Department of Mechanical Engineering

An Investigation into the Suitability of Air and Ground Source Heat Pumps to the UK environment with a Swimming Pool Complex Heat Pump Installation

Author: Paul Martin Livingstone

Supervisor: Doctor Nick Kelly

A thesis submitted in partial fulfilment for the requirement of degree in
Master of Science in Renewable Energy Systems and the Environment
2010

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Paul Martin Livingstone Date: 10/09/10

Acknowledgements

I would like to express my sincere gratitude to **Dr. Nick Kelly**, my Academic Supervisor, who offered me excellent guidance throughout the course of my individual project. His expertise and assistance were invaluable, and without those this project would not have been possible.

I am extremely grateful to **Mr. David Palmer** for giving me inspiration with regards to my field of research and for his enthusiasm and on-going support whilst aiding me in accessing key information and relevant case studies. I have huge admiration for your dedication to the progression of renewable technologies within Scotland.

I would also like to thank **Dr. Paul Strachan** and all of the Lecturers who contributed to the Master of Science in Renewable Energy Systems and the Environment degree course. It has been a pleasure to undertake and I have enjoyed it thoroughly.

I would lastly like to thank my family for giving their unconditional support to me throughout my education and in particular, throughout this academic year. Your confidence in me has given me great encouragement.

Thank you all very much.

Abstract

As the UK strives towards a low carbon future, strong attempts must be made to provide both space heating and hot water heating through sustainable generating methods. Ground Source Heat Pump (GSHP) and Air Source Heat Pump (ASHP) technologies have the potential to contribute significantly to this goal with highly efficient, electrically powered water heating capabilities. As the UK electrical grid turns increasingly towards renewable generation, the hope is that heat pump technologies can move towards being carbon neutral. With the amount of systems present in the UK today being reasonably low in comparison to other leading renewable generators within Europe, this technology needs both increased awareness and funding to fulfil its potential.

This thesis aims to address the current status of the current United Kingdom heat pump market and to investigate the suitability of both GSHPs and ASHPs to the UK environment. Both systems will be studied in detail and the respective attributes and deficiencies of each system will be analysed. The systems will be compared within various criteria in order to give an understanding of the financial implications of each and of their suitability to various environments within the UK.

Poolewe Swimming Pool Complex in the North-West of Scotland will be used as a case study in order to investigate whether a heat pump system would suit the heating requirements of a building with high quality building fabrics and therefore a low heating demand. A recommendation will be made to the complex about which type of system would be the most suitable option for installation and a financial analysis will be presented.

The deliverables of the thesis will be first to produce a comparison between both GSHPs and ASHPs with various criteria in mind, to recommend a suitable system to supply the Poolewe Swimming Pool Complex's heating demands and to suggest whether the UK market has the ability, awareness and backing to fulfil its potential over the coming years.

Table of Contents

List of Figures

List of Tables

1. Introduction

The global attitude towards the methods used to provide energy and the consequences of those processes has changed significantly over recent years. Increased awareness and understanding of the effect of conventional energy generation has led to a shift in opinion regarding the energy sector both at governmental level and within the general public. Currently, a massive 82% of today's primary energy requirements are satisfied by non-renewable generating techniques including fossil fuel combustion. [1] The burning of traditional fossil fuels; namely coal, oil and gas, and the associated detrimental impacts on our environment, added with the depletion of fossil fuel stocks, have led a global interest in seeking renewable methods to satisfy our electricity and heating needs.

This renewable progression and the proposal of considerable reductions in carbon pollution due to energy production has been encouraged and sanctioned both at domestic level and internationally. The Kyoto Protocol has set various CO_2 targets to be met by 2012. The EU Commission has set its own targets which have to be achieved by 2020. [2] These reductions will hopefully be achieved through the increased use of renewable energy systems.

Naturally, in the UK, the focus of our progression of the utilisation of renewable energy generation has centred on electricity production. Whilst this area is highly significant, it cannot be the only focus. With domestic heat demand for European countries at 42% of the total energy demands, its significance cannot be underestimated. [3] Renewable space heating and water heating alternatives have considerable scope to reduce energy use and to thus reduce carbon emissions.

With their use of a combination of energy reservoirs from their local environment, paired with use of electricity from the grid (ideally produced by renewables), heat pump systems can be considered a renewable method of space and hot water heating. The superior efficiency of these systems to their traditional electrical space and water heating alternatives, with the hope of an electricity grid dominated by renewables suggests this type of system can have a significant contribution to reducing CO_2 emission levels.

In December 2008, the European Parliament adopted an EU directive on the Promotion of Renewable Energy sources, which expanded its definition of renewable energy sources to include air and water source heat pumps, in addition to ground source heat pumps. Now all three technologies are being promoted as part of EU policy to get member states to increase their use of renewable energies and this ruling will make its way into UK legislation in 2010. [4]

2. Heat Pump Technology

2.1 What are Heat Pumps?

A heat pump is a device which extracts heat from one location (the heat source) and makes it available to another location (the heat sink) using a mechanised system. This can be done in order to cool an area by removing heat from it and to heat an area by releasing heat into it. This concept has been utilised for many years in every day modern living. An example of a heat pump system being used for cooling is a common domestic refrigerator or freezer system. In fact, a refrigeration system and that of a heat pump are thermodynamically identical. A refrigerator takes air from its internal environment and transports it into the surroundings in order to cool that internal area. Another common every day example is air conditioning. Recent technological advancements and environmental concerns have seen heat pump technology being employed for space and water heating.

The advantages of using a heat pump for this operation is that usable heat can be extracted from its natural surroundings, from various sources, and then transported to heat or cool domestic or commercial buildings elsewhere. Although the costs of installation and power consumption have to be considered, the heat source is free, abundant and low carbon. Typically, heat pumps are more efficient than running a conventional fossil fuel boiler, and are effective at absorbing heat from air in temperatures below zero degrees Celsius.

2.2 Thermodynamic Theory

Despite the fact that there many variations of heat pump system available, the fundamental thermodynamic theory and the components used are the same regardless of the system variety.

The Clausius statement of the second law of thermodynamics states that it is not possible to operate a cyclic device where the only effect is the transfer of heat from a cooler body to a hotter body. However, if the cyclic device receives an energy input, a net heat transfer from a cooler body to a warmer one is possible. When extracting heat from a body and dumping it into the surroundings the system is known as a refrigerator. When extracting heat from the surroundings and dumping it into a body, the system is known as a heat pump. The figures below show this net heat transfer for both a refrigeration system and a heat pump system respectively:

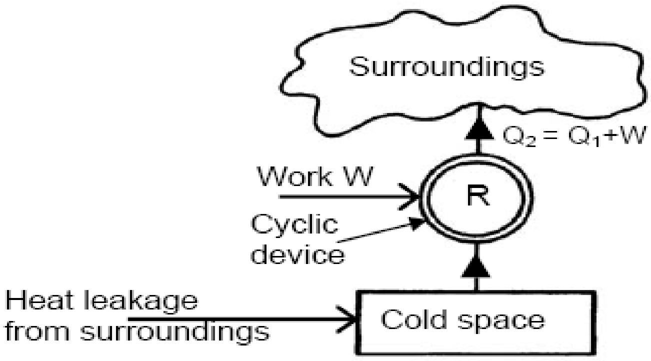


Figure 1 – Refrigeration System Schematic [5]

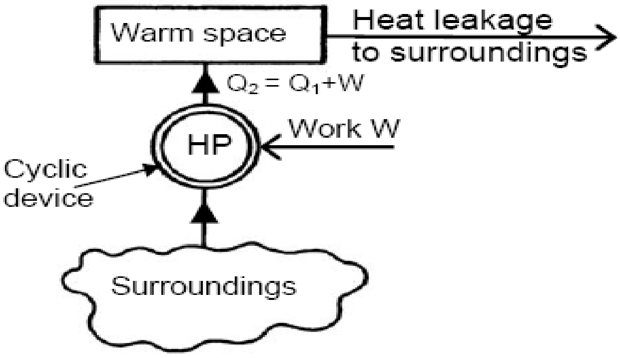


Figure 2 – Heat Pump System Schematic [5]

Coefficient of Performance

The efficiency of a heat pump is defined using the Coefficient of Performance (COP_H) (heating) or Energy Efficiency Ratio (EER) (cooling). These are the basic performance parameters used to analyse heat pump systems.

Using the notation from the above figures 3 and 4, the respective definitions are expressed as follows: [6]

$$\text{For refrigeration } COP_R = \left|\frac{Q1}{W}\right|$$

$$\text{For Heating } COP_H = 1 + \left|\frac{Q1}{W}\right|$$

The Carnot Cycle

Of course, it is desirable for the COP_H to be as high as possible; that is, for a certain work input, as much heat must be extracted as possible. It can be shown that for the greatest COP_H possible, a cyclic device must operate on the reversed Carnot cycle. The ideal Carnot Cycle is represented below on a Temperature-Entropy diagram:

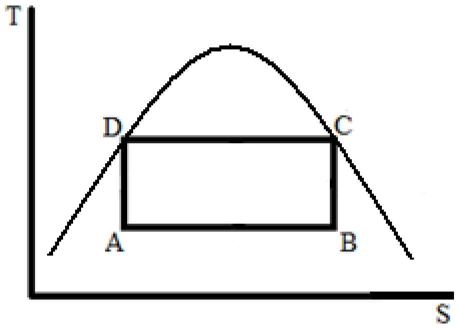


Figure 3 – The Ideal Carnot Cycle

The plant required to employ this system with condensable vapour refrigerant is also shown in figure 4 below:

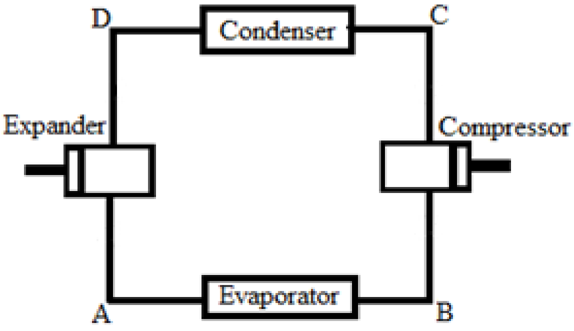


Figure 4 – Ideal Carnot Cycle Components

If we track the movement of the refrigerant through points A, B, C and D we begin to understand the various steps of the process. Processes B-C and D-A are reversible and adiabatic with no heat transfer occurring despite a change in temperature. Processes C-D and A-B are reversible, isothermal and isobaric. The entire process is assumed to be reversible.

The smaller the temperature difference between the evaporating and condensing temperatures, the larger the coefficient of performance will be. This is the opposite requirement for a high thermal efficiency in a cyclic work-producing device.

The Vapour Compression Cycle

There are various thermodynamic cycles which can theoretically conduct heat pumping operation but the vast majority of modern systems employ a vapour compression cycle which is considered the state of the art with regards to heat pumping.

There are some practical difficulties in designing a system based on the reversed Carnot cycle. Modifications must be made in order to manage these difficulties and the fact that the cycle is, in operation, not reversible. The most significant issues are:

- It would be extremely difficult to terminate the evaporation process at point B. This could lead to lubrication problems in the pump with severe compressor damage a possibility and thus we allow the evaporation process to continue until the line of saturation.

- Differentials between the expanding and evaporating fluids' specific volumes mean the expander work output is negligible in comparison to the work input of the compressor. So, in practice the expander would be replaced by a simple expansion valve as the expander would be of only marginal benefit to the system. [7]

The cycle is composed of two constant pressure processes and one constant enthalpy process and for that reason; it is effectively demonstrated on a Pressure-Enthalpy diagram. The

Vapour Compression Cycle T-s diagram including the above mentioned modifications is shown below:

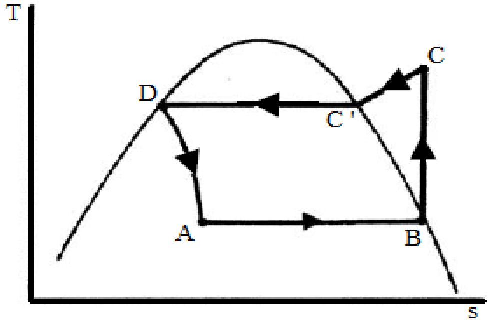


Figure 5 – Modified Vapour Compression Cycle

The components diagram is shown below in figure 6 below with an expansion valve replacing the expander.

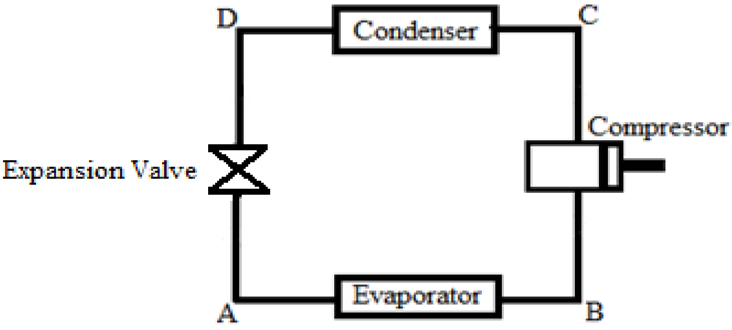


Figure 6 – Modified Component Diagram Schematic

The V.C. Cycle is effectively a reversed Rankine cycle. The above representation shows the working fluid moving in an anti-clockwise direction as opposed to the clockwise movement associated with the Rankine Cycle.

2.3 Heat Pump Components

The main components in a vapour compression heat pump system are the compressor, the expansion valve and two heat exchangers. These heat exchangers are referred to as the evaporator and the condenser. For illustrative purposes, a simple system schematic is shown in figure 7 below:

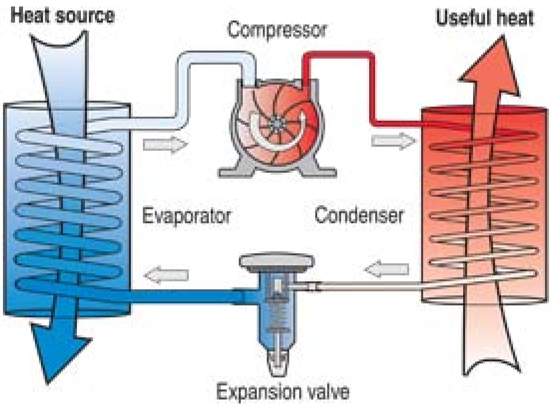


Figure 7 – Heat pump components diagram [8]

Compressor

A vital component, the compressor is effectively the heart of any heat pump. Vapour from the evaporator is compressed in order to increase pressure and temperature. The use of a quality compressor is integral to achieving high heat pump performance as considerable amounts of power may be needed to compress. Technological advancements in compressor production have been highly beneficial to the heat pump industry.

Traditionally, piston compressor systems were used in heat pumps with relatively low efficiencies. Now, modern hermetic (air-sealed) motor compressor units are used which improve the general performance, increase durability and thus lifespan, and significantly reduce the noise produced in operation. [9]

Evaporator

The air from the heat source is passed over the evaporator. Within the evaporator, the working fluid is kept at a lower temperature than the heat source in order to induce heat flow from the source to the refrigerant. The refrigerant then changes state from the liquid to gas. This change of state is achieved by a relatively minimal temperature change in the refrigerant.

Exchanger

The hot gas vapour can then be used to heat the destination water through another exchanger. The destination water is circulated by a pump so that the entire circuit is heated to the required temperature.

Condenser/throttle valve

The gas is then cooled back to a liquid by an evaporator, in a typical Rankine cycle an expander is used to do this, but in heat pump technology a valve is used to complete this part of the closed loop cycle.

2.4 Heat Pump Performance

As has been mentioned in the 'Thermodynamic Theory' section, the basic performance parameter used to analyse heat pumps is known as the coefficient of performance or COP. This parameter can be defined as the ratio of heat delivered by the heat pump and the electricity supplied to the compressor.

Another parameter for analysing heat pump performance is the primary energy ratio (PER) which is used for engine and thermally driven heat pump varieties.

The coefficient of performance for an ideal heat pump with various temperature increases and a source temperature of 0°C are shown below. Also shown are actual COPs for various system sizes:

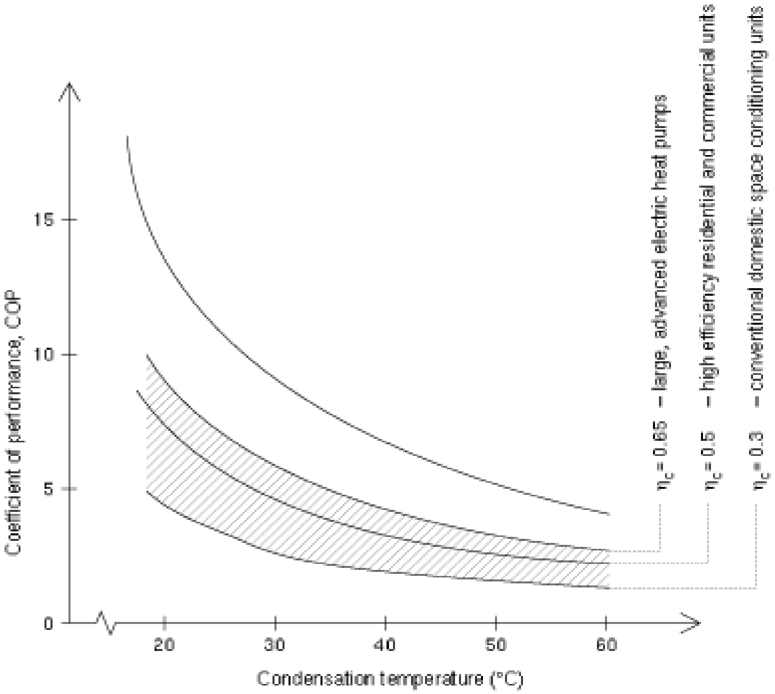


Figure 8 - Various COP vs. Condensation Temperature [10]

The heat pump centre details various factors which affect the performance of a heat pump: **[10]**

- the climate - annual heating and cooling demand and maximum peak loads;
- the temperatures of the heat source and heat distribution system;
- the auxiliary energy consumption (pumps, fans, supplementary heat for bivalent system etc.);
- the technical standard of the heat pump;
- the sizing of the heat pump in relation to the heat demand and the operating characteristics of the heat pump;
- the heat pump control system.

2.5 Refrigerants

The refrigerant is the working fluid within the vapour compression cycle and thus its selection is a critical consideration when constructing a high quality heat pump. In order to select a suitable refrigerant, we must understand the relationship between its boiling point, its temperature and its pressure so that the refrigerant can reach the required high temperatures without the involvement of excessive pressures.

There are many possible refrigerants which can operate within the vapour compression cycle. Toxicity, ozone depletion risks and unsafe working pressures discount many of these from practical use. Appreciation of the dangers associated with using traditional refrigerants and the subsequent development of modern equivalents has seen significant change in the availability and diversity of refrigerants on the market. Various refrigerants possess different qualities and are thus more suited to certain applications.

A table of desirable refrigerant properties and the reason for them is shown below:

Table 1 – Desirable refrigerant properties [11]

Desirable Properties	Reason
High latent heat	Reduces mass flow
Moderate pressure at condensing temperature	Reduces strength requirement for condenser and generator
Relatively low triple point	Limit evaporator temperature
Relatively high critical point	Limit on condensing temperature
Low liquid specific heat	Reduces effect of pre-cooler
Vapour specific heat equal to liquid	Precooler effectiveness
Low vapour specific volume	Ease of vapour transport

Traditionally, the most common working fluids for heat pumps are as follows:

- CFC-12 Low- and medium temperature (max. 80°C);
- CFC-114 High temperature (max. 120°C);
- R-500 Medium temperature (max. 80°C);

- R-502 Low-medium temperature (max. 55°C);
- HCFC-22 Virtually all reversible and low-temperature heat pumps (max. 55°C).

CFCs

A chlorofluorocarbon (CFC) is an organic compound that contains carbon, chlorine, and fluorine. Following the development of CFCs in the early 1930s, their low levels of toxicity and stable conditions meant they appeared to be the ideal refrigerant for heat pump systems.

However, since the early 1970s the use of CFCs has been heavily regulated following the realisation of their destructive effects on the ozone layer. In fact, it is the same chemical stability previously mentioned, along with their chlorine content, which makes CFCs so potentially harmful to the Earth's protective blanket. [12]

In 1987 the Montreal Protocol on Substances That Deplete the Ozone Layer was passed. The protocol is an international treaty designed to protect the ozone layer and thus banned the use of all CFC refrigerants. [13]

HCFCs

As a result of the Montréal Protocol, an increase in the use of hydrochlorofluorocarbons (HCFCs) proceeded. These compounds still contain chlorine but their ozone-depletive capabilities are somewhat reduced by the fact these compounds have a lower atmospheric stability than that of CFCs. However, despite this reduction, HCFCs still possess highly depletive properties. Under the 1987 Montreal Protocol and the 1995 Vienna Convention all CFCs and HCFCs are to be phased out by 2020. Some European countries have already phased out the use of HCFCs entirely. [14]

HFCs

Long term options may be HFC's (hydro fluorocarbons) which are chlorine free and are thus not ozone-depletive. 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 long term alternatives to more traditional and highly refrigerants. They do still, however, have some global warming effects. There are various types of HFC which may be used in the future, each with their own benefits.

HFC-32 has negligible global warming properties, is slightly flammable and is seen as a possible replacement for HCFC-22.

HFC-134a offers similar properties and COP potential to CFC-12 and is thus a possible substitute for it.

HFC-152a is limited to use in small systems due to its high flammability.

HFC-125 and **HFC-143a** can be valuable constituents of blended refrigerants but their global warming potential is three times that of H-134a making them a less attractive option. [10]

Blended Refrigerants

Another possible replacement for CFCs is the introduction of blended heat pump refrigerants. Many of the deficiencies associated with traditional refrigerants or HFCs can be eradicated by the use of synthetic mixing techniques.

