University of Strathclyde
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Air Source Heat Pump Installation

Performance Review

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Copyright Declaration

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Abstract

Current global targets to reduce CO_2 and raise energy efficiency awareness have made Air Source Heat Pumps (ASHP) an attractive option for domestic and commercial use. By drawing the main heat source from a free, abundant and endless reservoir (atmosphere), the widespread development and installation of ASHP has the potential to lower fuel poverty, CO_2 and network grid demand.

Air source heat pump technology has developed rapidly in the last 5 years enabling units to perform better under a wider range of external temperatures, a development which has increased interest across the globe. This thesis is based upon an installation of ASHP in a scheme of social housing in Westfield (Scotland). The research aimed to quantify the performance of an ASHP, to establish if ASHP is a viable alternative to existing heating technologies. Detailed yearly performance information is scarcely available and the results of this research show that ASHP can meet the heat demands and deliver the power needed. Furthermore, analysis of electric consumption over a twelve month period indicates that cost savings are available. The analysis utilises both acquired and simulated data, and the simulations carried out identified that ASHP units have good performance throughout the whole year, a quality which can be hidden by seasonal performance factors.

With the inclusion of weather compensation modelling, ASHP showed a higher level of energy efficiency by better matching supply to the demands of the house.

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Introduction

The global government targets which have been set in order to lower greenhouse gasses and increase energy efficiency will only be achieved if attitudes towards energy use changes. Domestic heat demand for European countries is 42%[1], with industry 40%[2] (fig 14), indicating that there are sectors in which a different approach to reducing energy demands may be beneficial. This thesis carried out research with a view to determine the development status of Air Source Heat Pumps (ASHP) within the UK, and then leads on to examine development in other countries. Thus attention is drawn to the measures undertaken internationally to aid heat pump technology. Finally, a detailed breakdown of an ASHP performance is carried out to highlight whether or not it is fit for purpose.

This thesis has 13 sections which cover the following areas.

1. Literature review
2. Current global development
3. Performance review of an ASHP installation

Literature review

The first section looks at ASHP technology, and the theory behind how it is possible to take usable heat from the air, and use it to heat a dwelling space or domestic hot water. This explanation covers the construction of the heat pump, and the current technology that allows the heat pump to function in this role.

Section two goes on to cover the benefits of using a heat pump, such as energy saved, compared to other heating methods. These sections also identify that there are a wide range of options to pick from, in selecting the low temperature source. Influencing factors are also considered in order to identify components of development such as fuel prices and better understanding.

Section three examines performance data, and explains the engineering cycles and process of the refrigerant, which is fundamental in being able to determine a value of performance. It is vital to benchmark in this way so that consumers can determine how well a heat pump will perform compared to the others. This is reinforced with the construction of a table that looks at CO_2 and performance covering a range of heating methods.

Section four examines the current legislation which affects ASHP. The main focus is upon building assessment procedures, which are the UK government's regulations on energy performance of buildings. In these procedures average values of performance are used, and the suitability of these values will be considered in the analysis.

Current global developments

Section five moves on to consider government initiatives. The extent of these in force in the UK serves to illustrate the level of commitment by the UK government in developing heating technologies. Installing heat pump technology can be expensive and so it is important to consider what help is available to prospective users within the UK.

This is followed by a review of current usage, and is covered under section six. Available case studies are limited, and it is often difficult to ascertain savings and accurate performance data. However, the studies included in this section give a balanced account of information regarding the reasons for installation and the benefits seen.

In order to gain a wider knowledge of development, the development of ASHP in other countries is considered. Section seven covers this in detail. The main focus is upon the incentives used by governments from a wide range of countries, to learn from their development of heat pump technology. The main source of information for this section was obtained from the IEA (International Energy Agency); due to the lack of data existing for ASHP, their data on Ground Source Heat Pumps (GSHP) has been used to demonstrate what has been done in developing the technology.

Performance review

The following sections of the thesis contribute to the ASHP installation. Section eight contains the project description, identifying the heat pump which was used, and why the project took place. Also covered is the description of the model used for simulation, and a description of how the heat demand for the house was generated. Two main tools used for simulating were ESP-r and Merit. ESP-r is an integrated modelling tool for the simulation of buildings and the assessment of energy use, associated with environmental control systems and constructional materials[3]. The program was developed by the University of Strathclyde and is a powerful tool in energy evaluation. Merit is also a tool developed by the University of Strathclyde, which was used to display the power output of the heat pump, combined with the heat demand of the house. This was vital in determining whether the heat pump can match the demand. The program is able to do this by using a climate file, which is in hourly intervals, to determine the output of the heat pump. Further detail on the sampling rate and data is included in this section.

Section nine and ten contains the information on all of the simulations carried out. This covers the simulations carried out with different climates and occupancy levels. It was important to model the heat pump in different configurations, to identify when the heat pump performs well or performs poorly.

Further to the performance review of the heat pump, it was important to look at better ways of operating the equipment to gain a higher performance, and reduce power consumption. Section eleven looks at weather compensation. This is a method of changing the water temperature relative to the external temperature. The heat pump reviewed in this thesis did have the capability of operating with compensation, but was not used until a later date. To model this compensation, the schedule was obtained by TEV Ltd, which made it possible to simulate the power consumption in Microsoft Excel.

The final section concludes the study and provides a detailed understanding of ASHP performance and feasibility. The performance review also delivers an extensive display of power consumption and output (Duty) over the full year. This allows an accurate presentation of the ASHP, to see if it is a viable alternative to other heating technologies.

1. Heat pump explanation

The term heat pump is not commonly known in a domestic environment, but they are present in all homes. A simple way to understand a heat pump is to consider a common home appliance, the fridge or freezer. This appliance takes heat energy carried by the air surrounding items to be chilled, then transports it into the atmosphere, hence the reason the back of the appliance becomes hot as heat is dissipated. Effectively, the heat is being pumped out of the chilled space, hence the term heat pump. The primary objective of a heat pump is to extract or absorb heat from one source, i.e. solid, liquid, or gas, and then transport it to heat or cool air and water.

The advantages of using a heat pump for this operation is that usable heat can be extracted from the air, water or ground, 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.

A heat pump is able to transfer heat due to the unique refrigeration system. The thermodynamics of refrigeration enables the heat pump to provide heat, or cooling. Although heat pump systems can be a very complicated, the principle is relatively simple to understand. The next few pages outline the two main working ambient sources for a heat pump. Although this thesis will be concentrating on air source heat pumps, it is important to highlight that all heat pumps work in the same way. It is only the source heat that is different for example, air, ground and water.

Types of system

There are two main types of heat pump system. There are systems that take the heat from the ground, and systems that take heat from the air. There are different conversions for the destination of the heat available, however this thesis will focus on a wet heating system where the heat from outside is transferred to water for heating.

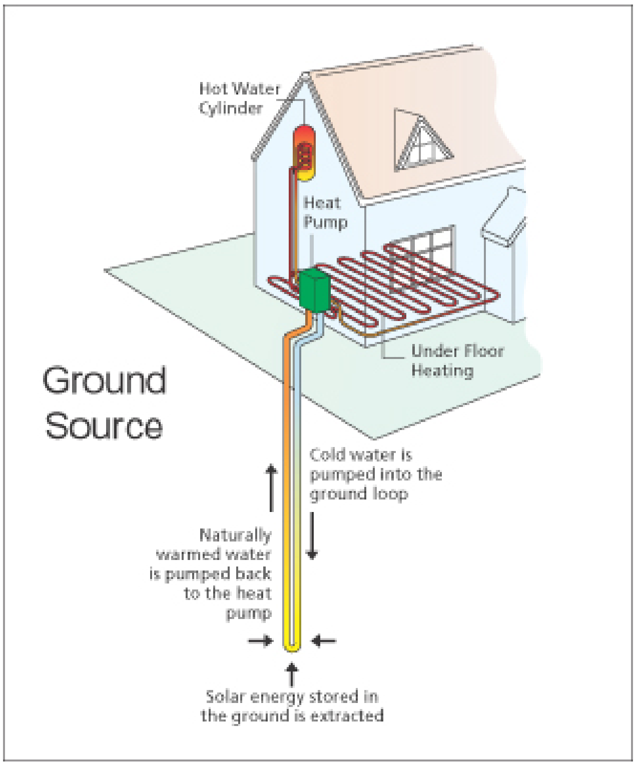

Figure 1. Ground Source Heat Pump Diagram [4]

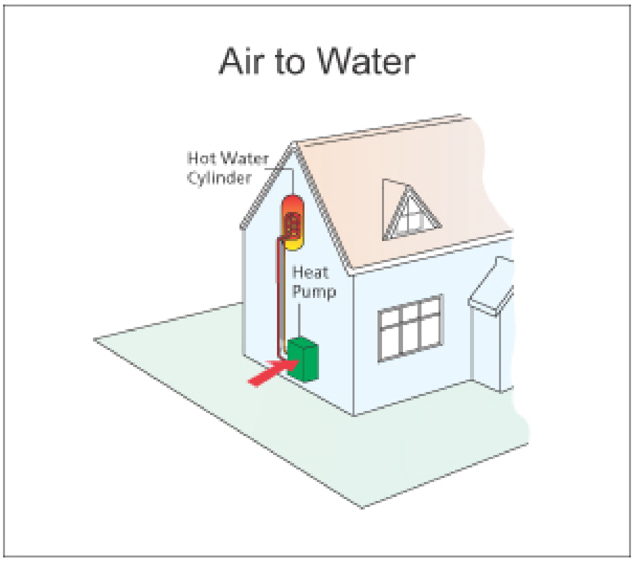

Figure 2. Air Source Heat Pump Diagram [5]

1.1. Heat pump construction

As mentioned above, the thermodynamic properties of refrigeration can be utilised to generate both heating and cooling systems. Two processes that are particular to heat pumps are expansion and compression of the working fluid.

Figure 3 below is a system diagram that provides a graphical explanation of the second law of thermodynamics, where the inclusion of a cyclic device which receives an input allows the heat to be transmitted from the cold temperature to the hot. Denoted by T_C and T_H in the figure.

A heat pump is relatively simple in construction. The main components are shown in figure 4 below.

The refrigerant that circulates the system is contained in a pressurised closed loop. Within most units the compressor is sealed within the refrigerant system. This is referred to as a hermetic seal, and this allows the heat to be recovered from the mechanical pump and windings. This makes the unit quieter and raises the efficiency. In this heat process it is possible to cycle the refrigerant either to induce heating or cooling, this results in heat pumping or refrigerating respectively.

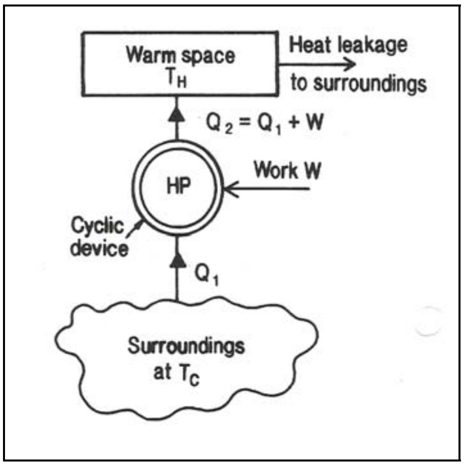

Figure 3. System Boundary Diagram [6]

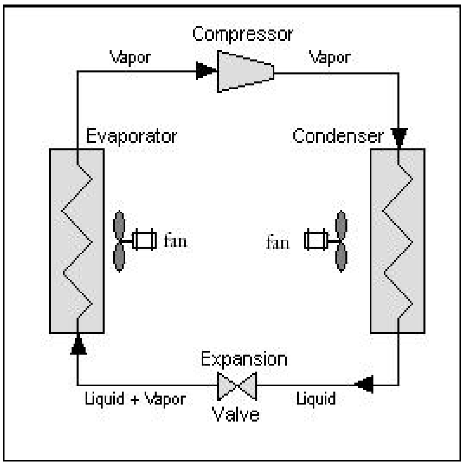

Figure 4. System Process Diagram [7]

1.2. Further explanation

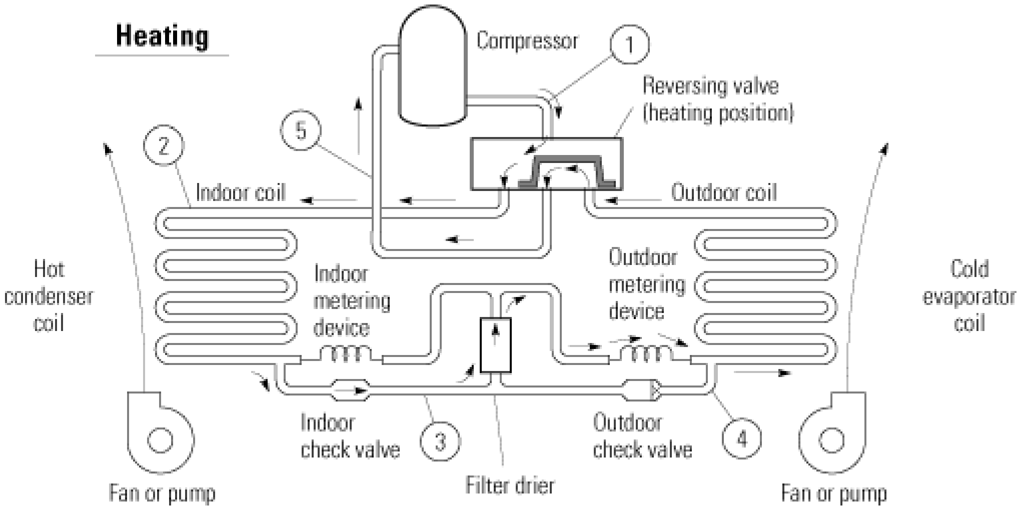

Figure 5. ASHP Component Diagram [8]

Low temperature source

It is important to note that heat can be recovered from temperatures down to 0 Kelvin (-273°C). In negative Celsius temperatures available heat is low, however it is still possible to recoverable heat. Higher external temperatures are favoured, as they result in greater efficiency and produce a higher coefficient of performance (COP).

To allow the heat pump to maintain a high COP the heat source must meet the following criteria:

- Cheap
- Abundant
- Maintainable heat levels that can be extracted
- Easily extracted

Heat pump components

Evaporator

The air from the low temperature source is passed over the evaporator. This in turn, increases the temperature of the refrigerant, and changes its state to a gas. This is achieved by increasing the temperature of the refrigerant by only a few degrees.

Compression

The gas pressure can be raised by using the compressor, and in carrying out this activity the temperature of the compressor itself also increases. COP can be greatly affected by the power consumed by the compressor, e.g. at low temperatures the pump has to work harder to raise the temperature of the vapour following the evaporator stage.

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

1.3. Refrigerant

In 1987 the Montreal protocol on substances that deplete the ozone layer was passed[9]. The protocol banned the use of all CFC refrigerants. As a result, chlorofluorocarbons (HCFCs) were used by industry, however, a later amendment of production and consumption HCFCs was developed under further legislation which will eventually phase out the use of HCFCs.

