduced down to 11%.

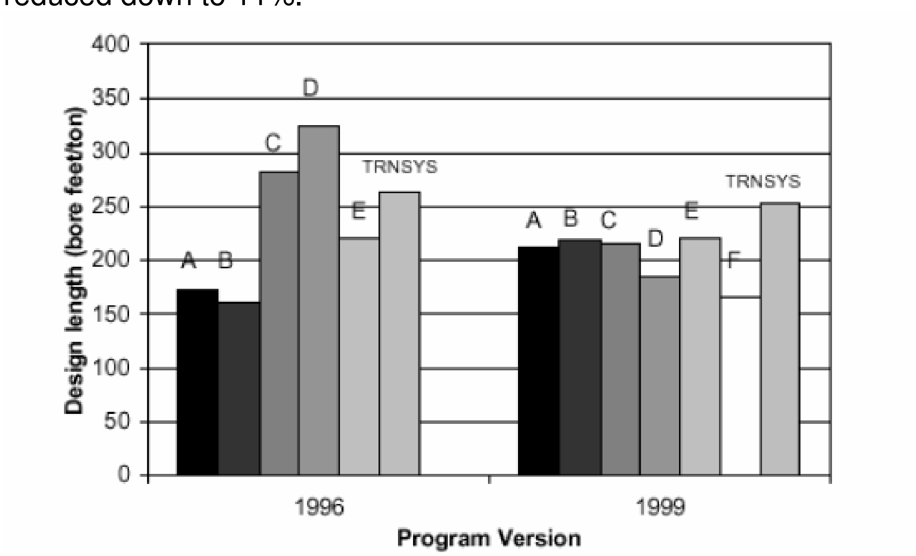

Fig 54. One Year Comparison of Design Lengths for a Cooling Based Residential Heat Pump System (max entering temperature of 35°C) [70]

6.7.2 This convergence in estimates would seem to suggest that the algorithms on which the packages are based have developed and become more accurate. These results however only hold for the particular case studied in that experiment i.e. the inputs specified. This case study will select a different set of basic circumstances and obtain the recommended lengths suggested by the sizing programmes available. From here however this case study differs from the research presented above in that it is not simply an analysis of the different estimates but also to look beyond them to the long term impacts of different sizing permutations.

7.4 TRNSYS:

7.4.1 **What is TRNSYS:** "TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings" (manual). Used for over 25 years this tool can be utilised by an engineer or researcher to:

- Validate new energy concepts, projects or technology.
- Design and simulate building energy performance.
- Design and preview the operation of conventional systems i.e. domestic hot water.
- Assess the potential and operation of renewable technologies.

7.4.2 The modular structure of the programme makes it easy to alter a model through adding or subtracting elements. A project is established through connecting components in the 'simulation studio', the graphical interface of the project. Each component has various inputs and outputs which represent the points of connection between different elements of the system. Components can also be connected to plotters in order to review how they behave throughout the simulation, produced by the simulation engine generating results. The building characteristics are specified in TRNbuild which is the visual interface for entering building data such as structure (defining zones), size, air infiltration rate and thermal properties of glazing, walls etc.

7.4.3 As regards ground source heat pump modelling TRNSYS differs from the sizing programmes covered in section six in that it:

- Requires a more detailed level of knowledge to construct a valid model i.e. building, heat pump system, pumps, correct connections etc.
- Will not give a defined answer for the optimal length of exchanger, the user must model different lengths and interpret which is offering the best performance.
- Far more parameters need to be defined in order to generate results not simply the key elements.
- Generating results is more time consuming.
- It can generate a building energy use profile.

7.4.4 It should become clear then that this programme is not a suitable method for a busy installer fitting systems. It is far more preferable to simply plug in the key elements and obtain a defined length almost instantly than construct a model of the building and build the heat pump system before running several simulations of different lengths.

7.4.5 **Role in the Case Study:** TRNSYS will be used in this project in order to assess the long term performance of the various sizing recommendations produced by the sizing software packages. Next to empirical data from an actual building or installation this offers the best means by which to assess performance. The programme has enough variability in its interface to be able to accommodate all the different specific inputs of the various sizing programmes in order to generate a relevant assessment of performance.

7.4.6 In this case study the demand (see 7.5.2) is fixed and it is assumed that it will be always be met by the heat pump. The heat extraction to meet this will have implications on the ground and in turn COP which will vary according to the size of the borehole used. If the demand cannot feasibly be met by a set length of exchanger the simulation will not run successfully. In such a case it can be assumed that the exchanger is of an insufficient size to extract enough heat and meet demand.

7.4.7 **Schematic Overview:**

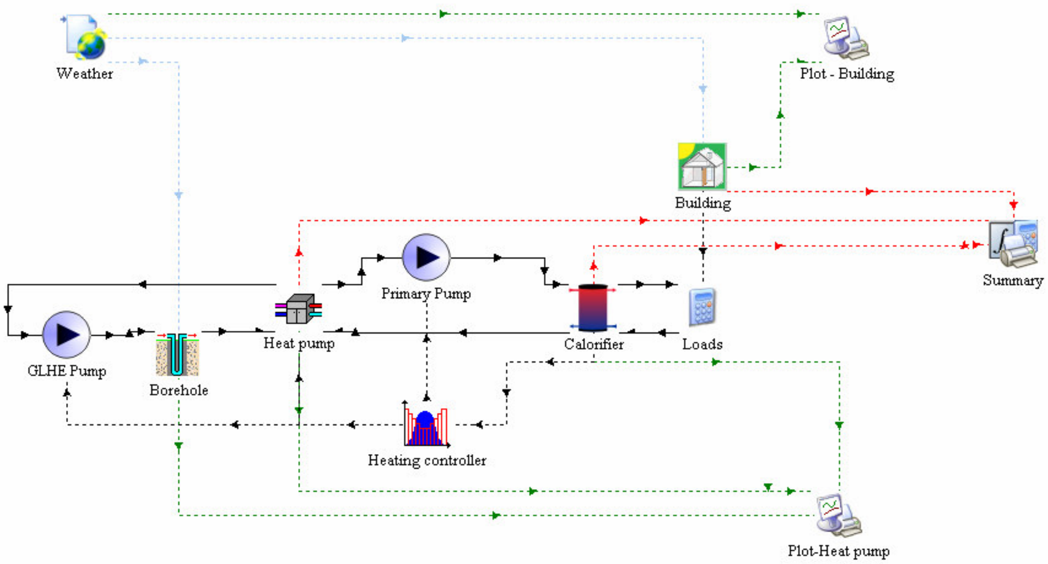

Fig 55. Schematic of Case Study in TRNSYS Simulation Studio

From viewing the above schematic the system which is being modelled can be explained. The icons represent components and the lines/arrows connections. In the top left a weather file is connected to both the building and the borehole 'storage volume'. The weather file used is that typical for London conditions. This 'storage' is the volume of ground for which temperature change (especially depletion) is measured, later referred to as 'average ground temperature'. The magnitude of this volume is considered to be a cylinder, as long as the borehole and with a diameter of 10m for a single borehole, 1.5 times the borehole spacing for a two borehole configuration and 1.8 times the spacing for a three borehole ground loop[71].

7.4.8 The building (see 7.5) is connected to a loads calculator which in turn is connected to a .2m³ volume hot water tank (calorifier). The loads calculator and hot water tank represent the building's the heat distribution system (7.5.2). The heat emitters (i.e. radiators or underfloor heating) are not modelled in detail. Instead, a constant supply temperature of 45℃ is assumed. Equations in the 'loads' component calculate the required flowrate out of the calorifier to match the load with a 10℃ difference. This approach

[71] The 10m spacing is arbitrary while the diameter for 2 & 3 borehole configurations is based on the following formula: 1.05 x √no. boreholes x spacing between boreholes (TRNSYS data)

was adopted to both ensure simplicity and allow easy variation in the supply temperature, as required for the case study in section eight.

7.4.9 A heating controller monitors the temperatures of the calorifier, which has a set point of 45°C, and operates a control signal to operate the primary (between heat pump and calorifer) and ground loop heat exchanger pumps; with flow rates of 1060 kg/hr and 2700 kg/hr respectively. The ground loop consists of the borehole, heat pump (see 7.6) and a circulation pump. The brine provides differing inlet temperatures/amounts of energy to the heat pump according to the energy available in the ground. Plotters and result summary generators are set to gather and display information from connections to the heat pump, borehole, calorifer, building and weather conditions.

7.4.10 The following describes how the component known as type '557'[72] calculates heat transfer between the ground and circulating brine. "A heat carrier fluid is circulated through the ground heat exchanger and either rejects heat to, or absorbs heat from the ground depending on the temperatures of the heat carrier fluid and the ground. The program assumes that the boreholes are placed uniformly within a cylindrical storage volume of ground. There is convective heat transfer within the pipes, and conductive heat transfer to the storage volume. The temperature in the ground is calculated from three parts; a global temperature, a local solution, and a steady-flux solution. The global and local problems are solved with the use of an explicit finite difference method. The steady flux solution is obtained analytically. The temperature is then calculated using superposition methods" (University of Lund from TRNSYS programme).

7.5 The Building:

7.5.1 The building in question is a two storey detached house with a total floor area of 140m² (see figure fifty six below). Although representative of the size of a typical detached house the building is larger than what would be considered a typical UK home of floor area 102m², which is closer to that of a smaller semi-detached house[73]. For modelling purposes the building is split into two zones, living and none living. The living zone encompasses areas such as the living/dining room which as they are regularly used will have a higher design temperature (20ºC) this represents 34m² of the overall floor area. The non-living area, 104m², is rooms that are not used for long periods of time such as bedrooms or bathrooms. These are hence subject to a lower temperature requirement of (19ºC).

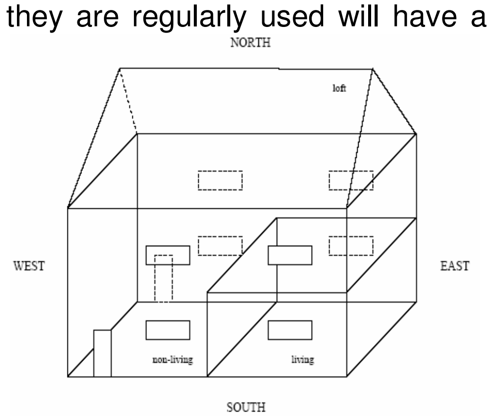

Fig 56. Detached House Used in Case Study (from ESP-r library)

[72] DST model in TESS libraries
[73] 2002 statistics show typical household has 2.31 occupants each with average of 44m² each i.e. 101.64m² [80]

7.5.2 The annual space heat demand (i.e. excluding domestic water heating and electrical appliances) associated with the building is 19,650 kWh. As would be expected with a heating dominated load in the UK climate it is highest from October – April, peaking in December and January.

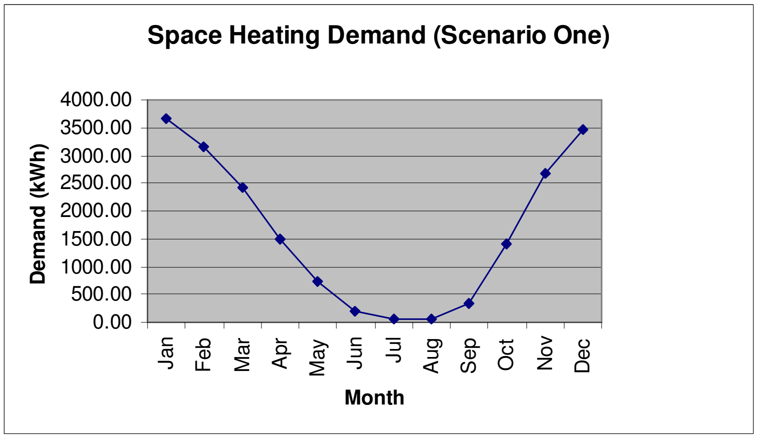

Fig 57. Heating Energy Use Profile of Detached House

This profile was obtained through utilising TRNSYS and is the demand which must be satisfied by the heat pump. The average annual heating demand per dwelling in 1996 was considered to be 14,000kWh/annum. The value associated with this home is significantly higher than this, however using the Building Research Establishment (BRE) figure for estimating heat demand by floor space, 140kWh/m²/yr, will give 19,600kWh which is a very close match to the figure generated by TRNSYS.

7.5.3 TRNSYS has also been utilised to evaluate the peak loads which the heat pump system will be subjected to in each month of the year. These are defined for a three hour period and shown in figure fifty eight below.

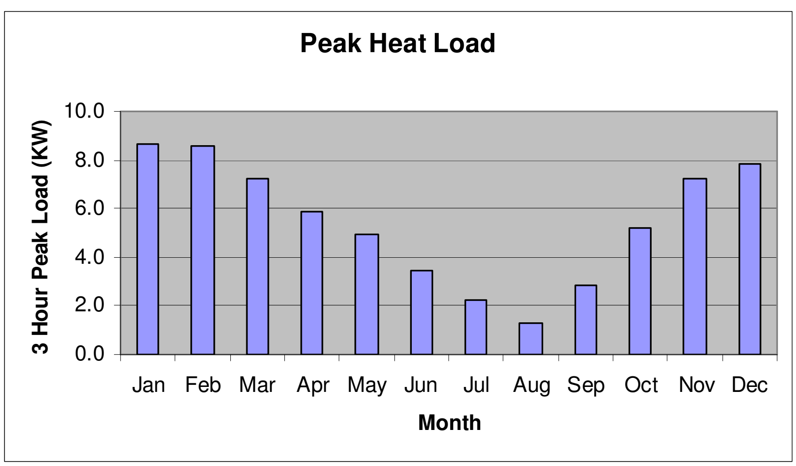

Fig 58. Monthly Peak Loads of Detached House

The importance of including peak loads is highlighted by the following diagram which highlights the increased energy demand (W/m) on the borehole in peak conditions as opposed to simply meeting the base load.

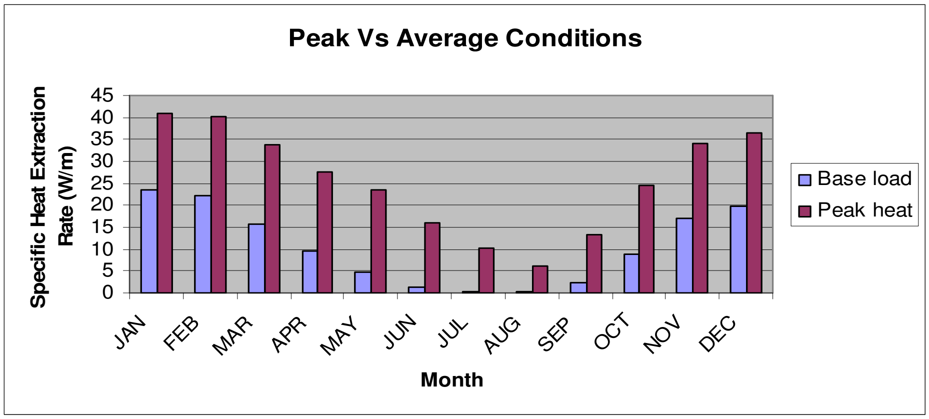

Fig 59. Peak Vs Base Specific Heat Extraction (EED Simulation Data)

7.5.4 A possible drawback of using this building is the fact it is not really representative of the kind of property that would usually be considered for a ground source heat pump system since it is relatively large and has a significant energy demand. The latter could be reduced through improving the thermal characteristics of the property, these are currently set at:

- Single glazed windows of u-value 5.68 W/m²/K.
- Only 100mm of loft insulation (glass fibre quilt).
- External wall with unfilled cavity, u-value 1.437 W/m²/K.

The building is far more representative of a retro-fit property than a new build home, considered more suitable for such systems. This problem is addressed in section eight's case study. The detached house model is however a good means by which to assess the heat pump for which performance data could be obtained (see next section)

7.6 The Heat Pump:

7.6.1 The heat pump selected was Viessmann Vitocal 350 brine to water model. The B0W35 system selected has a heating capacity of 11kW and cooling capacity of 8.45kW, the rated COP is 4.31. The maximum and minimum inlet fluid temperatures acceptable to the system are 20℃ and -5℃. The inlet temperature is that of the antifreeze fluid after it has been circulated through the ground loop to extract heat; this is shown by the pink area on the TRNSYS simulation graphs (appendix section seven). With a bivalent system (see 1.7.3) when the inlet temperature falls below -5ºC, or the load cannot be met by the heat pump, an auxiliary electric resistance heater would operate. In this study however the TRNSYS model does not consider the impact of an auxiliary system and it is assumed that either the heat pump can meet the whole load or otherwise i.e. it is monovalent. The required brine flow rate is 2700 l/hr and a 5ºC 'dead band' is utilised either side of the desired 45ºC 'value to watch' in the Calorifier, in order to limit on/off cycling. The maximum temperature this heat pump can achieve in the water heating circuit is 65℃. To view key statistics and performance maps for the heat pump consult the appendix section five.

Fig 60. Viessmann Vitocal Heat Pump [82]

7.7 Variables and Fixed Inputs of the Model:

7.7.1 In this case study the properties of the heat pump, building, weather and hot water tank all remain fixed. The only variations are made within the borehole component. The depth and number of borehole heat exchanger(s) will be varied. As will the thermal properties, conductivity, volumetric heat capacity and temperature, of the storage/ground areas.

7.7.2 The following factors within the borehole component will remain fixed however:

- The number of u-tubes per borehole will be fixed at one in all bar one of the simulations.
- Borehole radius of 76mm, spacing between u-tube pipes of 26mm.
- U-tube inner pipe diameter of 34mm with pipe thickness of 4mm.
- The thermal conductivity of the fill/grout will be fixed at 2.600 .772 W/m/k, similar to bentonite 20% solids grout mix, in all bar one of the experiments.
- The fluid flow rate (2700 kg/hr, 0.189 l/s per tube).
- Fluid specific heat (4.274 kg/kg k) and density 971.30 kg/m^3. Quite similar to an Ethanol (25%) / water antifreeze mix which would have a freezing point of -15℃ (from EED libraries).

7.7.3 The following sub-sections will outline the different scenarios simulated, results obtained and analysis.

7.8 Case Study Scenario One:

7.8.1 **Scenario One Outline:** On this first example ground properties data from the EED programme was utilised i.e. thermal conductivity of 3.5 W/m-K and volumetric heat capacity of 2160 kJ/m^{3}K; these are fairly typical of an igneous crystalline rock such as granite. The undisturbed ground temperature was selected to be 8℃. This was due to the fact that in the demonstration version these properties are fixed and therefore the programme could not be assessed otherwise. The borehole configuration selected was a standard single borehole with one u-tube.

7.8.2 The first step taken was to contrast the different recommended lengths from the three sizing programmes considered for the same base ground, borehole configuration/construction and heating loads (from 7.5.2). The results from the three programmes are given below. In this instance GLHE-pro encountered a problem and would not run simulations longer than 96 months (8 years). This will be taken account of in the analysis.

Table 11. Sizing Results for Scenario One

Programme	Recommended Length	Comment(s)
EED	142.1m	20 year simulation. Max average 8.54℃, year 20 Max 8.19℃. Min average -.94℃.
GLHE-pro	121.45m	8 year simulation. Max average 8.54℃, Min average -41.38℃ in March in year 20.
GS2000	114.8m	Multi-year simulation ran. Max average 7.4℃, Min average -4℃.

The large difference between EED and GLHE-pro recommended sizes highlights that although both use G-functions the calculation method utilised is not identical.

7.8.3 It should be noted that it was not possible to enter user defined values for pipe material in GS2000 due to the fact the programme would not except the values entered in the other two programmes and TRNSYS. Instead the characteristics of Polythene Series 160/SDR 11 (designated PE 16 in the GS2000 database) were used as these are most similar to the other values used in terms of wall thickness and thermal conductivity values. In addition a flow rate of .55 l/s also had to be used in GS2000 as it would not allow the flow rate of .75 l/s (i.e. 2700 l/hr see 7.7.2) to be entered. None of the programmes calculations take account of the effects of the ground freezing and therefore there may be a slight inaccuracy, this is discounted.

7.8.4 **Scenario One Simulation Results:** TRNSYS simulations for the three different recommended lengths (all other factors being the same) were run for 175200 hours (20 years) in order to assess the long term performance of the different recommendations. Where not shown in the main report the graph of each simulation will be in the Appendix section seven. Average ground temperature is that of the 'storage' volume (see 7.4.7).

7.8.5 For the EED recommended length of 142.1m average ground temperatures were highest at the start of the simulation, as would be expected, at 9.32℃ in August of year one; due to solar thermal recharge in the summer months. The minimum average temperature was 8.11℃ during March of the fifth year. In general average ground temperature (see appendix A7) varied between summer peaks at 9℃ and winter troughs at 8℃, a 1℃ variation. Overall no long term ground temperature depletion was detected, in year twenty the average high was 9.20℃ in September with a low of 8.25℃ in February. In fact the lowest average summer/winter temperatures are found from year three to seven, where there is a slight dip.

7.8.6 In terms of inlet temperatures to the lowest is found to be -5.67℃ in the January of year nine. The highest inlet temperature is 9.25℃ in the September of year one. From these it can be seen that that operating conditions of the heat pump (no lower than -5℃ and no higher than 20℃) are generally observed and the borehole is of a sufficient length to meet virtually 100% of the peak and average loads.

7.8.7 In terms of coefficient of performance (COP) this lack of temperature depletion in the ground is highlighted by a virtually unaffected value from year one to year twenty.

Table 12. COP data for EED Length Scenario One

Period	COP Value
20 Year Average	2.85
First year	2.86
Last year	2.85

Taking the median of the average costs, £25-40 [81], for borehole heat exchanger materials and installation gives £32.50 per metre. Therefore the approximate installation cost of a 142.1m borehole is £4618. Using an average electricity cost per kWh of 8 pence would give twenty year heating fuel costs of £11,030 to satisfy the heat load of the building at an average COP of 2.85. It is accepted that using a fixed cost per unit over twenty years is not an accurate approach since fuel costs will vary over such a long time period; however it offers a simple means of highlighting the difference between installation and running costs for various different configurations.