These blends consist of at least two pure working fluids and can be either zeotropic, azeotropic or near-azeotropic where azeotropic mixtures have the ability to evaporate and condense at a constant temperature.

Various mixtures can be created in order to suit different refrigerant needs.

Natural Refrigerants

A technology which is on the increase is that of the use of natural working fluids as refrigerants in heat pumps. Benefits of these include low global warming effects and high accessibility and storage. Natural refrigerants can have varying degrees of toxicity and flammability and so each much be controlled appropriately with its own respective properties in mind. Examples of natural working fluids are air, water, ammonia, hydrocarbons and carbon dioxide.

Water is ideally suited to large, industrial-size heat pump applications due to it having predictable thermodynamic properties, no toxicity and no flammability. However, the low heat capacity of water means that large, expensive compressors must be used, especially at low temperatures.

Ammonia is already a leading working fluid in refrigeration and cooling systems. It has the potential to be used in small heat pump systems (a significant percentage of the heat pump market) but there are concerns over its toxicity and flammability.

The considerable flammability involved with **Hydrocarbons** appears to be the main deterrent to using them as a working fluid. This flammability means that strict safety precautions must be taken. Hydrocarbons are used in transport refrigeration, domestic refrigeration/freezing and residual heat pumps.

CO_2 appears to have significant potential in the field of heat pump refrigeration. It is non-toxic, non-flammable and is readily available. There are concerns over poor performance coefficients and when asked his opinion on **CO_2** refrigerants he said,

> "Everything we know about conventional heat pump systems goes out the window."

There are then definite barriers to overcome but carbon dioxide is definitely a viable option. Applications in Norway and Japan (air-source) are now available. **[15]**

2.6 Low Temperature Source

Theoretically speaking, heat can be absorbed from any environment where the temperature exceeds 0 degrees Kelvin or -273 °C. Obviously, the higher the source temperature, the more likely it is that considerable heat can be absorbed from it. However, it is still possible to recover heat from areas of negative Celsius temperatures. A high source temperature will allow for high coefficient of performance and efficiency. An ideal heat source should:

- Have a high and stable temperature during the seasons in which it is most in use.
- Be abundant and readily accessible.
- Be cheap to access and exploit.
- Not be corrosive or polluted.
- Have favourable thermo-physical properties.
- Have a high specific heat per unit volume to minimise the temperature drop during exploitation. **[16]**

There are various different heat sources available which vary in their suitability to the above criteria.

2.7 System Variations

Introduction

The technical performance and appropriate installation of a heat pump system depends greatly on the heat source being exploited. There are many heat sources available to use, each have their own individual attributes and deficiencies. Different sources may be more suitable for small-scale and large scale exploitation. The appropriateness of each source to a specific use will likely relate to the temperature of that source.

The following table shows the temperature range of common heat sources:

Table 2 – Temperature Ranges of Various Heat Sources [17]

Heat 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

As can be seen from the above table, there are a multitude of primary heat sources and further sub-divisions within those. Heat pumps can source energy from the ground, from water and from air. The ability to utilise gaseous, liquid and solid sources shows the variability of heat pump systems.

Perhaps the two most common heat pump variations are:

- Ground Source and;
- Ambient Air source

Both of these systems can be used to effectively transport heat from the surrounding area in order to heat indoor spaces and/or a hot water supply.

These systems will be discussed later in more detail in chapters **two** and **three**.

Rivers, Streams and Lakes

The temperatures of these heat sources do not vary greatly from day to day, but follow the transformation of ambient seasonal air temperatures considerably slowly due to their large thermal inertia.

This means that at the beginning of a heating season (i.e. the beginning of winter in a UK climate); the water temperature will be significantly higher than the ambient air temperature. This will obviously be ideal for use but unfortunately the water temperature will be much lower than the ambient air temperature towards the end of the heating season. The main benefit of this is that when heating is needed most, during the coldest period, the water temperature is likely to be significantly higher than that of the ambient air. The heating output should be relatively constant until the end of the heating period nears.

No defrosting should be needed in the majority of cases, which will allow water-source heat pumps to have more impressive performance features than air source alternatives.

There are many methods of heat extraction from these water sources, but all of these require extended lengths of piping and refrigerants which can result in an increased initial expenditure and a possible energy loss through this increased piping. These losses can negate some of the value from the increased temperature source, but intelligent pipe work and finding the ideal location can minimise this negation. **[18]**

Ground Water

If employing this system, a bore-hole must be drilled to enable access to the water table. The water is then pumped towards the heat pump then the water is returned to the source through a second borehole. There may be some issues with the local water authority regarding the frequency of extraction and various other issues.

Underground, water table temperatures generally tend to be in the region of between 4 to 10°C and should remain constant all year round. **[19]**

Improved COP over air source and surface water source alternatives can be reached but this must be traded off against the risk of using water containing high sediment levels which may encourage corrosion and component damage.

Heat Reclamation

Heat pumps can be employed to usefully recover a proportion of heat energy which is lost to the surroundings of a dwelling or workspace. Examples of possible opportunities for this heat reclamation are as follows:

- Warm air from a mechanical ventilation exhaust
- Warm water leaving a building from bath, sink, wash machine or dish washer waste

Warm air is naturally leaked from buildings through small gaps within the structure. Naturally ventilated buildings could not use heat losses for useful purposes or certainly not in this respect anyway. A comprehensively sealed building that employs a mechanical ventilation system preferably with a single exhaust outlet would be ideal for heat reclamation.

A small percentage of the heating load the building requires will be available using this system but this heating load could be supported by an additional system. Other renewable technologies may be employed to provide this support. Possible supportive technologies include solar thermal panelling for space heating and domestic water heating.

A simple depiction of a heat recovery system is shown in figure 9 below:

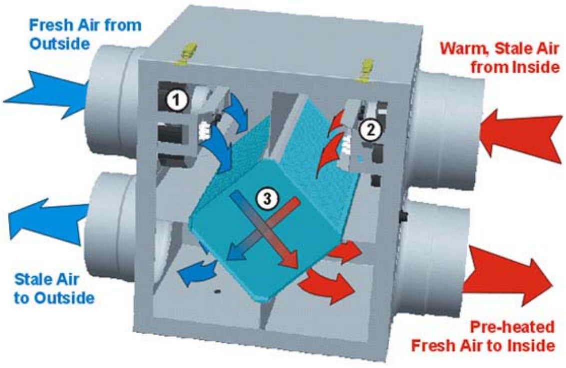


Figure 9 - Heat recovery system [20]

Waste water from sinks, baths, dish washers and washing machines leave dwellings with a relatively high temperature thus making it possible for heat pump source exploitation.

Additional storage, housing the heat exchanger is necessary. Not all waste water is useful due to high levels of waste debris which would affect the performance of the heat exchanger and clog up components.

The amount of energy that this system could provide is expected to be relatively low. It has been suggested that only a quarter of a home's energy requirement of DHW heating could be supplied by this source. [21] The need for comparatively bulky additional equipment paired with this low expected output makes this an unattractive option.

2.8Lifespan

When installing any mechanical system it is important to have prior knowledge of the expected lifespan of that system. When installing a heat pump, considerations between the lifespan of various alternative technologies may be taken into consideration as a costing issue. The possible maintenance cost and replacement periods of systems may contribute considerably to the decision of which system is chosen for installation.

The location of the installation and the associated climatic and environmental conditions of that area may impact on the lifespan of the system. For example, air source heat pump life span will be negatively affected by the surrounding ambient air containing a high salt or dust content.

Various sources suggest that possible life expectancy of a typical air source system is in the region of 10 years with more ambitious predictions suggesting the possibility of an ASHP lasting up to 15 years. [22] Ground source heat pumps tend to have a longer lifespan, expected to be between 20 and 25 years. [23] The compressor is the critical component of either technology and will generally dictate the system lifespan.

Both systems will inevitably require routine maintenance so this must be taken into consideration when performing a life-costing analysis.

With further research into both air and ground source heat pumps, system life expectancies will likely be increased.

3. Ground Source Heat Pumps

3.1 Introduction

Ground Source heat pumps use the ground beneath a building as a heat source. An example of a generic ground source heat pump system is shown in figure 10 below:

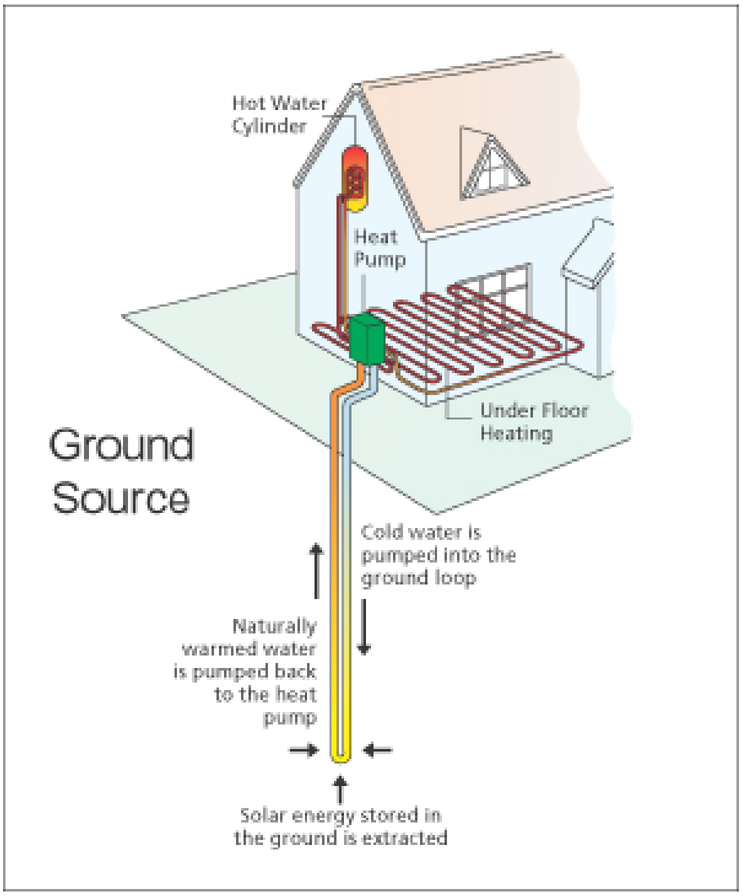


Figure 10 - Ground Source Heat Pump System [24]

Ground Source systems are ideal for both domestic and commercial use. The differentials in temperatures underground are much lower than that of the ambient air used for ASHPs and thus maintain a higher seasonal performance factor. Ground moisture contents and climatic differentials will only minimally affect performance. Pipes can be laid either vertically, horizontally, or in slinky loops. These variations and the reasons for the use of each will be discussed later.

3.2 Ground Temperature

The surface of the earth is heated by incident solar radiation. This energy source is responsible for daily and seasonal variations of surface soil temperatures at possible ground source heat pump installation sites. Daily variations tend to disappear below depths exceeding around 10cm whereas seasonal variations tend to become minimal after depths of approximately 15m. [25] Below this level however, the temperature is fairly constant and will roughly equate to the mean annual air temperature of the region, this is due to the fact the earth has a high thermal mass / inertia of soil and is able to store most of the heat absorbed. The only other factor that may affect underground temperatures is the possibility of absorbing heat from the Earth's core. This component of heat is known as the heat flow, a heat flow map for the UK is shown below:

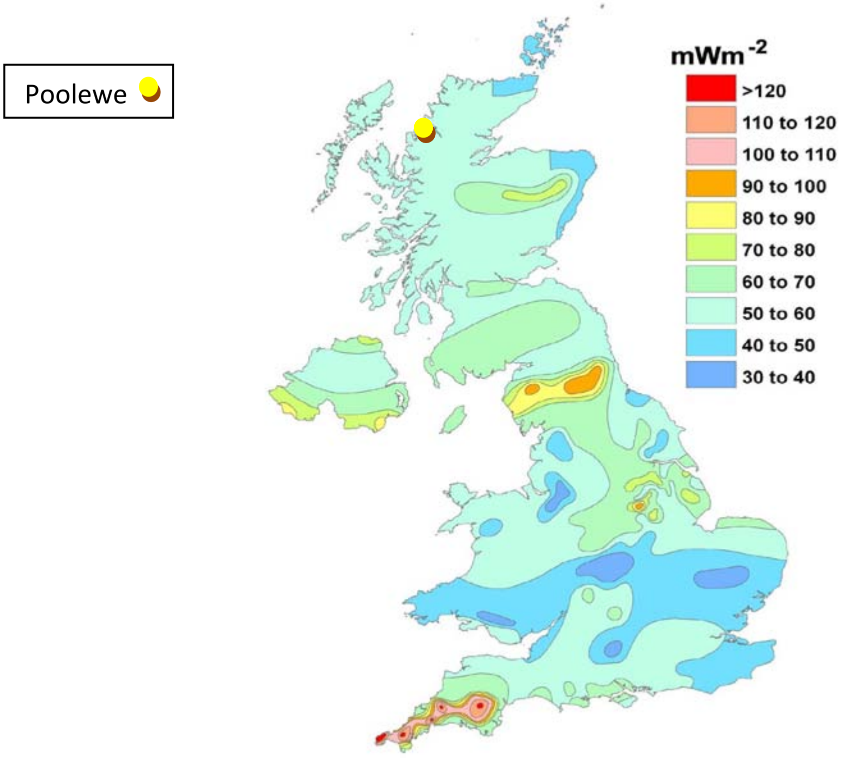


Figure 11 - UK Heat Flow Map [26]

Within the UK, it is unlikely to find an area where ground temperature is so unattractive that it would, in itself, discourage the installation of a ground source heat pump system. Underground temperatures throughout the UK appear to lend themselves to employing ground source heat pump systems.

3.3 Thermal Properties

The rate of heat transfer between the heat pump heat exchanger and the ground is mainly determined by the thermal properties of the earth at the location involved. The **thermal conductivity k** is the property of a material that indicates its ability to conduct or transmit heat. Porosity, composition and the nature of any saturating liquids will determine the value of any rock-type's thermal conductivity. Higher levels of porosity will result in lower conductivity levels. 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. Rock and soil can be either infiltrated by liquid (most probably water) or air and as water has a far higher thermal conductivity, saturated soils are preferable to those with high levels of air infiltrations.

The Thermal Conductivity of selected relevant materials is shown below:

Table 3 – Thermal Conductivity of Selected Materials [26]

Material	**Typical Thermal Conductivity, K, ($Wm^{-1}K^{-1}$)**
Air	0.0252
Water	0.6
Shale, sandstone, siltstone (<30% porosity)	2.2-2.6
Quartz sandstone (5% & 30% porosity)	6.5, 2.25
Clay, saturated clay	1.11, 1.67
Sand, saturated sand	0.77, 2.5
Silt	1.67
Schist, Serpentine	2.9
Quartzite	5.5
Igneous plutonic rocks	3.0
Loam	0.91

The **thermal diffusivity α** of a medium is the rate at which heat is conducted through it. A high thermal diffusivity value is desirable as it means the medium in question will adjust quickly to the surrounding temperatures. Thermal conductivity and thermal diffusivity are related by the following expression (m^2/s): [27]

$$\alpha = \frac{\lambda}{Cp\rho}$$

Where α = thermal diffusivity (m2s-1), λ = thermal conductivity (W m-1 K-1), Cp = specific heat capacity (J kg-1 K-1) and ρ = density (kg m-3).

The Thermal Diffusivity of selected relevant materials is shown below:

Table 4 – Thermal Diffusivity of Selected Materials [26]

Material	**Typical Thermal Diffusivity (m^2 day^{-1})**
Basalt	0.059
Clay	0.082
Granite	0.086
Limestone	0.091
Gneiss	0.106
Sandstone	0.143
Quartzite	0.255

Thus, the variety of underground material present at a site can be critical to the viability of a ground source heat pump installation.

Some interesting maps regarding the geology of the UK with regards to geothermal energy can be viewed in **Appendix A**.

3.4 Ground Source Variations

Indirect/Direct Systems

Ground source heat pumps can be referred to as either **direct** or **indirect** systems.

Indirect systems transfer heat to and from the ground using a mix of water and antifreeze as circulating fluid. The circulating fluid could be heavily saturated with salt or a glycol solution. It must be noted that glycol solutions in particular will increase significantly in viscosity which will result in lower heat pump efficiency.

It is generally advised to use a circulating fluid which has a freezing point in excess of 5°C. **[28]**

Direct systems are the oldest and most common methods of ground source heat pump technologies. Ground-coupling is achieved through a single loop circulating refrigerant in direct thermal contact with the ground.

This system offers several advantages over the indirect system resulting in increased efficiency.

Closed Loop Systems

Closed looped systems can be either horizontal or vertical in nature.

"The choice of horizontal or vertical system depends on the land area available, local ground conditions and excavation temperatures" **[29]**
Naturally, a horizontal system will cover far more land area which will need to be obstacle free and if this type of land is at a premium, a vertical system will be favoured. Similarly, shallow soil levels would mean that a vertical system would be more preferable. Drilling of vertical boreholes is expensive and will thus require a higher initial expenditure. However, thermal efficiency with a vertical system will be greater than that of the horizontal equivalent.

A **vertical** system consists of runs of piping which runs vertically into the ground. This piping can reach depths of between 20 and 160m depending on the capacity needed and the requirements of the system employed. Pairs of vertical pipes are connected at the bottom in a U-shape as shown in figure 12 below. The pipes should be installed in parallel with a space of approximately 5m between them against depending on the system capacity. A thermal connection is made between the ground and the pipe by cladding the pipe in a conductive grout. A common grout is 'bentonite' which is a clay based substance. This grout also helps prevent boreholes from being flooded and from general debris getting between the pipes and the rock surface. Under standard hydrological conditions, an average vertical borehole system will yield 50W/m pipe length. [30]

An artist's impression of a vertical closed loop system is shown here:

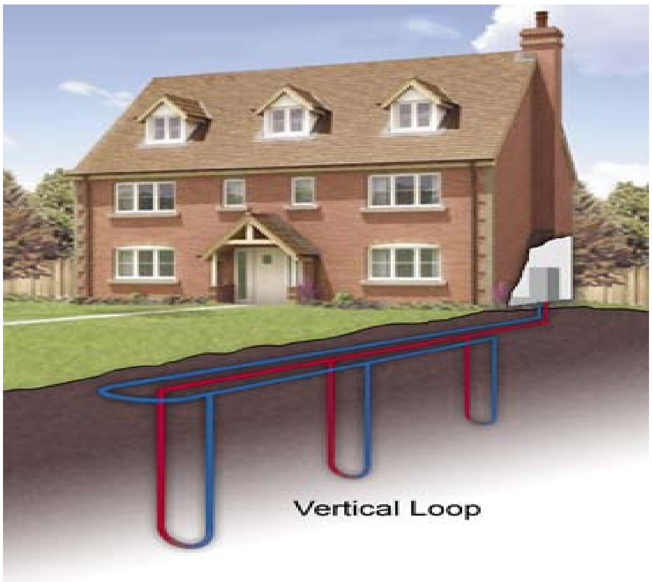


Figure 12 - Ground Source Vertical Closed Loop [31]

In a **horizontal** system the pipes are buried approximately 2m underground, or just below the frost line. Excavation for horizontal loop fields is about half the cost of vertical drilling. In order to ensure that the pressure drop along each pipe pair is equal throughout the system, the pipes must be of equal length. Approximately 35-60m of length is required for each kW of heating. [30] Insulation, flood prevention and debris guarding is provided by a bed of sand surrounding the piping.

Horizontal systems can be laid in either a series or parallel formation depending on the amount of land available on site.

An artist's impression of a horizontal parallel closed loop system is shown in figure 13 below:

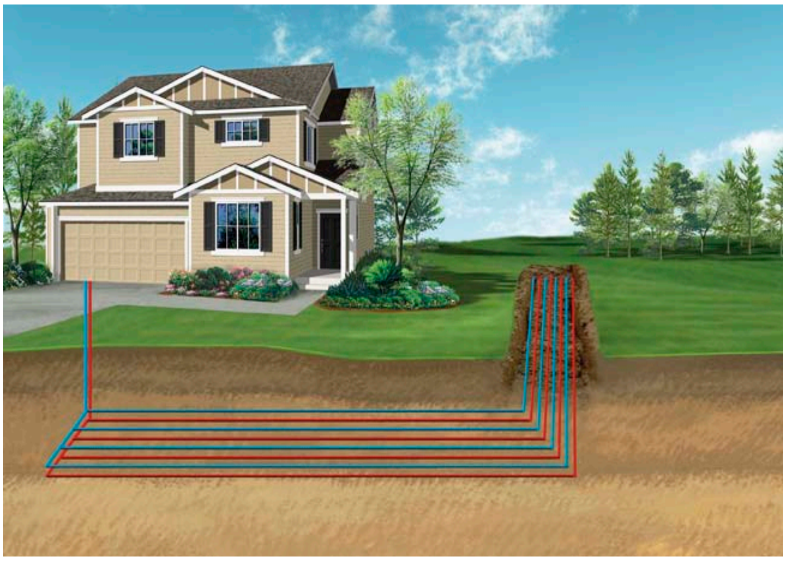


Figure 13 - Ground Source Horizontal Parallel Closed Loop [32]

Available to both horizontal and vertical systems, but perhaps more common in the horizontal variation, are what are known as **'slinky'** or **'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 but will require significantly less trench space and will thus save 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.