HFC22 (R22) has been the main refrigerant used in air conditioning and refrigeration, and is still used today as a replacement for CFC's. Given that the use of HCFCs will be phased out, new substances have had to be developed to replace this HCFC.

Of recent times, HFC's have proven to be the leading candidate for replacing of HCFCs

In particular R407C is the refrigerant more commonly used for replacement of R22.

With an introduction of a replacement refrigerant, there are inevitably potential changes in performance.

During winter when an ASHP is working in heating mode, formation of frost causes air flow maldistribution over the expander, which lowers COP[10]. By testing the differences under frosting and defrosting, it was found that whilst R407C does degrade faster, overall the thermodynamic performance properties were acceptable as a replacement[11] for R22. For this reason and due to environmental concerns, R407C is now used in the majority of heat pumps sold globally.

1.4. Lifespan

In the 1980's and 1990's heat pumps were undesirable due to poor technology, with short lifespan greatly discouraging the development of ASHPs. Recent investment in technology has seen the lifespan increase provided they are properly maintained. A survey carried out by the Air-Conditioning and Refrigeration Institute (ARI), stated that current models last around 14 years, but current technological development will see newer models lasting longer[12]. With global collaboration towards reducing $C0_2$ emissions, increasingly governments are investing in renewable technologies and driving towards better development plans.

1.5. Size

Heat pump designs can be built for both domestic and industrial use.

One of the more desirable features of heat pump installation is the cost. ASHP has the lowest cost of installation, ranging from around £6,000 to £8,000 for a 5kW unit[13]. With other technologies such as ground source heat recovery, installation costs are high due to the need to drill boreholes or the need to extract trenches for horizontal lying of pipes. In recent years however, subsidies from local councils have made these costs more acceptable. This is covered in greater detail under section five.

2. Heap pump benefits

Saving energy

Over the last 5 years, heat pumps have become more efficient and have obtained better rates of COP. Better designs of compressor have enabled the fluid to be able to extract more heat from low temperature sources (down to -15°C[14]). Overall, heat pumps have COP's of up to 4[1]. This means that for every kilowatt used, 4 kilowatts is transferred to the destination fluid. Conventional fossil fuel boilers work at 90 percent efficiency, so the energy efficiency of heat pumps is comparatively better. Figure 6 below is a chart which compares the fuel cost of various heating technologies. In this diagram, ground source is used as the comparison, this is because GSHP has similar values of COP to ASHP.

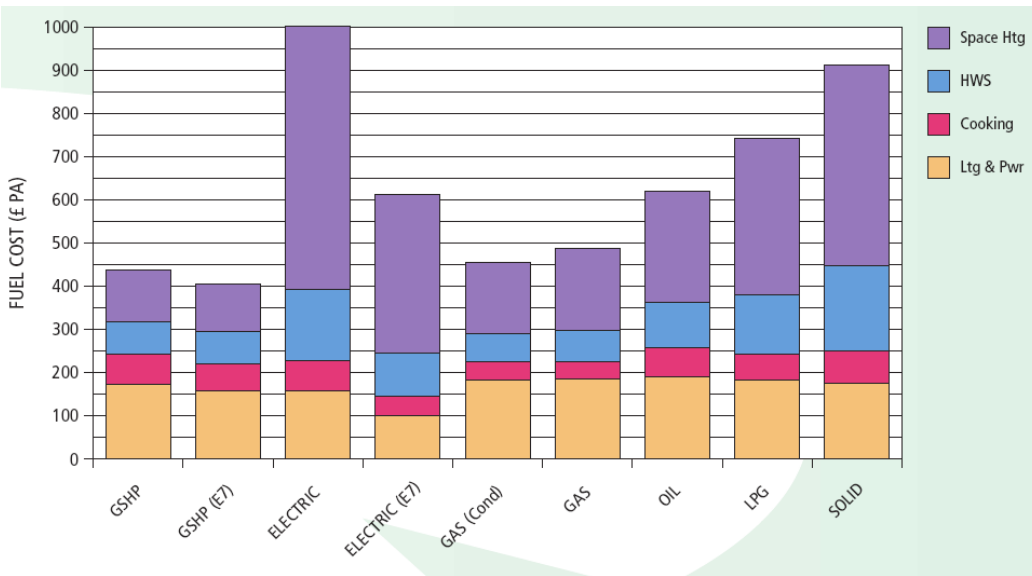

Figure 6. Annual Fuel Cost Comparison [15]

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[1] COP is further explained in section 3

Due to recent developments in heat pump technology, homes can now benefit from a wide range of systems, including

- Air to Air
- Water to Water
- Water to Air
- Air to Water
- Ground to Water
- Ground to Air

Heat loss can be very costly in commercial and industrial processes, substantially increasing overheads.

In both the manufacturing and food industries, a large quantity of heat is produced e.g. furnaces and forges due to the heavy plant installations which draw large amounts of power. In many situations the heat is simply rejected to the atmosphere, resulting in a missed financial opportunity e.g. the opportunity to sell that heat. In commercial situations such as leisure centres and hotels, a large amount of energy is used for space heating and swimming pools. In both of these situations above, heat pump technology could be utilised to generate and recover the costs of energy consumption. The primary principle that drives heat pump technology, and which its implementation is dependent upon, is its ability to recover heat and make efficient use of it. Generally heat pumps are reverse cycle and can actually heat as well as cool a dwelling or space.

2.1. Fuel prices

Fuel prices worldwide have risen dramatically over recent years, with the price of oil and gas increasing substantially in 2008. Currently, residential and industry heat demands are met primarily by gas and oil. Looking at Figure 67, 69 and 70 in Appendix B, it can be observed that gas and oil demand will likely increase rapidly, with the demand for gas mostly being driven by power generation. Figure 64 shows where proven gas reserves are located. Increased use of gas and oil from these countries leaves prices vulnerable to unexpected change, given the volatility of energy trade relations and the international political climate. Ultimately, this is a cost that power companies seek to recover from their customers; as in 2008 when gas and electricity prices increased by 40%. With heat pump technology achieving higher efficiencies and reducing electricity usage, it can be seen that better heating technologies are available.

2.2. Better understanding

Later sections of this thesis will seek to show how other countries have succeeded or failed in development of this technology. Often one of the largest hurdles in promoting a new system is a lack of public knowledge, and it is common that people do not like to change a system which they know already works. However, as mentioned earlier, rising fuel prices will entice the public look for new ways of lowering their utility bills. In recent years the installation of GSHP has increased significantly, due to a better understanding of the technology and proof of its performance. This is covered in section seven. This has been achieved through the implementation of programs that accredit trained installers and by learning from the lessons arising from earlier installations / case studies.

3. Performance Data

3.1. <u>COP</u>

Clausius statement from the second law of thermodynamics [16] indicates that it is impossible to operate a cyclic device in which its only effect is to transfer heat from a cooler body to a hotter body.

However, it is possible to cause a net heat transfer, by using a cyclic device that receives an energy input. In a heat pump the form of work comes from the inclusion of a vapour compression cycle. The system can be classified on two working classifications, depending on the arrangement of the plant in question.

When extracting heat from a body the system is classified as a refrigerator. In this condition, the temperature of the cold space is lower than that of the surrounding space.

When the aim is to supply heat to a space in which the surrounding temperature is lower than that of the space heated, then the plant is termed as a heat pump.

In either classification, the performance parameter of operation is considered as the coefficient of performance (COP)

As mentioned in section 4.2, there are practical difficulties in designing a system based on the reversed Carnot cycle. On the T-S diagram for a basic Carnot cycle it is shown that the fluid is between two phases. This is a serious problem, because this will cause lubrication problems in the pump, resulting in the compressor failing. This means that the evaporation must be allowed to continue up to the evaporation line, shown as point 1 in the figure 7 below.

Figure 8 below, shows an expansion valve, otherwise known as a throttle. This is used because in theoretical circuits the use of an expander or turbine would only be of marginal benefit to the system.

Further points to consider:

1. The actual compression process is not reversible, so adjustments have to be made in calculating efficiency.
2. The liquid that leaves the condenser will often not go under enough cooling when exiting the condenser, which can cause problems in climates of negative degrees Celsius.

There are two further ways of improving the practical running of this vapour compression process:

1. The addition of a low pressure accumulator ensures that dry vapour enters the compressor[17]
2. The use of multistage compression, where the vapour is compressed twice to reduce the work of the compression process and increase COP. In heat pump technology this is not common.

Manipulation of the refrigerant in this way enables the construction of a cyclic device that can transfer heat efficiently and effectively.

As this thesis is focused on air source heat pumps, those factors that influence the COP other than the thermodynamic processes experienced by the refrigerant, should be explained.

Using air as the low temperature source can give rise to fluctuating COP. Climates which have stable temperatures are more favourable for this type of installation for heating water and space.

If the temperature lowers too much, the compressor has to work harder to reach the set point of the thermostat. This generates a high draw of current and subsequently lowers the COP. Although COP can be calculated by analysing the enthalpies of the refrigeration process, usually the COP is determined by the total energy delivered to the hot water or air, divided by the total energy used run the heat pump. Typically COP can range from 2 – 4[18]. This is a very desirable performance compared to fossil fuel alternatives.

3.2. Fluid manipulation

For a desirable rate of work, the heat pump must extract as much heat from the low temperature source as possible. In the case of pumping heat, it is desirable to have a coefficient of performance (COP) that is as high as possible. The equation below is derived from the basic reversed Carnot cycle.

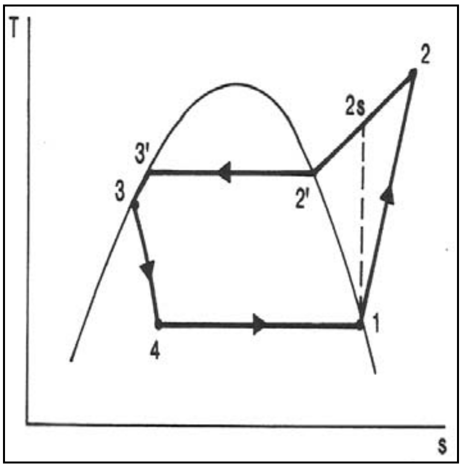

Figure 7. Temperature – Entropy Diagram [19]

$$COP_{HP} = \frac{|Q_{23}|}{|W12| - |W34|} = \frac{T_H \Delta_S}{(T_H - T_C)\Delta_S} = \frac{T_H}{T_H - T_C}$$

The following modifications show practical behaviours of the fluid,

Compressor: $[W_{12}] = h_2 - h_1$

Condenser: $[Q_{12}] = h_2 - h_3$ (heat effect, HE kJ/kg)

Evaporator: $[Q_{41}] = h_1 - h_4$ (refrigeration effect, RE kJ/kg)

Becomes:

$$COP_{HP} = \frac{|Q_{41}|}{|W_{12}|} = \frac{h_2 - h_4}{h_2 - h_1}$$

From figure 7 above, it is possible to see where the gas is compressed and evaporated, and the effects that this has on the temperature of the fluid.

All heat pumps work on this basic principle of compression and evaporation of the working fluid.

Range

Improved approaches to the refrigeration cycle. as mentioned in the previous section, have enabled current heat pumps to work more efficiently in lower temperatures. The majority of this research is based in America and China, where temperatures change dramatically from the South of the two countries to the North. As mentioned earlier, a good COP is maintained if the temperature difference between the low temperature source and the hot temperature source is kept low, therefore when the heat pump is in mild temperatures performance is generally high. However, in climates which have a high fluctuation in temperatures, performance can fluctuate and reduce the life of the unit. ASHP's are least likely to be able to supply heating or cooling at a high efficiency in extreme temperature variations. In 2003/4 work was carried out to increase the performance range of ASHP by employing a sub cooling system, run from a scroll compressor[20].

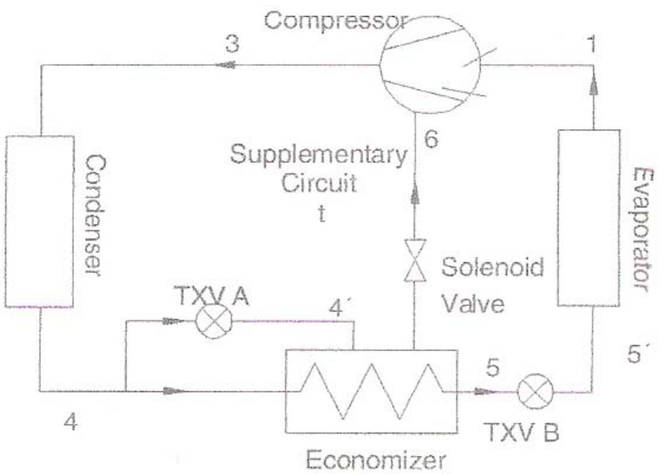

Figure 8. System Diagram- Principle of ASHP Improved Heat Pump Cycle [21]

Scroll compressors are much more reliable than conventional (reciprocating) compressors at the extreme conditions experienced by more varied climates. This makes ASHP more viable for installation and so encourages their use.

Looking at an average domestic system of capacity 6kW, the price to install the system is around £7000 - £10000[22].

When installed in an electrically heated home, an air source heat pump of the required capacity could save around £870 a year on heating bills and prevent almost six tonnes of carbon dioxide a year[2].

Fuel Displaced	**£ Saving per year**	**CO_2 saving per year**
Gas	£300	830 kg
Electricity	£870	6 tonnes
Oil	£580	1.3 tonnes
Solid	£280	5 tonnes

Fuel prices 22/12/2009.[3]

Table 1. Comparison of Approximate Fuel Savings [23]

[2] *Savings depending on the fuel prices 20/12/08*

[3] *All savings are approximate and are based on an air source heat pump providing 100% of space heating in a detached property*

CO_2 Emissions

System	Vapour Compression Cycle	COP	CO_2 emission kg/h
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	0.22 – 0.28
	Oil	0.7 – 0.9	0.30 – 0.38

Table 2. CO_2 Emission Comparisons with Other Technologies [24]

3.3. Situation/Positioning

The specification of the heat pumps depends upon the nature / type of building into which it is to be installed. With GHP there are three main options for installation.

1. If there isn't a horizontal space large enough for ground loops, then bore holes have to be drilled at a large cost.

2. If there is sufficient space for ground loops, then large trenches no shallower than one meter can be excavated to lay a significant length of pipe. This option is only available to a small fraction of the market due to the size of ground needed to install the ground loop.

3. The final option is to use a pond or lake, where the water can be used as the heat sink, however this scenario is very rare.

With ASHP, the unit is comparatively smaller and only needs to be attached to the outside wall, with pipes connecting into the building. This option is available to the majority of the market, and therefore ASHP has the ability to be adopted by people living in densely populated areas.

4. Legislation

4.1. SAP

The SAP (Standard Assessment Procedure) is the UK Government's Standard Assessment Procedure for Energy Rating of Dwellings[25]. In 2005, the SAP procedure was updated to take account of changes in energy technologies e.g. domestic generation and exportation of energy, as this had not been part of the SAP previously. This calculation looks at the energy balance, taking into account items such as materials, insulation and efficiencies of the heating system etc.