7.8.8 Simulating the GLHE-pro recommended length of 121.45m yielded the following results. In terms of average temperature the highest value, 9.1°C, was again found in the first year (September). The lowest average temperature in year one was 7.9°C (March). During the years 3→7 summer/ winter ground temperature fluctuations were surprisingly slightly lower than in the latter years of the simulation (by .1→.2°C). The minimum average temperature was found in the sixth year (February) at 7.77°C.

7.8.9 When the inlet temperatures are evaluated however a problem with the recommended design length is encountered. The temperature of the antifreeze entering the heat pump is regularly under the acceptable limit of -5°C. Even the fact that a the size was not based on a full twenty year simulation does not explain this fully since even in year one a temperature of -7.68°C is reached in February. The lowest inlet temperature found is -8.18°C in the February of the fifth year. The full extent of this problem is shown in figure sixty below. From the November in year one until March of year two (the area in the middle of the screenshot) the inlet temperatures are consistently below minus five meaning the heat pump cannot operate.

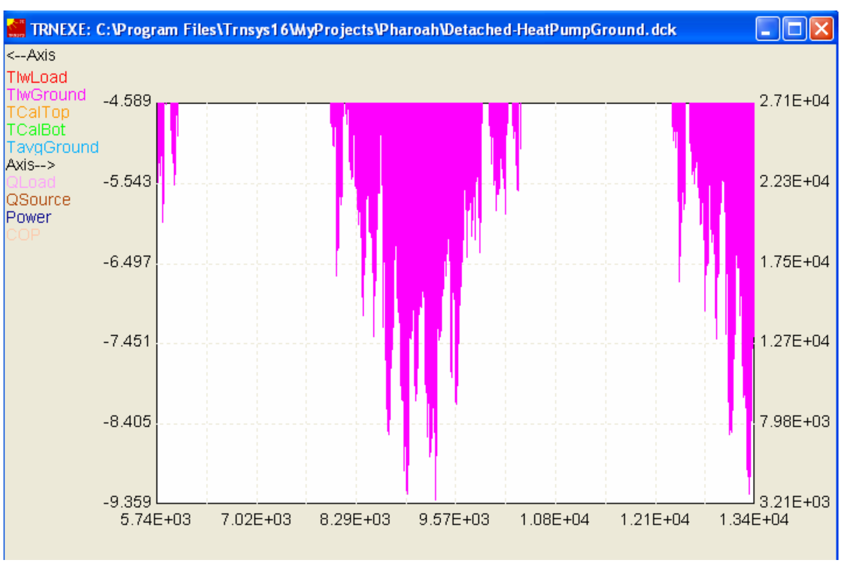

Fig 61. GLHE-pro Scenario One Inlet Evaluation

This can be compared with the same situation for the longer EED recommended length of 142.1m below.

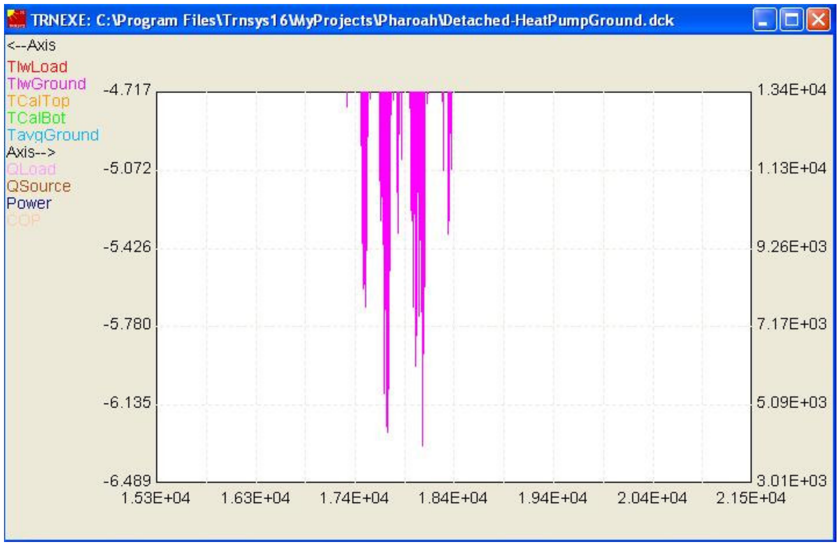

Fig 62. EED Scenario One Inlet Evaluation

This occurs since the TRNSYS model does not stop when the inlet temperature is below -5℃, as a heat pump would, but instead assumes that the inlet temperature is -5℃.

7.8.10 As regards COP a twenty year average value of 2.82 was found from the simulation. This is inaccurate however since the fact that for large periods of time the heat pump would not be able to cater fro demand has to be taken into account. In reality this configuration could not operate monovalently and an auxiliary system, most likely electric resistance with a COP of 1, would be required. Utilising this for long periods of time will lower COP and therefore increase CO_2 emissions and running costs. The latter cannot be evaluated however since the simple TRNSYS project used in this instance will not log how much energy would need to be supplied by any auxiliary system. Using the same £32.5/m fixed value the installation cost for this length of borehole would be £3,947.

7.8.11 As shown in table eleven GS2000 recommended a 114.8m borehole depth. It is clear at this point that the similar profile in terms of average ground temperature, i.e. little depletion, this is misleading. Since the length of the borehole is shorter than GLHE-pro's recommendation it is therefore of insufficient length to meet the full load of the building with long periods where inlet temperatures would be lower than minus five. Installation cost is approximated at £3,731.

7.8.12 **Scenario One Analysis:** The most striking outcome from the first case study scenario is that two of the programmes sized boreholes which were deemed by the TRNSYS simulation to be too short to meet 100% of demand. In GS2000's case this could possibly be explained due to the fact it can only size on average or peak demand figures and hence the former was used and a lower length would result. GLHE-pro has both demand figures to consider however. In no case does it seem likely that the criteria of inlet temperature exceeding 20ºC will be breached.

7.8.13 The fact that with these favourable ground conditions (i.e. high thermal conductivity) little, or indeed any, long term depletion of the ground was present is also highlighted. In the case of the undersized boreholes the average ground temperature figures are not representative of reality since actual inlet temperatures were not considered in the simulation when lower than minus five. However even in the case of the EED borehole, where the inlet temperature is rarely lower than minus five, there is little depletion; this can perhaps be attributed to the fact that the high thermal conductivity value is allowing a complete thermal recovery of the ground thanks to a quicker rate of heat transfer from solar recharge in the summer months.

7.8.14 Despite the fact that there is no depletion shown in average ground temperature low inlet temperatures are still shown to be occurring. This is as a result of relatively short term transients (i.e. periods of hours or days rather than years). One possible source of the discrepancies between GLHE-pro and TRNSYS is the modelling of thermal mass within the borehole, this being ignored in TRNSYS. Also operation of the heat pump could be subject to different assumptions. TRNSYS assumes an on/off controller which can induce strong variations in ground load.

7.8.15 interestingly however from viewing the simulation report from EED a higher, although still not significant, rate of ground temperature depletion in the region of 1℃ from years two to year twenty is highlighted.

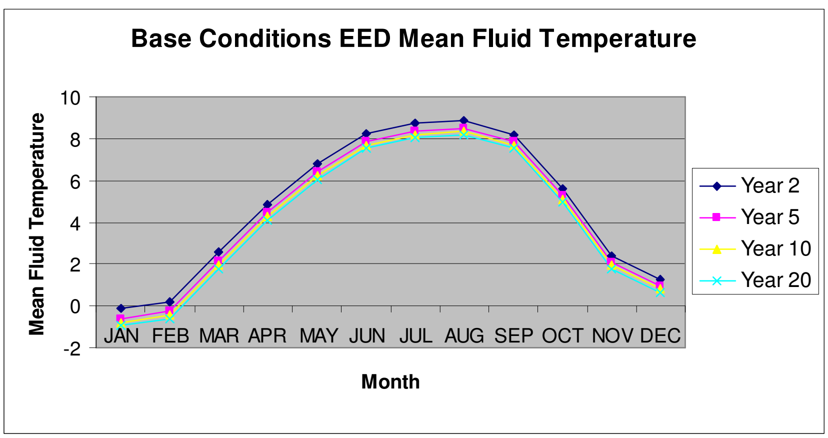

Fig 63. Mean Fluid Temperature Graph EED Scenario One (EED Results File)

7.8.16 Scenario one has also highlighted the importance of correct sizing when intending to operate a heat pump in monovalent mode. Without a backup auxiliary system the length specified by GLHE-pro and GS2000 would not be able to satisfy peak demand.

7.9 Case Study Scenario Two:

7.9.1 **Scenario Two Outline:** In order to investigate the implications of long term heat depletion in the ground it was decided to alter the ground conditions from those of the EED demonstration version to 'Average Rock Conditions' from the GLHE-pro library. These have a much lower thermal conductivity of 0.809 W/m-K and a slightly higher volumetric heat capacity of 2343 kJ/m³-K. The ground temperature chosen is 12ºC, a good average value for the UK (see figure thirty seven). The lower thermal conductivity should result in slower thermal recharge and more significant depletion. Since different ground conditions are being utilised EED cannot be utilised in this scenario.

7.9.2 The relevant data was inputted into GLHE-pro and GS2000 and the results are as follows:

Table 13. Sizing Results for Scenario Two

Programme	Recommended Length	Comment(s)
GLHE-pro	207.12m	20 year simulation. Max average 12.46ºC in month one, Min -4.99ºC in month 231.
GS2000	237.7m	Multi-year simulation ran. Max average 7.4°C, Min average -4°C.

As would be expected due to the less favourable thermal conductivity of the 'average rock conditions' the programmes recommend a longer borehole to satisfy demand. Also while GS2000 delivered a shorter borehole recommendation than GLHE-pro in scenario one it suggests a longer length in scenario two. The same input limitations as highlighted in 7.8.3 still hold.

7.9.3 **Scenario Two Simulation Results:** From TRNSYS simulations of the GLHE-pro recommended length of 207.12m the following average (storage volume) ground temperatures were found:

- Year One High 13.3ºC in October and low of 13.13 in May.
- Year Two High of 12.78ºC in October and low of 12.38ºC in May.
- Year 20 High of 11.20ºC in October and low of 10.62ºC in April.

7.9.4 In terms of inlet temperatures however the same problem as in Scenario one occurs in that they regularly fall below -5ºC. The highest inlet temperature of 12.99ºC is found in September of year one while the lowest of -7.47ºC occurs in January of year 12. The installation cost associated with this borehole would be £6,731 at £32.50/m. A high price if it would not be able to meet 100% of the load. Again running costs cannot be accurately established since it is not known how many kWh would need to be supplied by an auxiliary system.

7.9.5 Due to the longer length of the GS2000 borehole simulation the average temperatures are higher, peaking at 14.14ºC with a low at 11.29ºC. This point is clearly shown in figure sixty four below which shows the lowest average temperature from each year for the GS2000 and GLHE-pro lengths. It should be noted that for the reasons stated in 7.8.10 the average figures for the latter are artificially high. Apart from the differences in average temperature, with as expected a longer borehole resulting in less temperature reduction, the actual profile over the twenty year period is also of interest. Average temperature decreases each year but by a smaller amount leading, eventually, to a steady equilibrium ground temperature. This in turn should result in a stable COP from, for example years ten onwards. The same pattern is found for the maximum average temperatures.

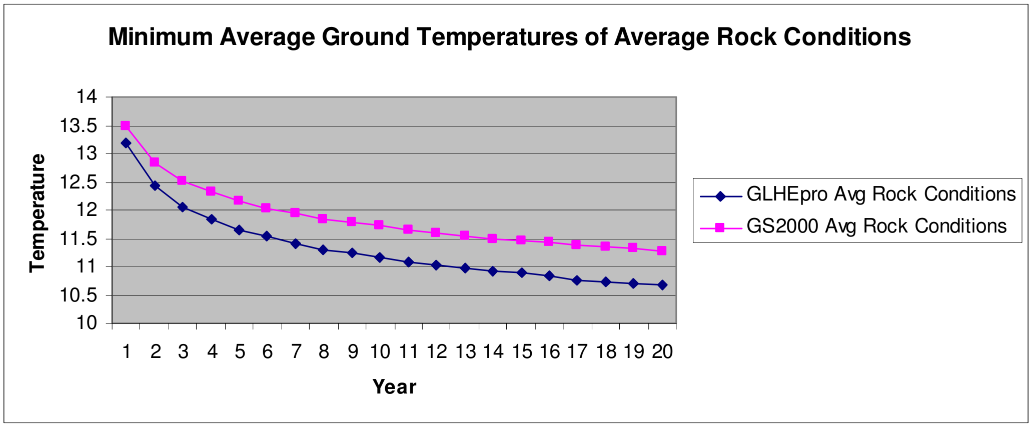

Fig 64. Average Yearly Minimum Temperatures Scenario Two

7.9.6 The criteria to stay above minus five degrees is satisfied with the GS2000 length of 237.7m making it a valid design according to TRNSYS. The highest value is found in August of year one at 13.26ºC while the lowest is -4.87ºC in the December of year seventeen. The same pattern of declining temperatures but at a gradually decreasing rate year on year, as found with average temperatures, again generally holds for the inlet temperatures. For example:

- Max inlet temperature year 1 = 13.26ºC (August), Year 2 = 12.79ºC (September) and year 3 = 12.56ºC (September).
- Min inlet temperature year 1 = -.53ºC (February), year 2 = -3.163ºC (January) and year 3 = -3.96ºC.

7.9.7 The resulting COP data for the GS2000 length is shown below. The fact that the final year COP is far closer to the average COP value underlines the statement made in 7.9.5 that the stabilising average ground temperature year on year will result in a stable COP value the longer the simulation runs.

Table 14. COP data for GS2000 Length Scenario Two

Period	COP Value
20 Year Average	2.95
First year	2.99
Last year	2.94

The lowering of COP from 2.99 to 2.94 over the twenty year period highlights the correlation between average ground temperature and performance. Although a SPF of 2.95 is creditable however it would come at a high installation cost of £7,725. Twenty year running costs are £10,656. The effect of COP/temperature depletion on running costs in this case is minimal. By comparing the year one and twenty results it is shown that in year one, at a COP of 2.99, annual running costs at 8p/kWh are £525.70 while in year twenty the lower COP of 2.94 will result in annual running costs of £534.64.

7.9.8 **Scenario Two Analysis:** From conducting the simulations in Scenario Two several interesting conclusions can be drawn. Firstly it is clear that the lower thermal conductivity of the 'average rock' results in more significant temperature depletion than is found in scenario one. Although it is accepted that the effect this has on performance is minimal. The fact that heat is replenished slower during thermal recharge, i.e. there is a slower heat transfer rate, is highlighted since the average winter low and summer high temperatures occurred in March and September respectively during scenario one. In scenario two however they occurred later in April/May and October respectively.

7.9.9 In terms of inlet temperature minimum values, and hence when any auxiliary system would be required, there is no distinction however. With both rock conditions the minimum inlet temperatures occur in January and February when energy demand is at a peak. The fact that heat pumps should never be sized on one year's data is also highlighted in scenario two. The most significant reduction in average ground temperature, minimum inlet temperature and COP always occurs from years one to two (again refer to figure sixty four). Taking the example of the GLHE-pro TRNSYS simulation in scenario two, during the first year minimum inlet temperatures do not fall below minus five degrees and the system will operate. During the winter of year two however they do and the system will have difficulty according to TRNSYS.

7.9.10 The COP values for both the GLHE-pro and GS2000 TRNSYS simulations highlight the effect temperature depletion of the ground can have on COP. In this case this may only be minimal i.e. for GS2000 from a year one high to year twenty high there is a reduction of 2.1ºC and from the year one low to the year twenty low shows a reduction of 2.5ºC. This fact is mirrored by a slight reduction in COP. However this highlights that with a more significant reduction in average ground temperature COP could be more severely affected. Although there is a strong possibility that if the borehole is undersized enough to cause such performance reduction it may consistently fall foul of minimum inlet temperature specifications and fail.

7.10 Case Study Scenario Three:

7.10.1 **Scenario Three Outline:** The borehole lengths indicated by the sizing programmes in scenario two, i.e. in excess of 200m, could in many cases be considered too deep for drilling contractors available within the financial constraints of a domestic project. Usually borehole depths for vertical systems lie between 150→200m deep (see 2.4.8).

7.10.2 In order to fit with this criterion a two borehole 'line' configuration will be required. This was therefore selected within GLHE-pro and GS2000, all other factors remaining the same (including 'average rock' conditions), and sized. GLHE-pro recommended each borehole should be 114.17m (total borehole length of 228.34m) with spacing of 4.57m. The programme specified that a max average temperature of 12.55°C, Min average temperature of -3.25 °C (month 230) and min peak temperature of -4.91°C (month 231). GS2000 again produced a longer borehole specification, with each borehole 142.3m deep (total borehole length of 284.60m). As a programme however GS2000 does not specify a recommended spacing between boreholes. The spacing was therefore set at 5.75m in TRNSYS for the GS2000 length simulation; this is scaled up from the GLHE-pro figure of 4.57m to the same proportion as the increase in borehole depth.

7.10.3 Analysing these two recommended depths in TRNSYS will not only allow further comparison of the sizing programmes but also the differences in performance between a single and two borehole line configurations i.e. in terms of COP and temperature depletion.

7.10.4 **Scenario Three Simulation Results:** For the GLHE-pro recommended length TRNSYS simulation produced the following average temperatures:

- Year one high of 11.95℃ (September) and low of 11.08℃ (April).
- Year two high of 10.96℃ (September) and low of 9.47℃ (April).
- Tear twenty high of 8.26℃ (September) and low of 6.39℃ (March).

7.10.5 As regards inlet fluid heat pump temperatures maximum values of 11.75℃ (year one) and 8.14℃ (year twenty) were found. Again showing the maximum inlet temperature of 20℃ will not be breached. However minimum temperatures were again consistently under -5℃ from year three of the simulation onwards; again highlighting that TRNSYS considers the recommended length too short to adequately meet demand without assistance from an auxiliary system. For example from the December of year six (hour 52439) to February of year seven (hour 53454) there is a period of forty-three days where inlet temperatures are consistently under -5℃. A minimum value of -8.6℃ was found in January of year 18.

7.10.6 The installation costs associated with this design are £5,366. TRNSYS calculates an average twenty year COP value of 2.96 although once gain this value is artificially high as periods where the heat pump could not operate are left unconsidered.

7.10.7 The TRNSYS simulation of the GS2000 recommended length gave a year one high of 12.55℃ and low of 12.09℃, in year twenty these have reduced to 9.61℃ and 8.50℃ respectively. A similar pattern of gradually decreasing ground temperature at a decreasing rate is found i.e. levelling off to a stable high/low value is shown.

7.10.8 The following data was produced from the simulation for inlet temperatures. Highs of 12.46℃, 11.72℃ and 11.27℃ were found in the September of years one, two and three respectively. Minimum values are shown in the graph below:

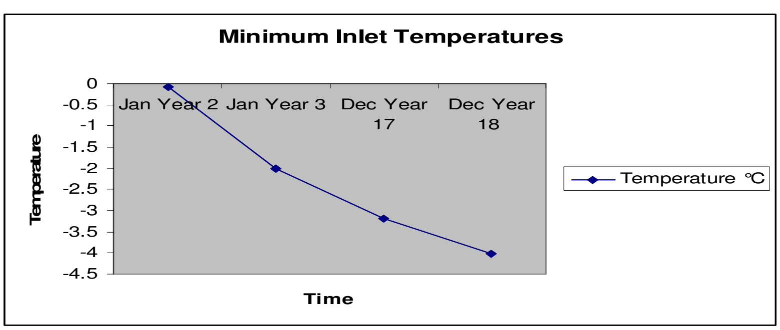

Fig 65. Minimum Inlet Temperatures GS2000 Scenario Three

As can be seen by figures sixty five above and A13 (in the appendix) the inlet temperatures never go below -5℃ within the twenty year simulation period thus meaning the design specified would run validly in a monovlent mode.

7.10.9 The COP data calculated in TRNSYS associated with the GS2000 length is as follows:

- Average over twenty years = 2.96.
- Year One = 3.01.
- Year twenty = 2.94.

Total drilling costs (at £32.50/m) are considerable at £9,249 however. Twenty year running costs using the average COP and 8p/kWh values are £10,620.

7.10.10 **Scenario Three Analysis:** Again, as in scenario two, GS2000 recommended a length which although considerably longer, and therefore £3,883 more expensive, than GLHE-pro was sufficient to meet 100% demand in TRNSYS. This extra length results in less temperature depletion than associated with the GLHE-pro suggested length, 1.35℃ higher for maximum year twenty values and 2.11℃ higher for minimum year twenty vales. Again though it is likely the average temperature figures for GLHE-pro are artificially high since inlet data does not take into account temperatures below -5℃.

7.10.11 As mentioned in the outline, running scenario three also allows comparison between a single and two borehole configuration. As regards heat flow in the ground, since demand and rock properties are the same in scenarios one and two any differences can be attributed to the configuration. In terms of when maximum and minimum average ground temperatures are reached, with a two borehole configuration maximums are reached in September and minimums March/April. Scenario two however shows annual highs in October and lows in April/May. This can perhaps be explained through the fact two boreholes result in more intensive heat extraction in a given volume of soil and therefore faster and more significant depletion occurs. This would result in a larger temperature difference for recharge (ΔT) and therefore faster rate of heat transfer resulting in a peak value generated sooner.

7.10.12 More significant temperature depletion with two boreholes is borne out by the simulation data. Comparing the valid GS2000 design lengths for a single and duel borehole designs shows the latter causes more significant ground temperature depletion. With a single borehole configuration the lowest value recorded for average ground temperature (i.e. year twenty minimum) was 11.29℃ while for the equivalent two borehole layout it reached 8.5℃.