An example of a slinky system within a dug-out trench is shown below:

Figure 14 - Ground Source Slinky Closed Loop [33]

4. Air Source Heat Pumps

4.1 Introduction

Air Source heat pumps use the immediate external air as a heat source. An example of a generic air source heat pump system and possible methods of heating are shown in figure 15 below:

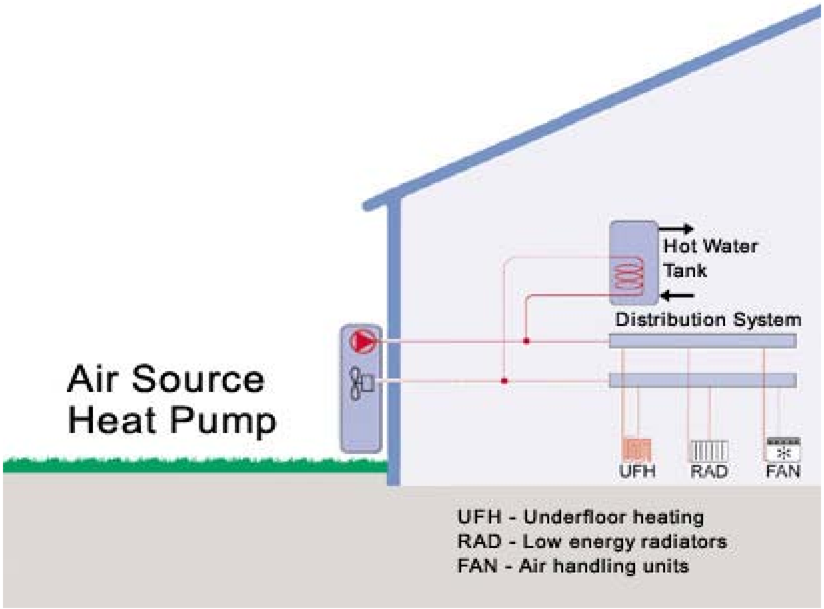


Figure 15 - Air Source Heat Pump System [34]

Ambient air is an abundant and easily accessible heat source. It is perhaps the most common heat pump heat source. With low outdoor temperatures (in autumn and winter), the seasonal performance factor of such systems can be lower than ground and water source alternatives. If installed in areas of sub-zero temperatures, energy may be required to defrost the system to free frozen fans.

4.2 The Air as a Heat Source

As has been mentioned previously, heat can be absorbed from any environment where the temperature exceeds 0 degrees Kelvin or -273 °C. Heat pumps have the ability to successfully provide heat from any air source which exceeds approximately -15°C in temperature.

Obviously, with these temperature restrictions, there are times of the year, namely winter, and certain geographical locations which may not suit air source heat pumps.

The problem with air source heat pumps used for space heating in a relatively cold climate is that the period during which heat is most needed is the period during which the heat source is at its least plentiful. If the system cannot support the needs of the building in which it operates then it is not the correct system to install.

Needless to say, locations which regularly experience temperatures below the -15°C cut-off are not suited to air source heat pumps, but what about the UK?

Our most recent winter, 2009/2010, was the coldest UK winter for over 30 years. [35] For this reason, our most recent winter thus will be used as the benchmark for assessing the UK climate's compatibility.

The following graph, courtesy of the Met Office, shows the average UK temperature during the winter (December, January and February) of 2009/2010 in addition to a trend line depicting the average temperatures between 1970 and 2000:

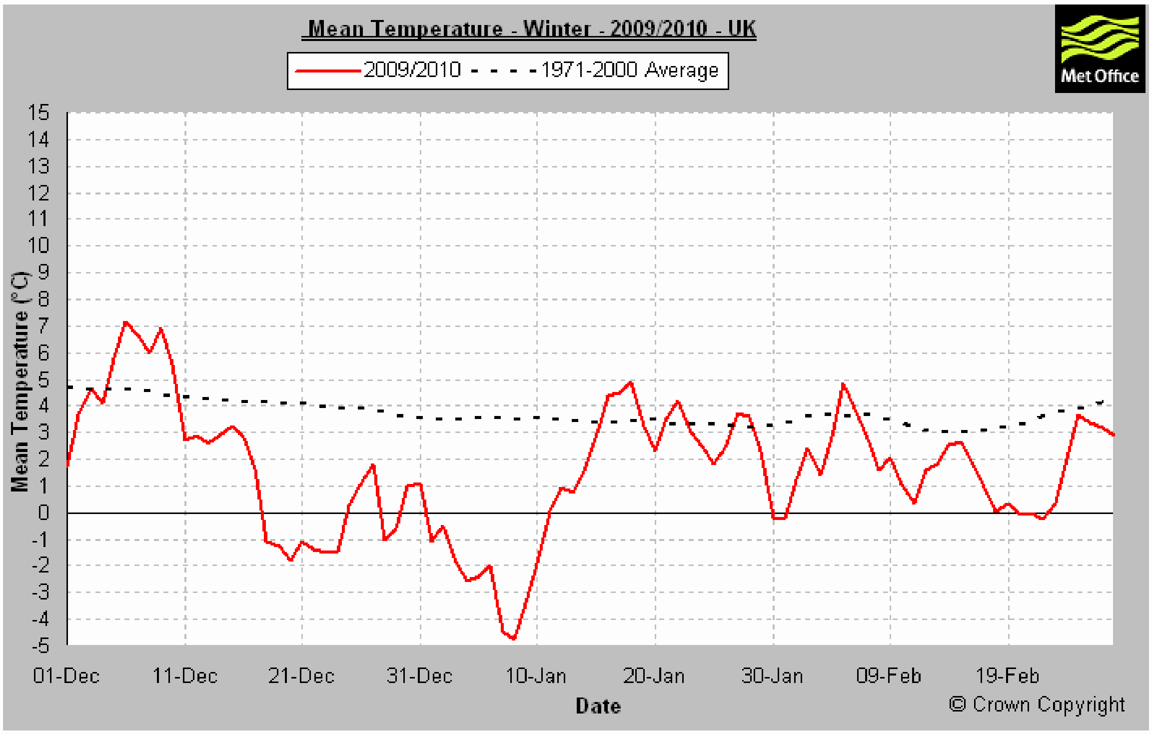


Figure 16 - winter 2009/2010 Average Temperatures [36]

The coldest day, at the beginning of January, had a UK-wide average of -5°C so this suggests that the air temperature is not a significant deterrent to the proposition of air source heat pumps.

To appreciate the average winter temperatures at specific locations within the UK, as they obviously vary from the average quite significantly, the following graph has been presented. The graph shows the mean temperature anomaly (difference from average) map for Winter 2009/10 (December, January and February):

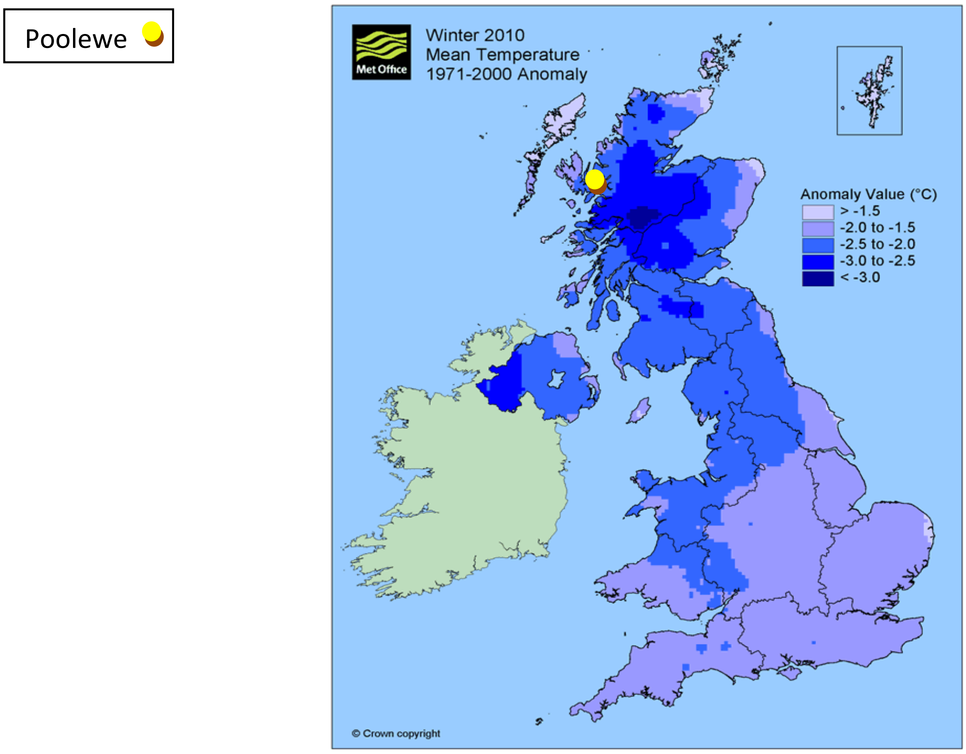


Figure 17 - winter 2009/2010, Mean Temperature Anomaly [37]

The deviations shown from the average are actually quite minimal and would suggest that whilst certain areas of the UK may experience temperatures below -15°C, these occurrences are extremely rare.

Of course, each location must be taken on its own merits and support systems may be put in place in the form of a traditional immersion boiler in order to back up the system throughout these rare but extreme cold-snaps.

4.3 Air Source Variations

Within the area of air source heat pumps there are various subdivisions. Primarily, air source heat pumps can either be known as:

- Air to air or
- Air to water

Air-Air Systems

As the name suggests, this type of heat pump system extracts heat energy from ambient air from the external surroundings of a building and transports that heat energy into the building's indoor space through a fan system.

They are relatively simple to install and their ability to both heat and cool, with adaption between both settings available at relative ease, makes them attractive to office buildings and other work spaces. They are unlikely to be used to provide hot water.

Their popularity can be reflected by the fact that they are the largest single group of Heat Pump systems marketed in the UK today.

These systems can be **single, twin** or **multi-split.**

Single-split systems have one external component and one indoor component and thus perform a relatively simple heat transfer. A schematic of such a system is shown in figure 18 below:

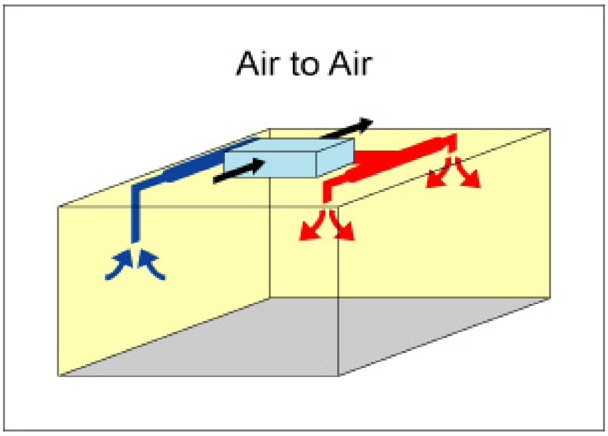


Figure 18 - Air to Air Single-Split System Schematic [38]

These systems can either be placed on a roof space (as shown above) or a wall area.

Multi-split systems have a similar configuration of one main outdoor unit but with two or more indoor units serving different locations in the building. In many cases these are capable of independent control of their own space. Or in other words, this system has the ability to heat one space and cool another.

A multi-split system schematic is shown in figure 19 below:

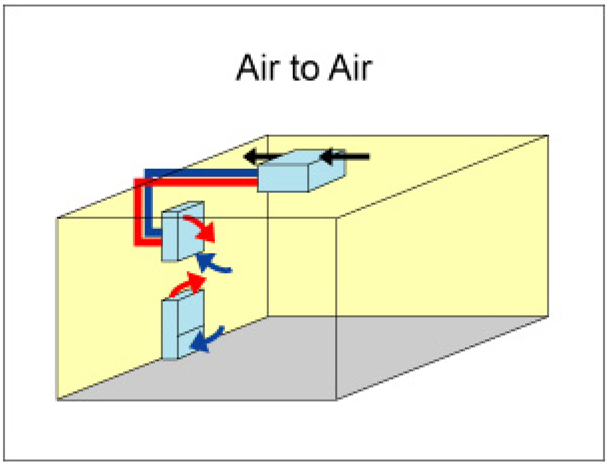


Figure 19 - Air to Air Multi-Split System Schematic [38]

Air-Water Systems

As the name suggests this variation of air source heat pump extracts heat energy from the external surroundings of a building in order to use that energy to heat water within a building. This water can be used to heat the building via conventional methods of space heating such as radiators or under floor heating.

4.4 Defrosting

An important requirement of an air-source heat pump system that is unnecessary for the ground source alternative is the ability to defrost its evaporator to remove ice build-up at low ambient temperatures.

This is most commonly achieved by switching the system into a reverse cycle. The evaporator effectively becomes the condenser, the condenser temporarily becomes the evaporator and the hot refrigerant is used to melt the ice.

This process consumes electricity through compressor work just like during normal heat pump operation. This means that if the defrost cycle is being operated, heating within the building must be supported by the use of a buffer tank or the required heating load cannot be provided.

Typically the defrost cycle takes place between ambient temperatures of approximately 10°C and 0°C which should pose no real issues during the UK winter period. [39]

5. Heat Pump Benefits

Whilst heat pumps cannot be considered a completely renewable technology in their own right, there are undoubted sustainable credentials involved with these technologies. The only way that a heat pump can be considered 100% renewable is where the compressor work input can be supplied via a completely renewable source. This could either be directly supplied by the grid or by a stand-alone renewable electricity generating facility on sight such as a wind turbine or photovoltaic system. Even though grid-supplied electricity in the UK is not 100% renewable, the potential for it to provide a considerable percentage of the total supply in the future is most definitely there.

5.1 Emissions

The most reasonable way of calculating emissions reductions due to heat pump use seems to be to compare their emissions to that of traditional fossil fuels. The higher the COP of a heat pump, the lower its consumption of power will be and thus its carbon emissions will be reduced. Modern heat pumps can achieve COP values of between 3 and 5 dependant on their heat source. Or in other words, for every 1kW of power consumed, the equivalent of between 3kW and 5 kW of work is transferred to the working fluid.

To emphasize the potential of what heat pumps can possibly offer, the International Energy Agency (IEA) Heat Pump Centre has assessed the global environmental benefits of heat pumps.

The study compared a traditional electrical boiler, a traditional gas boiler, and a traditional oil boiler to electric heat pumps with Seasonal Performance Factors (SPF) of 3 (representing the typical systems of today), of 6 (representing potential future systems) and of 0 (an electric heat pump using electricity entirely from renewables).

The annual CO_2 emissions for each system calculated (with an annual heating demand of 15,000 kW) were as follows:

Table 5 – C02 Emissions for 15,000 kW Demand [40]

Type	Heat Demand (kWh)	Efficiency (%)	Input Energy (kWh)	Specific CO_2 Emission ($kgCO_2/kWh$)	Annual CO_2 Emissions (kg)
Oil Boiler	15,000	80	18,750	0.274	5,138
Gas Boiler	15,000	95	15,790	0.202	3,189
Electric Boiler	15,000	95	15,790	0.472	7,454
HP SPF = 3	15,000	300	5,000	0.472	2,360
HP SPF = 6	15,000	600	2,500	0.472	1,180
HP SPF = 0	15,000	300	5,000	0	0

The CO2 emissions associated with these various technologies are shown in graphical form in figure 20 below:

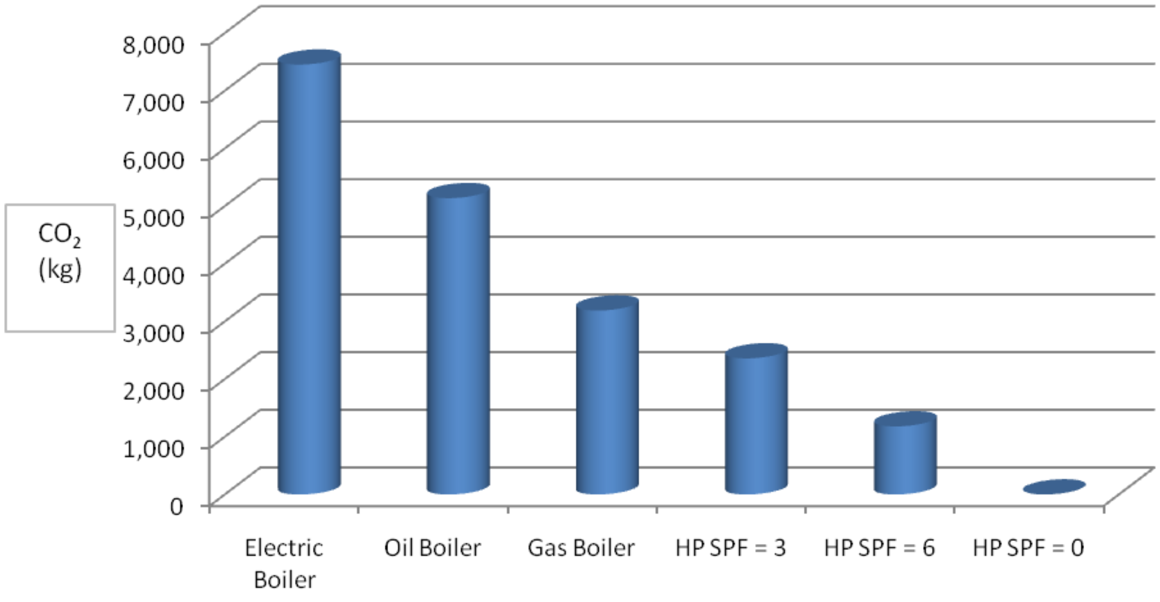
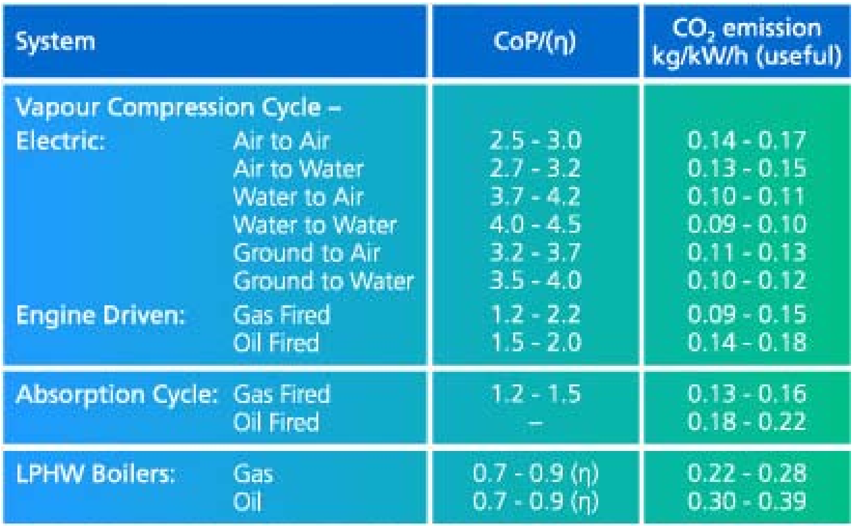


Figure 20 - C02 Emissions for 15,000 kW Demand [40]

The comparison that this study presents is interesting on two levels. Firstly, it is obvious from the table and from the graphical depiction that previous to heat pump technology being used for space a water heating, use of electricity as the energy source to do this resulted in considerable emissions values. Secondly, out of all the technologies tested, heat pumps in general result in far less carbon being emitted.

Another analysis and depiction of the low CO_2 nature of heat pump technologies is presented by the heat pump association. Their calculated ratings are given below and are as encouraging as the above analysis suggests. The table of CO_2 emissions is given below:



System		CoP/(η)	CO_2 emission kg/kW/h (useful)
Vapour Compression Cycle –			
Electric:	Air to Air	2.5 - 3.0	0.14 - 0.17
	Air to Water	2.7 - 3.2	0.13 - 0.15
	Water to Air	3.7 - 4.2	0.10 - 0.11
	Water to Water	4.0 - 4.5	0.09 - 0.10
	Ground to Air	3.2 - 3.7	0.11 - 0.13
	Ground to Water	3.5 - 4.0	0.10 - 0.12
Engine Driven:	Gas Fired	1.2 - 2.2	0.09 - 0.15
	Oil Fired	1.5 - 2.0	0.14 - 0.18
Absorption Cycle:	Gas Fired	1.2 - 1.5	0.13 - 0.16
	Oil Fired	–	0.18 - 0.22
LPHW Boilers:	Gas	0.7 - 0.9 (η)	0.22 - 0.28
	Oil	0.7 - 0.9 (η)	0.30 - 0.39

Figure 21 - C02 System Conversions [41]

5.2 Costs

Of course, as mentioned previously, heat pumps run off electricity. For the benefits of this study we will assume that said electricity will be taken from the grid. Electricity prices vary frequently, due to various things. Generally, electricity prices can be as high as 4 or 5 times that of gas prices so from the outset, heat pump use might be seen as expensive. The table below compares the costs involved in using various power sources. This study uses a ground source heat pump system.