The SAP rating is valued from 1 – 100. 100 being zero energy cost. Some dwellings can be higher than 100, representing dwellings that export energy e.g. houses which have photovoltaic panels of wind turbines. The dwelling CO_2 Emission Rate (DER) coupled with an Environmental Impact Rating, replaced the Carbon Index initiative. The SAP applies to all new buildings in an effort by the government to encourage reductions in greenhouse gas emissions and in particular, emissions of carbon dioxide. Within the assessment procedure, heat pumps have been included. Although a heat pump may be capable of achieving high COP's, the SPF used in the SAP averages over the whole year. In the SAP it is stated that there is a value of 2.5[26]. This value is to apply for all systems using ASHP, thus making seasonal performance factors (SPF) misleading. In the procedure this value is said to be general, and does not take into consideration the specific area within the UK in which the heat pump is situated, nor does it state the increases required in heat delivery due to seasonal variability. These generic values are detrimental to the overall SAP value. There is however, the option of utilising your own values, but the SAP rating has to be validated by the BRE.

5. Grants and initiatives

5.1. SCHRI

The SCHRI is the Scottish Community and Householder Renewables Initiative. This initiative is funded by the Scottish government and is target at householders and communities.

The objectives of the SCHRI are:

- To support the development of community scale renewable projects.
- To support the installation of household renewables.
- To raise awareness of renewable technologies and their benefits to Scotland.
- To provide support to the renewables industry

The SCHRI offers grants of up to £100,000 for renewable initiatives for communities. They also employ development officers to give support and advice to potential users on future renewable developments.

In the housing sector, they offer up to 30% of the cost of renewable technology up to a total of £4000.

The technologies that they provide help on are:

- Solar photovoltaic
- Micro hydro-electric
- Micro wind

- Solar water heating
- Solar space heating
- Automated wood fuel heating systems (boilers and room heaters/stoves)
- Heat pumps (ground, air and water source)
- Connections to the Lerwick District Heating Network

There are 11 accredited installers for ASHP, compared with 31 installers for GSHP [27] available through the accredited suppliers list from the Energy Saving Trust. In order to comply with the grant application process only accredited installers are permitted to install ASHP. Hence as ASHP increases in popularity so will the need for more installers.

5.2. LCB

The LCB is the Low Carbon Buildings Programme run by the Department for Business, Enterprise & Regulatory Reform (BERR). This is also a programme where grants can be applied for, but only if grants have not been applied for through other initiatives

For example:.

- Clear Skies
- Major PV Demonstration
- Scottish Community and Household Renewables programmes or the Environment and Renewable Energy Fund

Overall funding for heat pump installation is small considering that procurement and installation can cost up to £10,000, and that LCB only offer up to 30% or £900, whichever is lowest[28]. This is not a significant contribution towards development in view of initiatives in other countries.

5.3. Similar government programs

The energy technology list is compiled by the Department for Environment, Food and Rural Affairs (DEFRA). The energy technology list is a government programme that is managed by the carbon trust. This is an enhanced capital allowance that is only available to businesses as a tax relief incentive if the specified equipment is installed. The full amount of cost and installation will be paid back to the business. This is not available to the public and is exclusive to the business sector.

6. Current usage

6.1. Case studies

Whilst working though the literature review, it was identified that there are very few case studies which focus on ASHP. In recent years, ground source has been favoured as the preferred technology to use when considering a heat pump for heating. The reason behind this is because the COP for GSHP generally stays the same throughout the whole year, therefore giving an accurate prediction of energy use. However, GSHP has limitations such as the large area needed for horizontal pipes, and can expensive due to borehole drilling.

Over the last 5 years, ASHP technology has increased greatly in performance due to more reliable and efficient pumps being used in the refrigeration cycle. This in turn, has increased the COP and temperature range in which useful heat can be extracted from the air. The following case studies show how ASHP has been introduced to existing buildings

Case 1: Hertfordshire Leisure Complex

Figure 9. Hertfordshire Leisure Complex [29]

Faced with escalating energy bills, the Hertfordshire Leisure Complex operators called in Calorex Heat Pumps, who recommended a heat recovery and dehumidification system. An energy-efficient HRD heat pump was used to remove moisture, making use of the latent energy and therefore re-using this to assist with water and air heating. Heat pump technology dramatically cut down the cost of running the pool as it permits a high 'coefficient of performance' (COP) to be attained. An overall rate of 3.5:1 was seen as realistic design value by the manufacturer

Case 2: Berkhamsted Management College

Figure 10. Management Cyber Café and Office Space [30]

Management College in Berkhamsted is a grade 1 listed 12th century barn. The project was to convert the barn into a cyber café and office space. A Daikin VRV heat pump air conditioning system was installed. A major influence in the selection of this technology was the government's enhanced capital allowance, which allowed the whole system to be installed and paid for by the Enhanced Capital Allowances (ECAs), as the heat pump was included in the energy technology list.

Case 3: Beaverbrooks Jewellers

Figure 11. Beaverbrooks Jewellers [31]

Beaverbrooks Jewellers of Chester, became the first site in the UK to benefit from the new Mitsubishi Electric R410A inverter driven heat pump. The project was undertaken in order to replace the old R22 system. Mitsubishi Electric states from manufacture data that units installed offer cooling COPs of up to 3.8, and heating COPs of up to 3.7 and a 40% saving on annual running costs.

Case 4: Wiltshire Leisure Village

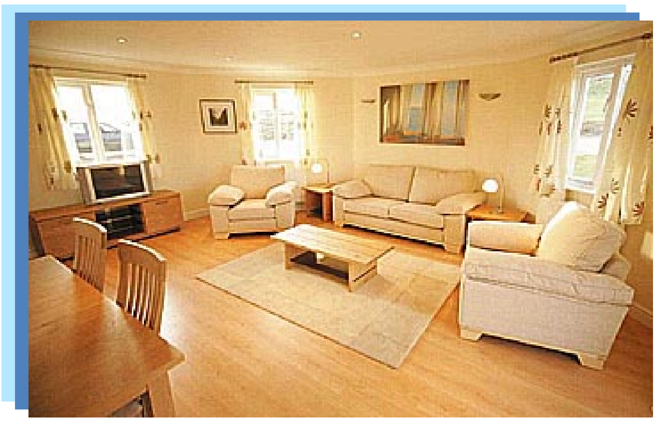

Figure 12. Wiltshire Leisure Village [32]

Forty four Scandinavian style, timber framed holiday homes were installed with air-water heat pumps providing both air and water heating. Altherma states that the system installed delivers at least three times more heat (kW) than the amount of electricity (kW) consumed. The Altherma will deliver water at 55ºC and operate in temperatures as low as –15ºC. A back-up electric heater can boost water temperatures when required. In addition to being significantly easier to install than ground source alternatives, "Air to water heat pumps have the potential in the UK to substantially reduce global warming carbon dioxide emissions"[33]

Case 5: Heat King Installation

Figure 13. Heat King Installation [34]

While air source heat pumps are traditionally less efficient over a heating season than ground source heat pumps, they can be helpful for people who are susceptible to fuel poverty because they are more efficient and so can result in reduced energy costs.

National Energy Action (NEA), the charity campaigning to eliminate fuel poverty, have installed Heat King BWarm units to test the practicality and potential for air source heat pumps. Arthur Scott, NEA's technical manager, believes these trials prove that air source heat pumps can make a significant impact on reducing fuel poverty in off-mains gas areas.

NEA installed a Heat King BWarm 8000 in a Peterborough housing scheme, which had previously been heated by solid fuel, at a cost to the homeowner of £40 a week. After the installation of the air source heat pump, costs were reduced to £10.60 a week, including lighting and cooking costs, a saving of £29.40

The BWarm range of air source heat pumps offer a COP of around 3 at 0°C ambient temperatures.

The above fact is substantiated in the performance study within this thesis. The units installed in the above situation are the same that have been used in this performance study for Westfield.

7. Worldwide policy

7.1. IEA

The International Energy Agency (IEA) is an independent body established in 1974[35]. The IEA's mission is to implement an international energy programme aimed at its members. It carries out programs with 28 member countries[4] that are members of the IEA. Listed below are the main aims of the IEA:

- To maintain and improve systems for coping with oil supply disruptions;
- To promote rational energy policies in a global context through co-operative relations with non-member countries, industry and international organisations;
- To operate a permanent information system on the international oil market;
- To improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use;
- To assist in the integration of environmental and energy policies.[36]

Recently, the IEA has introduced projects specifically designed to investigate heating and cooling by the use of heat pumps, in particular Annex 34, this has been implemented to reduce the environmental impact of heating and cooling by the use of heat pumps. This began in 2007 and is to be completed in 2010

[4] IEA Member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, the United States. The European Commission also takes part in the work of the IEA

The main objective of Annex 34 is to identify the working conditions and environments in which this technology could be best implemented.

The primary implementer of Annex 34 is Germany, with other contributions from countries such as Austria, the Netherlands and the USA. Once completed, the outcomes of the projects will offer a number of benefits, such as:

- An Internet website.
- A description of a standard to determine COPs of thermally driven heat pumps and sorption material properties.
- An online database about sorption materials for heat pumps and their properties.
- A reference guide describing presently available thermally driven systems with their applications. Existing software tools, their application and users' experience, will also be included.

7.2. Market development

As data on air source is limited, it is important to consider the growth of geothermal heat pumps in order to identify how air-source can be developed. Their properties are comparable, and can be seen in results section 16. Figure 14 below shows how heat demand is shared between European Union member states, and shows that industry and residential constitute the majority of heat demands.

With ever increasing populations, the extent of heat demand will also increase. It is important to look to the counties that are currently leading in market development, funding and promotion, to see where other countries are able to develop the use of heat pump technology and raise efficiency in heat demand.

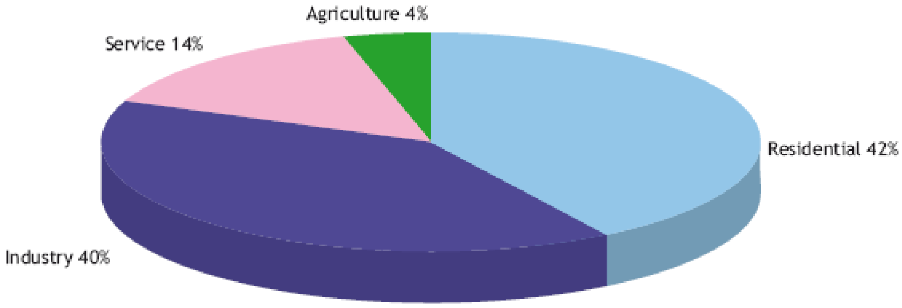

Figure 14. Heat Demand by Sector in European Union Member States. [37]

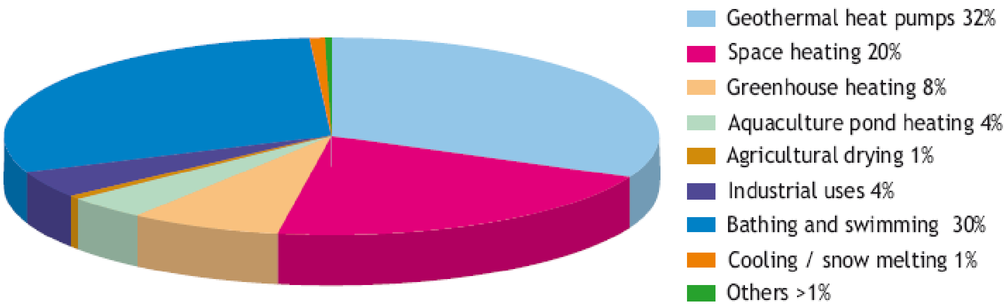

Figure 15. Heat Generated By Geothermal Heat Pumps in 33 Countries [38]

Switzerland

The growth seen in geothermal heat pump usage was achieved by the development of Swiss government subsidies. Two main programmes were set up; the Energy 2000 Action Plan and its successor, the Swiss Energy Action Plan (SwissEnergy)[39], which is still currently in use. The main areas covered are energy efficiency, transport, industry and development of renewable heat technology, and this is shown in figure 16.

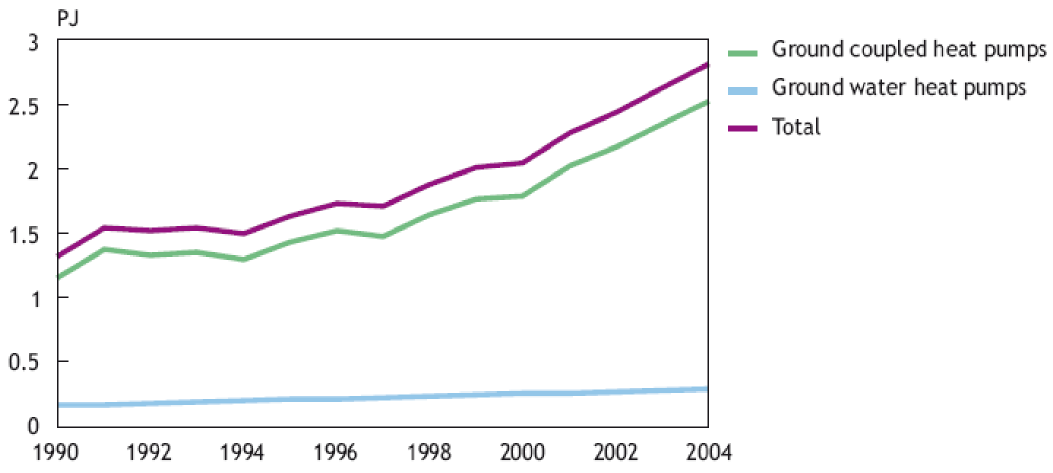

Figure 16. Heat Generated By Geothermal Heat Pumps in Switzerland from 1990 To 2004 [40]

The first program established by the Swiss had targets of achieving 3% of renewable heat by 2000[41]. In 2000 they were just 0.9% short of this value (IEA, 2004). Following on from this, the programme 'SwissEnergy' aims to increase this value by a further 3% by 2010 to 6%, when based on the levels of 2000[42].

A further initiative, the Heat Pump Promotion Group was introduced as part of the market strategy of the 2000 Action Plan. The main objectives of this were to develop trained installers, improve after sales service and to maintain the quality of installed equipment. This initiative helps establish a solid foundation which demonstrates commitment to the future development of heat pump technology. It is also important to note that subsidies of €200 per kW were offered to help this development[43].

Cooperation between government, local authorities, consumers and the environmental organizations is developed by voluntary measures based upon performance mandates, with companies and sectors specifying binding targets for each partner involved[44]. To further aid development, SwissEnergy award lump sum payments for promotion of heat pump technology and R&D

When considering the future of the SwissEnergy programme, the Swiss government had to look at what measures could be undertaken to reach the targets for 2010. They realised that the increasing in awareness of geothermal energy and promotion on a national level needed to be implemented. Responsibility was given to the Geothermal Society, which has the network of experts required to convince the public of the benefits of heat pump technology. The promotion included:

- Information
- marketing
- education
- quality assurance[45]

By covering these issues in national promotion and energy newsletters, the public become increasingly exposed to the benefits of geothermal energy, and as consequence become more likely to accept heat pump technology

Around 50% of the budget of the first energy program was allocated to renewable technologies. Between 1990 and 1997[46] the average annual expenditure for renewables was €13.7 M. This increased by 2000 in the last 3 years of its lifetime to between €21.5 M and €22.9 M. Approximately 46.5%[47] of funding for this was allocated to promotional activities, including incentives for the purchase of new renewable systems, we can see therefore, that significant sums have to be allocated to marketing.. A further 37.5% went to R&D and 16% to pilot and demonstration projects (IEA, 2004)[48].