7.10.13 In terms of COP figures generated the following table offers comparison:

Table 15. One and Two Borehole Configuration COP Comparison

Configuration	COP (Average, 1st, 20th)		
Single Borehole (237.7m)	2.95	2.99	2.94
Two-Borehole (284.6m)	2.96	3.01	2.94

It can be seen that despite more significant temperature depletion in the two borehole ground loop, the design offers a higher average and year one COP. This can be explained by the fact that the total borehole length of the two borehole configuration is 46.9m longer than the single borehole. The extra length calculated by the programme is used to offset the greater depletion associated with thermal interference between boreholes. This proves to be an accurate calculation since by year twenty the efficiency values are equal.

7.10.14 **Scenario Three-b:** To analyse the affects of spacing in a two borehole scenario another TRNSYS simulation was run utilising the GS2000 recommended length (each borehole at 142.3m). However in this simulation the spacing was doubled to 11.51m to assess the influence of reduced thermal interference between boreholes.

7.10.15 In terms of average ground temperatures year twenty highs and lows with 11.51m spacing were 10.55℃ and 10.26℃, an increase of .94℃ and 1.76℃ respectively on the 5.75m spacing simulation. Increasing the spacing also dramatically decreases the difference between summer maximum and winter minimum average ground temperatures (this is clearly shown through figures A13 and A14 in the appendix). In terms of inlet temperature this is reflected by the lowest minimum value being -3.18℃ (Jan of year 19) compared with a low value in excess of -4℃ with the original spacing.

7.10.16 This reduced depletion, especially in year twenty, is reflected in higher COP figures of 2.97 (average), 3.02 (1st year) and 2.96 (year 20). This correlates to whole simulation running costs of £10,584 at 8p/kWh; a saving of £36. However this small saving may be offset because although associated drilling costs will be the same for this scenario the greater distance between boreholes may slightly increase piping costs and pumping energy requirements. Although financial savings may be small in this instance, with a design length which is creating inlet temperatures close to going under the cut off point of -5℃, increasing spacing is a means of ensuring this does not happen without deeper drilling.

7.11 Case Study Scenario Four:

7.11.1 **Scenario Four Outline:** Scenarios one and two allowed comparison between two rock types with different levels of thermal conductivity i.e. a reduction of 2.69 W/m-K. The volumetric heat capacity of these two sets of conditions was broadly similar however (2160 KJ/m^{3}K to 2343 KJ/m^{3}K). In this scenario the effects of differing volumetric heat capacity (VHC) in ground conditions will be measured. VHC is the ability of a given volume of a certain substance to store heat while undergoing a temperature change while not undergoing a phase change. In order to calculate the thermal diffusivity associated with the ground conditions used the thermal conductivity value should be divided by the volumetric heat capacity figure and converted to m^2/day.

7.11.2 The ground conditions selected for this experiment were:

- 'Dry Clay', thermal conductivity .4 W/m-K, VHC 1600 KJ/m^{3}K, α = .022 m^2/day.

- 'Heavy Soil (Damp)' thermal conductivity .433 W/m-K, VHC 2018.66 KJ/m^3K, α = .018 m^2/day.

As can be seen they have similar thermal conductivity values but differing VHC values. This data was obtained from the GLHE-pro ground conditions library. Since the thermal conductivity values are very low a three borehole line configuration will be utilised to offset the significant depth required for a single borehole (in excess of 300m see 7.11.3). Although it should be noted this scenario is not designed to assess this particular configuration simply the effect of the differing conditions. Only GLHE-pro will be used in this analysis. Initial ground temperature will remain at 12°C (see figure thirty-seven).

7.11.3 With the same loads the sizing programme estimated:

- Dry Clay: Single borehole depth 346m, three borehole depth 145.64m each (total 436.92m) with a 4.57m space.
- Heavy Soil (Damp): Single borehole depth 334.5m, three borehole depth 132.57m each (total 297.11m) with a 4.57m space.

Initially it is recognisable that the increase in total length from one to three borehole scenarios is far bigger with the dry clay (low VHC) ground than heavy soil. Is this due to anticipated greater temperature depletion? A median length of 140m per borehole was selected and simulations ran in TRNSYS for each ground condition. One length was selected so the only differing factor between simulations would be the VHC value.

7.11.4 **Scenario Four Results:** In the 'Dry Clay' simulation average temperatures are as follows:

- Year one high 11.99°C (September) and low 11.42°C (June).
- Year twenty high 6.41°C (October) and low 4.79°C (March).

It should be remembered that the average ground temperature is calculated for a volume of ground 1.8 x the spacing between boreholes (see 7.4.7). The same pattern of a generally decreasing high/low temperature oscillation is shown. In terms of inlet fluid, the temperature does not fall below -5°C until the third year of the simulation. By the sixth year however it would be below this temperature for extended periods during the winter months (see appendix Fig A15). A minimum inlet fluid temperature of -7.58°C was found in the February of year twenty.

7.11.5 With the 'Heavy Soil (Damp)' ground average temperatures were as follows:

- Year one high 12.17°C (September) and low 11.72°C (May).
- Year twenty high 7.68°C (October) and low 5.76°C (March).

In terms of source temperatures although it does fall below -5°C from year 15 onwards it does not appear this is for a significant enough time to declare that the length would not be sufficient. A minimum value of -6.16°C is reached in February of year twenty.

7.11.6 The COP values for the simulations are shown in table sixteen. It should be noted again that the values for 'Dry Clay' are artificially high since the inlet temperature is regularly under minus five degrees Celsius.

Table 16. One and Two Borehole Configuration COP Comparison

Ground	COP (Average, 1st, 20th)		
Dry Clay	2.93	3.03	2.90
Heavy Soil (Damp)	2.95	3.05	2.92

7.11.7 **Scenario Four Analysis:** As would be expected with a higher ability to store heat the average ground temperatures are higher from years one to twenty with the higher VHC Heavy Soil (Damp). Overall depletion of the ground is over 1℃ less in year twenty when compared with the 'Dry Clay'. These simulations show the importance of considering VHC in design and not just thermal conductivity. Although the length of borehole and K-values are broadly the same in both situations the difference in VHC is what ensures that the inlet temperatures are suitable with 'Heavy Soil (Damp)' conditions while too low with 'Dry Clay' conditions.

7.11.8 Even with the artificially high COP values associated with the Dry Clay simulation efficiency is still superior with the high VHC heavy soil[74]; with the highest year one COP of all the simulations undertaken. This may have something to do with the three borehole configuration however. One of the key outcomes of this experiment is an illustration of why a long term simulation is needed. With the 'Dry Clay' ground conditions TRNSYS calculates the heat pump would work for a period, somewhere between 3→5 years, and then experience difficulties as inlet temperatures dropped too low. A short term calculation would not reveal this.

7.12 Case Study Scenario Five:

7.12.1 **Scenario Five Outline:** As mentioned in 2.4.8 and 5.3.4 the use of thermally enhanced grout is a key means of aiding heat transfer to the ground loop circulating fluid. This is due to the fact the grout, which supports the borehole preventing damage from unwanted movement and helps protect against contamination of ground water should antifreeze leak, is located in a critical heat transfer region where poor thermal conductivity material will increase borehole thermal resistance and consequently lower the heat transfer efficiency of the system. This in turn will result in the need for a deeper borehole and higher installation costs.

7.12.2. Previously bentonite was utilised by itself as a backfill material and although it has good sealant properties its relatively low heat transfer characteristics are not desirable. Neat cement has also been utilised with but "high water to cementitious material (W/C) ratios often create pores in the grout which cause a significant drop in thermal conductivity" [84]. Cement has also been known to be prone to shrinkage.

7.12.3 Many alternatives, for example coal slurry and sand clay mixes, have been tried in order to find an ideal mix of sealant properties, support and good thermal characteristics. Perhaps the most popular selection for thermally

[74] Although the slightly higher thermal conductivity of the 'heavy Soil (Damp)' should also be taken into account

enhanced cementitious grout is a mix of cement, silica sand, bentonite, superplasticizer and water. These are used in varying ratios but generally will yield a thermal conductivity in the region of 1.5→2.1 W/m-K as apposed to early straight bentonite and cement fill materials with a thermal conductivity in the region of .7 W/m-K.

7.12.4 This scenario will highlight the impact selecting the correct grouting material can have on a ground source heat pump installation. The grouts considered will be:

- Grout A: Bentonite 20% solids grout, K = .74 W/m-K, very similar to that used in the previous scenarios [83].
- Grout B: Thermally enhanced bentonite and silica mix (60% solids), K = 1.54 W/m-K [83].

GLHE-pro will be utilised to size the boreholes. This is due to the fact that GS2000 requires the user to select grout material from a predefined list and it was considered that utilising the EED default conditions with high thermal conductivity rock may not offer the best example of the impact of the grout on the model. Average rock conditions have been utilised again while all other factors i.e. undisturbed temperature (12℃), pipe type, spacing, flow rate etc are kept constant.

7.12.5 **Scenario Five Results:** Using the 'borehole thermal resistance calculator' in GLHE-pro gave a borehole thermal resistance of .2470 °K(W/m) for grout A and .127 °K(W/m) for grout B. This translates to a twenty year single borehole size of 209.52m for grout A and 186.14m for grout B. This difference in size alone would cost £759.85 at £32.5/m. It should be considered though that the thermally enhanced grout may well be more expensive to purchase. Unfortunately cost data could not be obtained in this instance for comparison.

7.12.6 A median length of 197.83m was selected and twenty year TRNSYS simulations undertaken to asses performance using grouts A and B. With Grout A the results were as follows in terms of average temperatures:

- Year one high 13.19℃ and low of 13.02℃.
- Year nineteen high 11.04℃ and low of 10.43℃.
- Year twenty high of 11.00℃ (October) and low of 10.39℃ (April).

These may well be artificially high however since in terms on inlet temperature from year three onwards during winter periods it is consistently under -5℃. The average COP (again higher than would be found with this design in reality) is 2.9.

7.12.7 With the thermally enhanced grout, B, average ground temperatures are as follows:

- Year one high 13.19℃ and low 13.01℃.
- Year nineteen high of 11.00℃ (October) and low 10.39℃ (April).
- Year twenty high 10.96℃ (October) and low of 10.39℃ (April).

The most important difference however is in the inlet fluid temperatures. Although there are occasional spikes below -5℃ it is not thought these are prolonged enough to rule to design length as invalid. The COP associated with the thermally enhanced grout is 2.97 (average), 3.01 (1^{st}) and 2.95 (20^{th}).

7.12.8 **Scenario Five Analysis:** This simulation gives a clear example of the influence the selection of grouting materials can have on a potential project. Of the two equal length boreholes TRNSYS predicts only the one utilising thermally enhanced grout will be able to meet demand consistently during winter periods. At first glance it does not appear to make sense that the higher COP with grout B is aligned with a higher degree of depletion in ground temperature, when compared to the simulation of grout A. This can be explained however by the fact that the lower thermal resistance of the borehole will mean greater thermal extraction of the ground. This in turn reduces power requirements in compression to meet the load (which is the same in both cases) and therefore a higher COP.

7.12.9 From a financial perspective selecting thermally enhanced grout would seem to make good sense since any increase in cost of materials as opposed to normal grout will be offset by less drilling and piping installation costs and lower pumping power (through shorter borehole lengths) and running costs (from the higher COP produced). This asks the question why thermally enhanced grout is not more common in actual installations; a fuller investigation into any potential disadvantages arising from its use could represent further study.

7.13 COP Analysis:

7.13.1 Through exploring the COP values found in scenarios one to five in more depth several conclusions can be made about the influential factors in determining ground source heat pump performance. The heat pump performance is interpreted by TRNSYS in the form of a performance map inputted in the model. In this model the performance map, obtained from the manufacturer Viessmann (see appendix section five), states the power usage and heating output (both in kW) for various values of inlet 'source' temperature (from -5℃→20℃) and outlet distribution 'load' temperature (15℃→65℃).

7.13.2 Figure sixty six below shows the variation in COP with difference in inlet/outlet temperature.

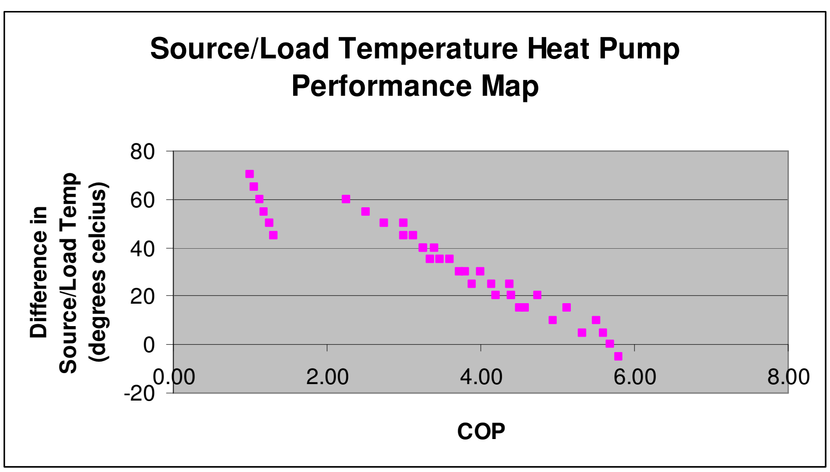

Fig 66. Graphical Representation of Viessmann Vitocal 350 Performance Map [adapted from 82]

As the graph logically shows the lower the difference between inlet and outlet temperatures, i.e. the energy which needs to be added through compression, the higher the COP. For example the assembly of data points in the top left with a COP of 1-1.25 represent a high[75] distribution temperature of 65°C. This backs up the statement made in 1.8.2 regarding the need to utilise low distribution temperature methods such as underfloor heating with heat pump systems to maintain high efficiency.

7.13.3 Although figure sixty six highlights all the possible COP's attainable from the performance map in the model utilised only a smaller subset are applicable. Firstly the distribution temperature for the Calorifier is fixed by the 'set point' of the controller on the schematic (figure fifty five) at 45°C. Secondly as shown by evaluation of the inlet temperatures from the simulation data they do not exceed a value of about 13.5°C (with an initial ground temperature of 12°C) and cannot go below -5°C otherwise the heat pump will not operate. Therefore the attainable COP values in this instance should lie in band set by the values in the performance map for inlet 'source' temperatures from -5 °C→15°C and entering 'load' temperature of 45°C as shown in figure sixty seven below.

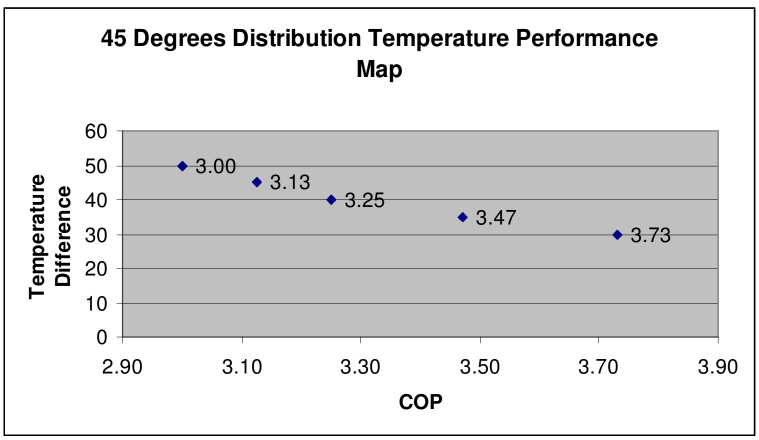

Fig 67. Case Study Performance Map

7.13.4 As figure sixty seven shows, through selecting the source range and load temperatures applicable to the case in question the achievable COP range narrows from 1→5.8 for the whole performance map to 3→3.73. The affect the distribution temperature of the heating system plays in determining COP is highlighted by the fact that if a 55°C distribution temperature was chosen the COP range would be 2.25 to 3.25. This highlights the challenge of utilising heat pumps in retrofit properties which have previously utilised wet distribution radiator systems based on a flow and return temperatures of 80°C and 70°C respectively. These temperatures are simply not achievable by heat pumps available at the current time and even at the 65°C maximum the Viessmann Vitocal can produce COP's are no higher than with electric resistance heating. Hence a new distribution system is required at considerable expense.

[75] For heat pump systems

7.13.5 As can be seen form the average COP's found from the valid simulations[76] however are between 2.85→2.97, below the lowest value of the scale shown in figure sixty seven. Values around a COP of 3 can be explained since at the time of heating demand, i.e. the winter heating season, inlet temperatures are most likely to be found in the -5℃→5℃ range. This would result in COPs between 3→3.25. The controller dead band should also be considered; this restricts the temperature of the heat pump fluid to 42.5℃ →47.5℃ thus resulting in lower COP's at the higher end of the scale. The fact the average values are below this could be due to the fact the building load is actually too high for the energy available in the ground, requiring more compression energy. This has links back to the recharge available from weather and also energy depletion of the ground, one of the key factors considered in the case study.

7.13.6 Variation in COP through temperature depletion of the ground is shown through the reduction in coefficient of performance from years one to twenty. This is summarised for valid simulations undertaken in table sixteen below.

Table 16. Effects of Temperature Depletion on COP

Sizing Programme	Simulation	COP Range (1st→20th)	Difference
EED	Scenario One	2.83→2.80	.03
GS2000	Scenario Two	2.99→2.94	.05
GS2000	Scenario three	3.01→2.94	.07
GS2000	Scenario Three-B	3.02→2.96	.06
GS2000	Scenario Four 'Heavy Soil'	3.05→2.92	.13
GLHE-pro	Scenario Five 'Grout B'	3.01→2.95	.06

As can be seen the biggest drop in COP associated with temperature depletion is .13. This is associated with a drop in mean[77] average ground temperature from years one to twenty of 5.22℃. The fact that alterations in distribution temperature are a far bigger influence in COP than drops in average ground temperature is shown by the fact that with identical inlet temperatures of 5℃ using a distribution temperature of 55℃, instead of 45℃, will lower COP by .5 (a drop from 3.25 to 2.75). So even though the temperature change is almost twice as large, at 10℃, the negative impact on COP is almost four times as strong.

7.13.7 When discussing coefficient of performance the importance of basing marketing claims on seasonal performance factors and not rated coefficient of performance is important. Taking this case study as an example, the heat pump used has a rated COP of 4.31 under standard test conditions[78]. The actual performance achieved however is far lower at approximately three. Using rated performance in order to make claims on running cost savings and

[76] Where inlet temperatures do not fall below minus five degrees
[77] Average of summer maximum and winter minimum temperatures
[78] Source 5℃, load 45℃

CO_2 emissions reduction will only serve to mislead customers. This issue was raised as part of the questionnaire feedback (section 4.7).

7.13.8 Finally it should be stated that, in terms of sizing programmes, ideally a programme will find the minimum depth for which the heat pump will operate for a twenty year period. This is because the increased COP associated with a longer borehole only delivers a small decrease in running costs compared to the increase in drilling installation expenditure. Unfortunately in this case, and assuming that the TRNSYS simulations are accurate, the lengths given either tended to operate or fail. Finding the minimum depth could necessitate undertaking repeated TRNSYS simulations with different depths, for which time was not available during this experiment. The advantage of finding the minimum depth would be to assess to what extent EED suggested length in scenario one and GS2000 lengths in scenarios two and three are 'oversized', if at all. Discrepancies between sizing programmes and TRNSYS are investigated in more detail in section 7.16.

7.14 Possibility and Effects of Human Error in Simulation and Sizing Software:

7.14.1 **Sizing Packages:** Although the sizing packages covered in this case study are designed to simplify the process of designing a GSHP system it is clear that potentially costly design flaws can still occur through utilising them without a clear understanding of the factors involved. Some of these have been identified in the scenarios covered, for example not appreciating the importance of ground thermal conductivity, volumetric heat capacity and grout characteristics.

7.14.2 In addition when specifying building loads in GLHE-pro and GS2000 there is an option to either enter data for space/building/heat pump load or ground loads. It is important the user can differentiate between these as entering values in the wrong area could lead to an incorrectly sized borehole. The ground load is simply the energy which needs to be extracted from the ground, given the efficiency of the heat pump, to satisfy the larger demand of the building. Therefore if building load data is entered into the ground load section the borehole will be oversized and if the opposite occurs and ground loads are entered in the building load section the ground loop will be undersized.

7.14.3 Knowledge of both peak and average load data is also essential for correct sizing and is especially crucial when considering monvalent systems such as that assessed in this case study. For example sizing for scenario one in EED with just average demand gave a size of 128.9m while including peak data increase the required length to 142.1m. Basing design on average demand alone, for which the sizing programme will produce results, gives potential that a borehole length will be selected which will not allow the heat pump to meet 100% of demand at peak times. For example in February, when in many cases the heat available in the ground is at its lowest and peak three hour demand is over 8kW. This is the case with the GLHE-pro and GS2000 length simulations for scenario one (figures A8 and A9 in appendix); while they are capable of meeting the base load over a sustained period they simply cannot cover 100% of demand in peak winter periods.

7.14.4 This again highlights one of the principal design difficulties raised by respondents to the questionnaire exercise (see 6.7.5 and 6.7.6), that of obtaining the heat load of the building and energy losses. Without the ability of the user to calculate building base and peak loads accurately these programmes will still not yield accurately sized borehole.

7.14.5 As mentioned previously this case study assumes the heat pump operates in mono-mode (see 1.7.2) and will therefore either met 100% of the demand or fail. In reality many heat pump systems will operate in mono-energetic mode (see 1.7.3), with a backup electric immersion heater to operate in extreme conditions, or duel-mode (see 1.7.4) where heat pump and back up can operate simultaneously. As has been shown by many of the simulations in the case study, when inlet temperature fell below -5℃, having a backup system is prudent. Although loads could be manipulated to size a bivalent system in EED/GLHE-pro/GS2000 none of the packages have a specific facility to guide the user in doing this i.e. selecting a suitable switchover temperature, size of back up system etc.