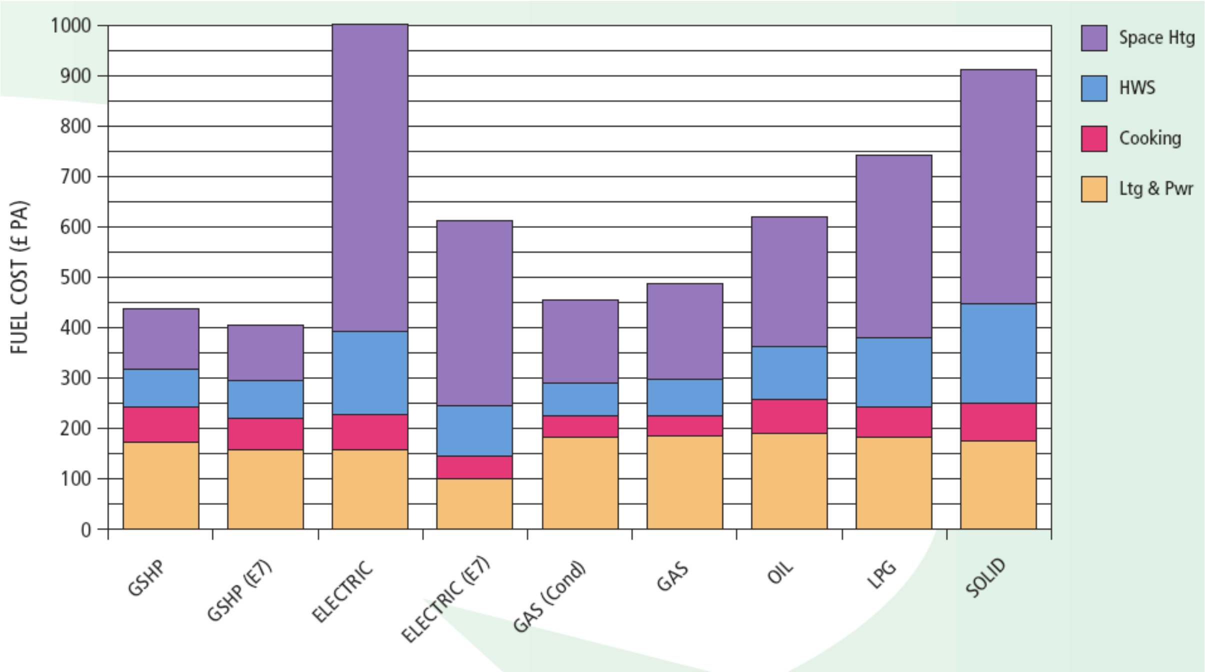


Figure 22 - Fuel Costs for Various Systems [42]

Being used for space heating, hot water heating, cooking, lighting and power, ground source heat pumps prove to cost less than any of the other power alternatives.

5.3 Additional Benefits

There are also several other advantages to utilising heat pump technology.
These include: **[43]**

- No combustive or explosive gases in the building, which is obviously key to ensuring the health and safety of building users.
- No need for an annual safety inspection.
- No local pollution as there is no combustion taking place.
- No flue/ventilation requirements again due to no combustion taking place.
- Low maintenance requirements, although these differ between system variations.

6. SAP Legislation

The Standard Assessment Procedure (SAP) is adopted by the Government as the UK methodology for calculating the energy performance of dwellings. [44] The legislation was updated in order to take into account sites which can generate and export their own energy.

The SAP calculation is based on the energy balance taking into account a range of factors that contribute to energy efficiency. These factors include:

- Construction materials used
- Insulation quality
- Ventilation style and quality
- efficiency of the heating system(s) and controllability
- passive solar gains
- fuel used for heating purposes
- fuel/energy used for cooling, if any
- renewable energy technologies

The calculation does not take into consideration factors which relate to the individual characteristics of the household for example:

- the size of the household and its make-up
- ownership and domestic appliance efficiency
- site-specific heating trends and efficiency

The SAP ratings range from 1-100 with 100 being a zero energy cost. Dwellings which can export energy into the grid can have a SAP rating of over 100.

7. Grants and Initiatives

There are various grants and initiatives available within the UK aimed at increasing the amount of renewable technologies present throughout the country. Many of these are applicable to heat pump installations.

7.1 SCHRI

The SCHRI is the Scottish Community and Householder Renewables Initiative. The initiative is fully funded by the Scottish Parliament and is aimed at aiding the installation of renewables in domestic dwellings. This scheme offers grants for 30 per cent of the installation cost and the total cost of products, of up to a maximum of £4,000, for heating technologies. **[45]**

Grant funding is available for heat producing renewables systems as well as electricity generating renewable technologies which are eligible for clean energy cash back incentives such as Feed-in Tariffs.

There are different types of renewable heating technologies available, and those covered by the grant scheme are:

- Ground source heat pumps.
- Air source heat pumps.
- Water source heat pumps.
- Wood fuel boilers.
- Automated feed stoves.
- Connections to the Lerwick District Heating System
- Solar thermal water heating.

This grant scheme applies only to residential buildings in Scotland. The application must be made by the owner and occupier of the property and the property must be used by said owner or their family as their principle private residence.

The grant is not available for businesses or leased properties but properties with a mixed residential and business usage may still be eligible for a grant.

To be eligible for payment of the grant, the applicant must undertake the following energy efficiency measures where these are appropriate and practical.

- Loft insulation to 270mm where practical.
- Cavity wall insulation (where there are cavity walls).
- Use low energy light bulbs in all appropriate light fittings.
- Install basic controls on your heating system, including thermostats and a programmer or timer for the property as a whole (applies only if not upgrading or changing the controls as part of a renewables heat installation).

7.2 LCBP (Now Closed)

The Department of Energy & Climate Change's Low Carbon Buildings Programme has unfortunately now closed. [46]

Those eligible for a grant included private individuals who own their own home and reside in properties located within England, Wales, Northern Ireland or Scotland (excluding the Isle of Man and the Channel Islands).

Technologies that were available for subsidy under this scheme were:

- Solar thermal hot water
- Ground source heat pumps
- Air source heat pumps
- Wood fuelled heating (Biomass)
- Solar photovoltaics (PV)
- Wind turbines
- Small scale hydro

The subsidies available for heat pumps specifically were as follows:

Table 6 – Heat Pump Grants under LCBP [46]

Technology	Maximum Grant Amount	Grant Offer Validity Period
Ground source heat pumps	Overall maximum of £1,200 **or** 30% of the relevant eligible costs, whichever is the lower	6 months for existing buildings 6 months for buildings under construction
Air source heat pumps	Overall maximum of £900 **or** 30% of the relevant eligible costs, whichever is the lower	6 months for existing buildings 6 months for buildings under construction

These subsidies will hopefully be replaced in the near future with equivalent schemes as the LCBP funding scheme was an extremely attractive funding opportunity.

7.3 RHI (Possible Future Incentive Opportunity)

On 1 February 2010, the Government published a consultation on the introduction of a Renewable Heat Incentive (RHI) scheme, which it aims to introduce in April 2011. The scheme was presented and opened for feedback until Monday 26th of April. This feedback will be used to amend the scheme before decisions are made about its implementation. **[47]**

The Renewable Heat Incentive (RHI) will provide financial support for those who install renewable heating systems which qualify for support under the scheme.

The range of technologies that are suggested to be included is as follows:

- Air source heat pumps.
- Ground source heat pumps.
- Other geothermal energy.
- Solar thermal.
- Biomass boilers.
- Renewable combined heat and power.
- The use of biogas and bioliquids.

The incentive is intended to support heating at various scales. Unlike the SCHR Initiative, in addition to including households, businesses, offices, public sector buildings and industrial processes in large factories will also qualify for subsidy.

Tariff levels have been calculated to bridge the financial gap between the cost of conventional and renewable heat systems at all scales.

A breakdown of the tariffs offered by the RHI can be found in appendix C.

8. Heat Pump Market

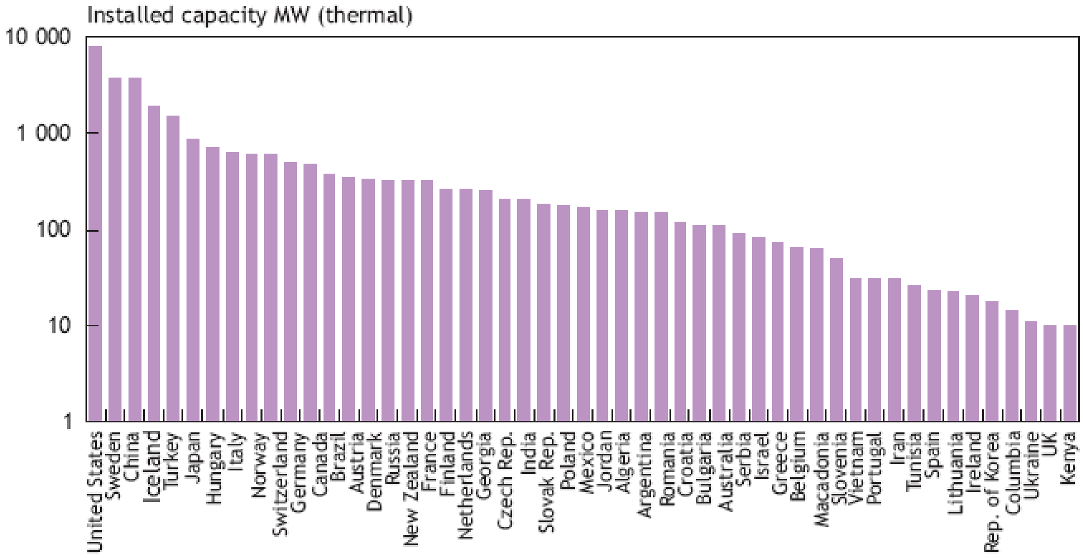
8.1 Introduction

The majority of information available on the usage of heat pump technology is for ground source heat pump systems. Therefore, the available information will be used as a guide only in order to indicate the level at which both the air source and ground source heat pump markets sit worldwide.

The popularity of heat pumps is steadily increasing, with many nations across the world, and in Europe in particular, having considerable capacities. Despite the impressive figures relating to these respective countries, the UK market lags significantly behind them. We will look at these countries, their heat pump capacities and we'll look at what the UK is doing to pull alongside other nations in order to fulfil the countries undoubted potential.

8.2 Worldwide Heat Pump Market

In 2005, geothermal energy was used to generate 56.8 GWh of electricity with an installed capacity of 8.9 GW in 24 countries worldwide, with three times as many countries claiming to produce useful heat using geothermal sources with a total capacity of around 28 GW of energy. The installed capacity of the leading countries is shown in figure 23 below:

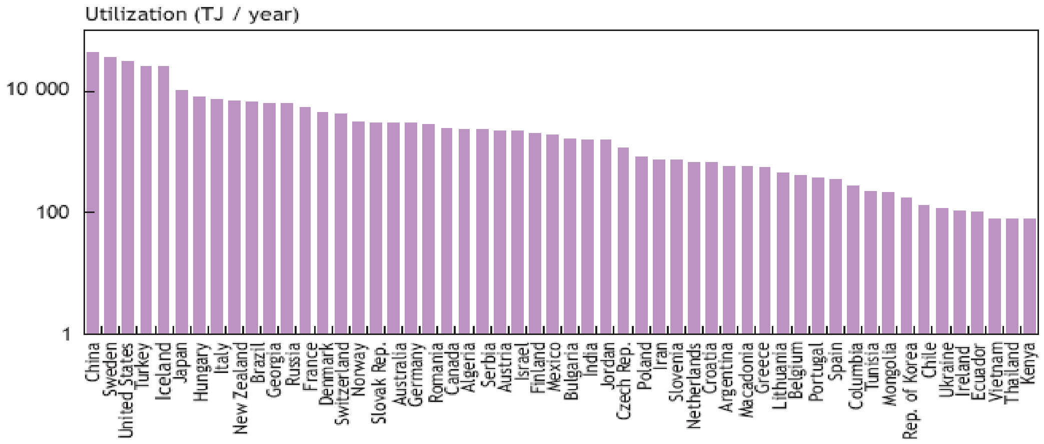


Source: GIA, 2006.

Figure 23 - Installed Geothermal Capacities of Leading Countries [48]

The majority of countries with considerable capacity can be found in Europe. The USA, China and Japan are the only non-European countries in the top list of geothermal heat capacities.

Of this installed capacity, the annual utilisation of that heat energy by country is as follows:



Source: Lund et al., 2005.

Figure 24 - Utilization of Geothermal Energy in Leading Countries [49]

Of this geothermal heat utilisation, the following pie-chart below gives a breakdown of the various usages of the geothermal energy produced and then consumed:

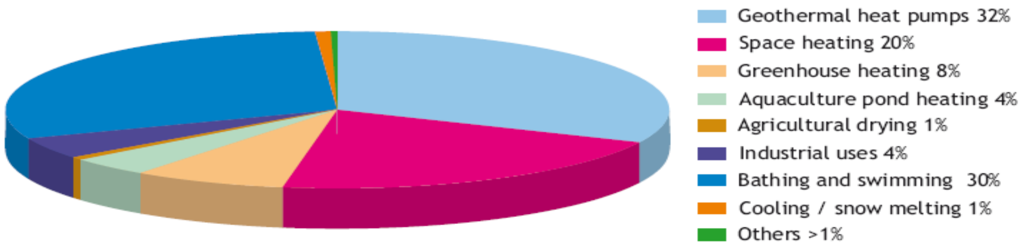


Figure 25 - Uses of Global Geothermal Energy [49]

With regards to useful energy produced by heat pumps as opposed to geothermal energy in its many forms, the following table is extremely informative. In order to form an understanding of who the major players are with regards to pure capacity and capacity in relation to the size and population of a respective nation, the following countries were ranked in order of Installed Capacity, Energy Use, Capacity per Area, Capacity per Capita, Energy per Area and Energy per Capita:

Table 7 - World Leaders in Heat Pump Utilisation [50]

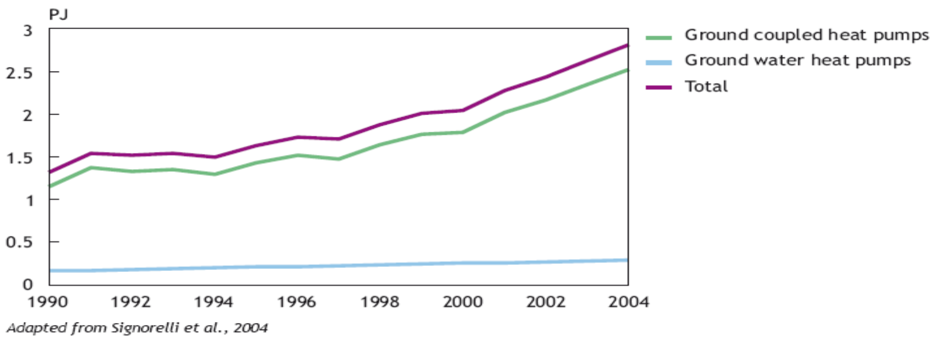
Rank	Installed Capacity (MWth)	Energy Use (TJ/yr)	Capacity per Area (MWth/km^2)	Capacity per Capita (MWth/Capita)	Energy per Area (TJ/yr/km^2)	Energy per Capita (TJ/yr/Capita)
1	USA	Sweden	Switzerland	Sweden	Denmark	Sweden
2	Sweden	USA	Sweden	Norway	Sweden	Denmark
3	China	China	Denmark	Switzerland	Switzerland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

As we can see from the table above, European countries again take up the majority of the high ranking positions in terms of heat pump utilisation. In terms of Energy per Area and Energy per Capita, European countries also dominate the top ranking positions.

The only countries outside of Europe that appear in the top 5 in any of our categories are the USA and China. Despite the fact that each of these has considerable capacity, their capacity and energy use with respect to their land area and capita ratios are relatively poor. Canada can be added to this category as it also has a considerable capacity but its ratio of capacity and energy against area and capita is considerably lower than European competitors.

What these European nations have in common is that governmental support in terms of subsidies and grants has been available for several years. Just glancing at a couple of European examples, we can see that the implementation of their incentive schemes were much earlier than the prominent ones introduced in the UK and that these have had a significant and positive effect on the heat pump market in their respective countries.

In **Switzerland geothermal** heat pump utilisation grew substantially between 1990 and 2004 as can be seen on the following graph:

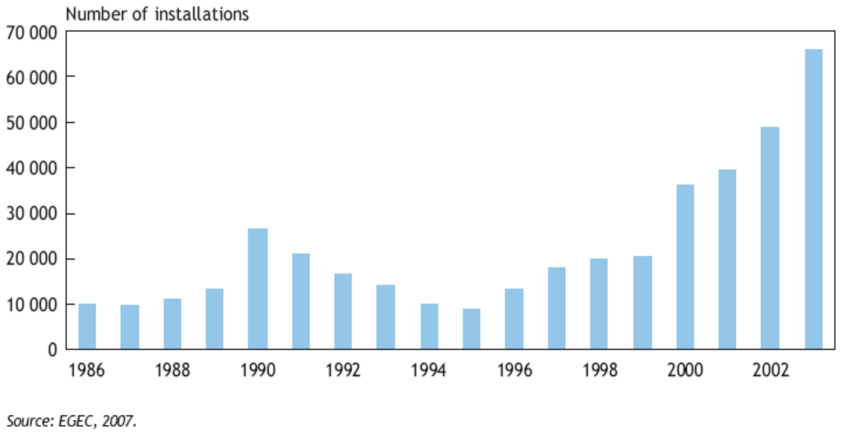


Adapted from Signorelli et al., 2004

Figure 26 - Swiss Geothermal Heat Pump Generation [51]

This growth was supported by the Energy 2000 Action Plan and its successor, the Swiss Energy Action Plan (Swiss Energy).

Similarly the Swedish market has boomed significantly during the 80s and 90s with varying government supported policies as can be seen in the graph below:



Source: EGEC, 2007.

Figure 27 - Geothermal Heat Pump Installations in Sweden [52]

This boom in the Swedish market was paralleled by the 1993 The Swedish Agency for Economic and Regional Growth Procurement Support plan.

Throughout the high ranking ground source heat pump using countries in Europe, there are similar incentives being introduced at similar times, from the late 1980s, throughout the ‘90s and onwards. For this reason, heat pump markets grew at a significant pace in these countries, whilst the UK lagged behind due to poor awareness levels and a lack of funding.

8.3 Improvements to UK Awareness and Available Incentives

The available UK heat pump incentives have been discussed in section 7. The nature of these and the fact that the Renewable Heat Incentive, which will come into play in April of next year, provides such attractive enticement will boost the UK heat pump market significantly.

It is clear that there is a heightened awareness of the global warming plight and the ability of heat pump technology to significantly reduce our carbon emissions. Many politicians and governmental representatives have been quoted in the press suggesting that there will be a bright future for heat pumps in the UK. Pressure from energy experts in influential positions can only strengthen the technology’s case:

Professor Mackay, the recently appointed Chief Scientific Officer for the Department of Energy and Climate Change, said recently: “Setting fire to chemicals like gas should be made a thermodynamic crime. If people want heat they should be forced to get it from heat pumps. That would be a sensible piece of legislation.” [53]

Tony Grayling, head of Climate Change and Sustainable Development at the Environment Agency, said: “Ground source heating is a rapidly growing technology that has the potential to produce at least 30 per cent of the country’s renewable heat needs, but it needs financial support in order to grow. We would like to see this technology given adequate financial support through the new Renewable Heat Incentive to meet its full potential in the UK.” [54]

The above quotes suggest that the level of awareness that was so lacking in previous generations has now been established.

So, how can we quantify the expected growth to the heat pump market over the coming years? Of course it is difficult and with any forecast, the results can only be taken as a guide. The Environment Agency constructed growth and high growth scenarios starting from a 2009 baseline. The rate of market expansion under each scenario is determined by assumptions made about market barriers and the effect of the Renewable Heat Incentive.

The results of the investigation produced a growth scenario that suggested that in 2020 there will be 320,000 GSHP systems installed in the UK, with an annual installation rate in 2019 of 40,000. The high growth scenario predicts an annual installation rate that is a factor of ten higher, at 400,000 in 2019, and results in a total of 1.2m installed systems. [54]

Whether these predictions can be achieved remains to be seen, but it is certain that the UK Heat Pump Market has a healthy future.

9. Poolewe Swimming Pool

9.1 Introduction

Poolewe Swimming Pool *(http://www.poolewepool.co.uk/)* was the first community owned and privately funded swimming pool to be built in Scotland, and possibly the UK. The facility is a registered charity managed and is supported by the Highland council. The building is 16 years old and provides swimming facilities for the local community all year round and is available for use to tourists during the summer months. The front entrance of Poolewe Swimming Pool is shown below:

Figure 28 - Poolewe Swimming Pool Front Entrance

The complex is situated in Poolewe, a small village about 75 miles (120 km) north-west of Inverness, Scotland. A satellite imagine of Poolewe can be seen below:

Figure 29 - Poolewe on the banks of Loch Ewe from Above [55]

9.2 The Complex

The small building covers approximately 230 square metres of area in addition to an external car park. From the front doorway, the office area and entrance hall can be reached. Adjoined to the entrance hall are a toilet facility, reception area and changing room facilities. The pool hall can then be accessed via either of these changing facilities.

There are two changing rooms, each of area approximately equal to 12.96 square metres (one for males and one female area). The pool hall itself amasses approximately 169 square metres of floor space. A simple plan layout of the complex from a bird's eye view is shown below:

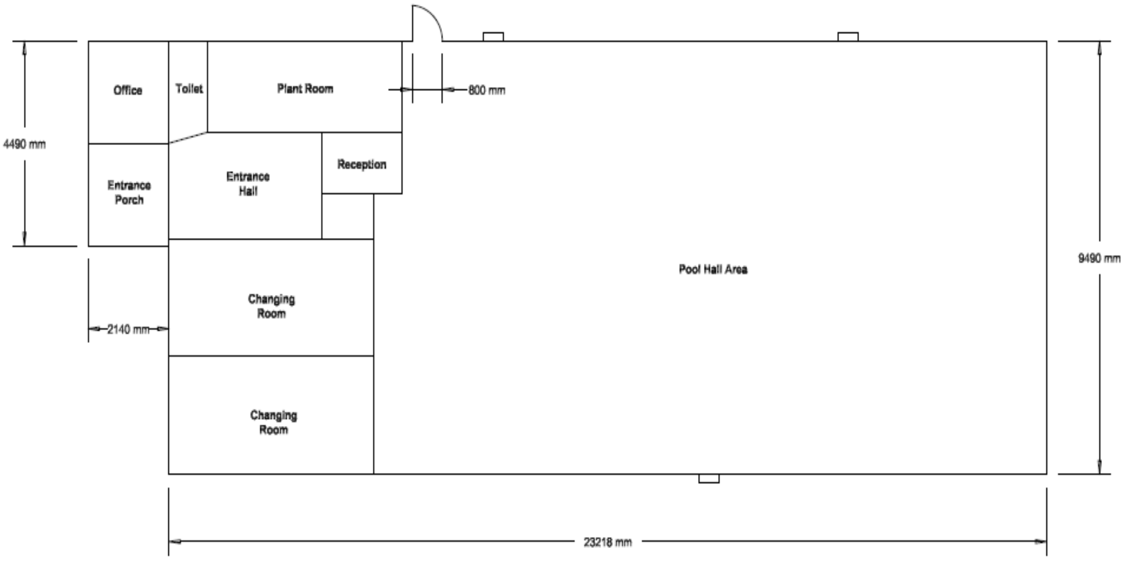


Figure 30 - Poolewe Complex Layout

Opening Times

The Pool facility is open between 10.00-13.00 and 15.00-18.00 from Monday to Friday, from 10.00-15.00 on Saturday and 10.00-14.00 on Sunday throughout the year. The facility aims to operate with ideal internal comfort conditions from opening until closing each day.