In addition to geothermal, heat pumps such as air and water source, received €0.82 M in 2003 (SwissEnergy, 2004). The promotional programme for geothermal energy was allocated a budget of €170 000 in 2001 and €310 000 in 2002[49]. Here they have invested in ASHP, but the allocation to geothermal is still considerably larger

Roughly 18% of the renewable heat generated in Switzerland is from geothermal heat pumps (SwissEnergy, 2004). It can be seen in figure 16, that the main achievement is the growth of heat pump installation over the last 10 years. Implementation of their energy programmes and extensive structuring of investment has encouraged this rise in installations. Private companies have also contributed to the development of the industry by cooperating with the Swiss government through training being made available through financial commitment, ensuring that competent qualified installers are made available, thus improving public confidence. Rigorous and thorough aftercare and maintenance programs, foster positive attitudes towards installing heat pump technology. It is due to the programmes mentioned above, encompassing both technical support and market development, that Switzerland has had recent growth in the use of air source heat pumps

Sweden

Upon reviewing Sweden's growth in heat pump utilisation, clearly development is a very sensitive process requiring constant attention and investment. In 1993 The Swedish Agency for Economic and Regional Growth (NUTEK) began a Technology

Procurement programme[50]. Initially this only encompassed small brine water units. In the 1980s Sweden experienced an increase in the market for heat pumps, but they were continuously plagued with issues of low quality and underperforming technology, with the effect that there was a negative public backlash.

As a result of this, sales declined in the late 1980s and early 1990s (see figure 17). To counteract this and protect previous investment, NUTEK sponsored the procurement programme to develop heat pump technology for detached housing. Subsequently, this encouraged the growth of heat pump sales until the programme ended in 1996. NUTEK managed the procurement of technology, until 1998, when it was handed to the Swedish administration. Since then, further initiatives and contests have been developed to entice manufacturers to build and develop their technology, in order to provide better working units. One particular example developed units 30% cheaper and 30% more efficient. Initiatives not only helped heat pump technology, but contributed towards building better efficiencies in household appliances. Promotional events took place in Sweden, Denmark, Norway, and Finland, and it was guaranteed that 2000 units would be sold of the most efficient unit[51]. Looking at the figure 17 below, it is clearly visible that initiatives can boost technology and increase the number of installed units. However, when the procurement began in the 80's, the program wasn't followed through by continually improving the technology, resulting in a loss of public interest as the technology stagnated. Sweden's improvement by the end of the 90's, indicates a much more creative plan whereby the whole infrastructure lifecycle from investment to manufacturer's involvement was better integrated.

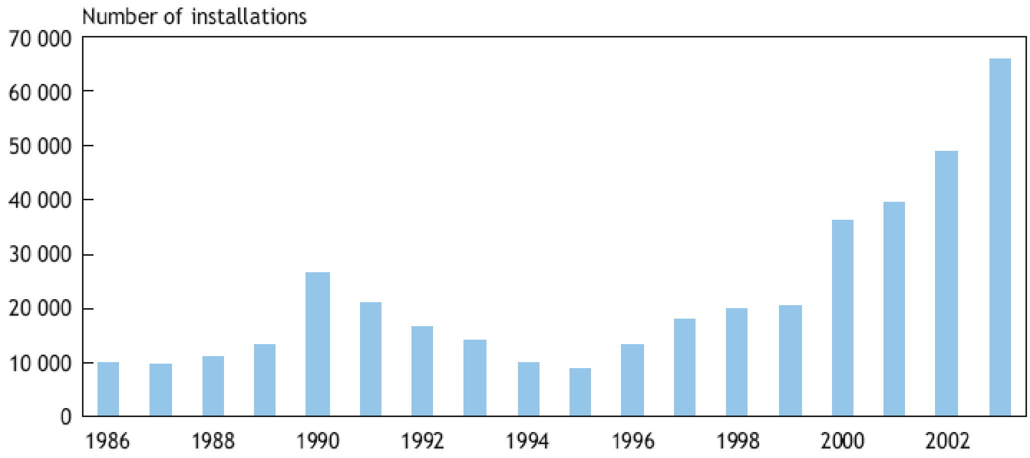

Figure 17. Geothermal Heat Pump Market Developments in Sweden from 1988 Till 2003 [52]

The growth of the Swedish GHP was a direct result of the technology procurement programme in 1993. Sweden's promotion of better quality GHPs restored the reputation of the heat pump. Figure 18 below shows how the investment in GHP moved from poorer technology, in the time of old models of air source heat pumps, to the current position. Recently Sweden has become the largest market in the EU with exports playing a significant part[53].

Figure 18. The Market Transition from Ambient Air-Source Heat Pumps in 1993 to Ground-Source Geothermal Heat Pumps In 2003 [54]

More recently Sweden has expanded into the field of integrated air source heat pumps. These pumps provide ventilation, space heating, domestic hot water, heating/cooling and dehumidification. The most common use in Sweden is the exhaust air heat pump. During the oil crisis in the 1970s, the allowable air leakage of the building has reduced to lower energy loss. However, this is one of the factors that gave rise to sick building syndrome, which lead to increasing numbers of individuals becoming sick due to unclean air. The remedy for this was to have a good rate of air change, but air being extracted then became one of main factors of energy loss. Due to this, exhaust air heat pumps were developed to recover the heat from air change, in areas where heat had already been supplied. Today 90 %[55] of new single-family houses in Sweden are equipped with them. The popularity of the system arises from the fact that all the HVAC processes mentioned above can be delivered in one package. Sales went from 5 000 units in 1998 to about 15 000 units in 2004[56]. Figure 19 shows how Sweden have dominated the heat pump market penetration per capita.

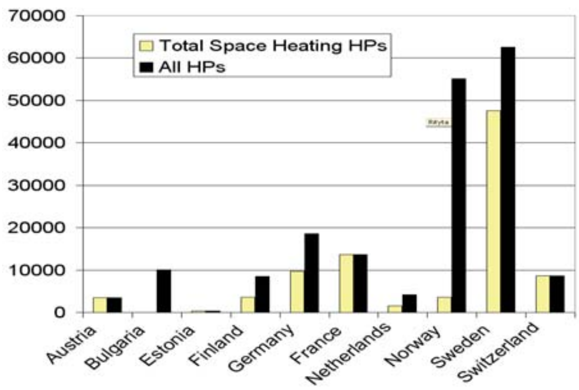

Figure 19. Unit Sales Per Capita [5,57]

Norway

Another area which carries analytical merit is that of the current state of development in Norway. When looking at the graph below, it is important to consider the reasons behind why growth has been so large over the last six years. In 1995, it was reported

[5] *The European heat pump market in 2003 (source: EHPA)*

that Norway had no shallow or deep geothermal capacity, yet by 2000 Norway had installed around 6MW of shallow GHP, which was further increased to 600MW by 2005[58]. The majority of the installations were commercial buildings or community dwellings. The recent increase evident in the graph is due to an increase in residential installations. The increase from 1999 to 2002 was influenced by the exemption of a 7% investment tax, coupled with incentives for a non-electric heating scheme. Funding was allocated from Enova[6].

Overall, Norway's policy change in 1998 occurred as a result of exhausting all available economically viable hydro possibilities[59]. With inevitable increases in heat demand, new policies had to be implemented to maintain energy delivery. Enova has been crucial for heat pump development, investing over 142 million Euros in the last 6 years[60]. It is predicted that renewable heat generation will further increase in Norway, due to government investment and policy on renewable heat. In recent years, retrofitting of housing and market development has increased the sales of air source heat pumps in Norway, and identified in figure 20 below.

[6] SF Energy Fund (a new state-owned central agency of the Norwegian Ministry of Petroleum and Energy 2001)

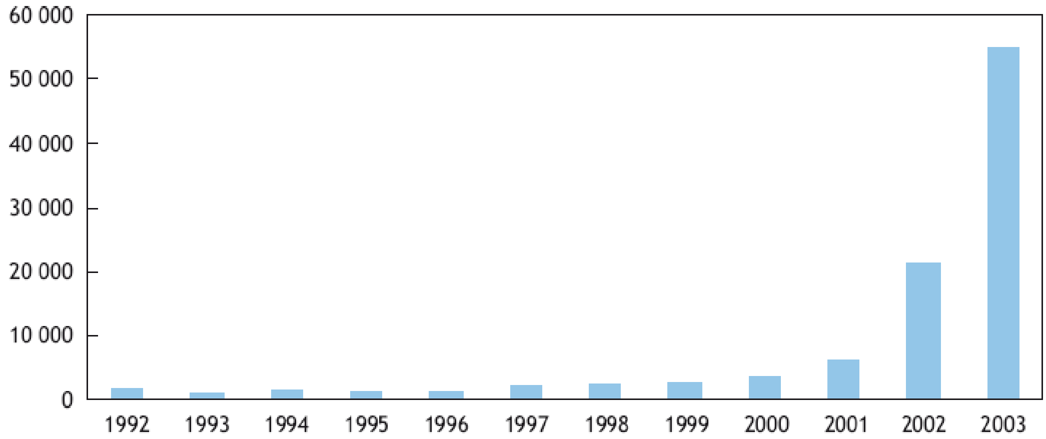

Figure 20. Annual Geothermal Heat Pump Sales in Norway from 1992 Till 2003 [61]

Canada

In Canada, GHP installation accounts for the majority of geothermal heat use with the remainder being deep geothermal[62]. The increase of GHP installations over recent years is illustrated in table 1 below; in 2000 Canada saw a growth rate of 10 – 15% rising to 40% in both 2005 and 2006. Currently, GHPs are not eligible for financial support from their renewable energy development initiative, but rather, a voluntary organisation called the Geothermal Heat Pump Consortium, promotes the uses and technology through the federal House in Order Initiative (2001). Geothermal heat use is relatively small scale in Canada and most perceive this to be due to lack of understanding and awareness from builders, industry and consumers.

Overall, Canada is in the early stages of understanding and implementing energy management schemes, with government support coming from a variety of financial and voluntary subsidiary programs. Currently Canada is primarily focused on energy efficiency within industrial and commercial buildings, a move which is supported by the Industrial Buildings Incentive Program and Commercial Building Incentive Program[63].

The most recent program to be developed and deployed by Canada is the Ecoenergy Renewable Initiative. This attempts to extend the work of the Renewables Energy Deployment Initiative (REDI) in the renewable heat use and home retrofit initiatives.

	1995	2000	2004
MW installed	1.68	377.6	461.0
TJ estimated	9.27	1023	2546

Table 3. Growth of Canadian Geothermal Heat (Including Heat Pumps) [64]

Denmark

Although other countries have used initiatives to encourage development, Denmark was one of the first countries to use aggressive regulation as a preferred method of development. From 1995 to 2005 the use of geothermal heat had increased from 3.5MW to 330MW[65], which was an effective annual growth rate of 43%[7]. Around 88% of heat pumps installed are used in single family housing.

In 1996 a code for low temperature heating systems, (part of Energy 2000) was implemented, and is the likely reason for the growth of geothermal applications. Like most countries, Denmark has an energy plan which in this case, is drawn up by the

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[7] Lund *et al*, 2005; EurObserv'ER, 2005; EC, 2006

Visionary Danish Energy Policy (which was implemented in 2007). The objectives focused on increasing energy from renewable sources by 30% and as a result, investment in energy research doubled from €65M to €130M until 2025.

Germany

In recent years, the growth of deep geothermal heat in Germany has been low, which gave rise to an increased development of heat pump sales. This was influenced by high costs of resource drilling and the high salinity of German resources. Subsequently this has brought Germany to the top of the European market. Stable market development has been secured by Germanys Market Stimulation Programme (MSP).

Japan.

Japan has significant geothermal capacity due to its geography and tectonic movement. The use of district heat has been a long tradition, however the use of heat pumping is not recognised as a new technology in Japan under the 1997 New Energy Law. The results is that the development of ambient temperature heat source energy has been impeded. DHW heating however, has been increasing in demand in Japan over the last 30 years and accounts for 33% of the energy used in the energy sector[66]. In 2001 an air source water heater was developed by the government, which used $C0_2$ as a refrigerant. These are called ECO-CUTE, and are sold by 17 companies in Japan. In 2004, 120,000 units were sold[67]. In Asia reversible air source heat pumps dominate the market. In china 12 million heat pumps were sold in 2003 to the residential and commercial market[68].

Conclusions

Tried and tested initiatives and policies have improved heat pump technology vastly over the last 10 years. Today, the market growth is rapidly expanding and considerable numbers of installations are being undertaken. As noted above, some countries are beginning to take a lead in the development and sale of heat pump technology i.e. Norway Sweden and Germany are amongst these. Ground source has benefited from effective development and overcome its reputation for faulty technology and is fast becoming favoured by the public. With large and intrusive installation problems, only a small band of customers can actually install the GHPs. However, the ASHP market is growing rapidly and efficiencies are increasing. The IEA are currently working on policy amendments which focus towards reporting on AHSP technology and defining working parameters. Unfortunately innovative heat pump systems are not included in existing IEA testing and calculation procedures, and this is due to the technology and development evolving too quickly for legislation to keep place.

8. ASHP Performance Review

ASHP Installation Background

In 2004 a small group of social houses situated in Westfield, Bathgate had ASHP units installed. This was a joint venture by TEV Ltd, Heat King and Scottish and Southern Energy. Ten houses in total took part in the project to serve as a basis from which to demonstrate the performance of ASHP. The University of Strathclyde was approached to carry out the study, and the data collected from each unit cover a broad range of properties e.g.

- Inside/External temperature
- Current drawn
- Flow temperature of heating system (In and Out of ASHP)

Each ASHP unit had a collection of sensors fitted, which logged this data. This was done on a half hourly basis and transmitted via wireless connection to a central hub. By having this regular frequency accurate profiling of the performance was achieved. The data from this hub was connected to an internet connection thus allowing the data to be downloaded and stored in a database. Logging the data in this fashion allowed the operation of the heat pump to be mapped along a time line. This analysis shows effectively showed performance of each pump in real time.

Unfortunately installation problems such as noise and start up currents delayed the ability to obtain usable data. Usable data started to build up from mid 2007.

The heat pump had been installed to deliver hot water into the existing wet radiator system as seen in figure 72. The set point of the water was fifty five degrees centigrade (which is typical for convective systems like this). The houses had double glazing and cavity insulation.

Whilst carrying out the research for this thesis, weather compensation control was implemented on the project. The data collected from this was not used in this thesis, however in section eleven it has been simulated using the schedule obtained from TEV ltd.