7.14.6 **TRNSYS:** As mentioned in 7.4.3 TRNSYS is not as 'user friendly' to the layman as the sizing programmes utilised in this case study and requires a greater base engineering knowledge. For example with the selected components in TRNSYS when the inlet 'source' temperature falls below -5ºC the simulation will not stop. The programme simply interprets the fact it does not have an acceptable inlet temperature, i.e. -7ºC, and takes the nearest value which is acceptable i.e. -5ºC, which occurred on several occasions in scenarios one to five. The impact of this is highlighted in figure sixty eight below, which shows a simulation with a 116.11m borehole, average rock conditions and two u-tubes per borehole.

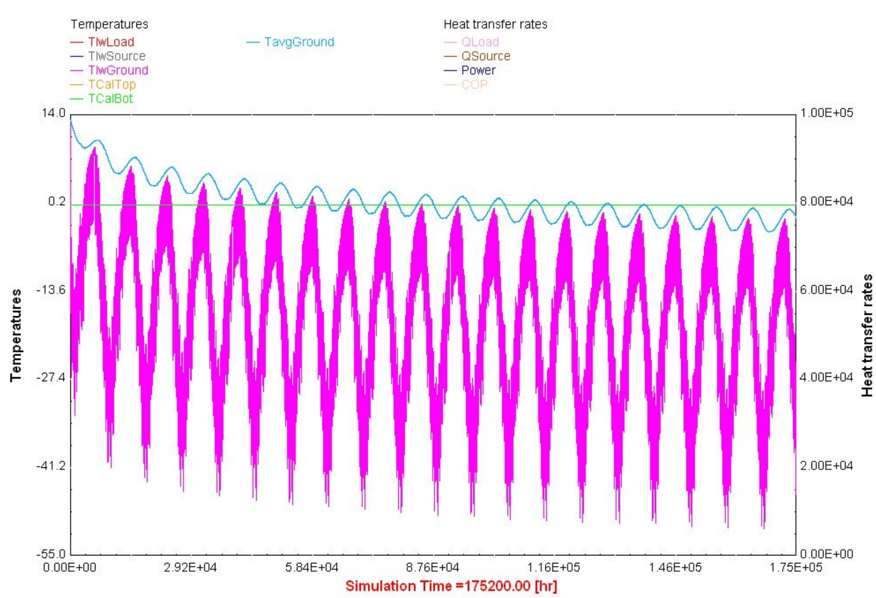

Fig 68. Two U-Tubes per Borehole Scenario

7.14.7 Apart from showing that the thermal interference form having two u-tubes in the same borehole is severe the diagram above shows the importance of the designer understanding the simulation. Even though the inlet temperatures fall below -40ºC (which is well below the freezing point of the brine) the simulation continues to run and analysis shows an acceptable average COP value of 2.81 is produced. In reality of course the low inlet temperatures would mean the heat pump could not operate for much of the year, and even when it did the COP would be very low. This is a slightly more extreme example than what occurred with undersized borehole in scenarios one to five but serves to illustrate that at least a good overview of all the factors to consider in the design process is required to avoid mistakes which may prove expensive at a later stage.

7.15 Financial Perspective:

7.15.1 **Outline:** Firstly it should be stated that the model used in the case study is not ideal for a financial analysis in that, as mentioned in 7.5, it is larger and has a higher energy demand that the type of property usually considered for a heat pump system and indeed the average UK house. In addition the primary focus of the case study was to address design issues and evaluate the sizing programmes no provide financial justification, or otherwise to GSHP systems.

7.15.2 It was mentioned, in 4.8.2, that the prospective market for the technology in the UK is focused on new build properties without access to mains gas. This section will provide a brief outline financial assessment to investigate why this is the case, taking into account both new build costs in comparison with fitting a gas condensing boiler.

7.15.3 **Installation Costs:** Throughout the case study the capital costs of a borehole installation of relevant size for the heat pump system have been quoted. These are based on a £32.50/m cost of drilling and materials (pipe/grout etc) [81]. This is just one estimate and it is not to say that boreholes cannot be fitted at a lower rate per metre. An accurate assessment of borehole fitting costs, both for the UK and case study nations in section three, would add considerable depth to the analysis in section three and four. Unfortunately there has not been time to conduct this.

7.15.4 In the best case scenario from the examples considered, the favourable high thermal conductivity rock conditions in scenario one, the only valid length produced was 142.1m from EED. This correlates to a total borehole cost of £4618.25 at £32.50/m, a significant percentage of total project outlay. The worst case of ‘Heavy Soil (Damp)’ ground conditions in scenario four would require a borehole cost of £9,656 and effectively rule a heat pump out of consideration financially. These examples show the value of an accurate sizing program which will find the minimum length required for the heat pump to operate and also improvements which shorten the length of borehole required such as thermally enhanced grout.

7.15.5 As this case study wanted to examine long term heat depletion of the ground and sizing programmes (many of which focus solely on vertical sizing) only vertical borehole systems were assessed. From the questionnaire results, which highlight finding space for horizontal systems as a key concern, the UK industry realises that use of horizontal systems is a means to keep installation costs as low as possible and make ground source heat pumps more financially attractive.

7.15.6 **Financial Assessment:** Utilising the best case from all the simulations undertaken (see 7.15.3) a new build project has been financially evaluated and compared to the alternative option of a condensing boiler (assuming mains gas is available). This represents a quick overview of the financial constraints facing GSHP market growth and therefore there are several assumptions made which mean there is scope for error in the analysis.

Table 17. Heat Pump Vs Gas Boiler Comparison

GSHP		Gas Boiler	
Project Component	**Cost**	**Project Component**	**Cost**
Viessmann Vitocal 350	£6873 (personal Communication)	Vaillient Condensing Gas boiler [86]	£996
Borehole	£4618	20 year Running Costs 'Space Heating' @ 3p/kWh and efficiency of .85	£13,869
20 year Running Costs 'Space Heating' @ 8p/kWh and COP of 2.85	£11,030	Annual Gas Safety Check (over twenty years)	£1,500[79]
Max Grant from LCBP [87]	- £1,200		
Total:	£21,321	**Total:**	£16,365

7.15.7 This calculation has several assumptions which must be taken into account. For example the cost of the heat distribution system is ignored in both cases i.e. 80ºC sized radiators for the boiler and 45ºC radiators or underfloor heating for the GSHP. The latter may of course differ in price. In addition it is assumed that the condensing boiler will last for twenty years still operating at top efficiency; should it require replacement before this time the costs will be equalised somewhat. The electricity associated with pumping the heat transfer fluid in a ground loop is also neglected.

7.15.8 In the case of a retrofit system however it is harder to make a financial argument. This is due to the fact if a gas system has previously been in place the additional cost, and disturbance, of replacing the radiators (most likely with those sized for 45º C water distribution and not underfloor heating) will have to be taken into account. If the previous heating system was electric or solid fuel however this cost can be applied to both the gas and heat pump

[79] Based on National landlords Association cost of £75/yr

systems. However even taking this basic analysis it is clear to see why GSHP technology is struggling to infiltrate the retrofit market, such as has been achieved in Sweden.

7.15.9 Of course there is scope for reducing the cost inequality highlighted in this analysis. The main means of lowering cost is in terms of the borehole, either through:

- Using a horizontal ground loop.
- A shorter borehole for a lower demand building.

While other means of making GSHP's more financially attractive could be:

- Competition lowering the price of installation and heat pump systems.
- Economies of scale lowering the price of heat pump systems.
- Increasing grant aid for GSHP systems.
- An equalisation between gas and electricity prices (as seen in Austria and Sweden).

These are investigated in more detail in the case study of section eight.

7.16 Sizing and Simulation Discrepancies Discussion:

7.16.1 It is surprising that in several cases TRNSYS and the sizing programmes GLHE-pro and GS2000 appeared to have a differing interpretation of the desired borehole length to meet demand. The result of this has been TRNSYS calculating that the borehole lengths stipulated were undersized as inlet temperatures drop below -5℃. This section will discuss several possible explanations for this. In an effort to ascertain the differences in estimated performance of a set borehole length between TRNSYS and GLHE-pro, which led to the design lengths produced by the latter in scenarios one, two and three being evaluated as too short by the former, a further hypothetical case was considered. Firstly the TRNSYS model was altered to reflect a situation of a constant year round load of 2kW satisfied by a heat pump with a COP of 2 under all source/load temperatures[80]. IN GLHE-pro the loads and heat pump were altered to reflect this scenario; all other factors in the two models i.e. fill thermal conductivity, flow rate etc were the same.

7.16.2 Using average rock conditions and an undisturbed ground temperature of 12ºC sizing in GLHE-pro produced a recommended borehole length of 73.95m for a ten year simulation. The programme also evaluated a maximum inlet temperature of 12.16ºC in month one and minimum of -4.91ºC at the end of the ten year period. Since loads and heat pump characteristics in both programmes and now identical TRNSYS should report a similar profile.

7.16.3 Running a ten year simulation in TRNSYS for a 73.95m borehole gave a reduction in average ground temperature from 12ºC→7.75ºC (blue line on figure sixty-nine) and inlet variation from an initial value of 12ºC to -4.06ºC (pink line of figure sixty-nine) at the end of the ten year period. From this it is clear that the temperature depletion of the inlet fluid (see figure sixty-nine) is broadly to the same degree in both programmes. It is unusual however that in the previous scenarios GLHE-pro would have been estimating higher inlet fluid temperatures than TRNSYS and hence producing a shorter borehole

[80] This was created in TRNSYS through removing the weather file and building and then altering the load calculator and heat pump performance map.

recommendation, while in this instance the programme predicts more significant depletion.

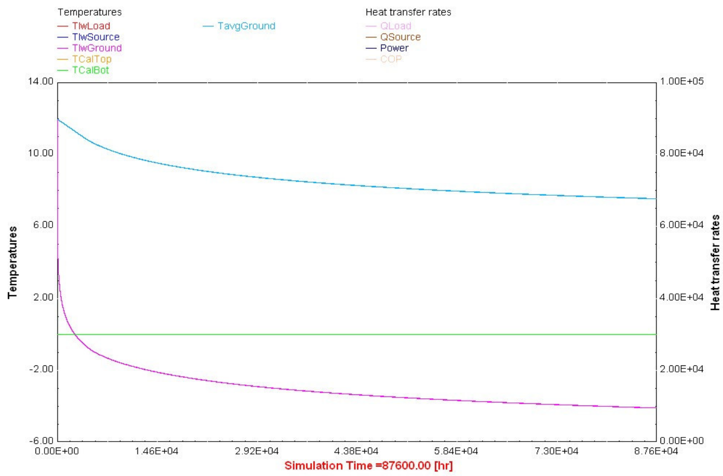

Fig 69. GLHE-pro/TRNSYS Test Simulation Results

7.16.4 It is difficult to pinpoint exactly why these differences occur. What this experiment can conclude however is that estimated performance between the programmes is far more attuned under constant load conditions than when a variable load is introduced. Apart from simply dismissing this as being due to the inevitable differing calculation methods between a design and simulation programme another possible explanation is in the load profile data used by each programme. In the scenarios TRNSYS estimates the load on the heat pump from the building and weather files with data at fifteen minute intervals, while GLHE-pro relies on the data inputted for a monthly base load and three-hour peak average. It could be therefore that since TRNSYS is experiencing a far more variable load, with greater demand spikes for a shorter period in peak conditions, it will estimate differing effects on ground loop brine/antifreeze temperature.

7.16.5 It can also be stated that since under the constant load/COP scenario performance estimates between the packages were broadly the same the possibility of differences in programme estimates from the scenarios due to incorrect data input in GLHE-pro can be allayed. Another possible explanation could be how the two programmes interpret ground conditions. From the scenarios evaluated it appears that the lower the thermal conductivity of the ground the more accurate the GLHE-pro estimation is in terms of keeping inlet temperatures above -5ºC (according to TRNSYS). The manner by which each of the two programmes interprets the required length to meet minimum inlet conditions for different ground conditions could represent a further area of study.

7.16.6 It should also be noted that the selected ground loop heat exchanger model in TRNSYS, type 557, does not take into account the thermal mass within the borehole itself and heat transfer fluid. In addition a constant borehole resistance i.e. constant convection resistance in the pipes is also assumed. This combined with the larger “spikes” in ground load may explain larger fluctuations in the ground outlet temperature than the ones estimated by GLHE-pro. In this case there would seem to be a relative mismatch between the assumptions within different sections of the TRNSYS model. Therefore the fact that TRNSYS states the boreholes are undersized does not mean this can be stated as absolute fact.

7.1.6.7 Another mitigating factor could be that both the sizing programmes and TRNSYS ignore the effects of groundwater movement and convective transfer of heat. Over a twenty year period this will play a role in mitigating ground temperature depletion. This uncertainty could potentially be larger than the differences between the programmes.

7.17 Section Conclusion:

7.17.1 Undertaking the simulations within this case study has allowed evaluation of the sizing programmes GLHE-pro and GS2000 under several different circumstances and EED in one case. It should be noted however that the observations only holds for this specific case study and in comparison with evaluation in TRNSYS. To fully assess the programmes different building types, ground conditions and configurations should be sized and compared with empirical data from actual installations.

7.17.2 Initial observations are firstly that in terms of usability GLHE-pro and EED are more user friendly than GS2000, which is prone to crash and has restrictions on data that can be entered. In terms of results however GS2000 gave longer borehole lengths which were deemed valid for monovalent heat pump operation in Scenarios two and three by TRNSYS. When GLHE-pro's sizing's would have lead to the heat pump requiring an auxiliary backup system at times of peak demand. On the one instance EED was utilised it produced a valid design length according to TRNSYS.

7.17.3 In terms of applicability from a UK perspective all the sizing programmes would be of more use if they contained data libraries i.e. of heat pump systems and ground properties/temperatures applicable for this country, rather than the United States/Canada in the case of GLHE-pro and GS2000. It is clear however that the systems do offer a simpler and quicker means of designing systems than either doing the calculations by hand or repeatedly running TRNSYS simulations.

7.17.4 Using different ground conditions has highlighted the impact thermal conductivity and volumetric heat capacity values have on design length and system performance. This data simply has to be known before a system can be installed. In terms of temperature depletion the impact of using a two borehole system should also be taken into account. These simulations have highlighted that two borehole ground loops, which may be required in certain geological and space availability situations, will cause greater temperature depletion. Increasing the size between boreholes is a means of reducing this. From analysing COP values however it was shown that although temperature depletion lowers COP the key factor in determining efficiency is the selection of distribution temperature. Finally it was found that thermally enhanced grout is a positive development in GSHP design, allowing shorter boreholes to be utilised and therefore making financial savings.

7.17.5 Although the sizing and simulation programmes aid the user in designing a GSHP system they are no substitute for a full understanding of all the parameters involved. Without this, as section 7.14 showed, there is still opportunity for incorrect design practice. From a financial perspective section 7.15 showed that, despite lower running costs, in many cases there will still be an overall cost differential between ground source heat pump systems and gas boilers; this explains the market focus on new build properties off the gas grid. The borehole size is a significant contributor to GSHP system costs thus demonstrating the importance of correct design practice to ensure it is not oversized (leading to unnecessarily high installation cost) or undersized (leading to higher running costs from lower COPs and the use of auxiliary systems).

7.17.6 Finally the discussion in section 7.16 should have made clear the fact that a comparison between two computer programmes is heavily influence by the assumptions used by each. Although TRNSYS has predicted that the sizing programmes have produced ‘undersized’ boreholes in reality this may not be the case. Several possible reasons for these discrepancies have been postulated from interpretation of load data to the assumptions made regarding thermal mass of the borehole and groundwater movement.

Section 8. Heating Demand and Financial Viability Case Study

8.1 Introduction:

8.1.1 As stated in 7.5.4 the building utilised in the sizing case study is not representative of that which would typically be considered for a ground source heat pump system. This is due to the fact that it is particularly large and has poor thermal characteristics; both factors leading to a large heat load. The overall result of this was an unfavourable indication of the financial competitiveness of a heat pump system being portrayed in section seven. This short case study will therefore present some modifications to the building and heat pump system costs used and assess what impact these will have on the financially viability of installing a GSHP system.

8.1.2 TRNSYS will be used as a means to assess both base and peak demand profiles for the building; this data will then be utilised to size the borehole required. The programme will also be utilised to run simulations in order to calculate COP and a total twenty year package cost. Several other financial scenarios will be presented and their effects on overall system costs quantified. This will be compared with a gas system in the same manner as 7.15.6.

8.1.3 As mentioned previously assessment of financial viability is not the central aspect to this study and therefore it is only covered in a basic manner. It does appear though that a more in-depth financial assessment, using demand from a new build house under the 2006 (Part L) building regulations and making comparison with alternative renewable and fossil fuel heating systems could represent logical further study.

8.2 Model Parameters:

8.2.1 As in section seven the 'Viessmann Vitocal 350' brine to water heat pump will be utilised. In order to present a 'best case scenario' thermally enhanced grout (1.54 W/m-K) will be selected as the fill material (see 7.12) and favourable sandstone ground conditions utilised (k = 2.3 W/m-K, α = .26 mm^2/day and VHC = 2000 KJ/K/m^3). Undisturbed ground temperature will again remain at 12°C. The only configuration which will be evaluated is a single borehole, with identical flow and pipe properties to section seven utilised. Weather conditions will remain those from the UK, London file. It should be noted that once again domestic hot water requirements are not considered as part of this study.

8.2.2 **The Building:** In order to reduce the base and peak energy demand modifications were made to the building file through using the TRNBuild function in TRNSYS:

- Loft insulation increased from 100mm to 150mm of glass fibre quilt, consequently lowering the u-value from .366W/m^2/K to .251W/m^2/K.
- External wall cavities received an additional 50mm of mineral wool insulation. Lowering u-value from 1.437W/m^2/K to .514W/m^2/K.

- The glazing was improved from single (u-value 5.68W/m²/K) to double (u-value 2.83 W/m²/K).
- The air change rate[81] was reduced from .65 to .55 per hour.

8.2.3 The result of these changes is a reduced peak and base energy demand. The initial building utilised had an annual heating energy demand of 19640kWh/year or 140kWh/m²/year. The alterations described in the preceding paragraph have reduced demand significantly to 9820kWh/year or 70kWh/m²/year. Since demand was reduced so considerably through the thermal improvements the size of the building was unaltered.

8.2.4 As can be seen by the following figures the new demand values are far closer to the low and stable loads optimal for a heat pump system.

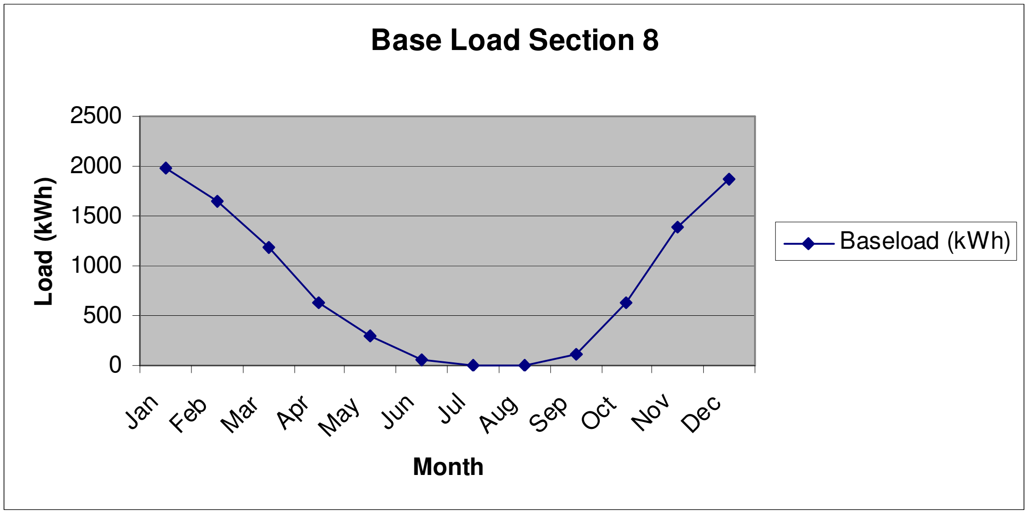

Fig 70. Monthly Demand with Thermal Improvements

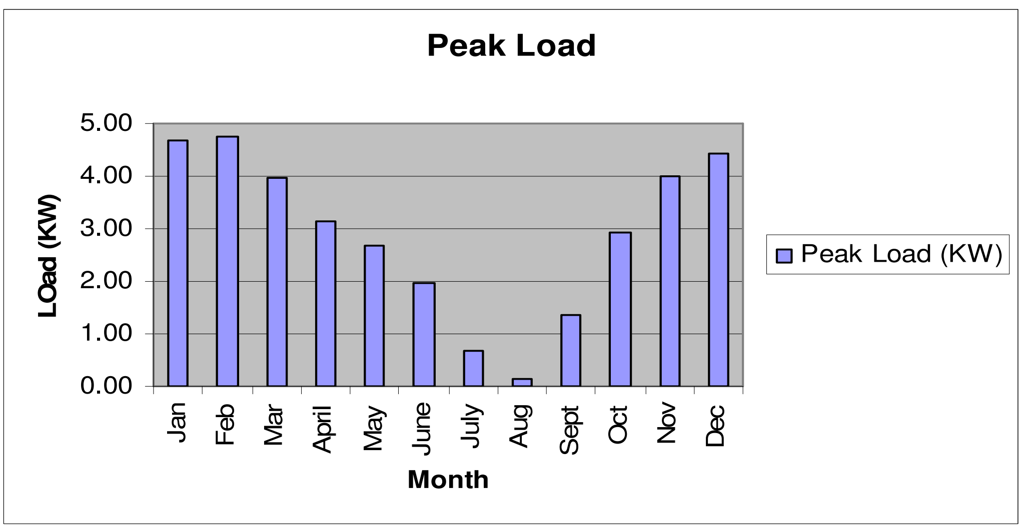

Fig 71. Monthly Three Hour Peak Demand

[81] A measure of the rate by which air in the interior space of the building is replaced by exterior air from ventilation or infiltration

In summation the thermal improvements made have effectively halved both base and peak demand figures. It is again assumed that the heat pump will meet 100% of this demand i.e. operate monovalently.