Roof Space and Building Fabrics

The roof space at the complex was originally a traditional triangular construction with steel beams over a thin, insulated plywood ceiling. The ceiling of the swimming pool has been absorbing moisture, causing the insulation to become soaked and, hence, ineffective at preventing heat loss. The Pool Committee intend to remove the suspended ceiling (rotting plywood) and open up the pool hall to ceiling height using a 'warm roof'. A picture of the roof spacing is shown below:

Figure 31 - Swimming Pool Roof Space

The existing single skin sheets are to be removed and replaced by 80mm composite panels as are the single skin wall cladding. A data sheet on the insulating material can be found in Appendix B.

This would improve the insulation standard of the pool building and reduce heating loads significantly.

Internal Comfort Conditions

Ideally the pool hall and the changing rooms will be kept at a constant temperature of 26 ˚C. This is slightly higher than one would keep the temperature in a typical workspace or home dwelling as the users will be wet and will require a slightly warmer environment. For similar reasons, the pool hall and changing rooms are kept at around 44-46% relative humidity.

The Pool water itself is kept at 30 ˚C.

9.3 Poolewe Swimming Pool Heating System

Existing Heating System

The existing annual heating demand for both space and water heating is estimated to be around 105,000kWh per annum (prior to building fabric upgrades). The system is an all electric pool using direct electric heating for both pool water and pool hall air heating by electric heater batteries. It has a modern heat pump dehumidifier used simply to dehumidify the pool room air. It also has a small direct electric hot water cylinder for the shower facilities. A schematic of the hydraulic system is shown below:

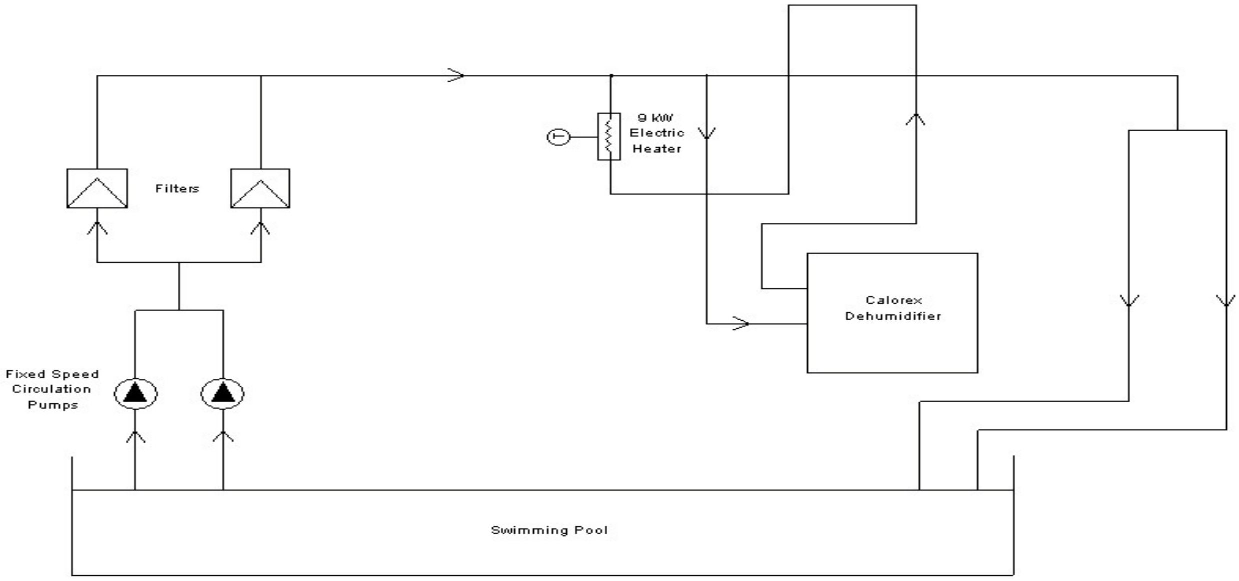


Figure 32 - Poolewe Complex Hydraulic System

Biomass Study

The Pool Committee have been interested in installing renewables into the building since 2003. With the original roofing and wall cladding, a study was carried out in order to investigate the feasibility of installing a biomass-fired heating system. The study included the costs of installing the boiler system, controls and pipe work integration and the boiler house extension. The wood supply would have come from the nearby Laide Forrest.

The eventual annual heating costs were around a quarter of the original costs per annum. This did not go ahead for various reasons, primarily involving problems with accessing an appropriate volume of wood stock.

Possible Heat Pump Installation

The Pool Committee is interested in looking at ASHP and GSHP options to heat the pool air, pool water and changing rooms and to supply DHW.

9.4 Poolewe Environment

Climate

When considering an air-source heat pump in particular, climatic considerations are crucial. As has been mentioned previously, if it difficult for an ASHP to operate efficiently in subzero temperatures. With Poolewe's location, in the far North West of Scotland, cold year-round temperatures would be expected, with considerably low readings during winter.

However, the nature of Poolewe's location is much different to the typical climate of North-West Scotland. Poolewe has a relatively warm climate for its latitude, thanks to the Gulf Stream. The North Atlantic Current of the Gulf Stream, along with similar warm air currents, helps keep Ireland and the western coast of Great Britain a couple of degrees warmer than the east. In Poolewe, with strong warm winds and the warm current he Gulf Stream produces an almost sub-tropical climate at times. While the winter in Poolewe is generally quite cold and wet, the maritime location means that it receives only a few days of snow a year.

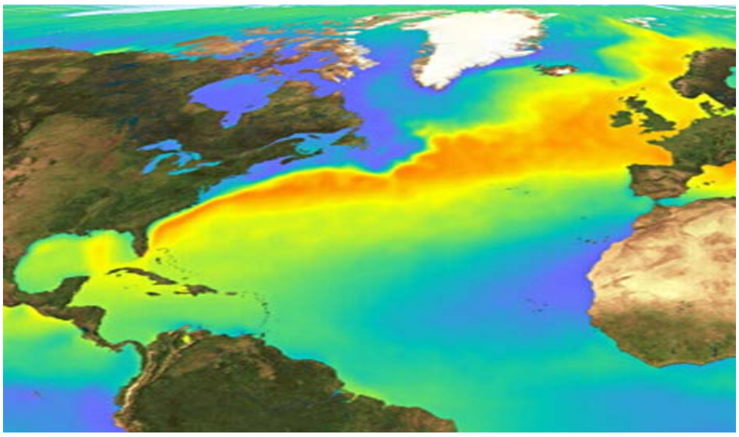


Figure 33 - Depiction of the Gulf Stream in the North Atlantic [56]

Underground Conditions

As has been previously mentioned, if a ground source heat pump is to be considered it is important to be aware of the underground conditions of the site. The top ground layer in Poolewe is peaty soil below which there is fairly coarse boulder clay which drains fairly well. There is probably a hard pan layer which prevents good drainage until it is broken up. This is common throughout the raised beach area around Poolewe and the pool itself sits on an area of raised beach.

A geological map of Scotland can be seen in figure 34 below:

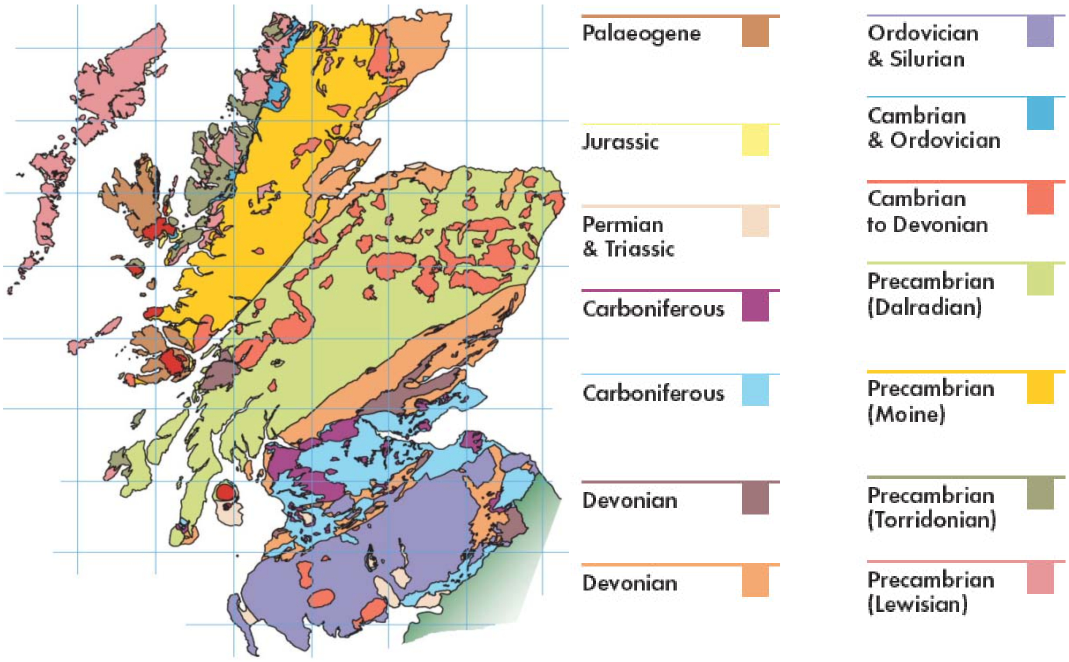


Figure 34 – Geology of Scotland [57]

10. Heat Demand Calculation

A detailed heat demand of the swimming pool centre was required in order to analyse the suitability of various systems with regards to matching supply and demand. Various heat loads under differing conditions were modelled using the ESP-r modelling tool developed at the University of Strathclyde.

ESP-r is an integrated modelling tool for the simulation of the thermal, visual and acoustic performance of buildings and the assessment of the energy use and gaseous emissions associated with the environmental control systems and constructional materials. In undertaking its assessments, the system is equipped to model heat, air, moisture and electrical power flows at user determined resolution.

To access the software and associated downloadable resources, please follow this link:

http://www.esru.strath.ac.uk/Programs/ESP-r.htm

Model Details

Due to the fact that ESP-r only has a limited number of climate files available. The information available for Belfast was used as its environmental conditions matched those at Poolewe remarkably well.

The year-round dry bulb temperatures at Belfast are shown in figure 35 below:

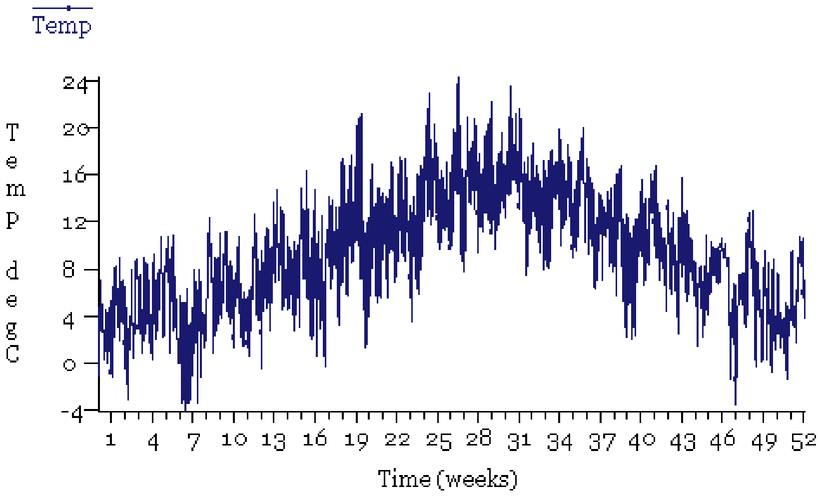


Figure 35 – Esp-r Belfast Dry Bulb Temperature

The trend above matches the Met Office's 'Scotland West' average temperatures graph from between 1970 and 2000:

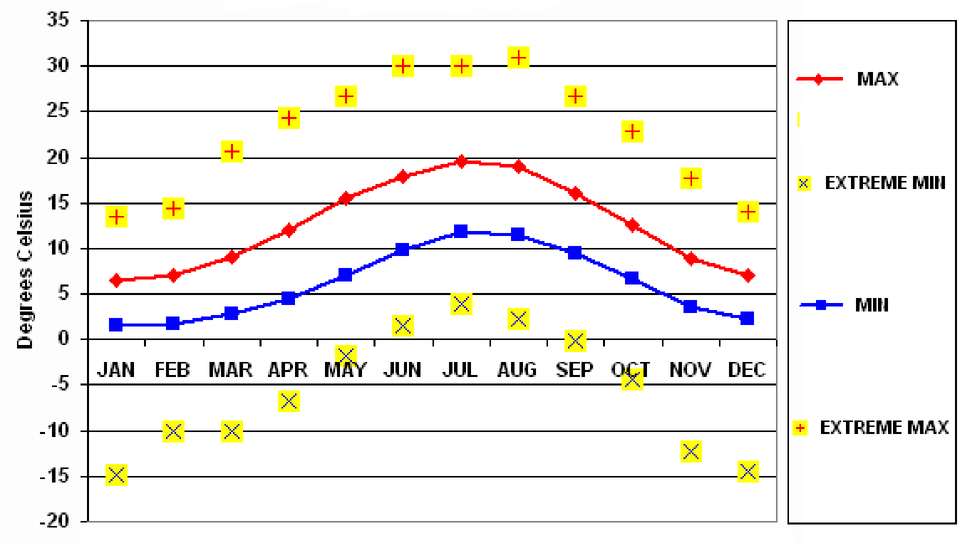


Figure 36 – Scotland West Average Annual Temperatures [36]

Occupancy Levels

The complex, being relatively small has occupancy levels of approximately 4.5 people per hour. Swimming lessons are run for individual children, as well as bulk swimming lessons for school groups of around 15.

Two different occupancy levels were used for Poolewe:

Low Occupancy

Table 8 - Esp-r Low Occupancy

Start	End	Occupants
0	7	0
9	10	1
10	13	5
13	14	5
14	18	5
18	24	0

High Occupancy

Table 9 - Esp-r High Occupancy

Start	End	Occupants
0	9	0
9	10	10
10	13	15
13	14	15
14	18	15
18	24	0

Key Model Details

The external walls have a U-value of 0.25 W/m^{2}K (80mm Trisomet composite panelling). The U-value of the ceiling (with 80mm Trisomet composite panelling) is also 0.25 W/m^{2}K. The roof area is of equal size to the floor area with 2.8m distance between ceiling and floor. The glazing at the North Façade occupies 12.5% of that area. It has a U-value of 1.8 W/m^{2}K. The infiltration rate is 1.5 air changes per hour.

The 2D model created in Esp-r can be seen below:

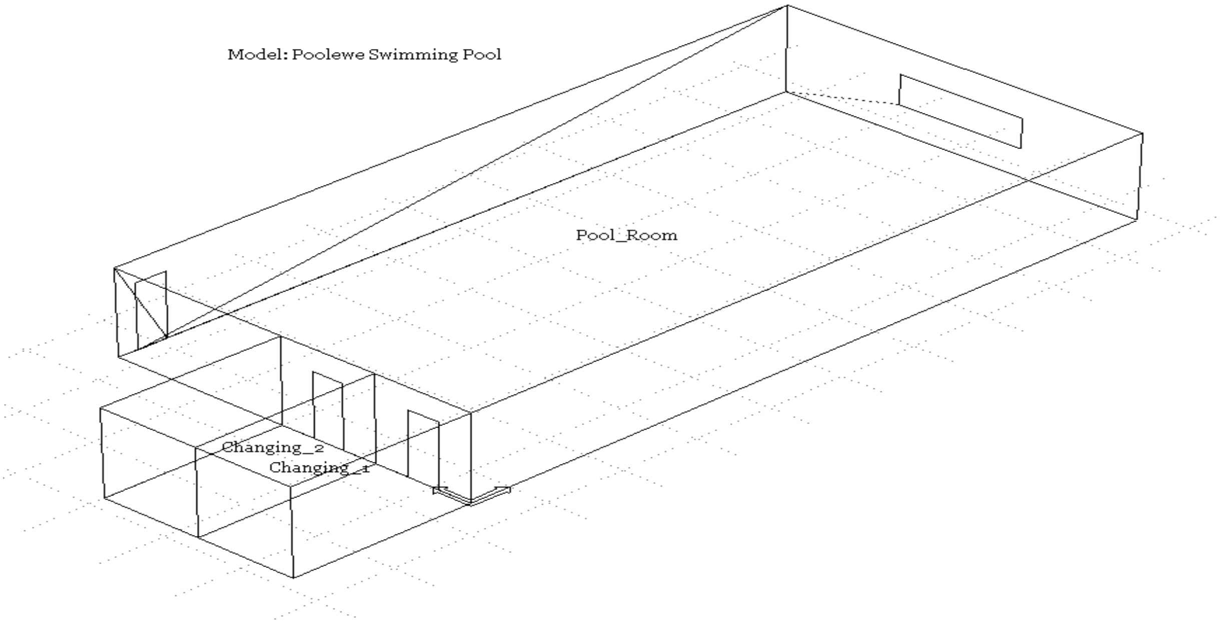


Figure 37 – Esp-r 2D Model

The heating demand calculation results will be used in the following sections.

11. Supply and Demand Matching

The software that we will use to analyse the demand matching capabilities of our air source heat pump will be Merit.

“Merit supports the development of new and renewable energy schemes by searching for matches between user specified demand profiles and possible supply technologies when deployed separately and in any combination. The system has in-built knowledge about typical energy demands and the different possible supplies.”

The software is available for free download here:

http://www.esru.strath.ac.uk/Programs/Merit.htm

The package will be used to calculate not only the ability of an air source system to meet the demands at Poolewe, but also to output the expected electricity consumption of a suitable air source system in order to calculate energy costs.

Air Source Heat Pump

The air source heat pump variety used was from the Delonghi MTD Climaventa Air Source Heat Pump range; the model chosen was the ‘0041’ 14.5 kW rated model. Manufacturer’s data is available in Appendix D. It is available at a variety of different specification.

Data from the manufacturer was entered into Merit in order to simulate that specific model’s performance. The important software model data took the form of a 2-D array from the manufacturer’s manual. This can also be seen in appendix D. Some of the figures were extrapolated from the limited data available.

Model Details

In order to be consistent with the Esp-r heating demand simulation, the Belfast climate data was used here.

The year-long period was split into three sections. Those were:

- January 1st to the 30th of April
- 1st May to the 31st of August
- 1st of September until the 31st of December

This was done in order to establish how the heat pump would respond to the most critical stages of the year. In other words, would the system be able to cope with high loads and low external temperatures throughout the winter?

The simulations were fixed at a set-point of 50°C to model an underfloor heating system requirement.

Results

The results are shown below for differing occupancy levels and varying periods. Note that the demand is displayed in red and the supply in green. Also note that the supply is taken at full power despite this not being necessary at all times when in practical operation. The graph scales have been altered slightly in order to show the supply/demand more effectively.

Low Occupancy: January 1st until April the 31st

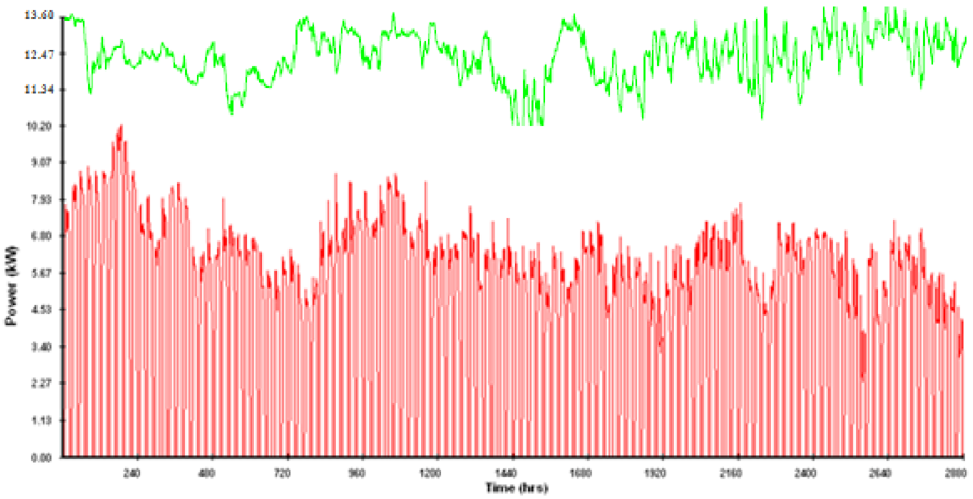


Figure 38 – Merit Low Occ. Jan-April

The heating demand throughout this period was supplied comfortably by the heat pump with considerable surplus.

May the 1st until August the 30th

Figure 39 – Merit Low Occ. May-Aug

Again, the heating demand throughout this period was supplied comfortably by the heat pump with considerable surplus.