ASHP details

Figure 21. BWarm 8kW Unit [69]

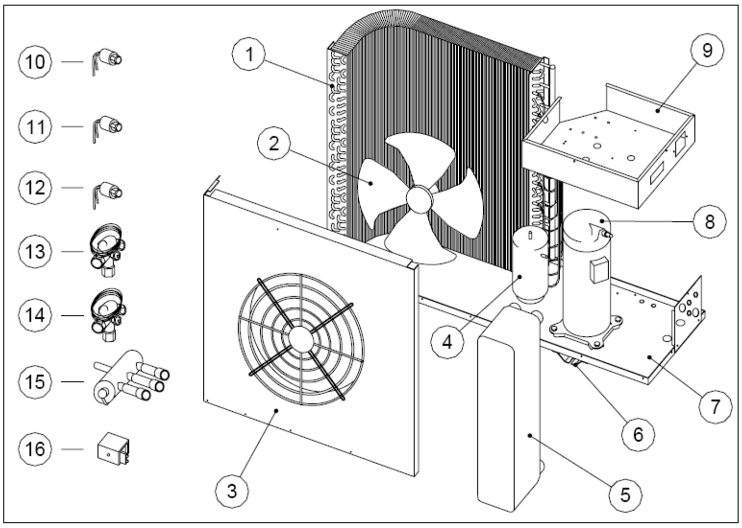


Figure 22. Exploded Diagram of Components [70]

Item	Description	Item	Description
1	Evaporator/outdoor coil	9	Electrics and controls panel
2	Fan/motor assembly	10	Refrigerant low pressure switch
3	Front panel/fan guard assembly	11	Refrigerant high pressure switch
4	Liquid receiver	12	Water low pressure switch
5	Condenser/Plate heat exchanger	13	Heating thermal expansion valve
6	Foot	14	Defrost thermal expansion valve
7	Base plate	15	4 way reversing valve
8	Scroll Compressor	16	Reversing valve solenoid

Table 4. Component description [71]

Each BWarm ASHP is fitted with a microprocessor controller. The controller can be programmed for use with either radiator heating or underfloor heating. The microprocessor in the heat pump controls the following key functions:

Water temperature: the heat pump is controlled on return water temperature. Once the water temperature reaches set point the unit will switch off until the water temperature falls to 3°C below set point.

De-frost: in periods of cold weather with high relative humidity, frost will form on the finned heat exchanger on the back of the unit. A sensor is fitted inside the heat pump that, instigates a de-frost. To do this the controller reverses the flow of refrigerant, passing hot gas through the heat exchanger.

Water pump: a pump is fitted to all units, capable of providing the minimum required flow rate to a system.

Fan: a single axial fan with external rotor motor is used to provide the necessary airflow across the unit. The fan is connected to a fan speed controller to modulate the fan speed according to the external temperature, as the temperature falls the fan speeds up to maintain the unit performance.

Fault Protection: a number of protective devices are fitted to the unit and monitored by the microprocessor. These include;

- **Pressure switches**: high pressure and low-pressure switches are fitted to the refrigeration circuit to switch off the system if the minimum and maximum parameters are exceeded. The switches re-set automatically when conditions have stabilized.

- **Water system pressure switch**: reduced coolant flow can cause a breakdown of the system. The unit will switch off if the system water pressure falls below preset levels.

- **Temperature sensors**: fitted to the flow and return of the wet system to switch the unit on and off within the preset parameters.

- **Current surge protection**: both mains and control circuits are protected by individual MCB's that will trip should there be an electrical problem.

- **Start current limiter**: a soft start device is incorporated, reducing the peak starting current to between 30 and 50 Amps.

- **Alarms**: the microprocessor controller is programmed with a number of alarms.

    1. **Critical alarm**: an alarm that shuts down the unit if there is a critical fault such as the tripping of one of the protective devices listed above.

    2. **Indication**: non-critical alarms will be displayed on the controller but will not switch off the unit.

Weather compensation: for units preset to operate with a radiator based wet system, weather compensation is programmed into the controller. As the external temperature rises the controller automatically adjusts the set point to maintain a balance between the outdoor temperature and the heating water temperature required, to provide the correct level of heating.

8.1. Acquired Data

By the time work had begun on this thesis, a significant amount of data had been collected from the scheme. Work which had already been carried out on the data, generated a regression graph that determined the independent (x) which was the COP and dependent (y) outside temperature. Due to the relatively short time that data was collected the minimum and maximum temperatures in which the heat pump had operated were between -1°C and 14°C.

The equations generated were:

- Single house with good quality data: $y = 15x - 30$ -------- eq^n 1
- Average over entire development: $y = 10x - 20$

It is important to highlight at this point that the average taken for all houses generated a trend line that has been discounted due to due to bad quality, and gaps in the downloaded data.

Equation 1 above was calculated from a house that had a complete data set. This equation will be used to model the heat pump in the following sections.

The graphical view of these equations is shown below.

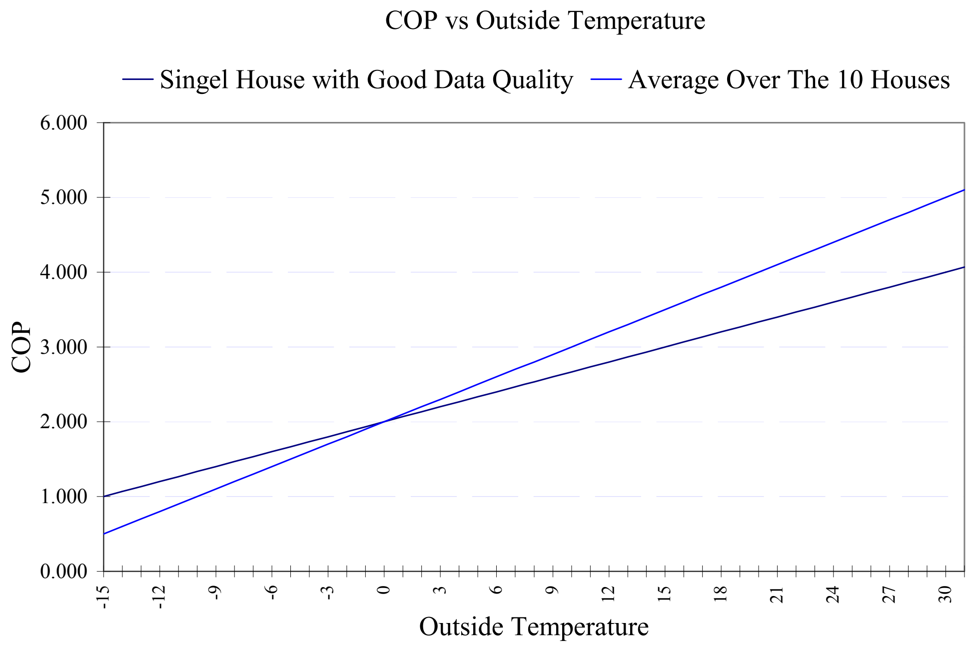


Figure 23. Regression: Linear Equation of COP vs. Outside Temperature

This graph is the first step towards determining the performance of the heat pump. However to get a clearer indication of performance, computer simulation had to be carried out over an entire year, thus simulating the seasonal effects and their influence on the performance of the heat pump.

8.2. Model description

The program used to simulate power delivery was Merit, a software program developed by the University of Strathclyde. The software allows the user to model supply and demand and look at where RE technologies can be matched to the demand profile of the building in question.

Demands covered:

- Heat pump power consumption
- Dwelling heat demand (demand based on 3 bedroom dwelling)

Supply:

- Power delivered by the heat pump, spanning different water set points.

Firstly, the data from the manufacturer had to be input into Merit. The heat pump modelled in the software (figure 21), was comprised of a 2D array[8] extracted from the manufacturer's manual (figure 71 in appendix C). The manufacturer gives output values in five degree intervals, starting from twenty five up to fifty. This data was imported into the program to allow the simulations to be carried out. The benefit of installing this array is that the model can then be used to simulate the performance of the heat pump in a variety of water set points. The two set points which will be focused on in sections nine and ten are for the purposes of simulating,

1. Underfloor heating (thirty degrees) and
2. Radiator system (fifty five degrees)

To produce an output that is dependent on the outside temperature, Merit uses a climate file to cross-reference the array which had been installed previously. This

[8] Example of 2D array in appendix C

allows the return of electric power consumption and duty (power output) over the range of temperatures contained in the climate file. Two climate files are used in the model, an average UK climate file and Dundee climate file. The average UK file was collected in 1967 from north east Stevenage. This file contains a mild climate with average temperatures for the UK. The Dundee file is from 1990, which contains a good range of outside temperatures, including cold winter temperatures down to -10 and warm summer conditions +27. Since the installation was in Bathgate, the climate file which was closest to the area was used to mimic the local climate profile. The closest file available was the Dundee profile. These climate files comprise of temperatures which have been recorded every hour from the first day of January until the last day of December. This allows for the whole year to be modelled taking seasonal change in to consideration.

8.3. Model validation

Before simulations were carried out, the heat pump operation was checked against the manufacturer's data to determine their accuracy. The regression graph in figure 23, gives the COP value of the installed heat pump. To determine the duty of the heat pump, this COP value has to be multiplied by the power consumption, however neither the consumption nor duty had been calculated to date. Either the consumption or the duty from the manufacturer's data could have been used to complete the 2D array at this point. Still, the consumption was chosen as a base point. By using the table generated from the manufacturer's data, the consumption for the fifty five degrees C set point was calculated by interpolation. This exercise was carried out in Microsoft Excel to determine the electric consumption depending on outside temperature. Using the COP values earlier calculated from the regression equation, the duty was generated. Figures 24 and 25 show how the output from the installed heat pump (55 degrees: Recorded Data) correlates with the outputs calculated from the manufacturer's data. The set points thirty, forty and fifty, are in a linear form, and positioning the 55 degrees data beside these other duties, shows that it follows the trend in both consumption and duty.

Due to constraints of the Merit software program, it was not possible to set operating limits such as time control. A time control had to be incorporated to simulate the real use of a timed program for example, the use of a programmable timer to switch the heat pump on and off following a heating schedule. It would not be practical or realistic to have the heat pump running twenty four hours a day, for the whole year. The time program was set to 'off' between 08:00 and 17:00 and "on" between the remaining hours, which simulates occupation. However, simulations with different occupancies were used to create fluctuation in the heat demand of the house. This shows the heat pump's ability to match the heating demand in different occupancy scenarios.

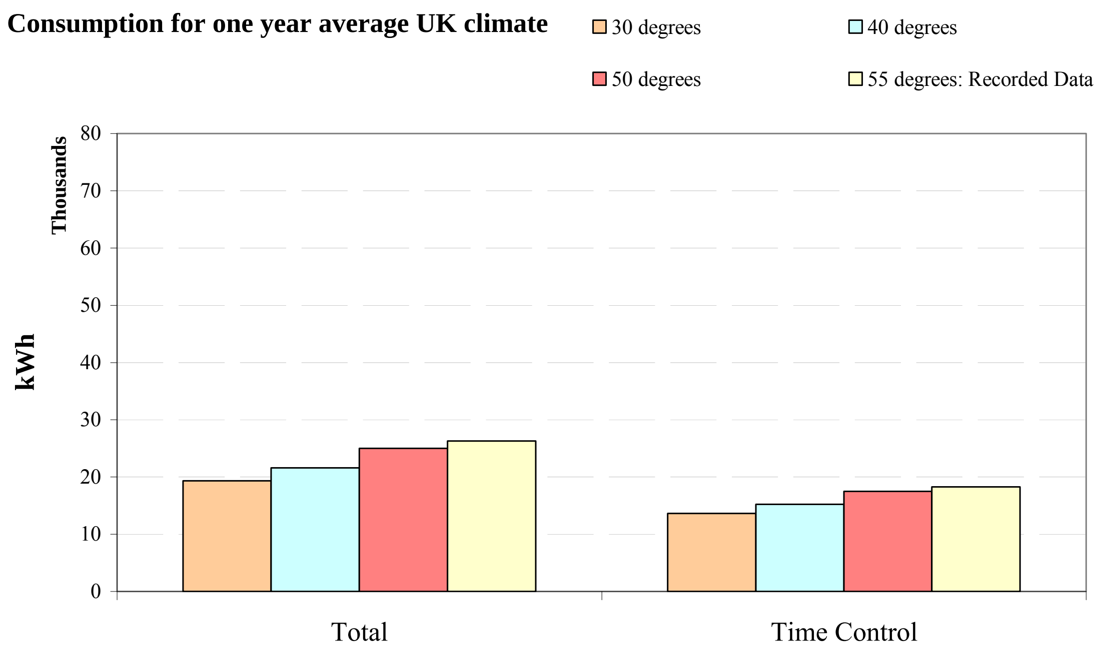


Figure 24. Consumption over One Year- Continuous / Time Control

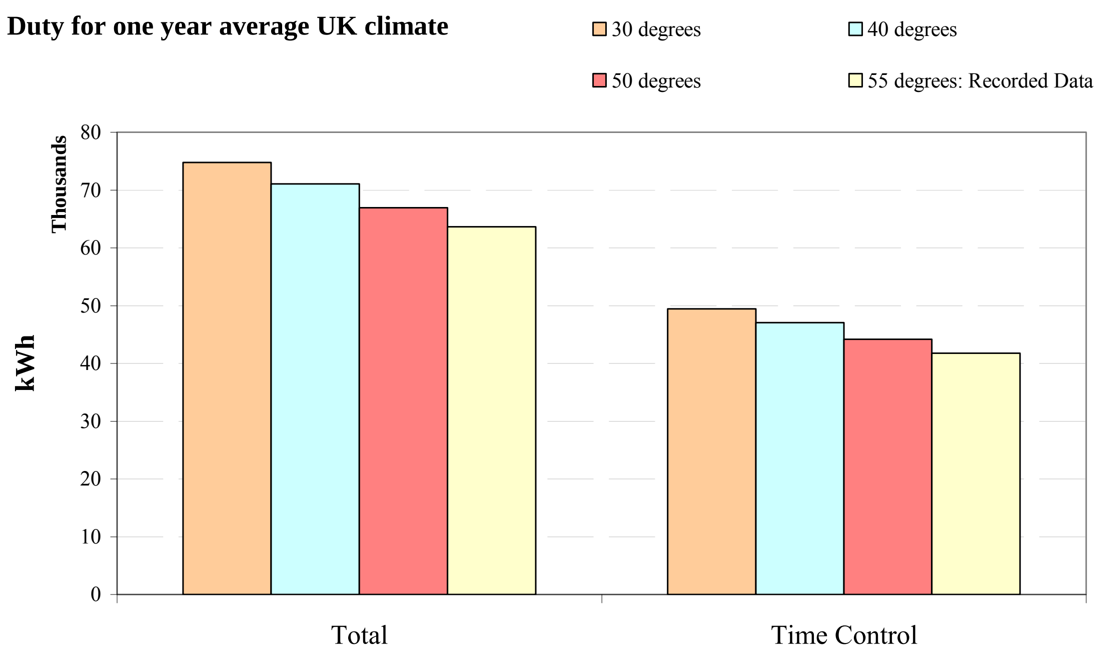


Figure 25. Duty over One Year- Continuous / Time Control

8.4. Heat demand calculation

To accurately map and match the use of the heat pump through Merit, a detailed heat demand is required in order to analyse the supply/demand criteria of the dwelling.