8.3 Design Sizing:

8.3.1 Utilising the GLHE-pro programme to size the borehole gave a required length of 52.11m with predicted minimum temperatures of -1.3ºC (average load) and -4.92ºC (peak load), both occurring in the twentieth year. GS2000 recommended a slightly longer length of 70.7m to meet demand. Upon running the simulation in TRNSYS however it was found that neither of these lengths were deemed long enough to ensure the inlet temperature of the fluid to the heat pump did not drop below -5ºC.

8.3.2 This is similar to what occurred in the first scenario of section seven's case study in which, with high thermal conductivity ground conditions, both programmes produced lengths considered too short by TRNSYS. This gives partial validation to the theory (see 7.16.5) that GLHE-pro assumes a shorter sizing than TRNSYS the more favourable the ground conditions.

8.3.3 The minimum borehole length for which the inlet temperatures specifications of the heat pump could be met in TRNSYS was 90m and this will be considered as the length utilised. Twenty year simulations were undertaken with this length in order to obtain the COP achieved by the system with both 35ºC and 45ºC distribution temperatures; the results graphs from these can be found in the appendix section eight. With the lower demand associated with the modified building it is noticeable that there periods during July and August where cycling is evident (see 1.8.3 and 1.8.4), these are shown by white lines in the inlet temperature plot (pink area). In reality with demand this low the heat pump would be turned off during this time and, if required, auxiliary heating used.

8.4 Simulation Results:

8.4.1 Simulations were ran for both 35ºC and 45ºC distribution temperatures since the financial impact of a higher COP, strongly associated with lower distribution temperature (see 7.13.4), is a factor investigated within the case study. As shown by table three distribution at 45ºC is akin to low temperature radiators while 35ºC is more in line with what is attainable from an underfloor heating system.

8.4.1 For the 45ºC simulation results were as follows:

- Year one average high of 12.13ºC and low of 11.43ºC.
- Year twenty average high of 11.60ºC and low of 10.54ºC.

This represents a depletion of .7ºC for the maximum temperatures and 1.06ºC for the minimum temperatures; a level to be expected with favourable ground conditions. This depletion resulted in a year one to twenty reduction in COP from 2.80→2.77. The average COP of the twenty year period being 2.78.

8.4.2 For the 35ºC simulation results were as follows:

- Year one average high of 12.62ºC and low of 11.31ºC.
- Year twenty average high of 11.51ºC and low of 10.40ºC.

This represents a depletion of 1.11ºC for the maximum temperatures and .91ºC for the minimum temperatures. As expected with a lower distribution temperature the COP figures achieved were higher. The average COP of the twenty year period was 3.33 while depletion through the twenty year period was from 3.35→3.33.

8.5 Cost Analysis:

8.5.1 **Cost Factors:** Various different alterations will be made to the twenty year packaged installation and running costs for the heat pump system to assess the influence of different changes. These are presented as cost scenarios, all of which assume a £1,200 grant from the DTI's Low Carbon Buildings Programme and electricity at 8p/kWh:

- **Base Case Scenario:** Viessmann Vitocal 350 cost of £6,873, borehole costs at £32.50/m [81] i.e. £2,925 for a 90m length, running costs at a COP of 2.78 i.e. 45ºC distribution.
- **Higher COP Scenario:** Viessmann Vitocal 350 cost of £6,873, borehole costs at £32.50/m, running costs at a COP of 3.33 i.e. 35ºC distribution.
- **Lower Heat Pump Cost:** Heat Pump Cost of £3,250 calculated as follows. A typical range for heat pump costs is £350→650 / kW capacity [11], of which the Viessmann model utilised, is at the top of the bracket. With a lower demand however the maximum capacity required is now 5kW so keeping £650/kW figure, 5 x £650 = £3,250. Borehole costs at £32.50/m, running costs at a COP of 2.78.
- **Lower Borehole Cost:** Viessmann Vitocal 350 cost of £6,873, borehole costs at £25/m i.e. £2,250 for a 90m length, running costs at a COP of 2.78. Borehole costs calculated as follows. A typical range for vertical ground loops is £450-600 / kW capacity [11]. Taking the £450/kW figure x 5 (capacity required in kW) = 2250 / 90 (m) = £25/m.
- **Best Case Scenario:** Heat pump cost of £3,250, COP of 3.33, borehole costs at £25/m.

8.5.2 **Cost Analysis:** The final twenty year packaged capital and running cost for each of these scenarios is shown in figure seventy two below.

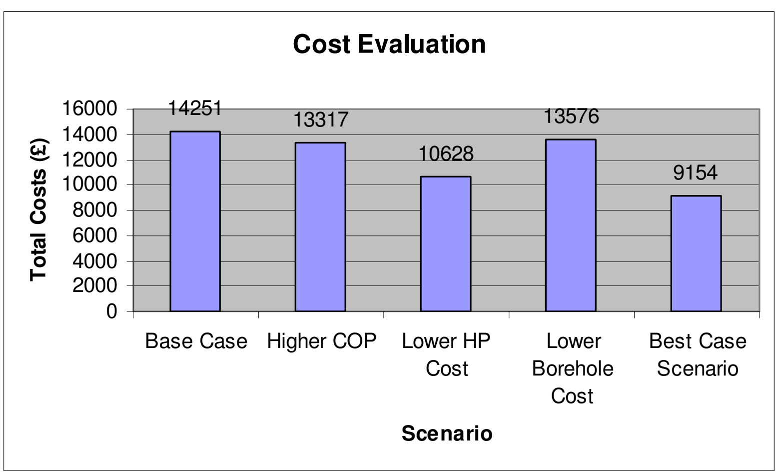

Fig 72. Scenario Twenty Year Costs

It should firstly be noted that lowering demand has considerably reduced the total costs associated with the heat pump system, from £21,320 to £14,251 in the base case. This is as a result of a saving in materials and drilling costs from a shorter borehole and lower running costs. In reality the base case figure would be lower still due to a reduced heat pump cost since there is no value in having an 11kW capacity unit when peak demand is only 5kW.

8.5.3 A higher COP value i.e. through using underfloor heating, reduced fuel costs by approximately £47 per year, a total saving of approximately £930 over the twenty year period. This would not justify the expense of fitting underfloor heating[82] when a wet distribution system is already in place but for a new build scenario it may be worthwhile. A higher COP will also lower CO_2 emissions. It should also be noted that the higher the building load the larger the savings accumulated from improved efficiency. For the case study in section seven for example a COP of 3.33 would save in the region of £1,586 (compared to the COP of 2.85 used) over the twenty year period.

8.5.4 The biggest reduction in costs from the base case was due to lowering the capital expenditure of purchasing the heat pump; thus validating the opinion of those who responded to the questionnaire that this was a significant barrier[83]. The potential saving indicated here shows the value of accurate demand profiling which would allow a heat pump top be sized correctly. This will also help to reduce the cycling shown in the simulations from using an 11KW heat pump for a low demand scenario. Apart from ensuring the system is not oversized other means by which the capital costs of the unit could be reduced is through larger grant support or competition and economies of scale in the growing market reducing costs.

8.5.5 Lowering borehole costs associated with materials and drilling, which will also occur with market development, saved £675 in this example. This again highlights the value of good design practice in ensuring design length is not overly conservative. As with the higher COP case the higher the demand and hence borehole length required the bigger the saving from a lower £/m cost, savings of £1065 would be achieved in the section seven case study at £25/m. Savings in this area will yield even more significant cost reductions for commercial installations.

8.5.6 Applying all the lower cost factors to one case reduced the overall twenty year costs to £9,150; under half that calculated for the section seven case study. This shows the value of reducing demand through energy efficiency measures, sound design practice (to accurately calculated load and borehole length required), new build flexibility (for underfloor heating) and a developed market (to lower heat pump and drilling costs).

8.6 Gas Cost Comparison:

8.6.1 Once again the costs of the heat pump scenarios will be compared with those of a gas system; currently the most cost efficient domestic heating

[82] If it is even physically possible

[83] It should be noted however that in the questionnaire the respondents stated total system costs i.e. including borehole were a barrier. The heat pump is a significant contributor to these however.

option. Two gas cost scenarios were assessed. Firstly gas at 3p/kWh, approximately the unit cost found in the UK in 2007, as used in section seven. And also gas at 5p/kWh which would represent a gas to electricity price ratio of 1:1.6[84] as found in Sweden; as opposed to the 1:2.6 ratio used in the case study or the 1:3.73 ratio of the UK in 2005 (see table ten). This will examine the impact of disparity between gas and electricity costs on the financial viability of heat pump systems. The total twenty year costs for these prices are:

- **3p/kWh:** £9,429 (boiler, fuel and annual safety check).
- **5p/kWh:** £14,052 (boiler, fuel and annual safety check).

For a more detailed breakdown see the appendix section eight. Logically since building energy demand is lower at 3p/kWh there is a reduction in total cost from that in section seven.

8.6.2 As can be seen by the large difference in total cost, the price increase per unit has a more significant effect on a gas boiler than it would on a heat pump system due to the lower efficiency of the boiler when compared to the heat pump COP. Figure seventy three below highlights the cost difference of the heat pump scenarios when compared with the gas price scenarios; increased costs are in blue while reduced costs are in purple.

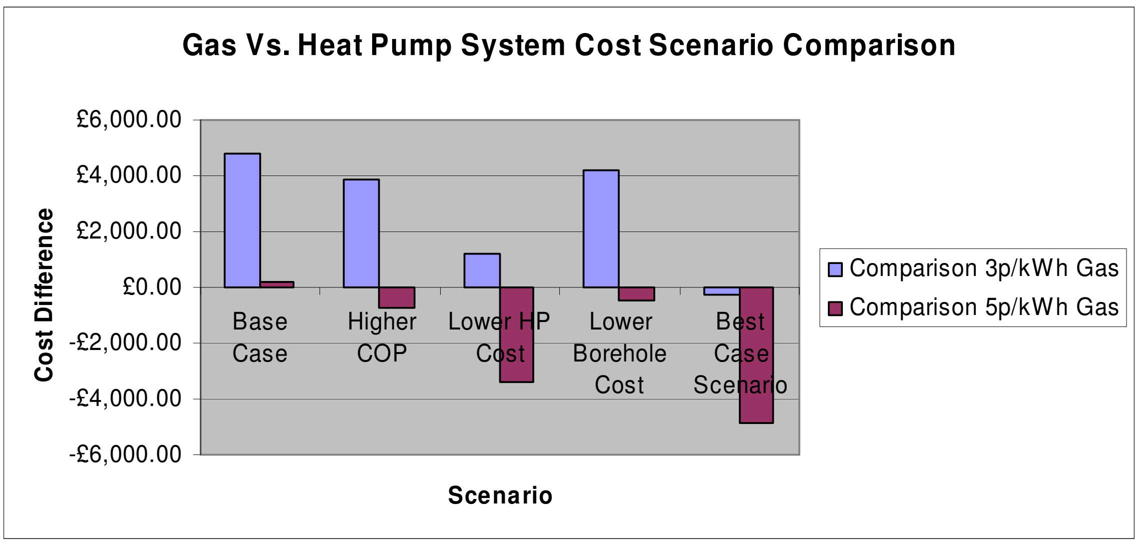

Fig 73. Heat Pump and Gas Scenarios Comparison

At the 3p/kWh price the gas system is cheaper than all the heat pump scenarios except the best case situation where it is marginally more expensive. However by closing the disparity between gas and electricity prices the heat pump system is the cheaper in all scenarios bar the base case, which is slightly more expensive. This shows that the unit cost of gas plays a large role in the financial viability of a heat pump system, where a connection is available.

8.6.3 In terms of assessing running costs it can be seen that the ratio of boiler efficiency to COP must be larger than the ratio of gas to electricity in order to achieve running cost savings from using a heat pump system. Taking this

[84] For electricity at 8p/kWh

case study as an example for a boiler efficiency of .85, COP of 2.78, gas price of 3p/kWh and electricity price of 8p/kWh the ratios will be 1:3.27 & 1:2.66 respectively. Therefore since the fist ratio is slightly higher running costs will be lower for a heat pump. For a situation with a COP of 3.33 and gas cost of 5p/kWh the ratios will be 1:3.91 to 1:1.60 and therefore savings will be more significant. Savings in fuel costs are essential for a heat pump system since the capital costs associated with such as system are so much higher than that for a gas boiler. It should be noted however that this comparison does not include the electricity which is required for the pump to circulate the brine/antifreeze fluid in the ground loop, this will increase costs in the heat pump scenario.

8.7 Section Conclusion:

8.7.1 This section has highlighted the fact heat pump systems can be competitive with gas fired boilers with the correct set of circumstances, the cost of the heat pump itself and gas to electricity price ratio being particularly influential. And therefore it is incorrect to marginalise them as purely an option for off-gas areas. The fact that heat pump systems are more financially attractive in lower demand buildings has been highlighted with the large reduction in total costs from the section seven case study. This also serves to underline the value of energy efficiency measures and the fact they should always be the first consideration in any domestic renewable energy project. Finally the financial importance of good design has been emphasised in terms of keeping capital costs associated with the heat pump and borehole to a minimum.

9. Conclusion:

9.1 Fundamental Aim:

9.1.1 The aim of this study was to evaluate ground source heat pump technology and to what extent it can play a role in meeting government energy policy i.e. to reduce the carbon footprint of the United Kingdom's space and water heating requirements, meet fuel poverty targets and increase security of supply. Key elements of the study were investigating the technology itself, considerations for utilising the ground as a heat source, market opportunities / barriers and the latest developments / best practice in the design of systems. This summation will state the principal elements from each section and means by which the analysis was conducted.

9.1.2 It is hoped that this study has assisted in broadening understanding of the technology itself, its current status in the UK and how it can best be utilised. This should in turn lead to an increased appreciation of where ground source heat pumps fit alongside other renewable technologies in terms of the country's energy future; at a time when a multitude of technologies are being postulated as the answer to balancing carbon reduction with increasing energy demand.

9.2 Literature Review:

9.2.1 Section one utilised an extensive literature review as the basis for an evaluation of how a heat pump operates and ascertain what represents the latest 'state of the art'. This was conducted since to ensure effective design and even understand the market for the technology at least a basic understanding of how a heat pump operates is required. The majority of modern systems utilise a vapour compression cycle to transport heat, from a cooler to hotter area, using electricity as the work input. Heat pump technology has shown considerable developments in terms of improved compressors, the use of accumulators and identification of preferable working fluids; these have all resulted in higher attainable coefficient of performance.

9.2.2 This initial overview also helped to scale down the focus of the study. For example cooling applications and air distribution systems were not considered further since they are not so relevant in a UK residential context. In addition a valuable understanding on how a heat pump system interacts within the context of the overall heating system was gained. For example the importance of keeping distribution temperature low in attaining competitive COP values and different operational modes from monovalent heat provision to operating bivalently alongside a fossil fuel system. Finally the value of a heat pump in terms of offering running cost savings and reducing carbon dioxide emissions was stated.

9.2.3 The second section, also literature based, narrowed the studies scope further to concentrate solely on systems which utilised the ground as a heat source; taking account of solar radiation stored in the high thermal mass of the earth and constant temperatures, higher than the ambient air, present at depth. The various factors which need to be considered when utilising the earth as a heat source were introduced such as undisturbed ground temperature, thermal conductivity and diffusivity; the impact of which were all investigated further in section seven.

9.2.4 The variety of different designs utilised for extracting heat from the ground were discussed i.e. the relative merits of open/closed, direct/indirect and horizontal/vertical configurations. Focus was then switched to the design subjected to further analysis, closed vertical borehole systems, and various relevant considerations such as spacing, grouting material selection, thermal interference between boreholes and long term temperature depletion of the ground introduced. These are all key inputs and considerations of the sizing programmes analysed later. Finally the potential for using heat pumps in the domestic heating market, the primary market growth area for the UK, was stated.

9.3 Market Evaluation:

9.3.1 Although again partly literature based, section three and four, involved a greater level of focused data collection, analysis and evaluation to postulate explanations as to the current status of the UK GSHP market. Firstly a world overview was given, showing positive factors such as encouraging overall growth trends and wide geographical spread of system utilisation but also a significant disparity in terms of installed capacity in different nations. The focus was then switched to the European situation with case studies constructed of the GSHP market and its development in Austria, Germany, Sweden and Switzerland; nations perceived as ‘success stories’ in terms of heat pump utilisation.

9.3.2 Growth trends were analysed and periods of decline and stagnation in the market explained; these due to poor installation quality affecting customer confidence or fluctuations in oil prices in the main. All four nations have been developing heat pumps since the late 1970’s or early 1980’s principally as a reaction to the 1979 international oil crisis. In many cases these countries show similar key elements which have attributed to their success such as substantial / proactive government involvement but also some differences in how the market has developed for example the lack of involvement from utilities in Sweden. Austria and Germany have highlighted boom and bust heat pump market growth while in Austria and Switzerland more steady trends are observed. These case studies were then compared and contrasted with the situation in the UK.

9.3.4 It is clear that there is defined difference between the market in the UK and other countries analysed. Although encouraging growth trends are present the number of actual installations is far smaller representing a significant opportunity for expansion. Key differences are shown in terms of a lower level of government endorsement, no defined installer support, lack of a quality label and limited interest from utilities. While progress has occurred, for example the establishment of a national GSHP association and some government support under the Low Carbon Buildings Programme, the market is far from the level of maturity found, for example, in Sweden where GSHP's have infiltrated the retrofit heating market and no longer require government grants as an incentive.

9.3.5 Section four utilised further focused data collection on the market factors highlighted during the case studies and common explanations postulated in literature to explain the less mature GSHP market in the UK. Understanding any barriers present is the first step to overcoming them and growing the market. To aid comparison a matrix was constructed to assess how each criterion differed in the five nations previously mentioned. A questionnaire was also designed at this stage to solicit the opinion of those in the UK GSHP industry as regards market barriers and opportunities.

9.3.6 From analysing the variety of different reasons postulated for the low level of GSHP utilisation in the UK it is clear that they vary in significance. The high degree of fossil fuel security (i.e. lower import dependency) previously enjoyed by the UK has undoubtedly led to a later, and less rigorous, evaluation of alternative energy technologies. For example Austria was utilising ground source heat pumps to limit import dependency in 1980 at far higher levels than present in the UK currently.

9.3.7 Furthermore domestic natural gas production in the UK has resulted in a more expansive gas grid than the other nations evaluated. This reliance on fossil fuels has also perhaps blinkered the general public as to what is and isn't a 'conventional' heating system thus lowering confidence in alternative technology. Awareness and acceptance of renewable technologies are also bound to be lower in the UK than the other nations investigated since the latter have far higher levels of renewable exploitation for electricity generation. On the other hand explanations such as UK geology and climate, while they may play a small role, are certainly less influential.

9.3.8 It is clear from reviewing barriers present that the UK government could do more to promote and harness the potential of GSHP's; and there a numerous easily replicable positive examples which can be found from the case study nations considered. It should be mentioned that many of these issues, such as higher installed cost, poor market networks and guidance for installers can be remedied.

9.3.9 Feedback from the questionnaire highlighted capital costs (later a consideration in the simulation case study) as the perceived primary barrier followed by poor government support, limited installer capacity and a single phase electricity supply. Lack of space to install a, less expensive, horizontal loop was also stated; this vindicates the decision to concentrate on the design of vertical borehole systems in the case studies. In terms of potential solutions clear support was shown for larger financial subsidies and carbon taxation (such as is being introduced in Switzerland) to increase financial viability. Furthermore to assure customer confidence is gained a quality label and installer training programme were backed. Rather surprisingly raising public awareness and increased utility involvement received less support from those in the industry.

9.4 Design Analysis:

9.4.1 Section five represented a change of tack from market to system design considerations. The fundamental issue of borehole sizing was discussed alongside its implications for system cost, ground temperature depletion and performance. Concepts later explored in the simulations. A brief evaluation of the methods utilised for sizing of borehole collector loops i.e. software, rules of thumb or calculations were covered; as was the possibility for overly conservative (and therefore needlessly expensive) or risky (potentially unable to meet demand) design practice.

9.4.2 This was followed by an overview of the commercially available design programmes which could be obtained. In an attempt to understand these better the underlying assumptions and calculation methods were discussed; these are primarily either g-functions or the Cylindrical Line Source Method. The data required by each programme to formulate a borehole size was compared and it was found that in most cases this is generally the same; as is the level of information which can be obtained. There is at present no UK specific sizing programme available. Feedback from the questionnaire as regards design practice and challenges was also reported at this point.

9.4.3 Of respondents who installed systems 40% reported using sizing software while 30% stated they utilised rules of thumb. It was perhaps surprising that a higher number stated they utilised 'in-house' software as opposed to commercially available systems. Further investigation of these systems would represent an interesting study in itself. The most numerous answer as regards the biggest design challenge was obtaining the building heat load; a crucial input to any sizing programme.

9.4.4 Section seven represents the main technical element of the study, presenting the results and analysis from a simulation case study constructed to analyse not only the sizing programmes GLHE-pro and GS2000 (over several scenarios) and EED (one scenario) but also some of the design issues and considerations highlighted earlier in the study. Such as ground conditions, borehole configurations and spacing. Performance was calculated in terms of COP, temperature depletion of the ground and outline installation and running costs. The simulation programme TRNSYS was utilised to assess twenty year performance of the various predicted borehole lengths and base conditions.

9.4.5 In scenario one, selecting ground conditions with a high thermal conductivity resulted in no long term thermal depletion of the ground. However in terms of sizing, according to TRNSYS, only EED was able to give a length suitably long enough to ensure the heat pump could meet the full building load over a twenty year period. The GS2000 and GLHE-pro lengths resulted in inlet fluid temperatures falling below the -5ºC acceptable to the heat pump. In scenario two the ground thermal conductivity was lowered (meaning EED could not be utilised due to demonstration limitations) and as expected ground temperature depletion was evident. In this case TRNSYS deemed only the GS2000 borehole length was sufficient. The value of taking a long term view in design was highlighted as initially using the GLHE-pro length would have operated in the first year but not afterwards.