September the 1st until December the 31st

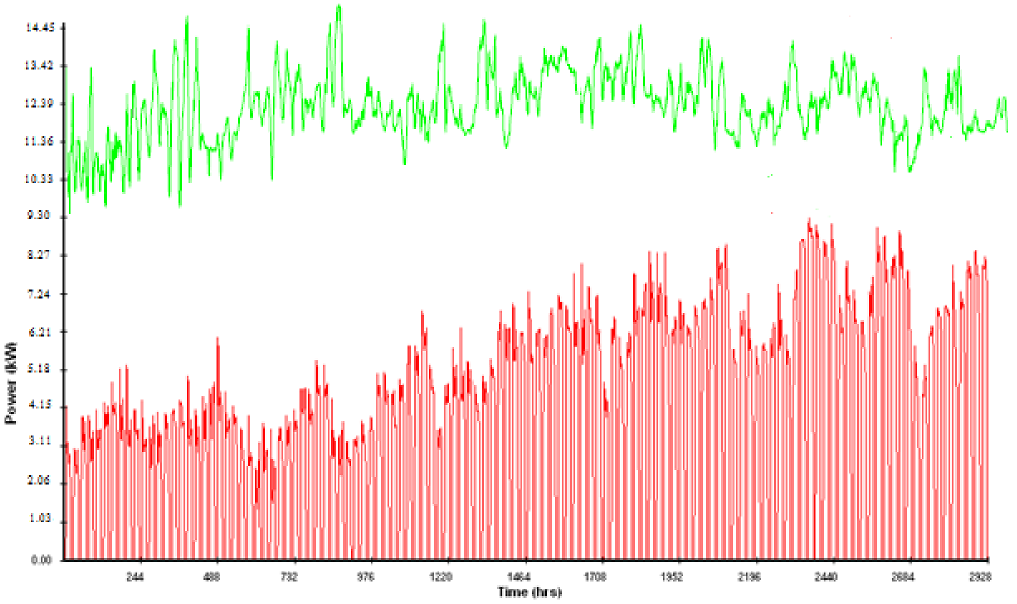


Figure 40 – Merit Low Occ. Sept-Dec

The heating demand was supplied comfortably by the heat pump extremely comfortably with demand only nearing supply capacity towards the end of the year.

As can be see in the above graphs for low occupancy levels at Poolewe, the air source heat pump model chosen can easily supply the heating demands at the complex with some surplus.

High Occupancy: January 1st until April the 31st

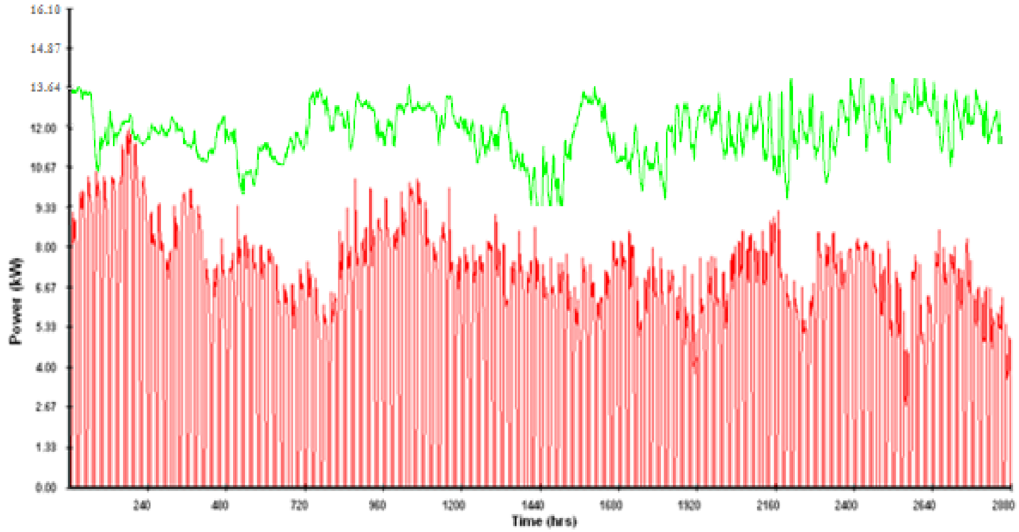


Figure 41 – Merit High Occ. Jan-April

The heating demand is supplied to 100% satisfaction by the heat pump. The heat pump is just able to supply a spike in the demand in mid-January. Generally, this period does not have the same level of security as we had previously, i.e. the gap between demand and supply capacity is not as substantial as during the equivalent period with low occupancy levels.

May the 1st until August the 30th

Figure 42 – Merit High Occ. May-Aug

The heating demand throughout this period was supplied comfortably by the heat pump. Despite being not as comfortable as during low occupancy, the gap between demand and supply capacity is still relatively secure. There is a reasonable level of supply surplus.

September the 1st until December the 31st

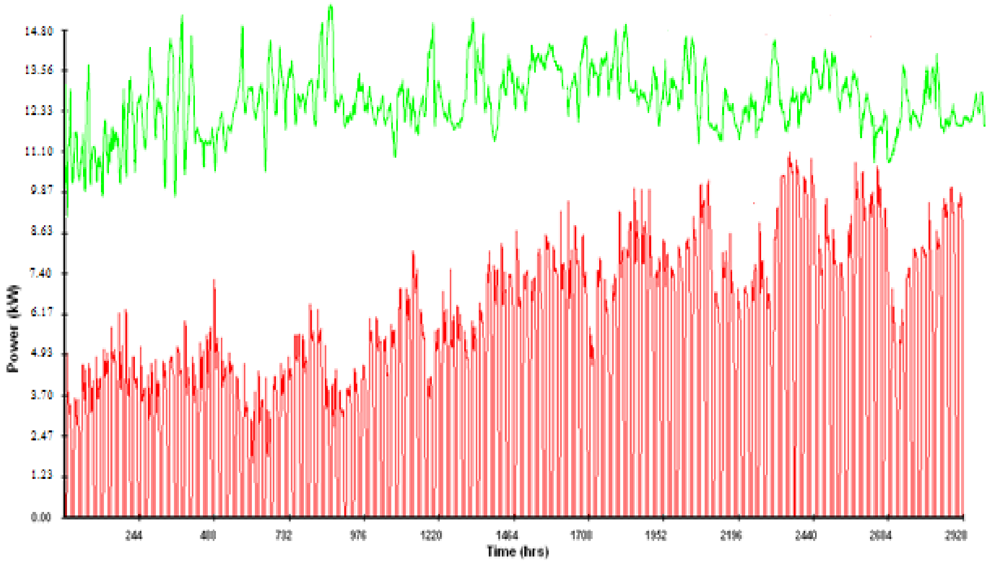


Figure 43 – Merit High Occ. Sept-Dec

The heating demand is supplied to 100% satisfaction by the heat pump. The gap between demand and supply capacity is not significant but this should not cause any major concerns.

During periods of high occupancy, the air source heat pump can comfortably supply demand levels for the majority of time but with less security and supply surplus then throughout periods of low occupancy.

Conclusion

As can be see in the above graphs for supply and demand levels at Poolewe, the air source heat pump model chosen can easily supply the heating demands at the complex with regular surplus.

Using the 14.5 kW air source systems, we can achieve 100% matching with no deficit regardless of whether the building has a low occupancy level or a high occupancy level.

This type of system is more than capable of supplying the heating demand at the Poolewe Swimming Pool Complex.

12. Ground Source Heat Pump Sizing

Introduction

With regards to a ground source heat pump system, the challenge is not whether a ground source heat pump system can satisfy the energy needs at Poolewe, but what size of system the site will require.

There are various programmes available to aid in the sizing of a ground source heat pump system. We will use 2 modelling packages; one for sizing the heat pump and one for analysing its performance.

The GH_{2000}, GLHG-pro and EED software packages were investigated and considered for use.

GH_{2000} is a tool used to size ground heat exchangers for ground-source heat pumps in both commercial and residential systems. It was developed by the CANMET Energy Technology Centre and uses a line/cylinder calculating method.

GLHE-pro is used as an aid in the design of vertical bore-hole ground loop heat exchangers. The programme was developed by Jeffrey D. Spitler of Oklahoma State University. This package uses finite difference modelling.

EED is a PC-program for bore-hole heat exchanger design. Its development has been contributed to by various experts across Sweden and the USA. This package uses a 'G-functions' calculation method.

In this study, the **EED** programme will be used after receiving advice from a ground source heat pump specialist.

The results from the EED programme will be used in a **TRNSYS** analysis. **TRNSYS** is a flexible tool designed to simulate the transient performance of thermal energy systems. The software was developed at the University of Wisconsin and has been used for over 25 years by engineers and researchers to design and simulate the energy performance of systems. [58]

This software will be used to assess the performance of the system suggested by the EED sizing software. It is assumed that the heat pump will meet the demand at Poolewe and TRNSYS will analyse the implications of the necessary heat extraction on the ground and the COP of the system.

Model Details

The air source heat pump variety used was from the Delonghi MTD Climaventa Ground Source and Geothermal Heat Pump range. The model used was the 12.1 kW 0031. Manufacturer's data is available in Appendix E. It is available at a variety of different specification.

We will only use the high occupancy demand levels here. If this demand can be met then the low occupancy levels will be met with ease.

We will use a standard **borehole radius = 80mm** with a **U-tube spacing = 25mm**. The **flow rate = 2700 kg/hr** with a **fluid specific heat = 4.274 kg/kg k** and **specific density = 971.30 kg/m^3**. To mimic the bentonite grouting, **thermal conductivity of fill = 2.600 .42 W/m/k.** [59]

Similar values are suggested by the EED manual.

The simulation was run over 20 years. Underground temperatures were given a **Max Average Temp = 9°C.**

The standards ground properties data from the EED programme were utilised with a **volumetric heat capacity =2160 kJ/m^{3}K** and **thermal conductivity = 3.5 W/m-K**. These figures match the rock-type at Poolewe reasonably well.

The configuration selected was a standard single borehole with a single U-tube as this is the standard for EED. A different configuration may produce a more accurate and attractive output.

Results

The EED simulation suggested an appropriate pipe length of **152.7m** for the heating demand calculated at Poolewe.

This length (along with the model details) were input into the TRNSYS tool and run.

The **average ground temperature** was at its highest in August of in year 1 with a temperature of **9.18°C**. The average temperature was at its lowest in February of year 6 with a temperature of **7.96°C**. Average summer temperatures were of around **9°C** and average winter temperatures were at just below **8°C**. Ground temperature depletion levels are relatively low across the 20-year simulation. This low depletion rate suggested that a positive COP would be found throughout the year.

The **coefficient of performance** levels produced throughout the simulation varies very little. This can be accustomed to the low levels of ground temperature depletion as detailed above. The high COP value of **3.12 in year 1** dropped to a value of **3.08 in year 20** with a **20-year average of 3.11**. Minimal variation from the high original COP value suggests the system is well equipped to supply the demand required comfortably.

The operating conditions of the system state that the inlet temperatures must be between **-5°C and 20°C.** The following graph shows the expected temperatures of the system:

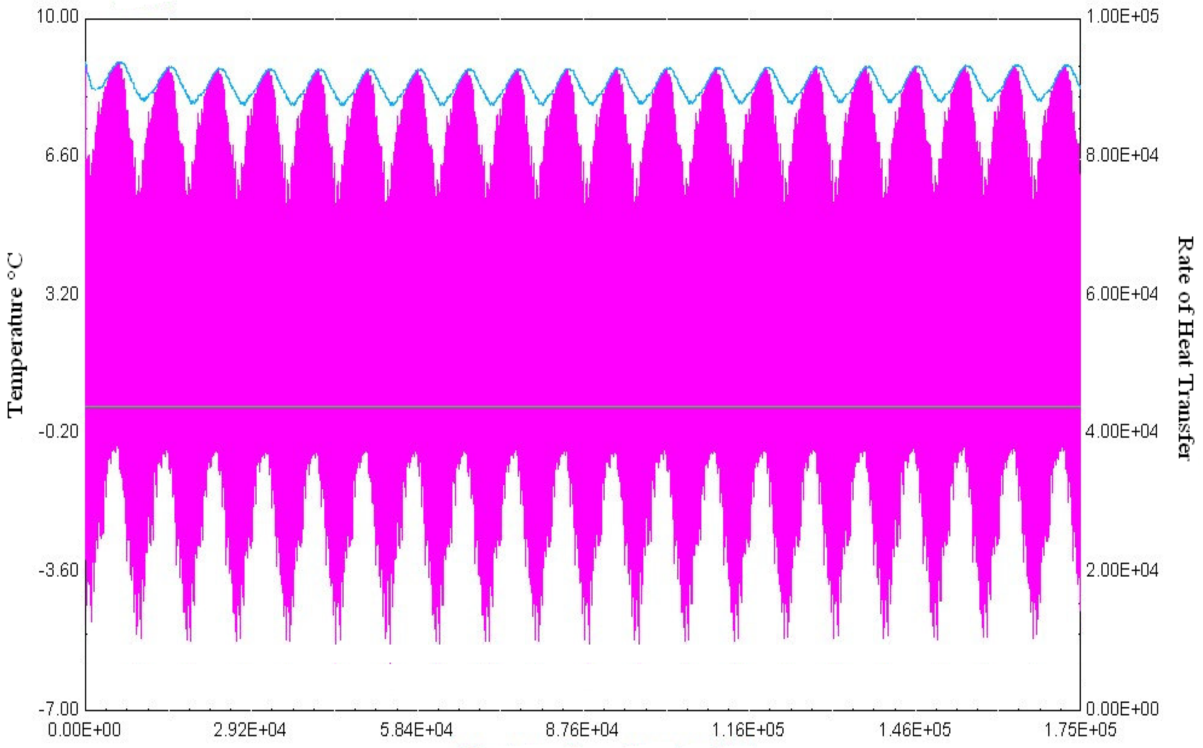


Figure 44 – Poolewe TRNSYS Output

Generally, the system can operate successfully with only extremely rare occurrences of inlet temperatures nearing -5°C. There are instances when the temperature flirts with this boundary, but it is never exceeded. The ability to operate within these boundaries throughout yearly and life-span cycles shows the system has a comprehensive ability to supply the high occupancy demands.

Conclusion

As can be seen in the above results, this type of system is more than capable of supplying the heating demand at the Poolewe Swimming Pool Complex.

A 12.1 kW Ground Source System, with a single borehole with U-tube configuration, using a 152.7m length of pipe would be recommended for installation at Poolewe, based on the system's demand matching capabilities.

13. Heat Pump Costing

Introduction

In this section, we will not take into consideration the cost of the improvements to the building fabrics, as this has been dealt with in another study.

At this particular moment in time (prior to the building fabrics upgrade), Poolewe Swimming Pool Complex pays approximately **10p per kWh** of electricity including VAT.

With a current electrical load of approximately **105,000 kWh per annum**, their annual energy bill is around **£10,500 per annum** or an average of **£875 per calendar month**.

After the building fabrics update, but with the original electric heating system, the annual energy bill would be approximately **£6,214 per annum** or an average of around **£618 per calendar month.**

With the addition of a new air source or ground source heat pump system, significant savings to monthly and yearly energy bills should be expected. We will look at the energy costs involved using each of these technologies. We will also take into consideration the grants and incentives available to the respective technologies and the expected lifespan's (and thus replacement periods) of each.

Air Source System

With the addition of the Air Source Heat Pump system suggested, a **saving of £3090 per annum** or an **average monthly saving of £257.50** would be expected.

Total installation and component costs are expected to be approximately **£13,500** (including controls and pipework).

Under the Renewable Heat Incentive Scheme, a 'small capacity' air source heat pump system is entitles to the following tariff:

Table 10 – RHI Tariff for ASHPs

Technology	Scale	Tariff (p/kWh)	Deemed/Metered	Tariff Lifetime (Years)
ASHP	Up to 45 kW	7.5	Deemed	18

From the information detailed in **section 2.8** we will assume that the expected lifespan of the ASHP with Poolewe's environment to be 10 years.

If we first discount the saving on electrical bills, the initial capital outlay against savings due to the RHI provides a payback period of just over **7.5 years.** A profit of around **£4,500** may be realised if the system lasts the expected 10 years.

Ground Source System

With the addition of the Ground Source Heat Pump system suggested, a **saving of £3,380 per annum** or an **average monthly saving of £282** would be expected.

Total installation and component costs are expected to be approximately **£16,650.**

Under the Renewable Heat Incentive Scheme, a 'small capacity' air source heat pump system is entitles to the following tariff:

Table 11 - RHI Tariff for GSHPs

Technology	Scale	Tariff (p/kWh)	Deemed/Metered	Tariff Lifetime (Years)
GSHP	Up to 45 kW	7	Deemed	23

From the information detailed in **section 2.8** we will assume that the expected lifespan of the ASHP with Poolewe's environment to be 20 years.

If we first discount the saving on electrical bills, the initial capital outlay against savings due to the RHI provides a payback period of just over **9.5 years.** With a significant profit of around **£17,000** being possible if the system lasts the expected 20 years.

Conclusion

Whilst the initial costs of installing a ground source heat pump system are considerably larger than those of installing an air source alternative, a long-term financial study proves that with the attractive incentives available and a significantly longer life expectancy, the most financially viable option would be to install a ground source system.

14. Conclusions

14.1 Ground Source Heat Pumps vs. Air Source Heat Pumps

Introduction

When attempting to find the most suitable form of renewable system to suit a project, several factors must be considered. These factors circulate around the practical, technical and economic aspects associated with the system and its possible installation. Ground source heat pumps and air source heat pumps suit these requirements to varying degrees and so we must understand how these variances relate to our requirements in order to select the most suitable system.

Whether the site is a domestic dwelling, a small office space, a large workspace or a large area within a social housing sector, the requirements are fairly similar.

Installation Expense

Perhaps the most attractive feature of an ASHP is the fact that is relatively simple and cheap to install, especially in comparison to a GSHP. The considerable expense of installing a GSHP, with the need for borehole digging and the installation of a large array of piping, make it very costly indeed. An ASHP installation would be considerably cheaper. Even with the need for additional buffer tank equipment, the ASHP would still be more financially attractive at the point of installation.

Installation Time

With regards to time, the nature of an ASHP system and the fact that it effectively comes 'in a box' makes its installation extremely quick. Similar to the installation expenses above, the digging of boreholes and the fitting of piping arrays makes a GSHP installation a considerably time consuming process.

Space Needed

In a similar vein to the installation time discussed above, ASHPs require significantly less space in which to operate. The compact nature of the ASHP system makes it much more efficient with regards to space usage. This type of system would thus be ideal for a more built up area. Boreholes and other external components mean GSHPs need available outdoor space. The amount of space needed can be considerable but there are methods available to minimise space usage as much as possible.

Geographical Location

With regards to air source systems, the climatic restrictions which have been mentioned discount a minimal amount of locations. Individual areas may have high levels of particle contamination in their air source and these must be taken on their own individual merit. With regards to air temperature, and the related limitations of the systems with regards to this, incompatible sites are uncommon. With a glance at a world average temperature map, we can have some indication of the areas which would not satisfy the low temperature criteria. Such a map can be viewed in figure 45 below:

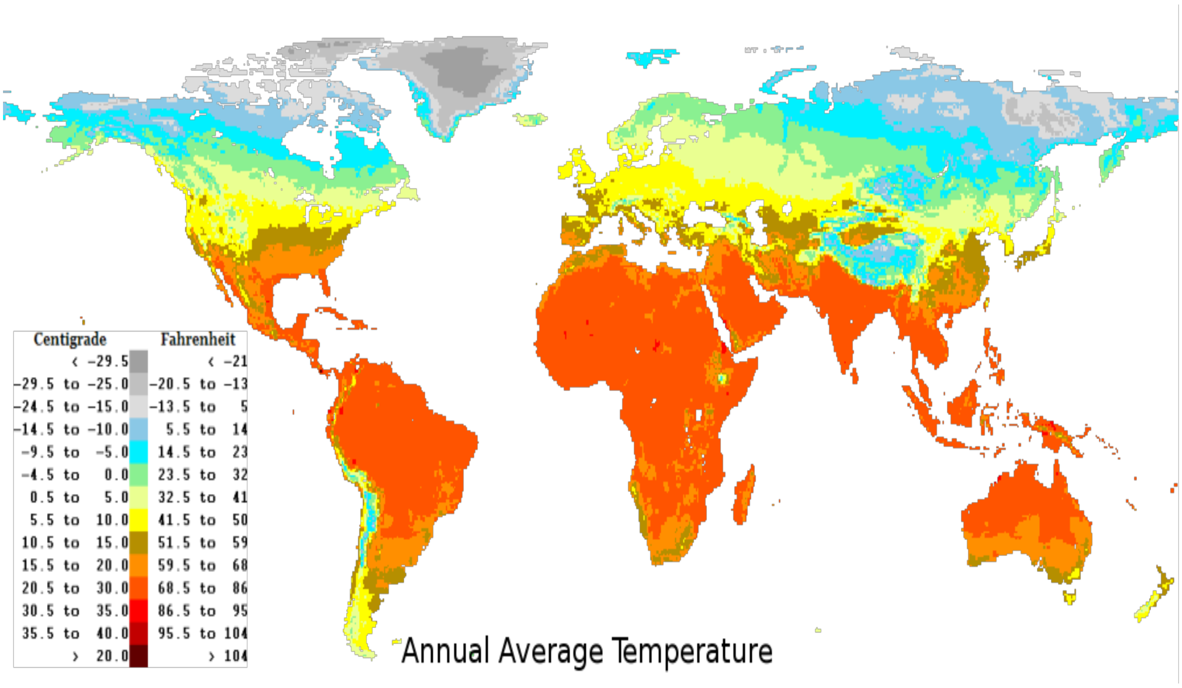


Figure 45 - World Map of Annual Average Temperatures [60]

As can be seen from the above figure, the areas which seem to be unsuitable for ASHPs (namely those in blue and grey) are minimal. The scope for ASHP utilisation is considerable and the temperature issues should have minimal impact on its potential within a global market.