With the use of ESP-r, (an integrated building simulation tool which models thermal, visual and acoustic performance of buildings) various heat loads can be calculated, simulating different occupancies and associated heating loads. ESP-r does this by calculating heat loss in the building through the building materials, taking into account the number of people in the living space and the associated heat gains. Once a simulation is complete, the result can be exported in per hour. This load was used to determine the heat demand for the Merit program. The tables below show the values that were used to configure the occupancy levels and heat gains, to enable a simulation to be done which reflected differing levels of occupancy for the thesis. For this installation, two main loads will be used

Low occupancy

In this example there are two residents occupying the building.

	Time of day				
	00:00 to 07:00	07:00 to 09:00	09:00 to 16:00	16:00 to 19:00	19:00 to 24:00
Monday	No	Yes(180w)	No	Partial(90w)	Yes(180w)
Saturday	No	Yes(180w)	No	Partial(90w)	Yes(180w)
Sunday	No	Yes(180w)	No	Partial(90w)	Yes(180w)

Table 5. Levels for Low Occupancy

High occupancy

	Time of day				
	00:00 to 07:00	07:00 to 09:00	09:00 to 16:00	16:00 to 19:00	19:00 to 24:00
Monday	No	Yes(180w)	Yes(180w)	Yes(180w)	Yes(180w)
Saturday	No	Yes(180w)	No	Partial(90w)	Yes(180w)
Sunday	No	Yes(180w)	No	Partial(90w)	Yes(180w)

Table 6. Levels of High Occupancy

Following the table:

No indicates: No heating required

Yes indicates: Two occupants

Partial indicates: One occupant

The following values for heat gains from the occupants are 90 watts sensible heat.
The simulation is configured to match the schedule above e.g. two occupants are equal to 180 watts for the time period shown.

The model used in ESP-r which is similar to the Westfield buildings, with similar floor areas and volumes. Model U values and infiltration rates are detailed in appendix C.

9. Simulation standard UK climate File

The standard UK climate file has temperatures gathered in a manor such as that described in section 8.2 shown on figure 76 in appendix C. It shows average temperatures seen across the whole of the UK. Using the heat demand mentioned earlier, three preliminary simulations were carried out to identify the performance of the heat pump, for both set points of fifty five and thirty degrees Celsius. The fifty five degrees C set point indicates that the heating installation in the house is convection radiator type and the thirty degrees C set point indicates underfloor heating.

The simulations carried out were:

1. Beginning of the year, until the end of March
2. The final three months of the year, points one and two constitute as the winter season.
3. Then, a simulation is carried out for the summer season, April to the end of September, for both set points

Simulations were carried out in this fashion due to the climate file starting at January and finishing in December.

.

These simulations help to identify where the heat pump is performing to meet the demands of the house. Below are the graphs exported form Merit.

The graphs below illustrate when the pump meets the demand of the dwelling, and following these results, further investigation is carried out to determine when the pump is unable to meet demand. This is collected in a table, where it is shown as a percentage over the time when it could not deliver heat at the required.

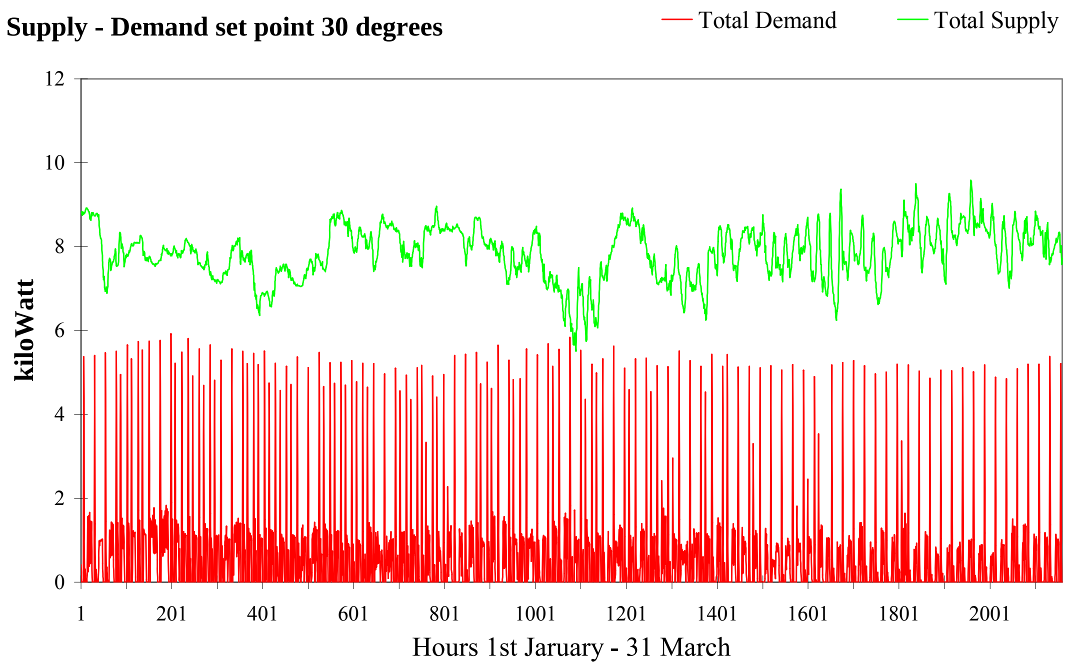


Figure 26. Supply and Demand Winter - Low Occupancy 30˚C

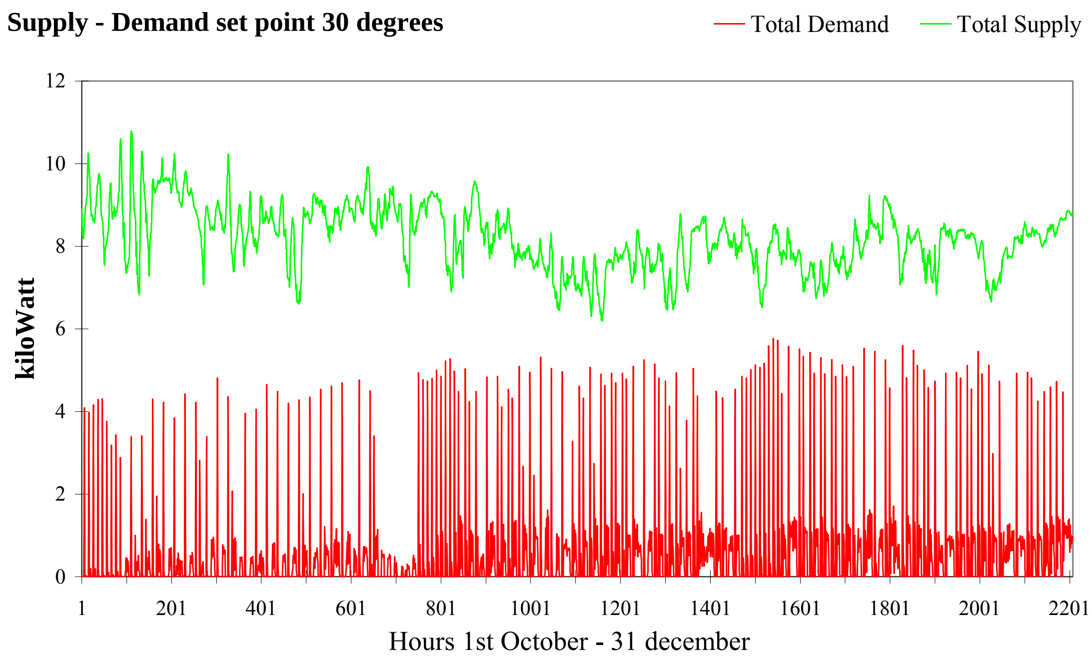


Figure 27. Supply and Demand Winter-Low Occupancy 30˚C

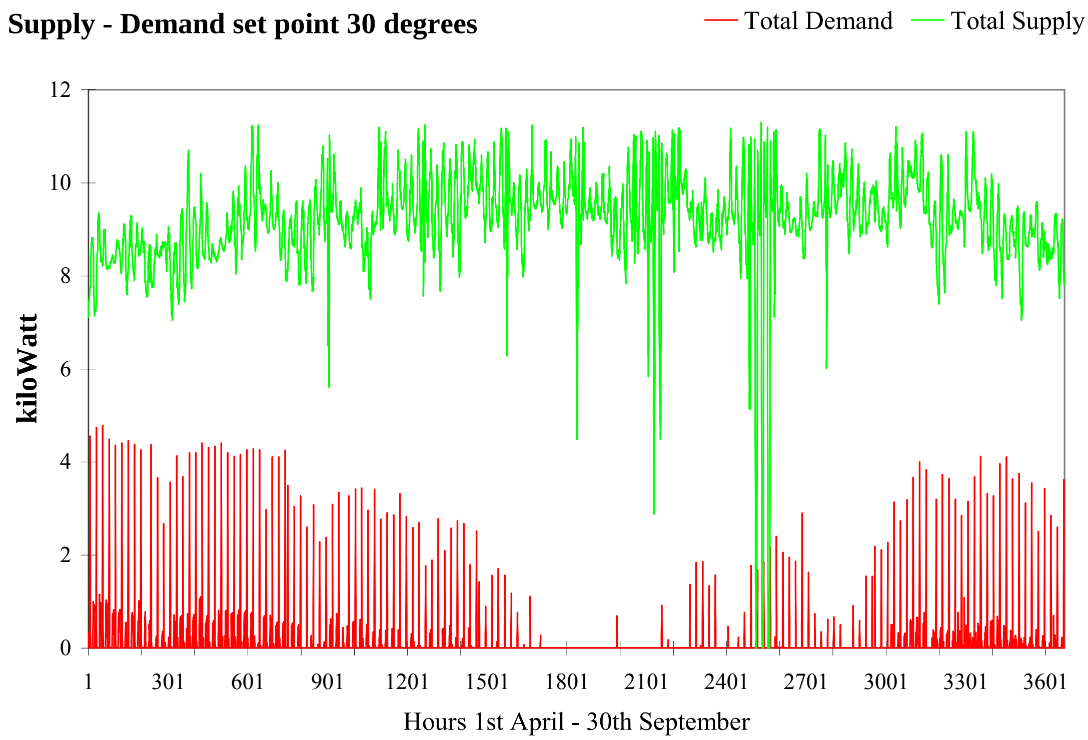


Figure 28. Supply and Demand Summer-Low Occupancy 30˚C

9.1. Supply analysis

- Low occupancy configuration 55 degrees

The first observation in the initial simulation is that there were occasions when the heat pump was unable to meet the demand of the house. Similarly, the same observations are also true of the end of year simulation, but with fewer instances.

In the summer condition there are no periods when the heat pump is unable to meet the demand of the house. In fact there is excess capacity with the temperatures that are achievable during the summer climate seen in appendix A.

Where the green line dips under the top level of the red line, then the heat pump is unable to meet the demand of the heat load. It is these areas which are identified for further investigation, seen in figure 29 below.

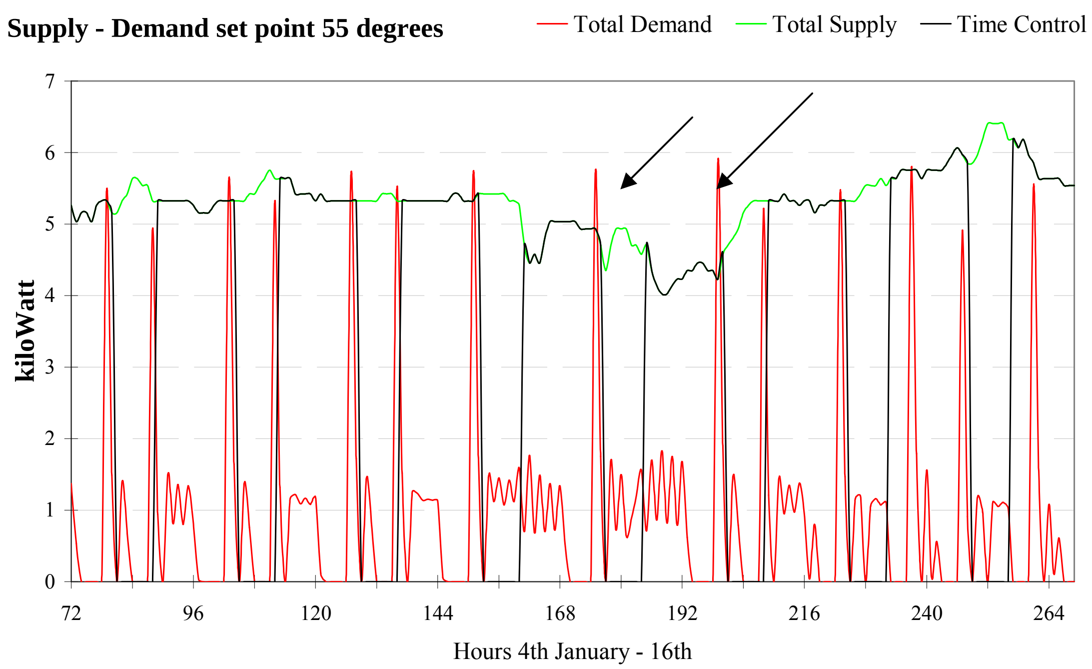


Figure 29. Supply and Demand Detailed View of Delivery

The graph above shows where demand is higher than the power delivery from the heat pump. The black line shows the control envelope when the heating is on timing control. The two instances highlighted are where the pump cannot supply enough heating.

It can be seen on figure 29 between hours 72 – 144 that the heat demand is frequently above the supplied heat from the heat pump. Further investigation determined that the quantity of power not met in these instances was not significant, and the effect on heat delivery would be negligible.

Summary:

- Analysis of the end of year period showed that there was no large deficit in power delivery.
- The deficit of power was extracted from the spreadsheet and was found to be 5.256 kWh.
- Over the last three months of the year, a total of 0.524 kWh was unable to be delivered to meet the heat demand.

Hence, by reviewing the simulation output, it can be seen that the deficit in power is not significant considering the amount of energy that is delivered.

-Low occupancy configuration 30 degrees

As Mentioned in the previous section, the heat pump can be used in different heating simulations. The ability to lower the set point of the heating water should result in greater COP.

In this section a set point of 30 degrees will be simulated. This temperature would be far too low for convection type radiators, but it is sufficient for an underfloor heating system as shown in figure 73 in appendix C.

In all of the simulations carried out, there is no instance where the heat pump is unable to meet the demand of the house. In the simulation for the first three months, the data seems close to under performance, but on closer analysis the heat pump was within limits.

- High occupancy configuration 55 degrees

For this simulation, the high occupancy level is described in the table 5.

The simulation follows the same pattern as in the previous section, looking first at convection heating, then looking at the under floor heating configuration. This shows the differences in performance when in a house with higher heat gains.

- Analysis of the simulation for the start of the year showed that with the increased occupancy, a higher heat load was required. In this configuration there seemed to be a greater overlap of heat to supply. The spikes where the demand is higher than the supply are clearly seen.

- In the first three months, the heat pump is unable to meet supply by 14.55kWh. In the final three months of the year, the loss is 5.41kWh.