9.4.6 A double borehole configuration was then considered and again only GS2000 delivered a length suitably long enough for the simulation. This configuration also showed that when two boreholes are present depletion of ground temperature is more significant. This is reduced the bigger the spacing between the boreholes. The fact that volumetric heat capacity needs to be taken into account in borehole sizing was highlighted as simulations of an identical length but differing ground conditions showed that despite similar thermal conductivity values a higher volumetric heat capacity in one of the cases was the difference in determining the ability of the heat pump to operate as the sole heat source.

9.4.7 The value of thermally enhanced grout in improving performance and keeping installation costs down was validated through simulation and sizing analysis. From analysing attainable Seasonal Performance Factors in these cases it is clear that the values achieved, in the region of 2.9, are far lower than the rated coefficient of performance value (4.31) for the heat pump. This is strongly influenced by the distribution temperature selected for the heating system. Although temperature depletion of the ground does lower COP in these scenarios it is to a far lesser extent.

9.4.8 From undertaking the case study it is clear that sizing, and to a lesser extent simulation packages, greatly simplify and speed up the borehole design process. Even so however there is still opportunity for error, especially when the system is utilised by an individual without full comprehension of how a GSHP system operates. And it should be remembered that in several cases, for this case study example, programmes recommended borehole lengths too short to satisfy demand in the TRNSYS simulation. Furthermore sizing programmes will only produce an accurate length if predicted load of the building is correct; accurate evaluation of which is seen as a major challenge by those in the UK industry.

9.4.9 Since case study seven was not entirely representative of a typical GSHP application, i.e. the building was large and had poor thermal qualities, the twenty year lifetime cost did not reflect favourably when compared to a gas system. This was mainly due to the excessive borehole lengths required to meet the significant demand. A more favourable comparison, case study eight, highlighted that heat pumps can be competitive with gas systems under certain circumstances. This evaluation also highlighted that an increase in gas prices, relative to electricity, would greatly aid the financial attractiveness of heat pump systems.

9.4.10 An attempt was made to explain the differences in predicted performance between the simulation package TRNSYS and the sizing programmes GLHE-pro and GS2000. Initial explanations were postulated including how the programmes interpret demand data and assumptions regarding the thermal mass of the borehole itself. It is not possible to state at this point that one programme has the definitive answer to the correct borehole length and therefore further research to pinpoint the reasons behind different predicted performance of simulation and sizing programmes would be worthwhile.

9.5 A Role for GSHP Systems in the UK?

9.5.1 From reviewing the latest developments in heat pump technology, the UK and European markets and fundamental design considerations it is now possible to make an informed assessment of what role the heat pump can play in meeting the government targets discussed in 9.1.1. From a technical standpoint the technology is well developed, with today's units the product of twenty years research and development. If designed and operated correctly a ground source heat pump should be able to offer reduced running costs and save on CO_2 emissions when compared to other domestic fossil fuel systems. Further technological development, in order to obtain competitive COP values at high distribution temperature, will aid penetration of the retrofit market; as could the development of systems to operate on a single phase electricity supply.

9.5.2 Leading the market to a point where a significant number of systems will be installed UK-wide however will require an increase in support from government, not just financially but also in strategic guidance to learn from the successes in GSHP market stimulation from abroad. This should be matched by development from those involved in the industry to establish installer training schemes, quality labels and gain the interest of utility companies. Specific grant schemes for ground source heat pump units, as utilised in Austria, Germany and Switzerland, would also act as more of a stimulus than generic renewable energy funding. Until the market has reached a point where installation costs are competitive with fossil fuel heating systems it is unlikely the general public will be sufficiently convinced in order to install in such numbers to meet technical potential.

9.5.3 To ensure customer confidence is not damaged by poor quality installations it is essential that correct design practice is followed. Only with well designed systems will the anticipated running cost savings and CO_2 emissions reductions be obtained. Sizing programmes are a significant aid in this respect but, as this study has shown, they are not foolproof. Achieving widespread good quality installations will require training and knowledge transfer from experienced installers.

9.5.4 It seems clear that ground source heat pumps can play a more significant role in assisting the government reduce the CO_2 emissions associated with space and water heating, especially domestically, and with the right support encouraging recent growth trends should continue. Whether the level of installations found in Sweden for example will be met remains to be seen, with the large scale gas distribution grid a significant constraining factor on installation numbers. Considering this it is clear that the technology should be utilised alongside other low carbon heating methods such as combined heat and power and biomass, aided by greater utilisation of energy efficiency measures, to reduce the carbon footprint of space and water heating in the UK.

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Appendix:

1. Alternative Heat Pump Cycles:

1.1 The main body of the report has centred on explaining heat pump technology based on the Vapour Compression Cycle. There are however many different cycles which can, and are, utilised for heat pumping as described in 1.2.3 of the main report. This section will briefly explain absorption and adsorption heat pump technology.

1.2 Firstly it should also be stated that in the main body of the report the work provided to drive compression is described as being electricity. Although this is the most popular energy source, other fuels (such as natural gas, diesel or bio-fuels) can be utilised to provide this energy. If using these it is important to ensure the combustion engine is as silent as possible. In these cases the waste heat generated in driving the combustion engine can be utilised in the heating cycle where as when electricity is generated in a power station this is usually lost to the atmosphere.

1.3 Sorption is a physical-chemical process in which a liquid or gas is absorbed by another liquid (absorption) or returned on the surface of a solid object (adsorption). These reversible reactions will only occur under certain conditions however.

1.4 **Absorption Heat Pumps:** These systems work on the same principles as a vapour compression heat pump but use a thermal compressor (powered by natural gas) instead of a mechanical compressor. Ammonia is usually utilised as the working fluid in this technology as it has a low boiling point. This evaporates and captures energy from the environment. The vapour will then flow to the absorber where it is dissolved by the solvent (i.e. water) this releases the heat which is transferred into the system via a heat exchanger. When these enter the thermal compressor they are separated due to the fact the refrigerant has a lower boiling temperature. This high temperature/pressure vapour is passed through a condenser top release heat to the target area and then re-circulated via an expansion valve, as is the solvent.

1.5 This represents an efficient use of primary energy since it is only utilised in the electricity to drive solvent pumping and the gas utilised in the thermal compressor. There are also few moving parts. Traditionally absorption cycles are for high output cooling applications (above 50kW). “No standard production solutions are as yet available as heat generators in the medium output range” [5].

1.6 **Adsorption Heat Pumps:** These use solid substances such as active charcoal, silica gel and zeolite. The latter will, for example, take in water vapour and bind to it, releasing heat energy (at 300℃) in an exothermal reaction. Adsorption heat pumps use a similar cycle to the one described for absorption systems except they operate periodically. There is two phases, desorption and adsorption.

1.7 In desorption the heat exchanger, coated in a substance such as zeolite or silica gel, is supplied with heat. Any water retained by this substance is released as vapour. This is then transferred to a heat exchanger where it condenses are releases the heat. This phase ends when there is no more water in the solid substance and the heater is then turned off.

1.8 At this point the adsorption stage commences. The heat exchanger acts as a evaporator and environmental heat acts on the water condensed on it (this is performed at a high pressure of approximately 6 bar). This water vapour is then absorbed by the zeolite or silica gel. The heat transferred during this exchange is also passed to the system via a heat exchanger. When the water vapour is fully absorbed the cycle is complete and desorption can commence again [5].

1.9 Adsorption heat pump systems are being developed for the domestic heating market but are at an expensive prototype stage. The technology is already being utilised for high capacity refrigeration applications however.

2. Heat Pump Market Outline:

Table A1. GSHP Installed Capacity, Energy Use and Units at WGC 2005 [25].

Country	Installed capacity (MW_{th})	Annual energy use (TJ/yr)	Equivalent 12 kW units*
Australia	5.5	30.0	458
Austria	300.0	1'450.0	25 000
Belarus	1.0	3.3	83
Belgium	60.0	324.0	5 000
Bulgaria	0.3	4.4	25
Canada	435.0	2 160.0	36 250
China	631.0	6 569.0	52 583
Czech Republic	200.0	1 130.0	16 667
Denmark	309.0	3 940.0	25 750
Finland	260.0	1 950.0	21 667
France	16.1	468.8	1 342
Germany	400.0	2 200.0	33 333
Greece	4.0	39.1	333
Hungary	4.0	22.6	333
Iceland	4.0	20.0	333
Ireland	19.6	83.6	1 633
Italy	120.0	500.0	10 000
Japan	4.0	22.4	333
S. Korea	3.4	11.9	283
Lithuania	3.3	29.0	275
Netherlands	253.5	685.0	21 125
Norway	600.0	3 085.0	50 000
Poland	103.6	574.4	8 633
Portugal**	0.2	0.0	17
Russia	1.2	11.5	100
Serbia	6.0	40.0	500
Slovak Republic	1.4	12.1	117
Slovenia	3.3	69.9	275
Sweden	3 840.0	36 000.0	320 000
Switzerland	532.4	2 854.0	44 367
United Kingdom	10.2	45.6	850
United States	7 200.0	22 215.0	600 000
TOTAL	**15 332.0**	**86 550.6**	**1 277 665**

*) 12 kW is the typical size for a residential unit
**) the one unit in Portugal is not operational – thus zero value for annual energy.

3. Geological Maps from Barriers Matrix **(see 4.5 in main document)**:

3.1 UK:

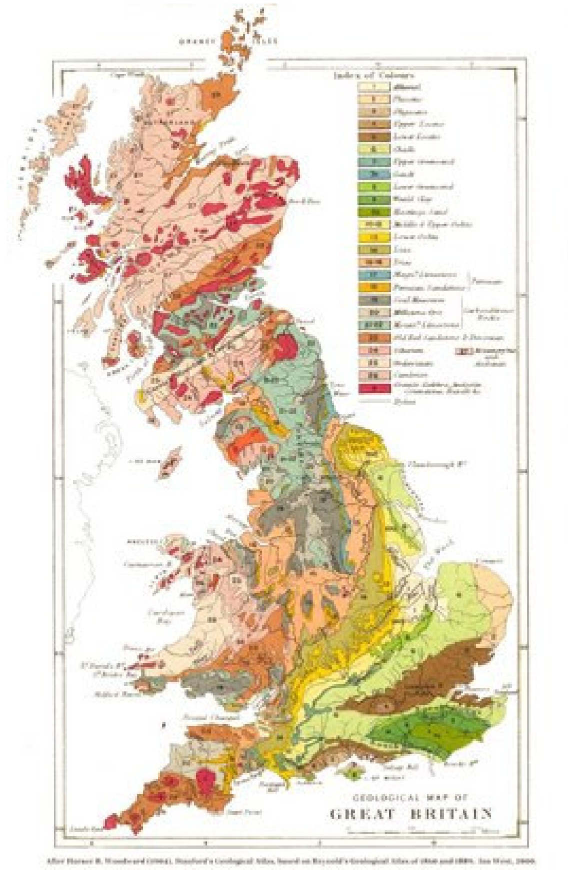

Fig A1. Geological map of Britain [62]

3.2 Austria:

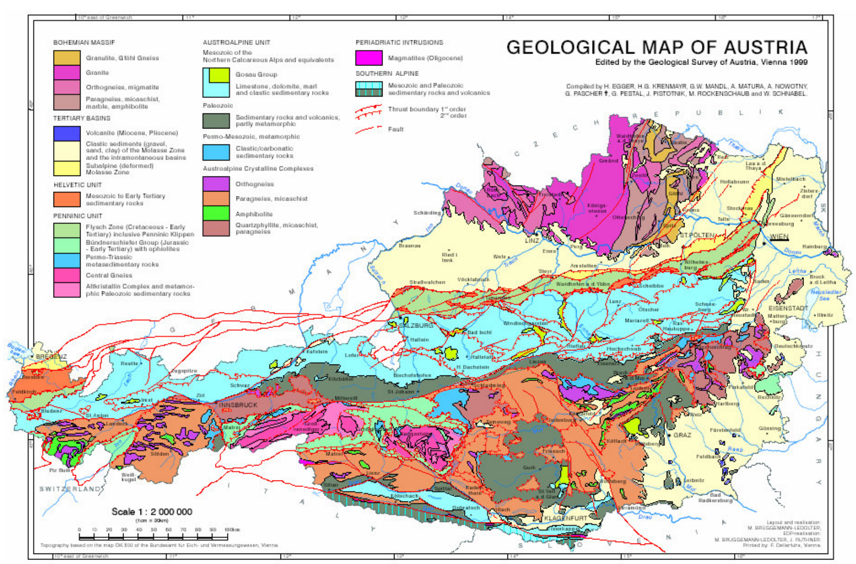

Fig A2. Geological map of Austria [60]

3.3 Germany:

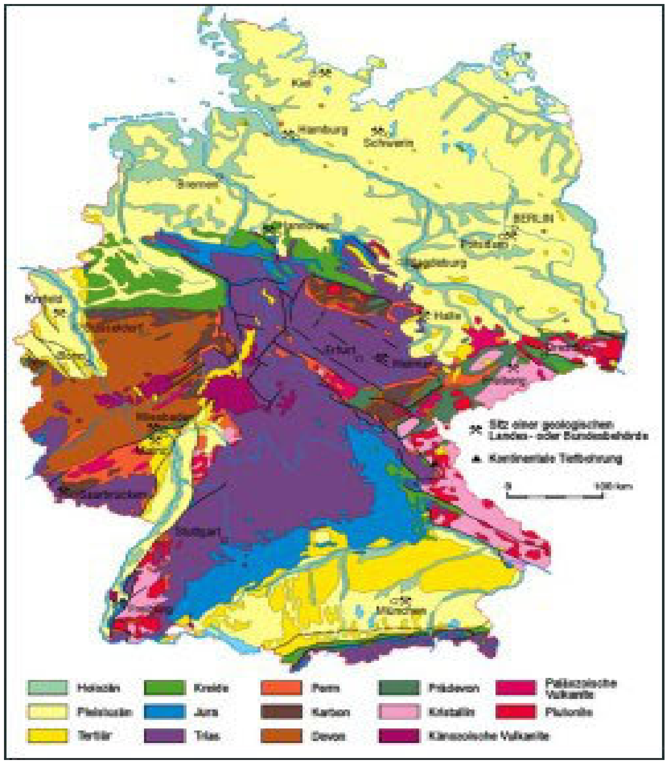

Fig A3. Geological map of Germany [59]

3.4 Switzerland:

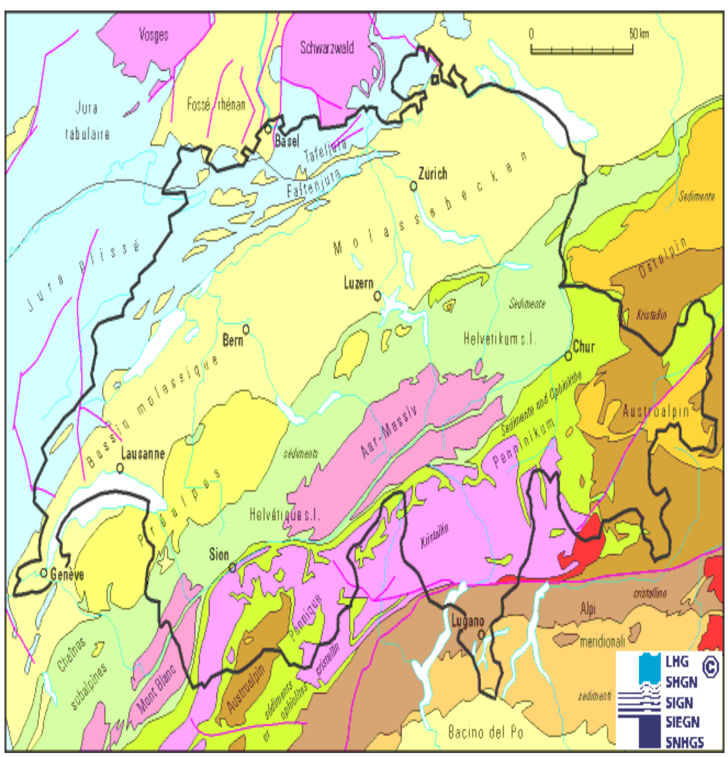

Fig A4. Geological map of Switzerland [61]

4. Underlying Equations of Borehole Sizing Programmes:

4.1 The Carslaw and Jaeger equation is as follows [74]:

$$Q = L\,(Tg - Tw) / R$$

Where, Q = heat transfer rate (Watts)
Tg = undisturbed ground temperature (°C)
Tw = liquid temperature (°C)
R = effective thermal resistance of the ground (K/W/m)

4.2 While the 1948 Ingersoll and Plass algorithm (SI Units) is as follows [72]:

$$\Delta T = (.1833\ Q / K)\ [\log 10\ \alpha\ t / r^2 + .106\ r^2 / \alpha\ t + .351)^{85}$$

Where, ΔT = temperature change at time t and radius r (°K)
r = pipe radius (m)
k = thermal conductivity (W/m/K)
Q = heat flow per m borehole (W/m)
α = thermal diffusivity (m^2/h)
t = time (h)

4.3 Eskilson's approach is shown below. The following equation will give the borehole wall temperature at the end of the nth time period [79]:

$$T_{borehole} = T_{ground} + \sum_{i=1}^{n} \frac{(Q_i - Q_{i-1})}{2pk}\, g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right)$$

Where, t = time (s)
g = the g-function itself see 6.2.6
t_s = time scale = $H^2/9\alpha$
H = borehole depth (m)
K = ground thermal conductivity (W/m-°C)
$T_{borehole}$ = average borehole temperature (°C)
T_{ground} = undisturbed ground temperature (°C)
Q = step heat rejection/absorption pulse (W/m)
r_b = borehole radius (m)
i = index to denote the end of the time step (i.e. 2nd hour, 3rd month etc)

4.4 Analytical approach to estimate a peak pulse in GLHE-pro [79]:

$$\Delta T_{borehole} = \frac{Q_{rejection,peak}}{4\pi k}\left\{\ln\left(\frac{4\alpha t}{r_b^2}\right)\right\}$$

Where:
$Q_{rejection,peak}$ = heat rejection rate, above monthly average heat rejection rate (W/m)
a = ground thermal diffusivity (m^2/s)

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[85] Only holds if $\alpha t/r^2 > 1$

5. Heat Pump Statistics and Performance Maps:

5.1

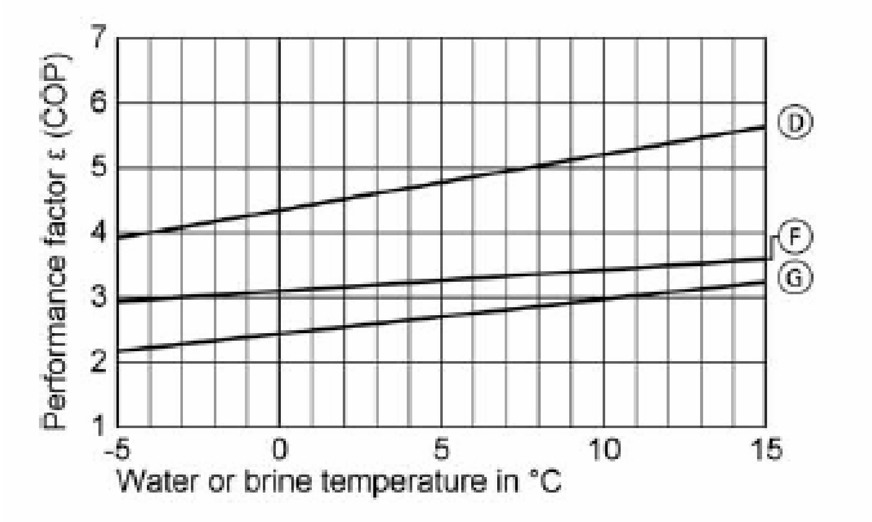

Fig A5. Viessmann Vitocal 350 performance Map 1 [82]

5.2

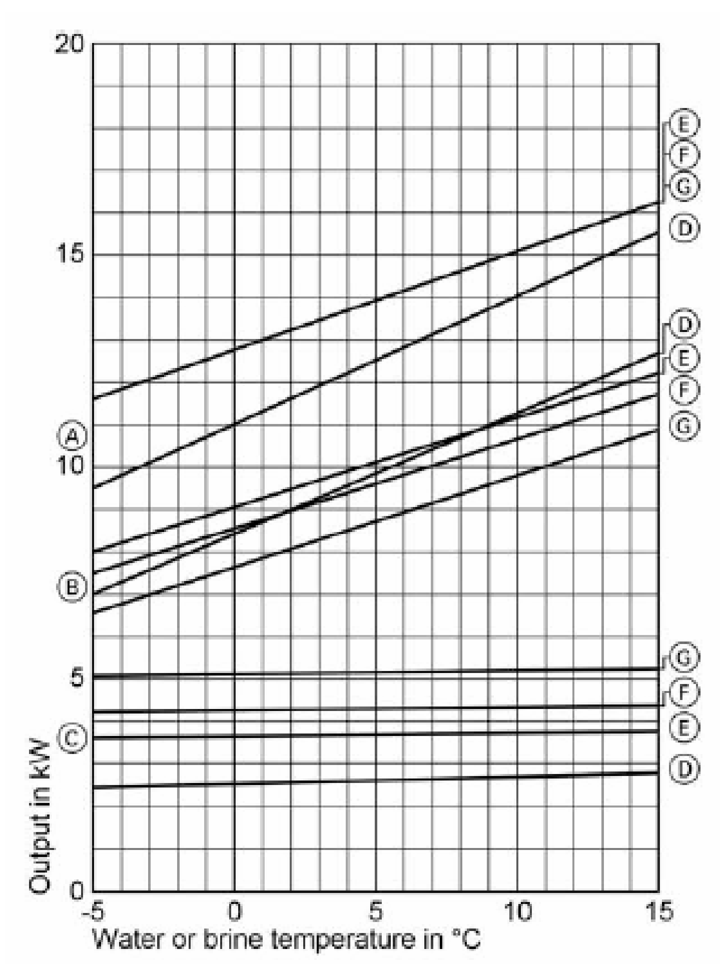

Fig A6. Viessmann Vitocal 350 performance Map 2 [82]

5.3

Table A2. Viessmann Vitocal 350 Key Stats [82]

Vitocal 350 brine/water heat pump (single stage)

Vitocal 350 (single stage)	Type	BWH 110			BWH 113		
Performance data							
Operating point*1		B0/W35	B2/W55	B2/W65	B0/W35	B2/W55	B2/W65
Rated output	kW	11.0	13.2	13.2	16.2	17.7	17.7
Cooling capacity	kW	8.45	9.00	8.10	12.45	12.00	10.60
Power consumption*2	kW	2.55	4.20	5.10	3.75	5.70	7.10
Performance factor ε (COP)		4.31	3.14	2.59	4.32	3.11	2.49
Brine (primary)							
Capacity	litres	3.7			4.7		
Min. flow rate*3	l/h	2700			3800		
Pressure drop	mbar	90			100		
Max. inlet temperature	°C	20			20		
Min. inlet temperature	°C	-5			-5		
Heating water (secondary)							
Capacity	litres	3.3			3.3		
Min. flow rate*3	l/h	1060			1350		
Pressure drop	mbar	40			35		
Max. flow temperature	°C	65			65		
Electrical values							
Heat pump							
Rated voltage		3/N/PE 400 V~/50 Hz					
Rated current (max.)	A	9.1			14.0		
Starting current	A	23*4			26*4		
Starting current (with stalled armature)	A	59.5			70.5		
Fuse (slow)	A	3 × 20			3 × 20		
Protection		IP 20					
Control circuit rated voltage		230 V~/50 Hz					
Fuse (internal)		6.3 A H slow					
Refrigerant circuit							
Process medium		R 407 C					
Fill volume	kg	2.9			3.2		
Compressor	Type	Hermetically sealed scroll compressor with injection					
Dimensions							
Total length	mm	650			650		
Total width	mm	600			600		
Total height	mm	945			945		

Ground Source Heat Pumps - Barriers and Opportunities

University of Strathclyde

Name (optional): **Appendix Section 6.1**

Organisation (optional):

To complete text boxes click in the top left of the box once. A black area will appear then type

Q1. Which three of the following do you consider to be the greatest inhibitors to more widespread utilisation of Ground Source Heat Pumps (GSHPs) in the UK? Check three or less boxes.