Underground temperatures vary much less than air temperatures do. However, the need for the correct soil varieties and structure and the possibility of poor underground temperatures makes implementing GSHPs globally a similar proposition in terms of worldwide location.

Efficiency

Whilst the general efficiencies of either system are comparable, GSHPs are slightly more effective. Their increased efficiency is due to the fact that their heat source is more constant in its supply and the fact that the defrosting requirements of the system consume useful energy.

Likewise, the SAP ratings of either system show that the GSHP alternative is lower in its carbon and energy efficiency.

Operating Expense

Due to the higher efficiencies discussed above, a GSHP system will have a lower operating expense than the ASHP equivalent.

Short-term Maintenance

Both GSHPs and ASHPs should be low maintenance systems. However, as many of the ASHPs components are located outdoors, they are more susceptible to weather damaging and will thus need to be cleaned or replaced more regularly than their GSHP counterparts.

Lifespan

The external nature of the ASHPs components described above also impact on the systems expected lifespan. As discussed in **section 2.8**, the average ground source system should outlive its air source counterpart by a number of years.

Conclusion

To condense the previous discussion into a more simplistic display, a table below shows the variation of heat pump system which succeeds in fitting positive criteria the most comprehensively? The most compatible system is attributed with a green tick, the least compatible with a red cross and if both systems are considered identical then a blue equals sign will be placed under each.

Table 12 – GSHPs vs. ASHPs

Factor	**GSHP**	**ASHP**
Installation Expense	✗	✓
Installation Time	✗	✓
Space Needed	✗	✓
Geographical Location	=	=
Efficiency	✓	✗
Operating Expense	✓	✗
Short-term Maintenance	✓	✗
Lifespan	✓	✗

In essence an ASHP system would only be installed if both space and time were at a premium. Climatic considerations and geological problems are unlikely to be a factor throughout the majority of the world and especially not in the UK. Assuming initial financial constraints and limited space were not an issue; a GSHP would usually be recommended.

14.2 Poolewe Swimming Pool Recommendations

The study that was undertaken involved calculating the annual heat demand of Poolewe Swimming Pool complex, attempting to match heat pump technologies to supply this heating demand and to calculate the expected payback periods on the expenditure of the installation.

The results of the study suggest that the most appropriate system to install would be a ground source heat pump system. The geological environment around the site lends itself to this technology and it can definitely meet the heating demands of the complex. The system will be able to match the complex's needs fully. An air source system could also supply the site's demands but a financial investigation showed the ground source system to be far favourable.

With a life expectancy of approximately 20 years, the heat demand study, the supply/demand investigation and the financial analysis carried out suggest that installing a ground source heat pump system at Poolewe Swimming Pool Complex should be strongly advised.

14.3 UK Heat Pump Future

As has been alluded to throughout this thesis, the potential for heat pumps within the UK heating market is substantial.

With the availability of attractive schemes and grants such as the imminent Rewneable Heat Incentive, along with an increased awareness of the technologies available and their ability to reduce our carbon emissions, air source and ground source heat pump systems should thrive within the UK heating market.

14.4 Future Work

Future work for this project would be to look at how integrating other renewables in addition to heat pumps would benefit heat pump installations at Poolewe swimming pool and at other low demand sites. This type of investigation may perhaps result in a suggestion to install an air source heat pump (with additional systems) as opposed to the currently proposed ground source alternative.

Typically ground source heat pumps can be supported by a solar thermal system. In this instance, the solar thermal collectors heat water using the sun's energy in order to support the heat pump's own water-heating endeavours.

Typically air source heat pumps are supported by a photovoltaic system. In this instance, photovoltaic panels use the suns energy to generate electricity which can be used in the building or exported back into the electrical grid.

There are many cases in the UK and elsewhere which use these technology mixes in order to satisfy the building they supply's energy needs.

This is most definitely something that could be investigated.

Another possibility would be to look at using alternative heat sources. Within this study, only air source and ground source systems were fully considered. Whilst these systems have undoubted benefits, a more thorough investigation could consider the merits of installing other heat pump variances such as water source technologies.

With ASHPs and GSHPs being by far the most popular system available there is much more data available and the general exposure is superior. However, as heat pumps in general become more popular, it is possible that the further development of alternative heat source pump technologies will produce attractive benefits.

References

[1] - Weiss, W., (2003), Solar Heating Systems for Houses: A design handbook for solar combisystems. London: James and James (Science Publishers) Ltd.

[2] - BBC news: UK to miss CO2 emissions target, 2006, http://news.bbc.co.uk/1/hi/sci/tech/4849672.stm

[3]- International Energy Agency, Renewables For Heating And Cooling EcoheatCool, 2006, P 202

[4] – Design of air source heat pump systems for heating and hot water. February CIBSE Journal P 63

[5] – McLean RC. Energy Systems Analysis: Course Notes. 2006.

[6] - Sumner JA. Domestic Heat Pumps. Dorchester: Prism Press, 1976.

[7] – R.D. Heap, Heat Pumps, Halsted Press, 1979, page 11.

[8] – Heat Pump Centre, About Heat Pumps
http://www.heatpumpcentre.org/en/aboutheatpumps/Sidor/default.aspx

[9] - R.D. Heap, Heat Pumps, Halsted Press, 1979, page 33.

[10] – Heat Pump Centre, About Heat Pumps, Heat Pump Performance
http://www.heatpumpcentre.org/en/aboutheatpumps/heatpumpperformance/Sidor/default.aspx

[11] - R.D. Heap, Heat Pumps, Halsted Press, 1979, page 22.

[12] – Heat Pump Centre, About Heat Pumps, Heat Pump Working Fluids
http://www.heatpumpcentre.org/en/aboutheatpumps/heatpumpworkingfluids/Sidor/default.aspx

[13] – UNEP, the Montreal Protocol on Substances that Deplete the Ozone Layer, 2000

[14] – Iain Hazell, the HCFC Refrigerant Ban – Are You Ready? Ezine Articles, 2009.

[15] - Sanyo CO2 ECO Air Source CO2 Heat Pump, Aircon Warehouse

[16] - R.D. Heap, Heat Pumps, Halsted Press, 1979, page 53

[17] – Heat Pump Centre, About Heat Pumps, Heat Sources

http://www.heatpumpcentre.org/en/aboutheatpumps/heatsources/Sidor/default.aspx

[18] – P Grigg and M McCall, Domestic heat pumps: performance and economics, Crown 1988, P 27

[19] - Models for Assessing and Monitoring Groundwater Quality (Proceedings of a Boulder Symposium, July 1995).

[20] – EB – Eco Build, Heat Recovery Ventilation http://www.ecobuild.ie/images/Heat-Recovery.jpg

[21] - T C O’Connor and J a McGovern. Air source heat pumps under northern European climatic conditions, 1980

[22] – Danfoss Heat Pumps, Recent Air Source Heat Pump Project, 2008

[23] – Damon Hart Davis, Earth Notes, Domestic Ground Source Heat Pumps, 2007

[24] – Heat Pump Association, What is a Heat Pump? Types of Heat Pump http://www.heatpumps.org.uk/TypesOfHeatPumpSystems.htm

[25] - Rybach, L. and Sanner, B. (2000), “Ground-source heat pump systems – The European experience”.

[26] - British Geological Survey. Ground Source Heat Pumps: Development of Geo-Reports for Potential Site Characterisation. British Geological Survey 2004; CR/05/217N; Issue 1.2.

[27] – Jim Wilson, Electronics Cooling, Thermal Diffusivity, August 1st 2007

[28] - Curtis R. Earth Energy in the UK. In: Popovski K, Sanner B, editors.

International Geothermal Days; 2001; Skopje, Bad Urach.

[29] - Energy Efficiency Best Practice in Housing. Domestic Ground Source Heat Pumps: Design and Installation of Closed Loop Systems. Energy Saving Trust 2004; CE82.

[30] - Florides G, Kalogirou S. 2007. Ground Heat Exchangers – A review of

Systems, Models and Applications. Renewable Energy

[31] – SB Geothermal, Types of Geothermal Heat Pump Loop System http://www.sbgeothermal.com/sbgeothermal/images/vertical-loop.jpg

[32] – Bec Solar, Geothermal Systems, System Types http://www.becsolar.com/images/horizontal-loop.jpg

[33] – Filterclean Water Technologies, System Components http://www.filterclean.co.uk/images/info2geothermal/slinkies.jpg

[34] – Econis Rewnewable Energy Solutions, Air Source Heat Pumps http://www.econicres.com/charts/airsource1.jpg

[35] – Adam Gabbatt, The Guardian, ‘British winter was coldest for 31 years’, 2 March 2010

[36] – The Met Office, Winter 2009/10, UK Statistical Summary, Provisional graph of UK daily mean temperature for Winter 2009/10 (December, January and February)

[37] - The Met Office, Winter 2009/10, UK Statistical Summary, Mean temperature anomaly (difference from average) map for Winter 2009/10 (December, January and February)

[38] - Heat Pump Association, What is a Heat Pump? Types of Heat Pump http://www.heatpumps.org.uk/TypesOfHeatPumpSystems.htm

[39] - Design of air source heat pump systems for heating and hot water. February CIBSE Journal P 64

[40] – IEA, Heat Pump Centre, Renewable Energy for a Cleaner Future

[41] - Heat Pump Association, What is a Heat Pump? Glossary of Technical Terms http://www.heatpumps.org.uk/GlossaryOfTechnicalTerms.htm

[42] - Heat Pump Association, Heat pump news: Saving energy, 2006

[43] – Energy Efficiency Best Practice in Housing, Domestic Ground Source Heat Pumps: Design and Installation of Closed Loop Systems, 2004

[44] – SAP 2009, The Government’s Standard Assessment

Procedure for Energy Rating of Dwellings

[45] – Energy Savings Scotland Home Renewables, Energy Savings Trust http://www.energysavingtrust.org.uk/scotland/Scotland-Welcome-page/At-Home/Grants-and-offers/Energy-Saving-Scotland-home-renewables-grants

[46] – Dept. of Energy and Climate Change, Closure of the Low Carbon Buildings Programme http://www.lowcarbonbuildings.org.uk/

[47] - Dept. of Energy and Climate Change, Renewable Heat Incentive (RHI) http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/policy/renewable_heat/incentive/incentive.aspx

[48] - International Energy Agency, Renewables for Heating and Cooling, Page 51

[49] - International Energy Agency, Renewables for Heating and Cooling, Page 52

[50] - Rybach L. The Advance of Geothermal Heat Pumps World-wide.

Newsletter IEA Heat Pump Centre 2005.

[51] – International Energy Agency, Renewables for Heating and Cooling Adapted from Signorelli et al., 2004, P 87

[52] – International Energy Agency, 2007, Renewables for Heating and Cooling EGEC, P193

[53] – Solar News Portal, The UK heat pump market to experience double-digit growth http://www.solarnewsportal.com/solar_article9557.html

[54] – Environment Agency, Underground technology could produce a third of UK's renewable heat needs http://www.environment-agency.gov.uk/news/114130.aspx

[55] – Google Earth

[56] – Sign of the Times, The Day After Tomorrow http://www.sott.net/articles/show/125454-Fire-and-Ice-The-Day-After-Tomorrow

[57] – Mappery, Scotland Geology Map http://mappery.com/Scotland-Geology-Map

[58] –TRNSYS, The Transient Energy Simulation Tool http://www.trnsys.com/

[59] - Anh-Minh TANG, Yu-Jun CUI, Trung-Tinh LE, A study on the thermal conductivity of compacted bentonites, 2008

[60] – Climate Charts, World Climate Maps, Annual Average Temperature http://www.climate-charts.com/World-Climate-Maps.html#temperature

[61] – Renewable Heat Incentive, Tariff Level Tables http://www.rhincentive.co.uk/eligible/levels/

[62] – Delonghi Climaventa, MTD Air Source Heat Pumps, Data Sheet

[63] - Delonghi Climaventa, MTD Ground Source & Geothermal Heat Pumps, Data Sheet

Appendix

A. Geological Maps of the UK

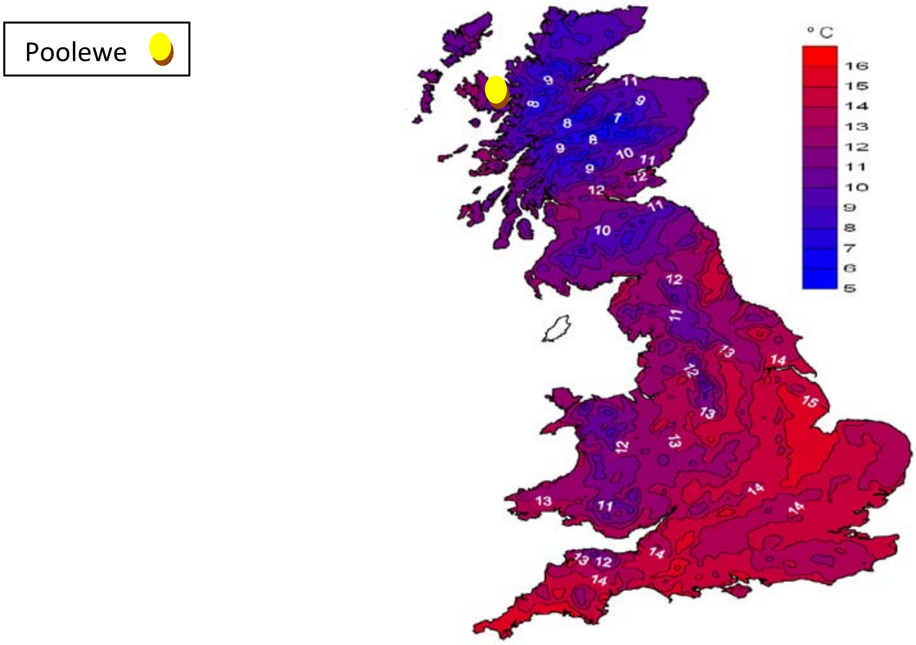


Figure 46 - Estimated temperatures for Great Britain at 100 m depth [26]

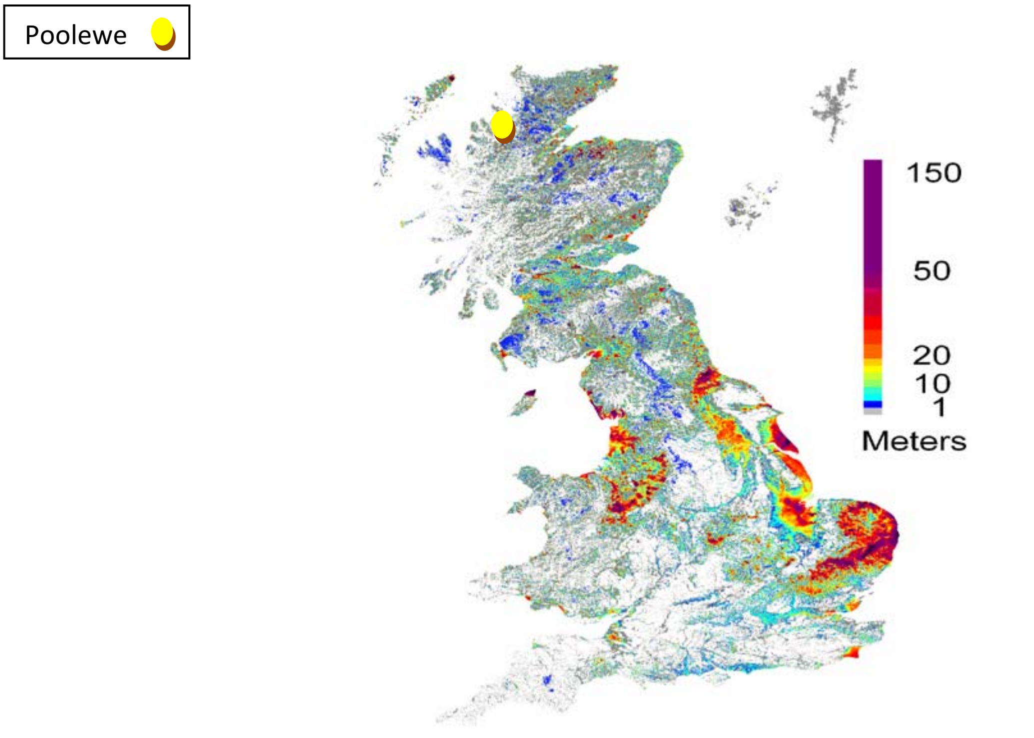


Figure 47 - Superficial Thickness map of Great Britain [26]

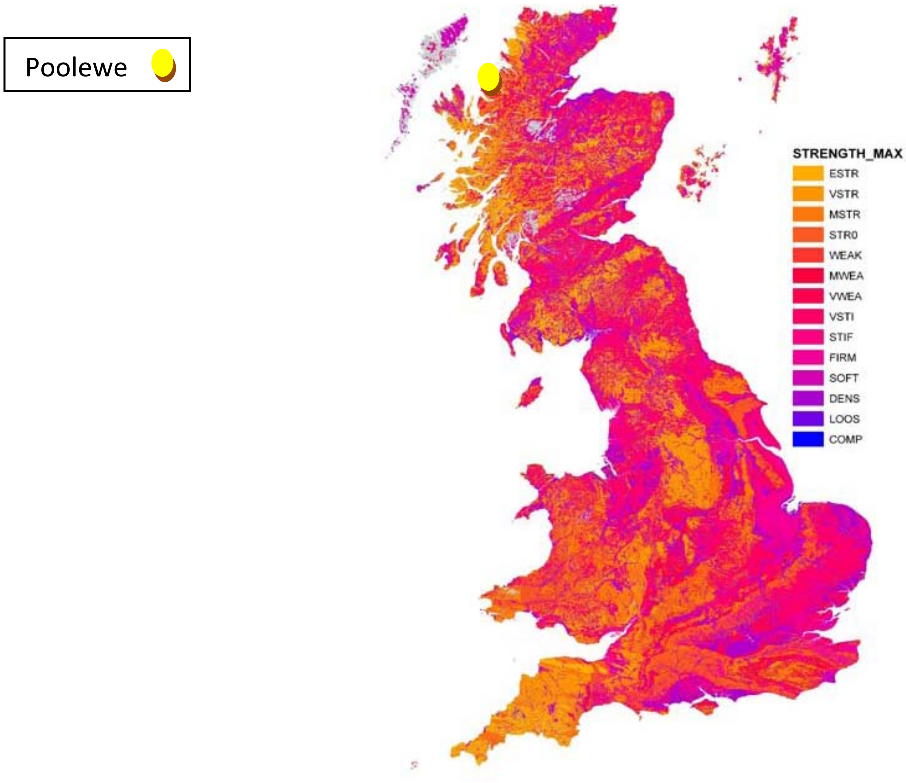


Figure 48 - Engineering Strength and Density Maximum Map of the UK [26]

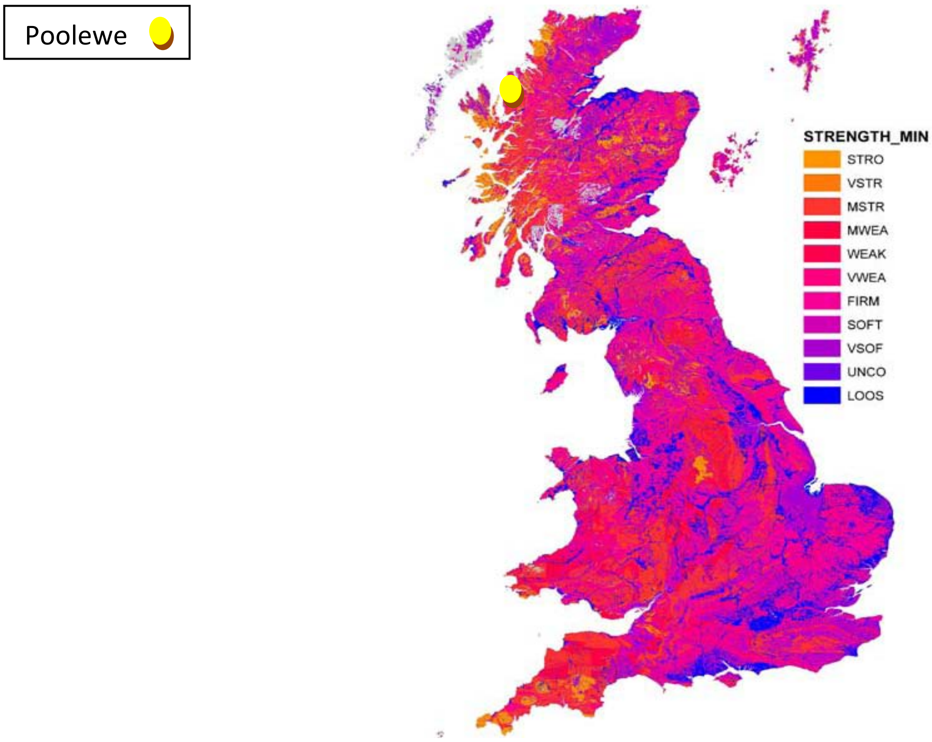
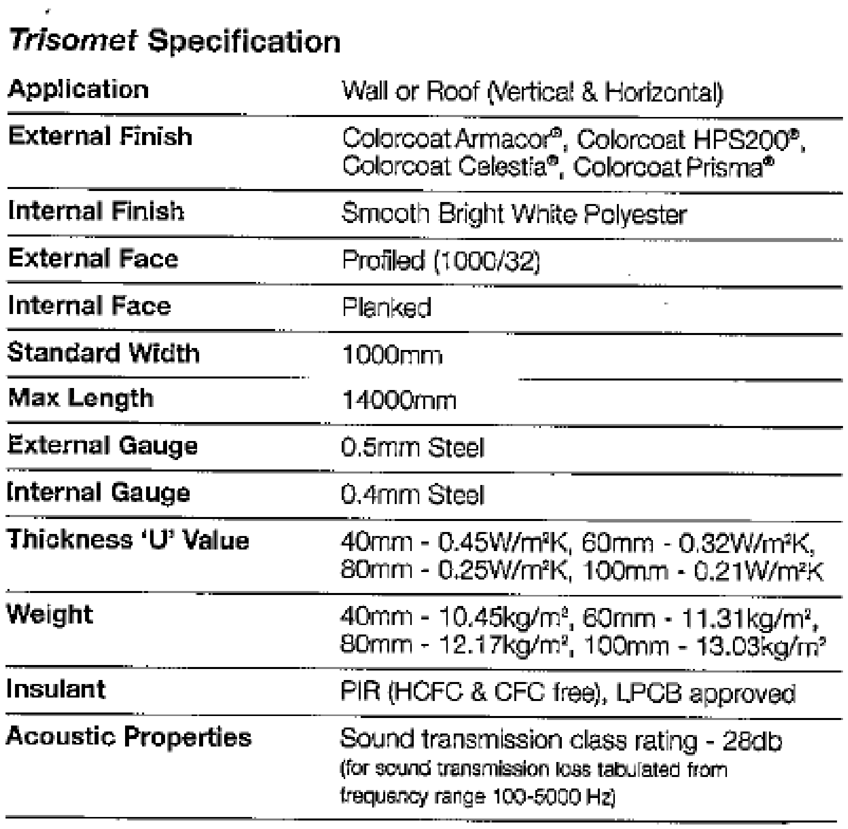