- The summer graph in appendix A shows that there are no periods where the heat pump is unable to achieve the demand of the house.

-High occupancy configuration 30 degrees

Upon reviewing all three simulations for this configuration, the result showed that all the periods achieved the required demand of the set point for 30 degrees.

Summary:

The table below shows the summary of total power delivery observed over the four simulations. It was important to quantify the amount of power which was unable to be met. This reveals the duration for which the heat pump under performs. Due to large quantities of data only the specific points where the demand experienced a deficit, were recorded. Then, in order to get the availability figure, the deficit in power over this period was used, the values from which are recorded in table 7 below. For the thirty degrees simulation, zero is entered into the "total heat demand column" this was due to the fact that there was no deficit in the demand throughout the year..

Configuration UK	Total heat demand which experienced deficit kWh	Deficit in power kWh	Availability %
Low occupancy 55 degrees	100.23	5.78	94.23
Low occupancy 30 degrees	0	0	100
High occupancy 55 degrees	259.28	19.96	92.30
High occupancy 30 degrees	0	0	100

Table 7. UK Climate Simulation Summary

10. Simulation Dundee climate file

10.1. Supply analysis

Climates vary considerably across the UK, and therefore it is important to consider a climate file that is specific to, or close to, that of the Westfield housing scheme. Unfortunately climate files are not widely available and the closest available file was that for Dundee.

Below are examples of where the pump performance does and does not meet demands simulated from the Dundee climate file

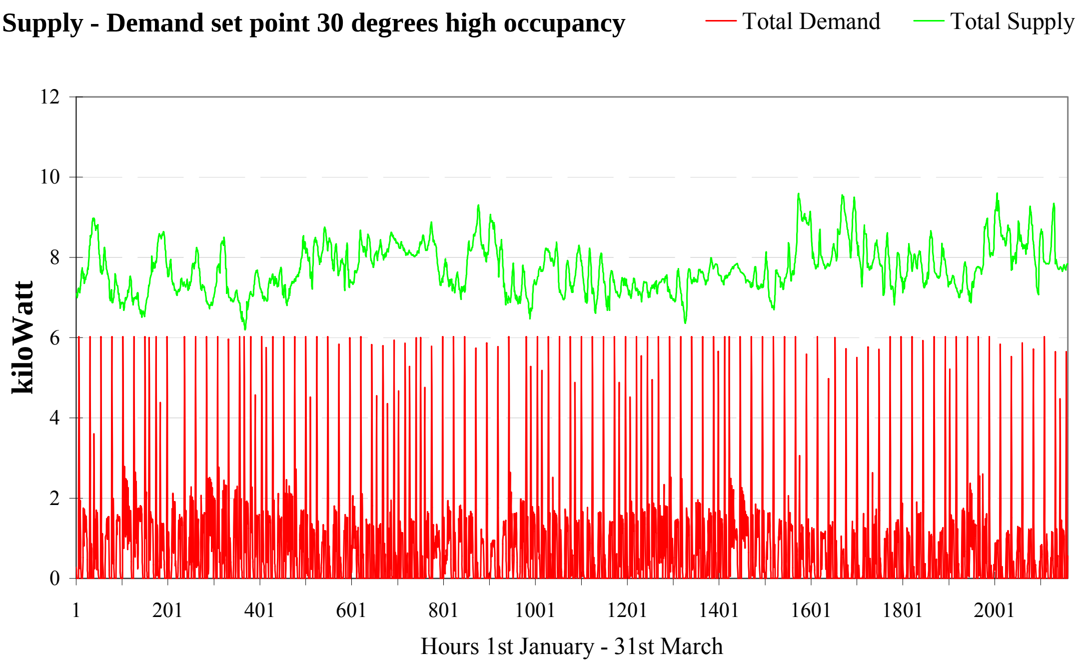


Figure 30. Supply and Demand 30°C High Occupancy

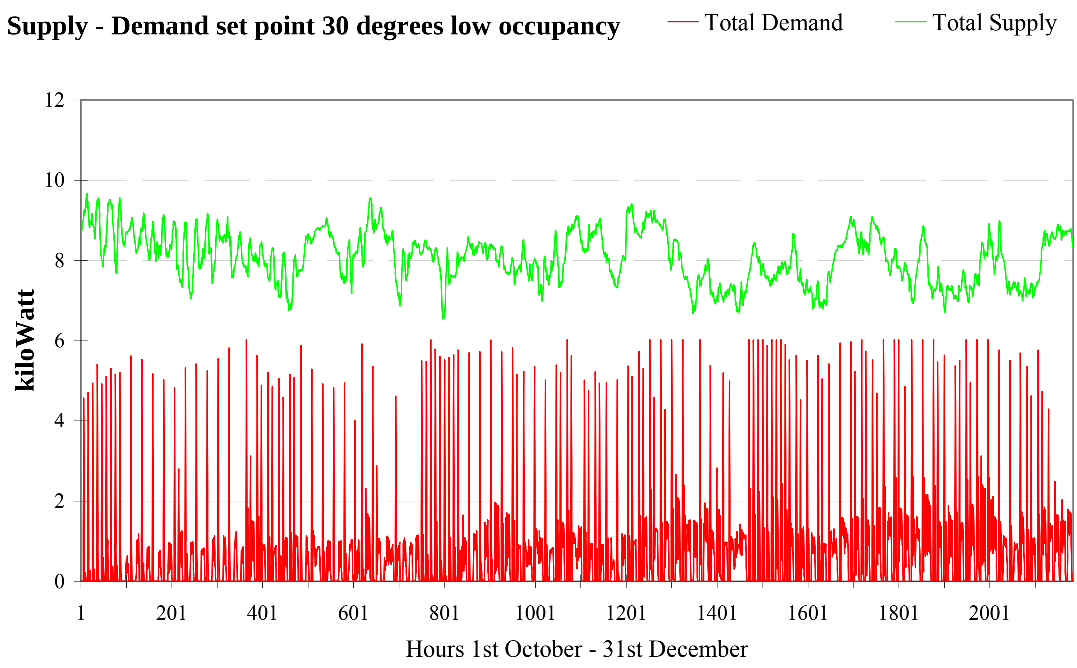


Figure 31. Supply and Demand 30˚C Low Occupancy

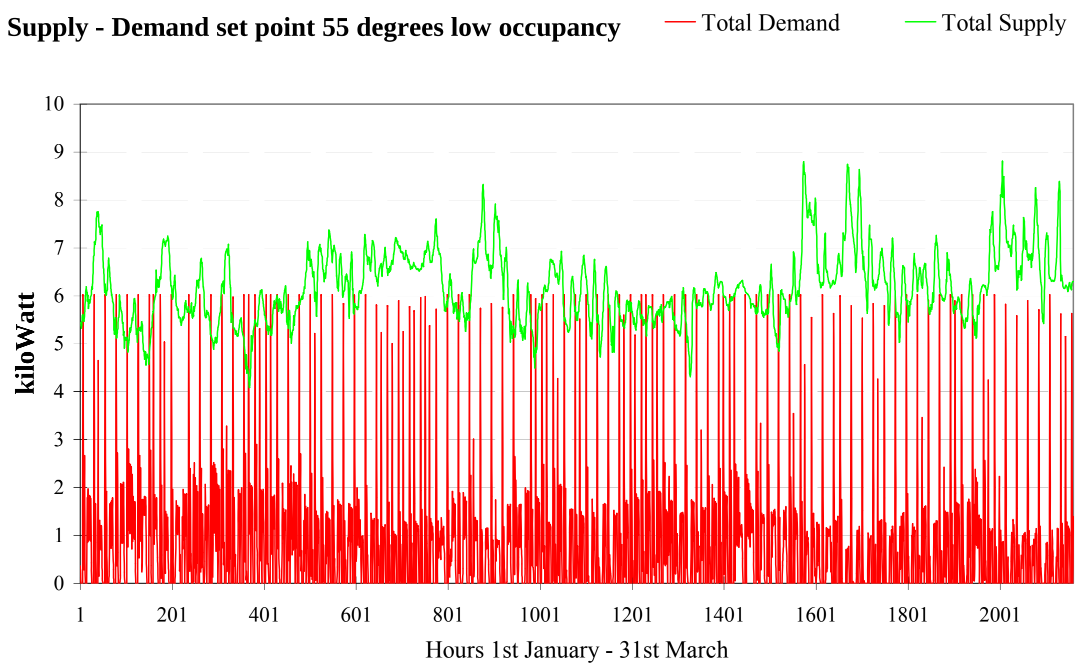


Figure 32. Supply and Demand 55˚C Low Occupancy

-Low occupancy configuration 55 degrees

Figure 32 indicates that the supply is unable to meet the demand on several occasions. This simulation requires to be analysed further in order to calculate the extent of the deficit in power delivery.

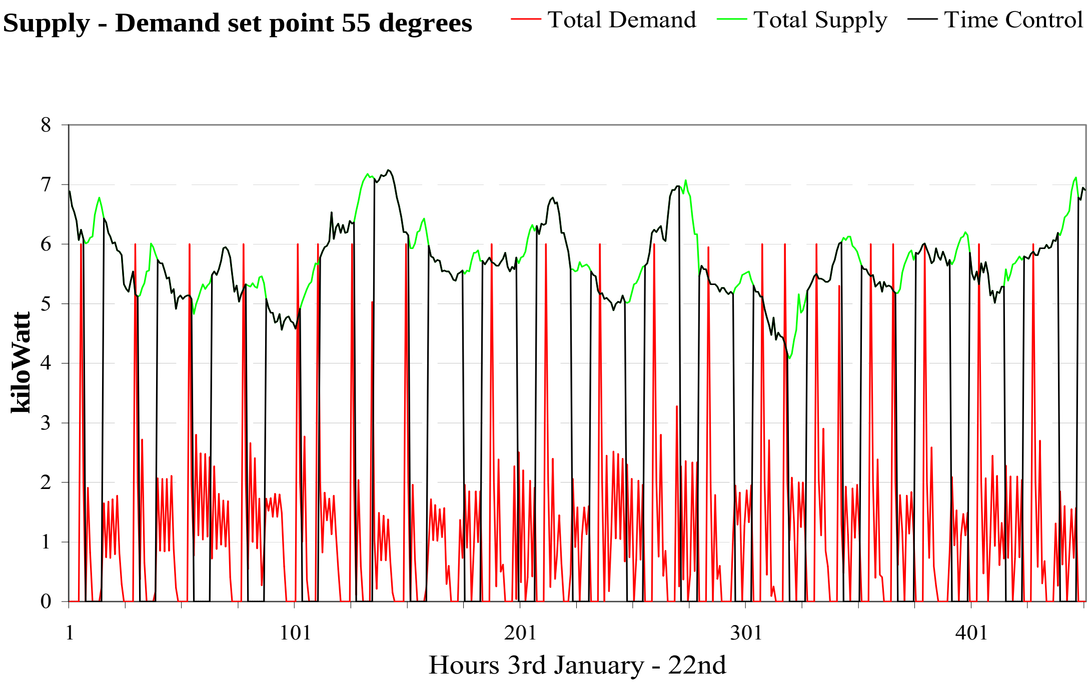


Figure 33. Supply and Demand Detailed View of Delivery

Upon initial review of the original output in figure 33, the deficit of power delivery is not significant. Figure 33 displays the period within the simulation which showed the most amount of instances of the heat pump unable to meet demand.

- In the full season simulation, the amount of power lost from January to March is 28.264 kWh.
- Using the same process of calculation in the end of year simulation, the amount of power lost was 2.808kWh.

-Low occupancy configuration 30 degrees

As previously observed, the simulations carried out at the 30 degrees setting showed no deficit in power delivery. This observation also stands true for the Dundee climate file simulation.
Again, for the end of year calculation there were no periods of power loss under these conditions.

-High occupancy configuration 55 degrees

Using the same method of calculation for determining the amount of power loss over time:

- Deficit of power for the start of year is 21.47kWh.

- Analysis for the end of year winter simulation showed that the deficit is not as great as the low occupancy configuration at 55 degrees.

- Over the entire period from October to December, the total loss is 2.793kWh.

-High occupancy configuration 30 degrees

The analysis for the 30 degrees set points show there is no deficit in power over the summer and winter period.

The table below shows only the total demand that saw a deficit in supply over the four simulations.

Configuration Dundee	Total heat demand which experienced deficit kWh	Deficit in power kWh	Availability %
Low occupancy 55 degrees	338.67	31.07	90.83
Low occupancy 30 degrees	0	0	100
High occupancy 55 degrees	320.55	24.27	92.43
High occupancy 30 degrees	0	0	100

Table 8. Dundee Climate Simulation Summary

11. Weather compensation

In warmer temperatures, less heat output from the heating system is required in order to maintain room temperature. With heat pumps it is possible to implement control via the micro processor, which allows the adjustment of the heating set point relative to the external temperature. The diagram below shows the process.

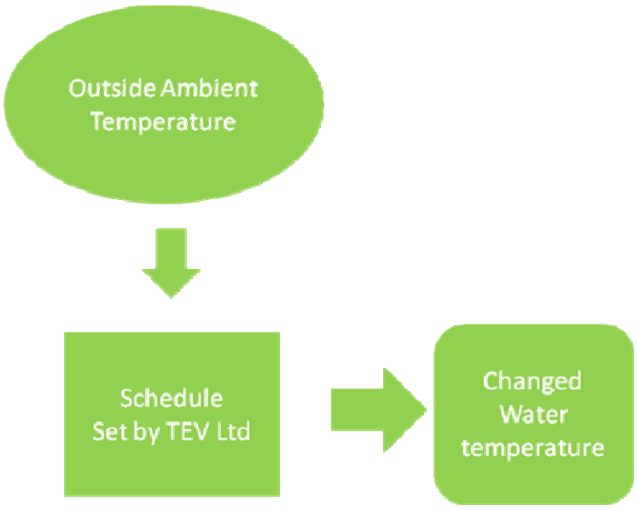


Figure 34. Compensation Flow Diagram

The set point of the water temperature is determined by a set schedule which is shown in figure 74 in appendix C, this schedule is initially set by TEV Ltd.

By utilising a sensor that records the outside temperature, the processor can adjust the water set point to suit the environmental requirements. The weather compensation is only for use in systems where wet system convection radiators are used order to lower the water temperature. As seen in the simulations in the previous sections there is no need for the heat pump to deliver maximum output during times in the year where the heat demand is lower. Therefore reducing the water set point should lower the power consumption and increase the COP. Thus, the heat generated is not wasted and is managed efficiently.

The construction of the heat pump is designed to be able to adjust the water set point quickly and accurately. This presents an advantage over conventional heating systems where the temperature is controlled locally at the radiator. Controlling the delivery temperature makes ensures that only the power needed is being delivered.

The heat pump installed at the houses at Westfield project did not have compensation activated when work begun on this thesis, however it was activated whilst work commenced. It was vital that the effects were modelled and included in this thesis to highlight the energy saving possibilities and improvement of heating delivery weather compensation can bring.

Compensation modelling

The schedule which was obtained from TEV was entered to Microsoft Excel. Using both this schedule and the climate file, look-up tables were constructed from which to model what the duty of the heat pump would be over the whole year. This could also be repeated for the COP

The first simulation carried out was to establish any effects that compensation may have had on COP over the whole year.