- Single Phase Electricity ☐
- Varied UK Geology ☐
- Poor Standards of Insulation ☐
- UK Climate ☐
- Limited Installer Capacity ☐
- Capital Costs ☐
- Poor Government Support ☐
- Low Public Awareness ☐
- Extensive Gas Supply Network ☐

Q2. Do you believe there are any other significant barriers to GSHPs entering the UK market not mentioned in question one? If so please state in the box below (three lines max).

Q3. Which three of the following do you feel would have the greatest affect in supporting the growth of GSHP utilisation in the UK? Check three or less boxes.

- Greater Utility Involvement ☐
- Larger Financial Subsidies ☐
- Renewable Heat Targets ☐
- Installer Training Programme ☐
- Greater R&D Funding ☐
- Awareness Raising Measures ☐
- GSHP Quality Label/Accreditation ☐
- Carbon Tax ☐
- Local Authority Support ☐

Q4. Do you believe there are any other significant support measures to aid GSHPs entering the UK market not mentioned in question three? If so please state in the box below (three lines max).

Q5. How does your organisation go about designing GSHP systems? N/A We Do Not Install Systems

Q6. If you answered 'Design Software' to question five which programmes?

EED ☐ GLHE-Pro ☐ Other (specify)

Q7. What are the main challenges you find in designing a GSHP system? Please specify in box below, four lines maximum.

Section 6.2 – Questionnaire Responses (Tables A3, A4 & A5)

Organisation										
	Q1. Barriers to UK GSHP Development									Q2. Other Barriers Suggested by Responsdant
	Single Phase Elec	Varied UK Geology	Climate	Poor Insulation	Limited Installer Capacity	Capital Costs	Poor Gov Support	Limited Public Awareness	Extensive Gas Supply Network	
Consultancy						1			1	Cost of ground works and availability of groundwork contractors
Installer	1									
Consultancy, Reseller, Installer					1	1		1		Limited drilling capacity, awareness amongst professionals
Manufacturer				1			1			Poor building regs, confusion over funding system, misinformation in market, lack of testing facilties
Local Authority					1	1		1		
Drilling/Trenching Contractor		1				1	1			
Installer/Consultant				1		1	1			Finding space for systems and borehole drilling costs
Consultancy	1						1	1		Grant application system, other organisations profiteering
Consultancy, Reseller, Installer				1		1			1	Space for ground collectors
Consultantcy / Reseller	1				1	1				Low technical knowledge at specifier level i.e. architechts/consulting engineers, competition with ASHP
Consultancy / Installer	1			1		1		1		Cost of boreholes due to lack of slinkie space, dsitruption of retrofit
Installer (underfloor Heating)	1					1		1		Relatively high cost of electricity (compared to gas?)
Consultancy					1	1	1			
Consultancy, Reseller, Installer						1	1		1	Lack of space for horizontal systems
Consultancy	1		1						1	Lack of installation experience
Installers / Drilling	1	1			1	1		1	1	Poor installations damaging the market, grant application procedures (too long/complex)
Consultancy, Reseller, Installer					1		1	1		
Consultancy	1									
Consultancy / Design					1	1	1			Poor levels of installer training and expertise. - no training, no installers, no market growth! No government support to establish adequate level of training for installers Knowledge - installers, consumers and suppliers - lot of (technical) misinformation
Manufacturer					1	1				
TOTAL	8	2	1	4	8	14	8	7	5	

Organisation										
	Q3. Factors to Support GSHP Market Growth									Q4. Support Measures Suggested by Respondant
	Greater Utility Involvement	Larger Financial Subsidies	Renewable Heat targets	Installer Training Programme	Greater R&D Funding	Awareness Raising Measures	Quality Label/Accreditation	Carbon Tax	Local Authority Support	
Consultancy		1	1						1	Competition Between Suppliers
Installer		1		1			1			
Consultancy, Reseller, Installer	1					1		1		Part L of Building Regulations and PPS22 Requirements
Manufacturer	1			1			1			
Local Authority					1		1	1		
Drilling/Trenching Contractor		1								
Installer/Consultant	1	1	1							Building Regulations increased, Energy Targets for New/Refurb Homes
Consultancy		1				1			1	
Consultancy, Reseller, Installer							1		1	
Consultantcy / Reseller			1	1				1		
Consultancy / Installer			1					1		Increasing Fuel Costs
Installer (underfloor Heating)			1			1	1			
Consultancy			1	1		1				System Design Quanitification
Consultancy, Reseller, Installer		1	1					1		GSHP Electricity Tariffs
Consultancy	1			1			1			
Installers / Drilling	1	1		1						Training in Sales/Design to Stop Misselling/Poor Design Damaging Customer Confidence
Consultancy, Reseller, Installer		1	1					1		
Consultancy										3-Phase Power at a Competative Rate (?)
Consultancy / Design				1	1		1			
Manufacturer			1	1				1		
TOTAL	5	8	9	8	2	4	7	7	3	Use Scheme Similar to SEDBUK for Boilers instead of Generic COP of 3.2

Organisation									
	Q5. Design Method Used			Q6. Software Used					Q7. Design Challenges Suggested by Respondant
	Software	Rule of Thumb	N/A	GLHEpro	EED	In-House	Other	Other	
Consultancy	1					1			Energy Analysis in Complex Buildings
Installer		1							
Consultancy, Reseller, Installer	1			1	1		1	Manufacturers Technical Guides	Obtaining Building Load
Manufacturer			1						Heat Loads, lack of Consultant Knowledge in Commercial Applications
Local Authority			1						
Drilling/Trenching Contractor			1						
Installer/Consultant	1					1			
Consultancy	1					1	1	Manufacturers Information	Varience in Retro-fit Cases
Consultancy, Reseller, Installer		1							Heat Loss Calulations and Levels of Insulation
Consultantcy / Reseller	1						1	HevaComp, AutoCad	Knowledge of Ground Conditions
Consultancy / Installer		1							Finding Space for a Horixontal Ground Loop
Installer (underfloor Heating)			1						Design Tool for Specifying Size of Heat Pump
Consultancy	1					1			Thermal Properties of Ground
Consultancy, Reseller, Installer		1							Calulating Heat Loss, Space for the Ground Loop
Consultancy	1			1			1	Geothermal International/GAIA	Sceptacism about Outputs
Installers / Drilling	1			1	1		1	Pilesim and GLD	Lack of Understanding re: Input Requirements i.e. Load Profiles
Consultancy, Reseller, Installer		1							Heat Loss Data for Buildings, Space for a Horizontal Loop
Consultancy		1					1	Manufacturers Information	
Consultancy / Design			1			1	1	In-house, from heat loss.	Accurate Drawings from Clients
Manufacturer			1						Lack of Experienceof of Installer Base, Unwillingness to Offer Training as it Will Create Competition
TOTAL	8	6	6	3	2	5	7		