Figure 49 - Engineering Strength and Density Minimum Map of the UK [26]

B. Poolewe Building Fabric Details

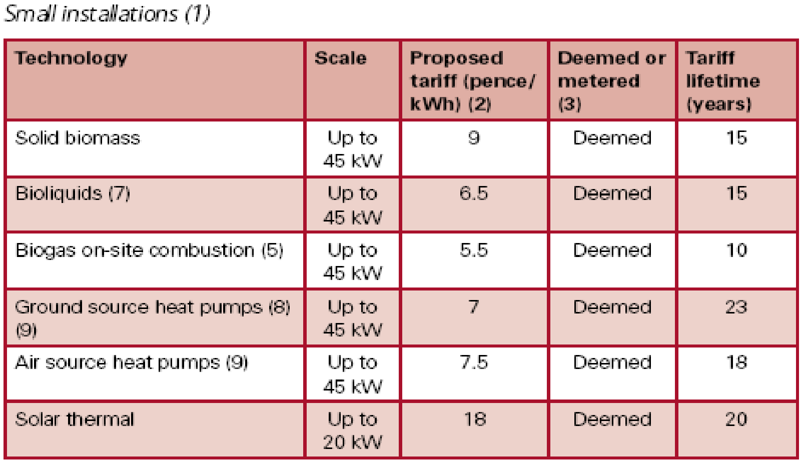


***Trisomet* Specification**

Application	Wall or Roof (Vertical & Horizontal)
External Finish	Colorcoat Armacor®, Colorcoat HPS200®, Colorcoat Celestia®, Colorcoat Prisma®
Internal Finish	Smooth Bright White Polyester
External Face	Profiled (1000/32)
Internal Face	Planked
Standard Width	1000mm
Max Length	14000mm
External Gauge	0.5mm Steel
Internal Gauge	0.4mm Steel
Thickness 'U' Value	40mm - 0.45W/m²K, 60mm - 0.32W/m²K, 80mm - 0.25W/m²K, 100mm - 0.21W/m²K
Weight	40mm - 10.45kg/m², 60mm - 11.31kg/m², 80mm - 12.17kg/m², 100mm - 13.03kg/m²
Insulant	PIR (HCFC & CFC free), LPCB approved
Acoustic Properties	Sound transmission class rating - 28db (for sound transmission loss tabulated from frequency range 100-5000 Hz)

Figure 50 - Poolewe Building Fabrics Upgrade Specification

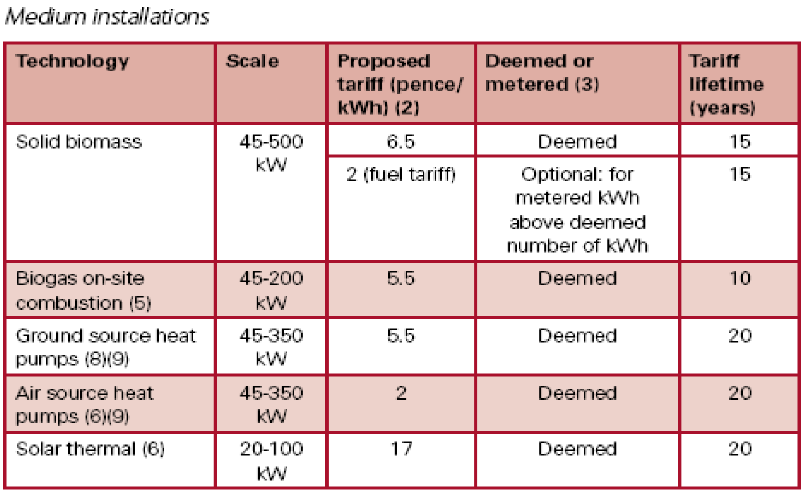
C. Renewable Heat Incentive Tariffs



Small installations (1)

Technology	Scale	Proposed tariff (pence/ kWh) (2)	Deemed or metered (3)	Tariff lifetime (years)
Solid biomass	Up to 45 kW	9	Deemed	15
Bioliquids (7)	Up to 45 kW	6.5	Deemed	15
Biogas on-site combustion (5)	Up to 45 kW	5.5	Deemed	10
Ground source heat pumps (8) (9)	Up to 45 kW	7	Deemed	23
Air source heat pumps (9)	Up to 45 kW	7.5	Deemed	18
Solar thermal	Up to 20 kW	18	Deemed	20

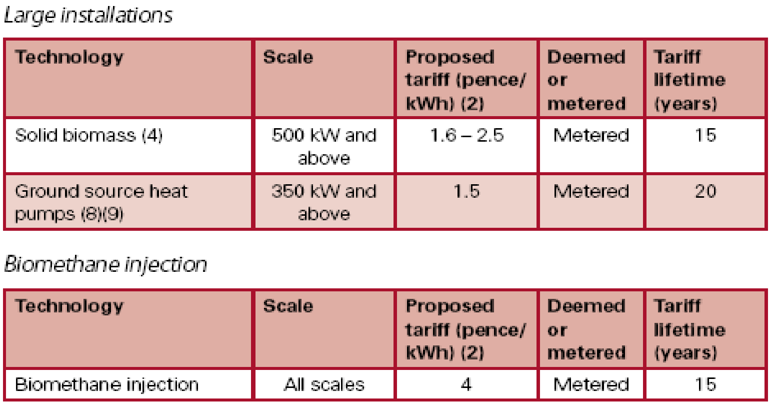
Figure 51 - RHI for 'small installations' [61]



Medium installations

Technology	Scale	Proposed tariff (pence/ kWh) (2)	Deemed or metered (3)	Tariff lifetime (years)
Solid biomass	45-500 kW	6.5	Deemed	15
		2 (fuel tariff)	Optional: for metered kWh above deemed number of kWh	15
Biogas on-site combustion (5)	45-200 kW	5.5	Deemed	10
Ground source heat pumps (8)(9)	45-350 kW	5.5	Deemed	20
Air source heat pumps (6)(9)	45-350 kW	2	Deemed	20
Solar thermal (6)	20-100 kW	17	Deemed	20

Figure 52 - RHI for 'medium installations' [61]



Large installations

Technology	Scale	Proposed tariff (pence/ kWh) (2)	Deemed or metered	Tariff lifetime (years)
Solid biomass (4)	500 kW and above	1.6 – 2.5	Metered	15
Ground source heat pumps (8)(9)	350 kW and above	1.5	Metered	20

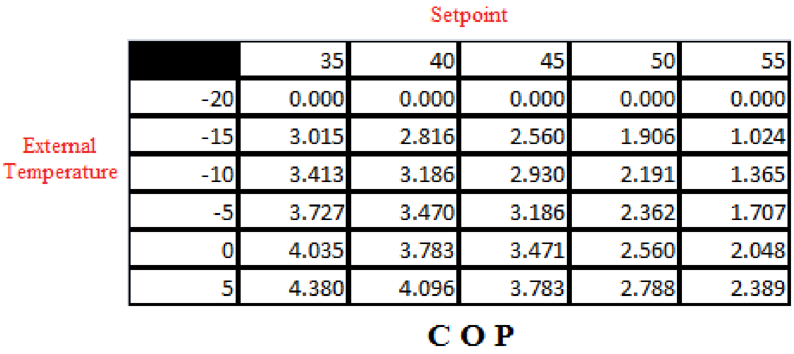
Biomethane injection

Technology	Scale	Proposed tariff (pence/ kWh) (2)	Deemed or metered	Tariff lifetime (years)
Biomethane injection	All scales	4	Metered	15

Figure 53 - RHI for 'large installations and biome thane injection' [61]

D. Air Source Data

Figure 54 - Delonghi Climaveta Air Source Heat Pump [62]



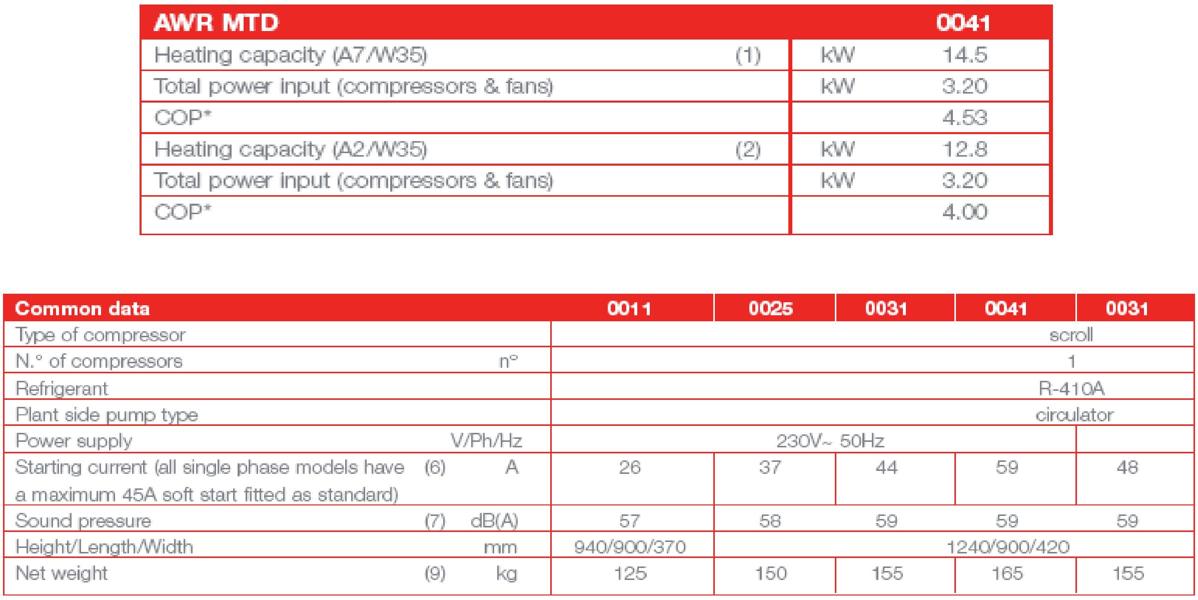
Setpoint

External Temperature

	35	40	45	50	55
-20	0.000	0.000	0.000	0.000	0.000
-15	3.015	2.816	2.560	1.906	1.024
-10	3.413	3.186	2.930	2.191	1.365
-5	3.727	3.470	3.186	2.362	1.707
0	4.035	3.783	3.471	2.560	2.048
5	4.380	4.096	3.783	2.788	2.389

C O P

Figure 55 - COP Variation [62]



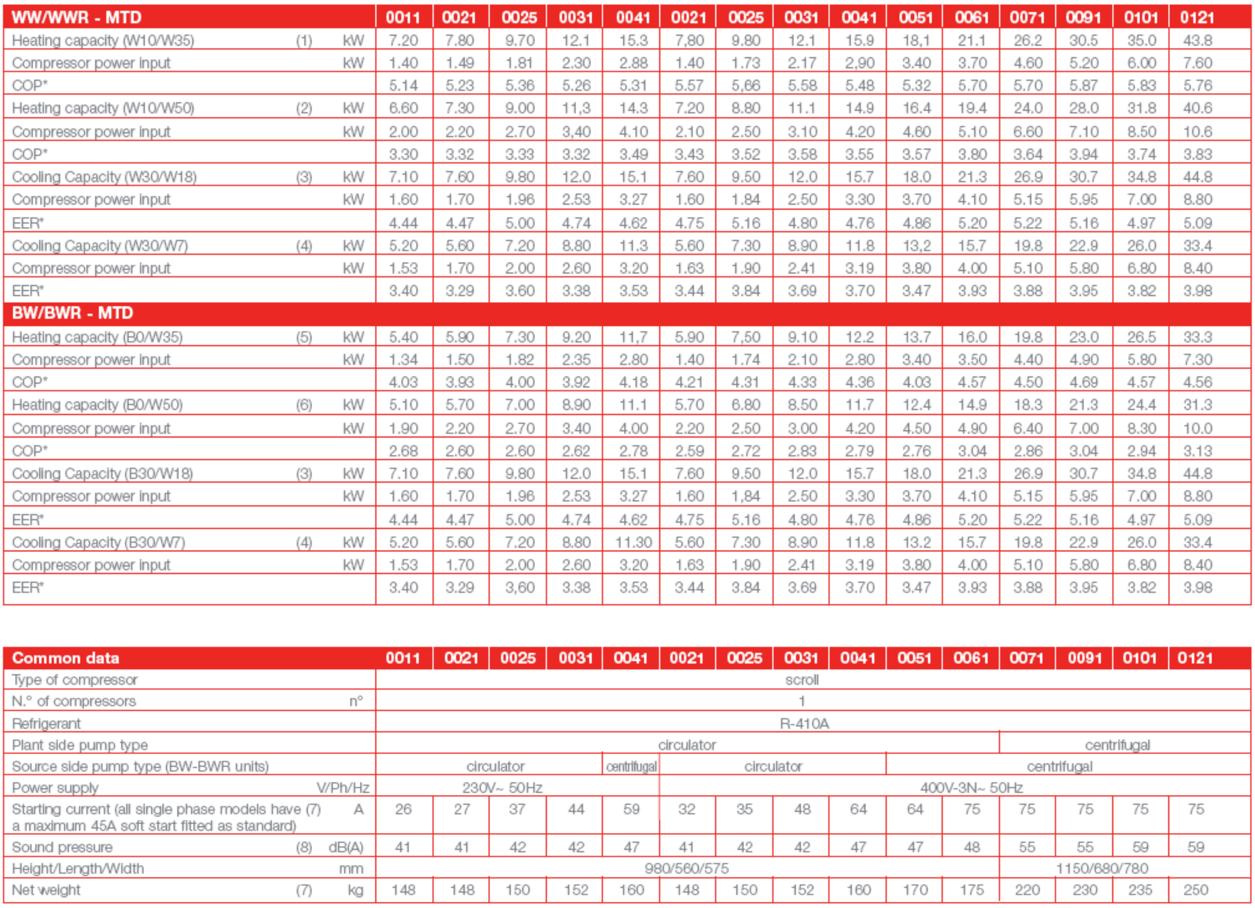
AWR MTD			0041
Heating capacity (A7/W35)	(1)	kW	14.5
Total power input (compressors & fans)		kW	3.20
COP*			4.53
Heating capacity (A2/W35)	(2)	kW	12.8
Total power input (compressors & fans)		kW	3.20
COP*			4.00

Common data			0011	0025	0031	0041	0031
Type of compressor			scroll				
N.° of compressors		n°	1				
Refrigerant			R-410A				
Plant side pump type			circulator				
Power supply		V/Ph/Hz	230V~ 50Hz				
Starting current (all single phase models have a maximum 45A soft start fitted as standard)	(6)	A	26	37	44	59	48
Sound pressure	(7)	dB(A)	57	58	59	59	59
Height/Length/Width		mm	940/900/370	1240/900/420			
Net weight	(9)	kg	125	150	155	165	155

Figure 56 - Air Source Manufacturer's Data [62]

E. Ground Source Data

Figure 57 - Delonghi Climaventa Ground Source Heat Pump [63]



WW/WWR - MTD			0011	0021	0025	0031	0041	0021	0025	0031	0041	0051	0061	0071	0091	0101	0121
Heating capacity (W10/W35)	(1)	kW	7.20	7.80	9.70	12.1	15.3	7,80	9.80	12.1	15.9	18,1	21.1	26.2	30.5	35.0	43.8
Compressor power input		kW	1.40	1.49	1.81	2.30	2.88	1.40	1.73	2.17	2,90	3.40	3.70	4.60	5.20	6.00	7.60
COP*			5.14	5.23	5.36	5.26	5.31	5.57	5,66	5.58	5.48	5.32	5.70	5.70	5.87	5.83	5.76
Heating capacity (W10/W50)	(2)	kW	6.60	7.30	9.00	11,3	14.3	7.20	8.80	11.1	14.9	16.4	19.4	24.0	28.0	31.8	40.6
Compressor power input		kW	2.00	2.20	2.70	3,40	4.10	2.10	2.50	3.10	4.20	4.60	5.10	6.60	7.10	8.50	10.6
COP*			3.30	3.32	3.33	3.32	3.49	3.43	3.52	3.58	3.55	3.57	3.80	3.64	3.94	3.74	3.83
Cooling Capacity (W30/W18)	(3)	kW	7.10	7.60	9.80	12.0	15.1	7.60	9.50	12.0	15.7	18.0	21.3	26.9	30.7	34.8	44.8
Compressor power input		kW	1.60	1.70	1.96	2.53	3.27	1.60	1.84	2.50	3.30	3.70	4.10	5.15	5.95	7.00	8.80
EER*			4.44	4.47	5.00	4.74	4.62	4.75	5.16	4.80	4.76	4.86	5.20	5.22	5.16	4.97	5.09
Cooling Capacity (W30/W7)	(4)	kW	5.20	5.60	7.20	8.80	11.3	5.60	7.30	8.90	11.8	13,2	15.7	19.8	22.9	26.0	33.4
Compressor power input		kW	1.53	1.70	2.00	2.60	3.20	1.63	1.90	2.41	3.19	3.80	4.00	5.10	5.80	6.80	8.40
EER*			3.40	3.29	3.60	3.38	3.53	3.44	3.84	3.69	3.70	3.47	3.93	3.88	3.95	3.82	3.98
BW/BWR - MTD																	
Heating capacity (B0/W35)	(5)	kW	5.40	5.90	7.30	9.20	11,7	5.90	7,50	9.10	12.2	13.7	16.0	19.8	23.0	26.5	33.3
Compressor power input		kW	1.34	1.50	1.82	2.35	2.80	1.40	1.74	2.10	2.80	3.40	3.50	4.40	4.90	5.80	7.30
COP*			4.03	3.93	4.00	3.92	4.18	4.21	4.31	4.33	4.36	4.03	4.57	4.50	4.69	4.57	4.56
Heating capacity (B0/W50)	(6)	kW	5.10	5.70	7.00	8.90	11.1	5.70	6.80	8.50	11.7	12.4	14.9	18.3	21.3	24.4	31.3
Compressor power input		kW	1.90	2.20	2.70	3.40	4.00	2.20	2.50	3.00	4.20	4.50	4.90	6.40	7.00	8.30	10.0
COP*			2.68	2.60	2.60	2.62	2.78	2.59	2.72	2.83	2.79	2.76	3.04	2.86	3.04	2.94	3.13
Cooling Capacity (B30/W18)	(3)	kW	7.10	7.60	9.80	12.0	15.1	7.60	9.50	12.0	15.7	18.0	21.3	26.9	30.7	34.8	44.8
Compressor power input		kW	1.60	1.70	1.96	2.53	3.27	1.60	1,84	2.50	3.30	3.70	4.10	5.15	5.95	7.00	8.80
EER*			4.44	4.47	5.00	4.74	4.62	4.75	5.16	4.80	4.76	4.86	5.20	5.22	5.16	4.97	5.09
Cooling Capacity (B30/W7)	(4)	kW	5.20	5.60	7.20	8.80	11.30	5.60	7.30	8.90	11.8	13.2	15.7	19.8	22.9	26.0	33.4
Compressor power input		kW	1.53	1.70	2.00	2.60	3.20	1.63	1.90	2.41	3.19	3.80	4.00	5.10	5.80	6.80	8.40
EER*			3.40	3.29	3,60	3.38	3.53	3.44	3.84	3.69	3.70	3.47	3.93	3.88	3.95	3.82	3.98

Common data			0011	0021	0025	0031	0041	0021	0025	0031	0041	0051	0061	0071	0091	0101	0121
Type of compressor			scroll														
N.° of compressors		n°	1														
Refrigerant			R-410A														
Plant side pump type			circulator											centrifugal			
Source side pump type (BW-BWR units)			circulator				centrifugal	circulator				centrifugal					
Power supply		V/Ph/Hz	230V~ 50Hz					400V-3N~ 50Hz									
Starting current (all single phase models have a maximum 45A soft start fitted as standard)	(7)	A	26	27	37	44	59	32	35	48	64	64	75	75	75	75	75
Sound pressure	(8)	dB(A)	41	41	42	42	47	41	42	42	47	47	48	55	55	59	59
Height/Length/Width		mm	980/560/575											1150/680/780			
Net weight	(7)	kg	148	148	150	152	160	148	150	152	160	170	175	220	230	235	250

Figure 58 - Ground Source Manufacturer's Data [63]