7. TRNSYS Simulation Graphs:

7.1

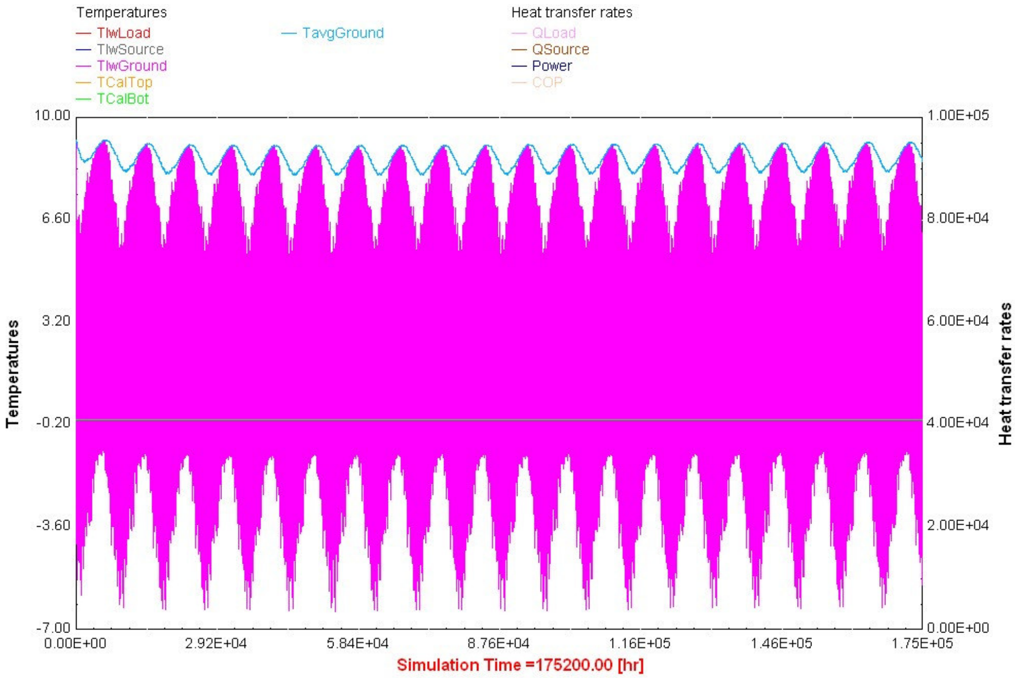

Fig A7. EED Scenario One Results

7.2

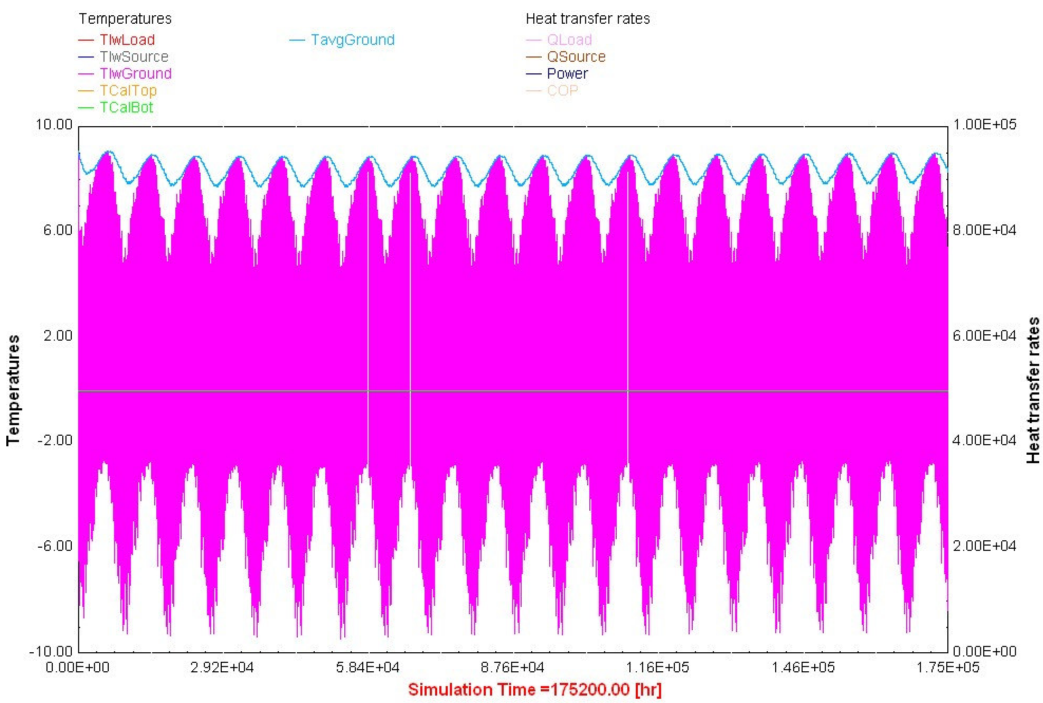

Fig A8. GLHE-pro Scenario One Results

7.3

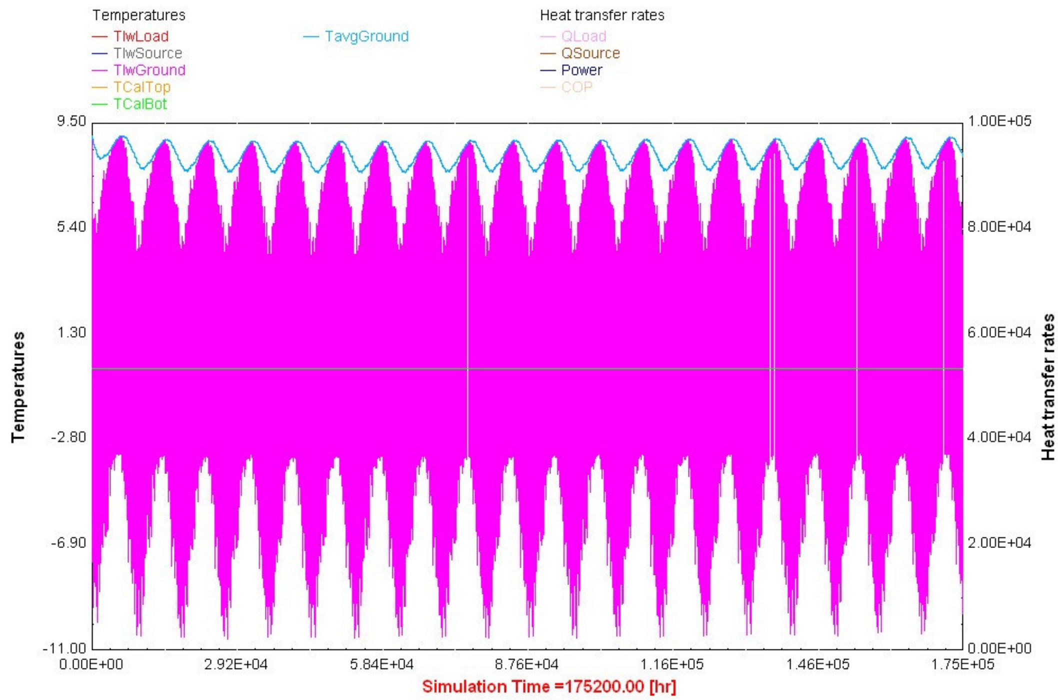

Fig A9. GS2000 Scenario One Results

7.4

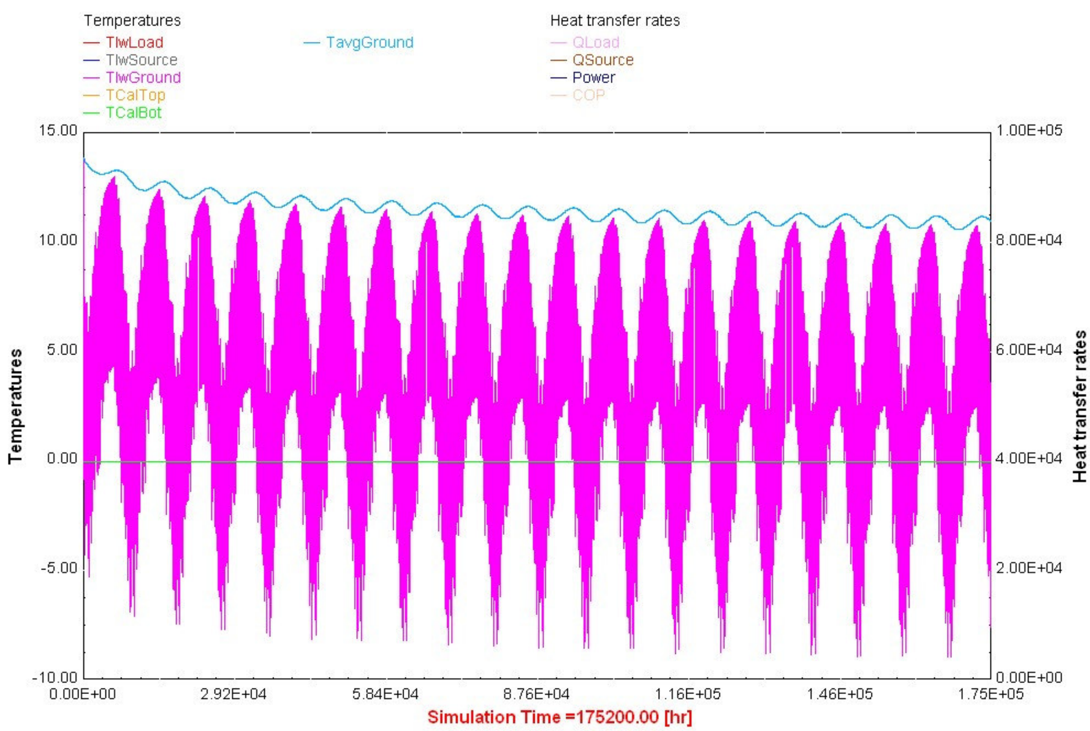

Fig A10. GLHE-pro Scenario Two Results

7.5

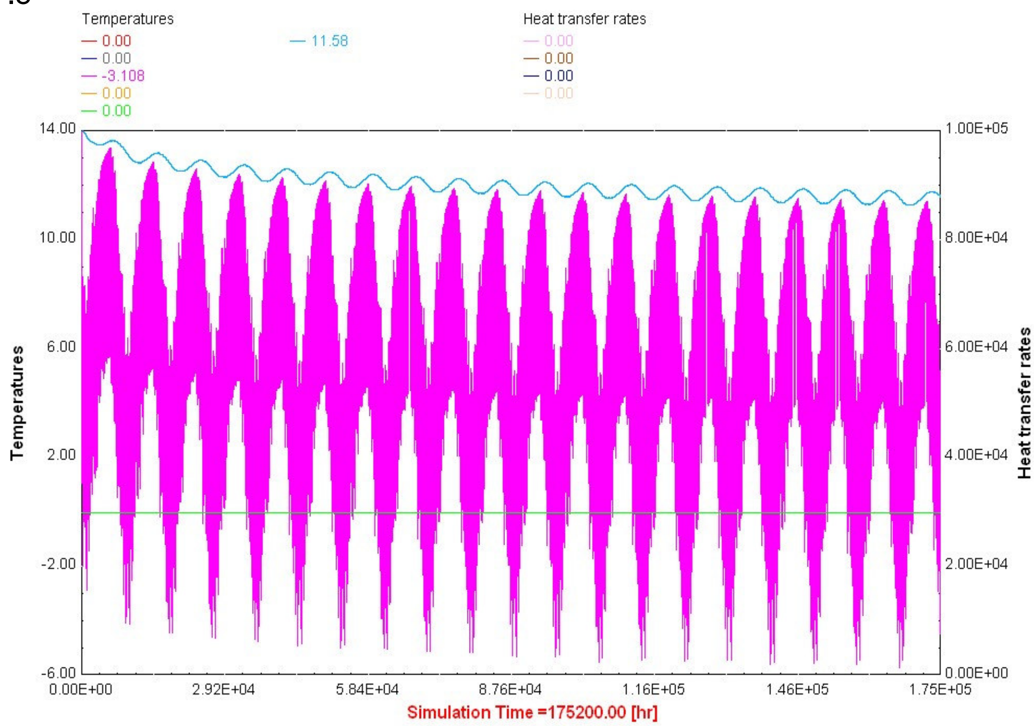

Fig A11. GS2000 Scenario Two Results

7.6

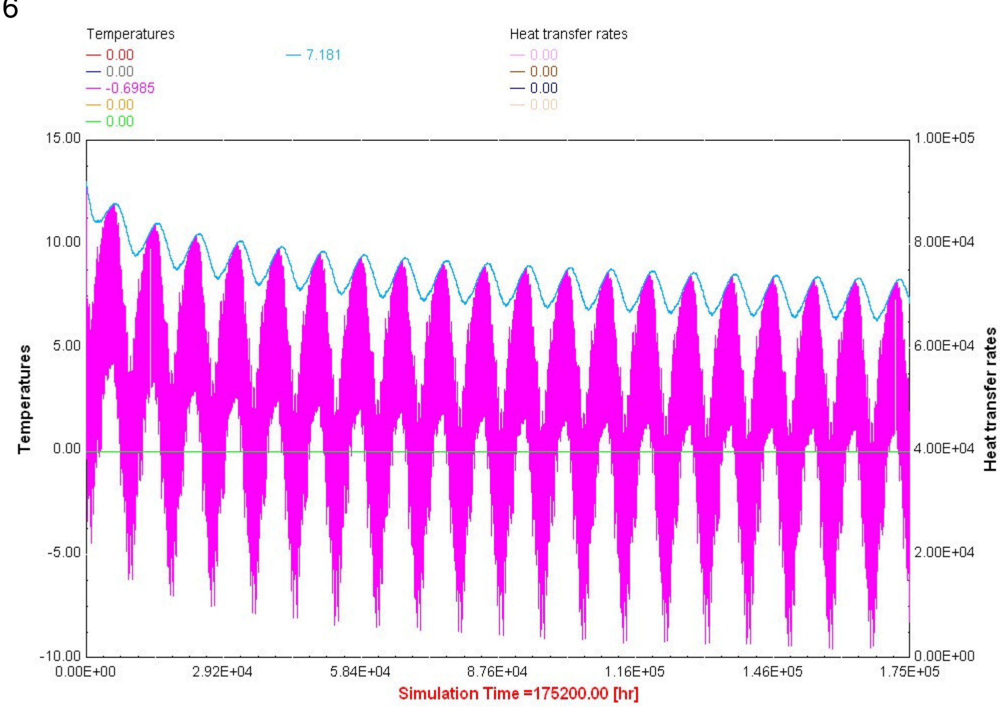

Fig A12. GLHE-pro Scenario Three Results

7.7

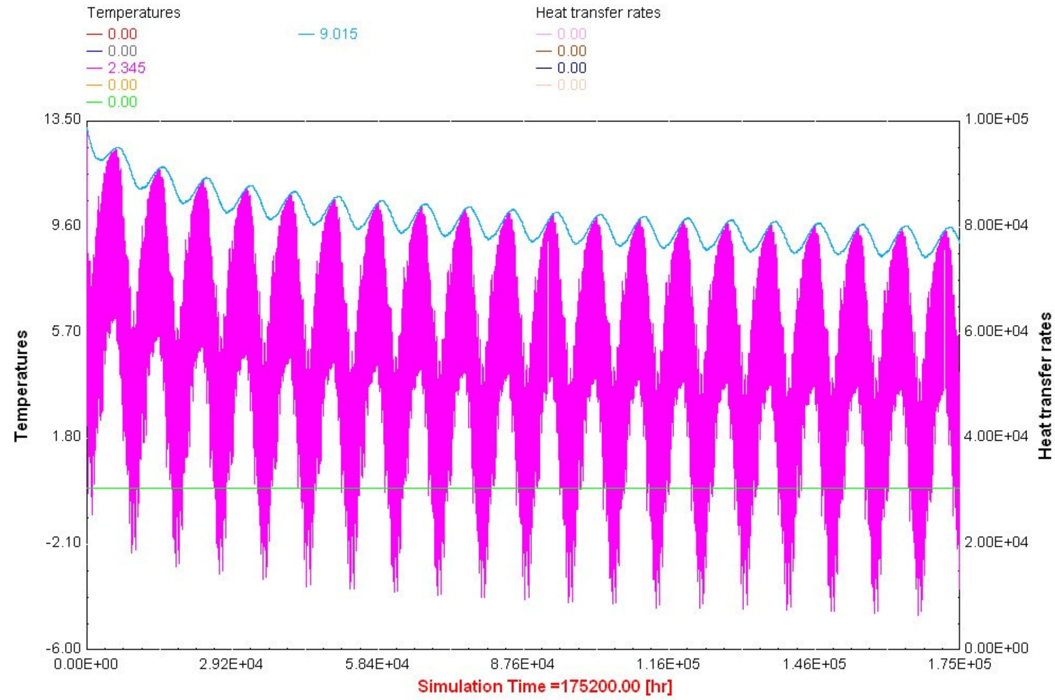

Fig A13. GS2000 Scenario Three Results

7.8

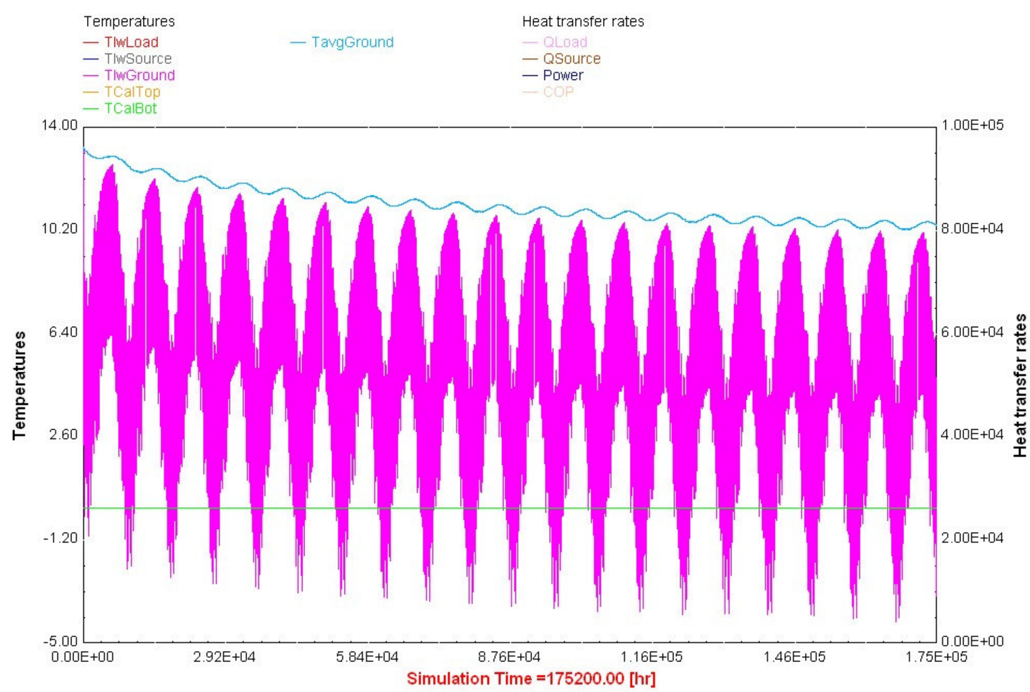

Fig A14. GS2000 11m Spacing Scenario 3-b Results

7.9

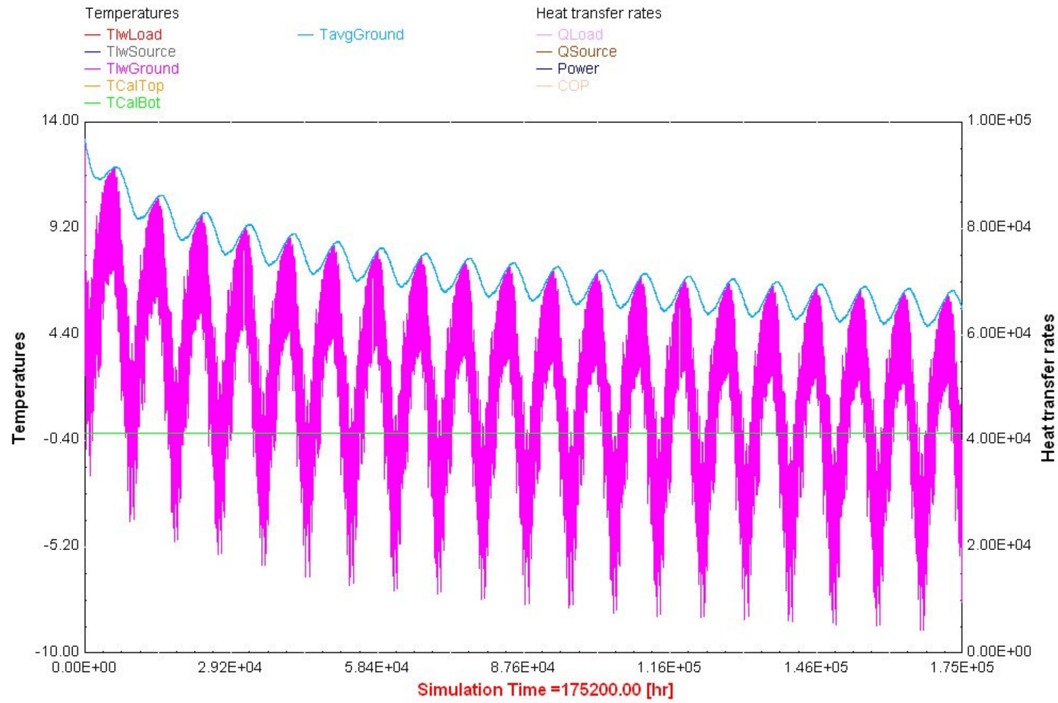

Fig A15. Dry Clay Scenario Four Results

7.10

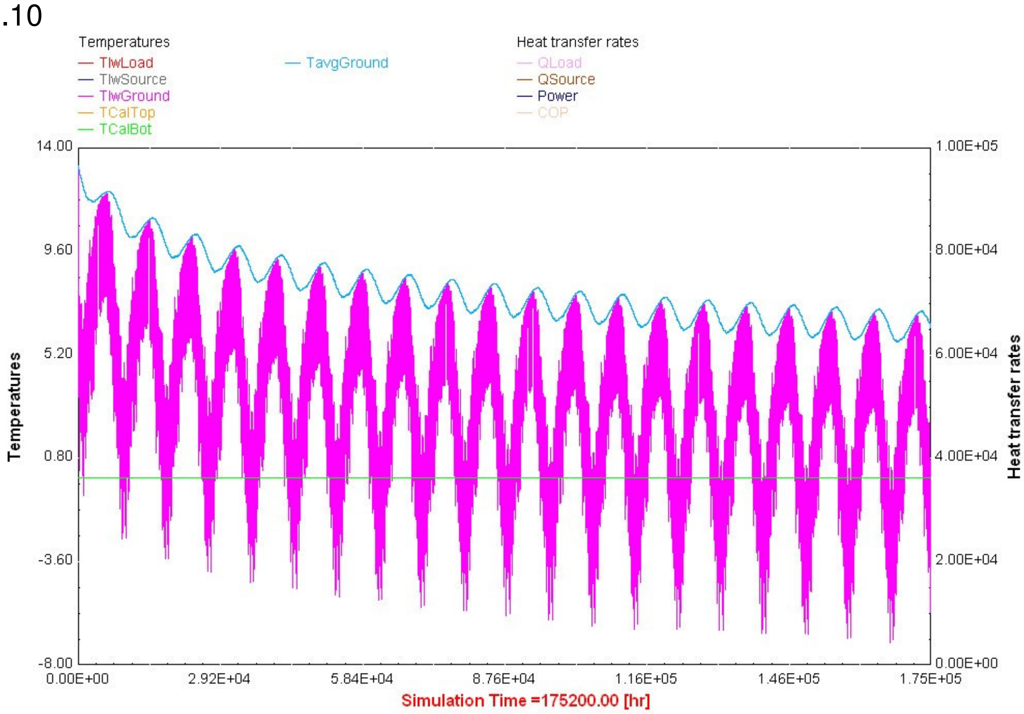

Fig A16. Heavy Soil (Damp) Scenario Four Results

7.11

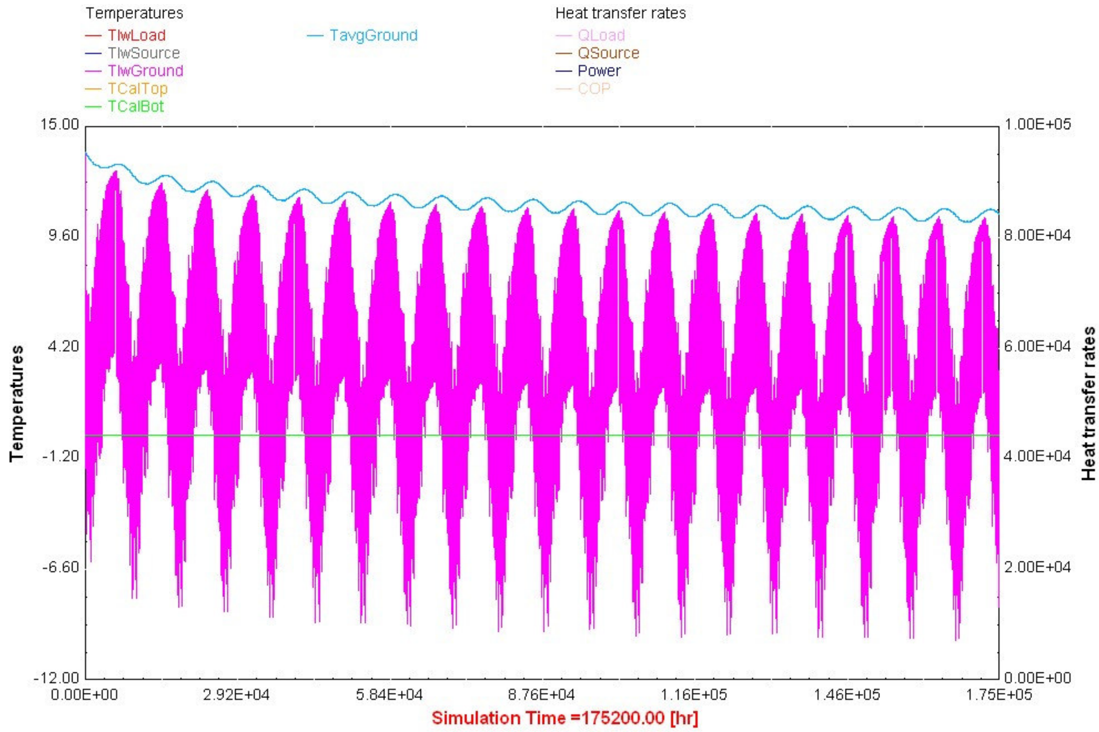

Fig A17. Grout A Scenario Five Results

7.12

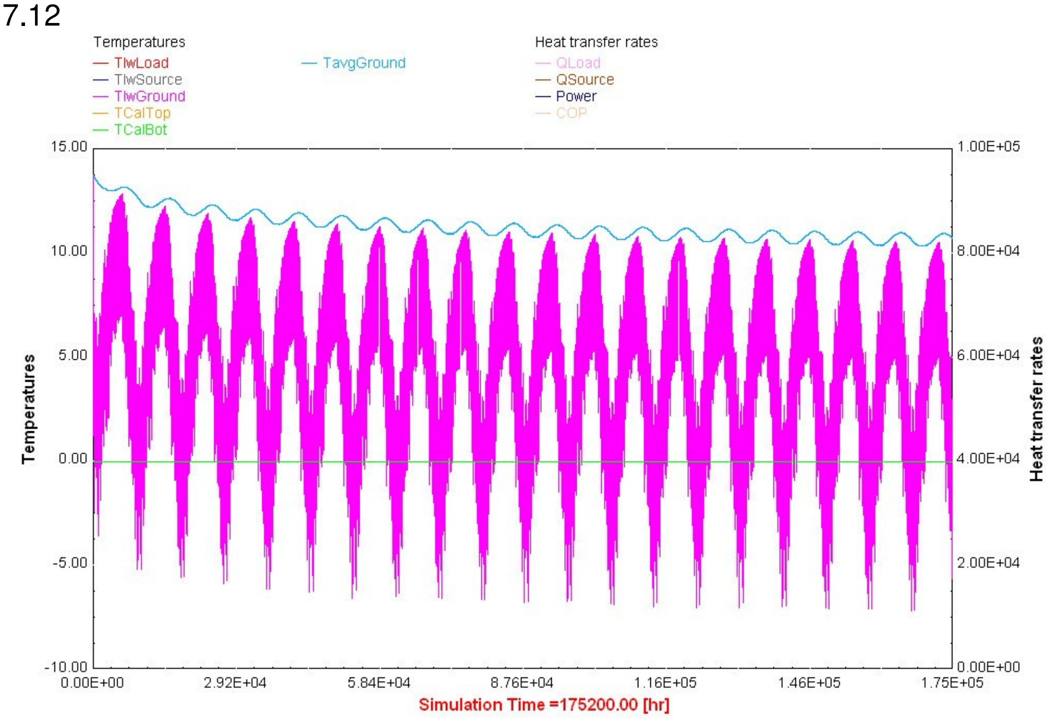

Fig A18. Grout B Scenario Five Results

8. Financial Evaluation Graphs and Tables:

8.1

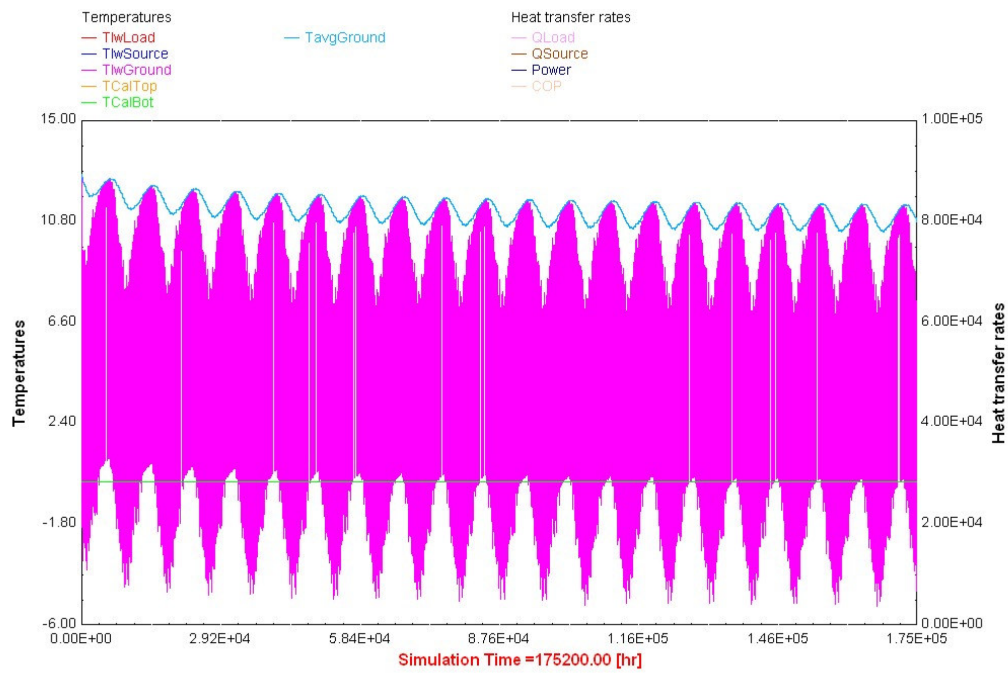

Fig A19. Section 8 TRNSYS Graph (45℃ Distribution)

8.2

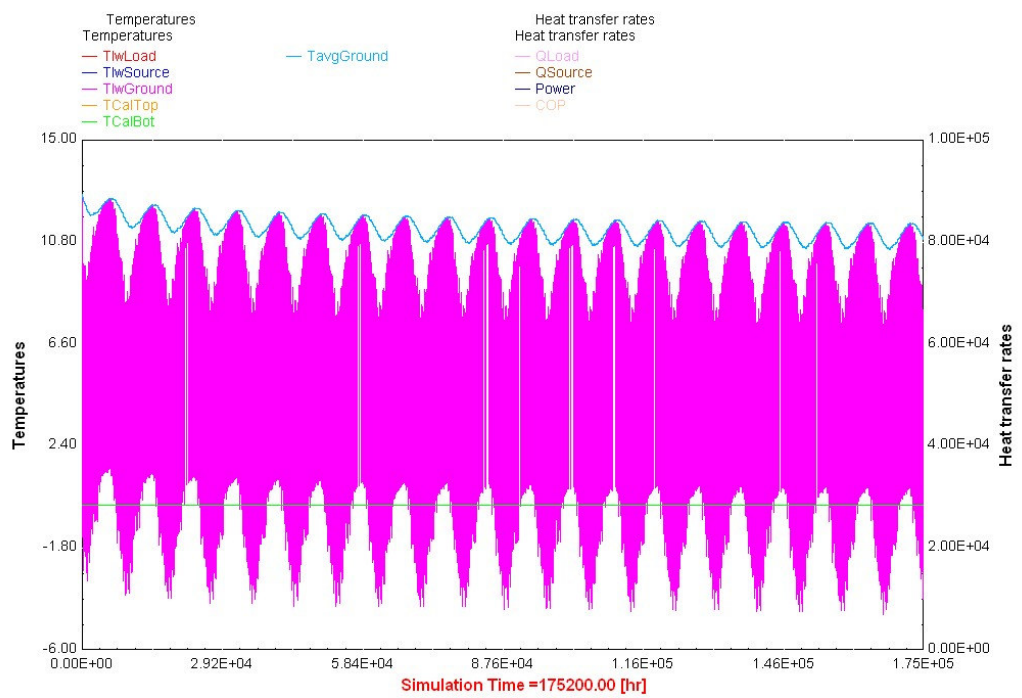

Fig A20. Section 8 TRNSYS Graph (35℃ Distribution)

8.3 **Table A6. Section 8 Scenario Costing**

	A	B	C	D	E	F
1			Heat Pump Scenarios			
2	**Scenario**	**Heat Pump Cost**	**Borehole Cost**	**20yr Running Costs**	**Grant Assistance**	**Total**
3	Base Case	6873	2925	5653	-1200	14251
4	Higher COP	6873	2925	4719	-1200	13317
5	Lower HP Cost	3250	2925	5653	-1200	10628
6	Lower Borehole Cost	6873	2385	5653	-1200	13711
7	Best Case Scenario	3250	2385	4719	-1200	9154
8						
9						
10			Boiler Scenarios			
11	**Scenario**	**Boiler Cost**	**20yr Running Costs**	**Gas Safety Check**		**Total**
12	3p/kWh Gas	996	6933	1500		9429
13	5p/kWh Gas	996	11556	1500		14052
14						