Due to the volume of data a maximum, minimum and average is used in the graph below. Also the other set points are included to provide comparable data

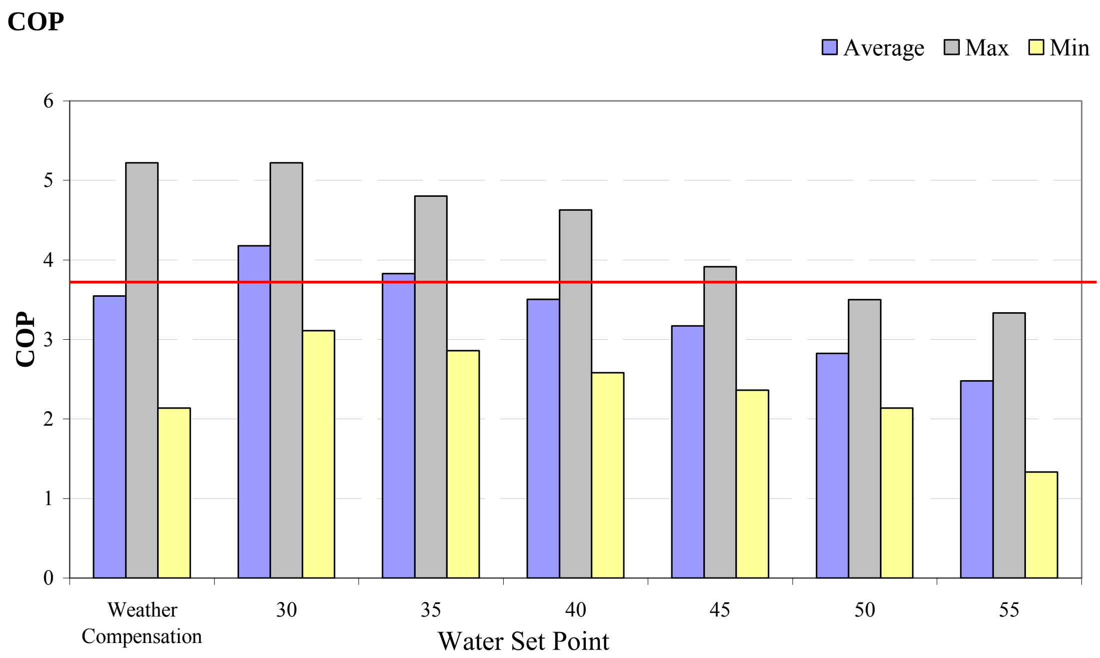


Figure 35. COP over Whole Year

From figure 35 observations are:

- With compensation, the pump still manages to reach a maximum COP
- Minimum COP is still greater than the simulations to the far right.
- The average COP is considerably higher than the water set point of 55 degrees

Here, the average COP for the radiator system is close to the thirty five degrees set point. This is a considerable increase in efficiency compared to the fifty five degrees set point to the far right.

The effect that weather compensation has on power consumption is important because ultimately the reason for using compensation is to increase COP and reduce power consumption. The graph below displays the result of compensation on power consumption.

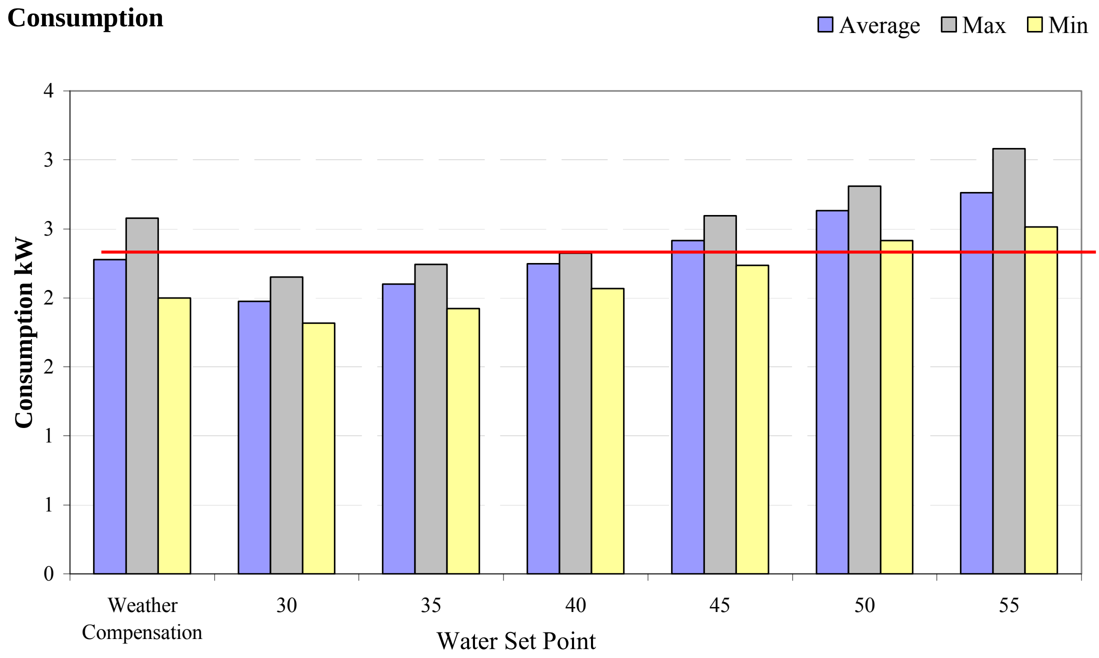


Figure 36. Consumption over Whole Year

Overall the consumption has been reduced relative to the consumption at fifty five degrees, and results in a considerable saving over a whole year. It can be seen that compensation delivers efficient use of energy. The set points to the right of the graph show that all the power above the line was effectively wasted.

Seasonal effects

Up to this stage a good representation of the advantages of compensation has been given. However, if we consider the points raised in section four, it was emphasized the SAP values can discount variable power delivery. The following simulation investigates this further to determine changes in performance over the changing seasons and to highlight the energy which is produced that is otherwise missed in SAP calculation.

Further analysis led to a decision to divide the year into summer and winter. This was done in order to examine the data more accurately.

In figure 37 below, there is a significant jump between summer and winter. Due to compensation, a large increase in COP can be seen in the summer months, which indicates that the pump is working more efficiently and effectively

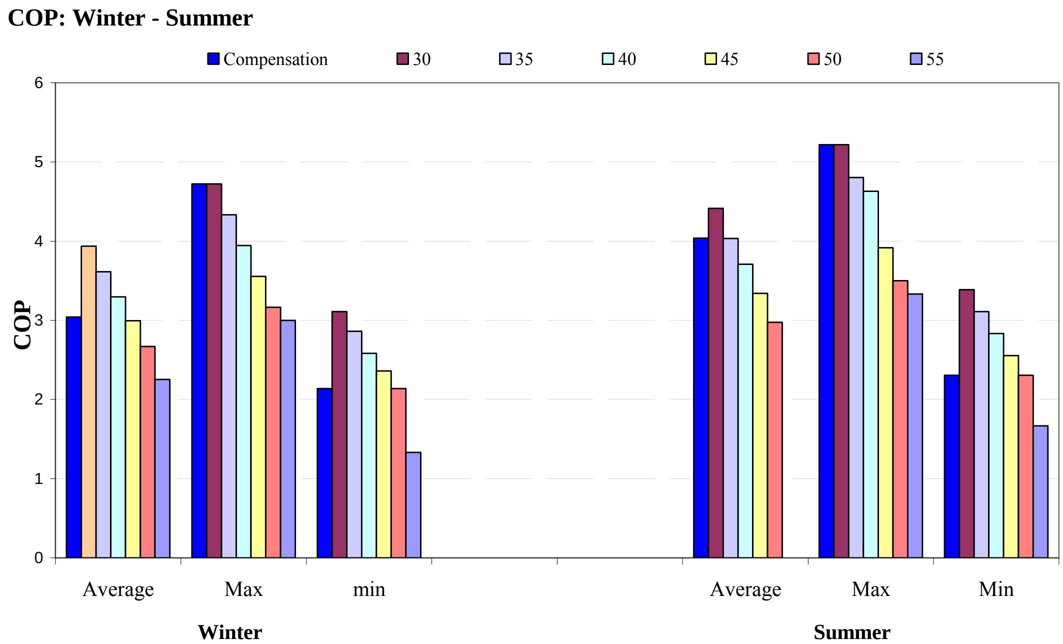


Figure 37. Seasonal Changes on COP

Consumption was also calculated to determine the changes in seasonal performance. Again, the graph below shows that the heat pump is able to use on average less power over the summer

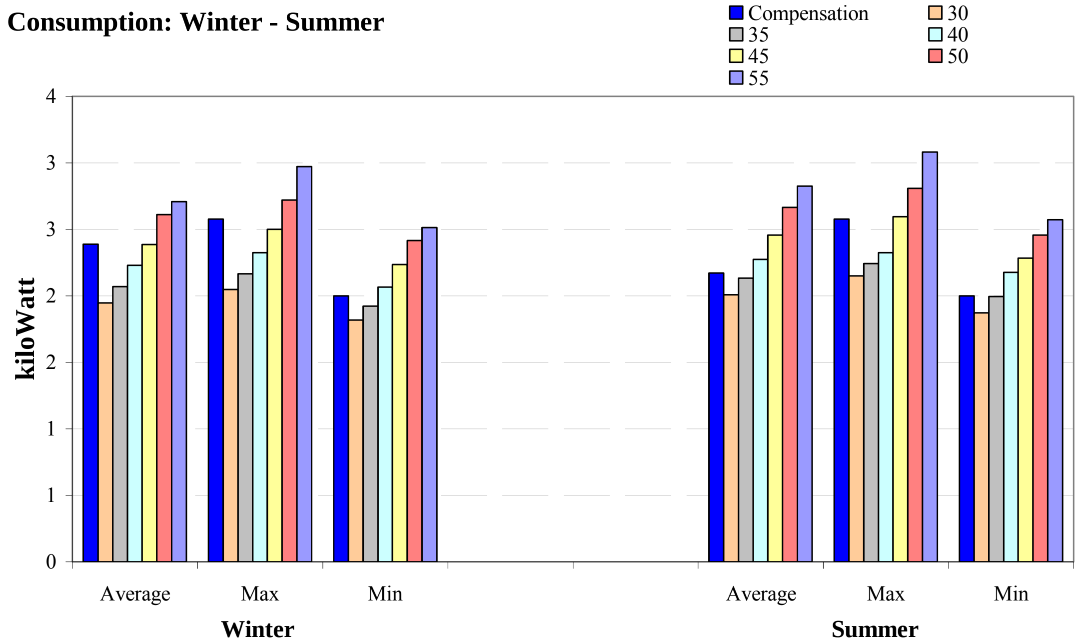


Figure 38. Seasonal Effects on Consumption

Tables 9 and 10 below, show the actual values that were calculated on the spreadsheet.

The values that were observed at the set point of 55 degrees were very close to the values taken directly from the downloaded data from the Westfield scheme.

Upon further review of the compensation values, a more accurate representation of performance has been identified, compared to manufacture pledges. The value of 5.22 for the summer does seem high however; the conditions were for a thirty degree set point with external temperatures in the mid twenties.

COP

	COP	Set point degrees					
Winter	Compensation	30	35	40	45	50	55
Average	3.04	3.94	3.61	3.30	2.99	2.67	2.25
Max	4.72	4.72	4.33	3.94	3.56	3.17	3.00
min	2.14	3.11	2.86	2.58	2.36	2.14	1.33
summer							
Average	4.04	4.41	4.03	3.71	3.34	2.98	
Max	5.22	5.22	4.81	4.63	3.92	3.50	3.33
Min	2.31	3.39	3.11	2.83	2.56	2.31	1.67

Table 9. Simulation Summary COP

Consumption

	Values in kW	Set point degrees					
Winter	Compensation	30	35	40	45	50	55
Average	2.39	1.94	2.06	2.22	2.38	2.60	2.70
Max	2.58	2.05	2.17	2.32	2.50	2.72	2.97
Min	2.00	1.82	1.92	2.07	2.24	2.42	2.51
Summer							
Average	2.17	2.01	2.13	2.27	2.46	2.67	2.82
Max	2.58	2.15	2.24	2.32	2.60	2.81	3.08
Min	2.00	1.87	2.00	2.18	2.28	2.46	2.57

Table 10. Simulation Summary Consumption

The final graphs below show the inclusion of weather compensation beside the original graphs shown in section 9.3. These graphs show the performance improvements over the whole year clearly. Consumption is approximately the same as the thirty degrees set point and the duty is around five kilowatts higher than the fifty five degrees set point.

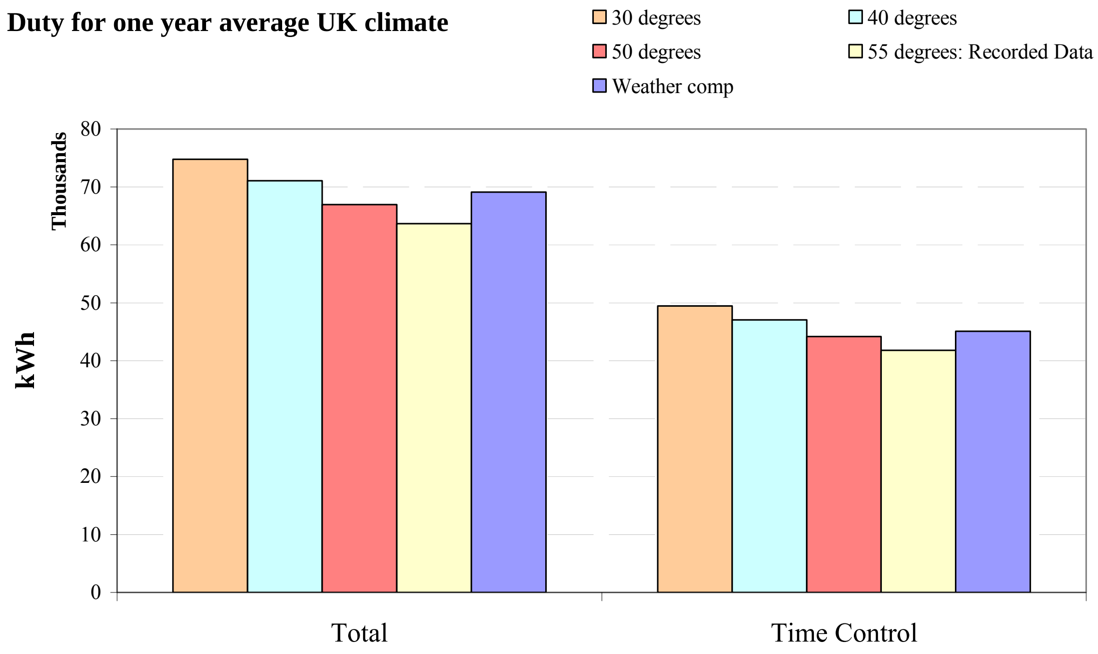


Figure 39. Yearly Duty with Addition of Weather Compensation

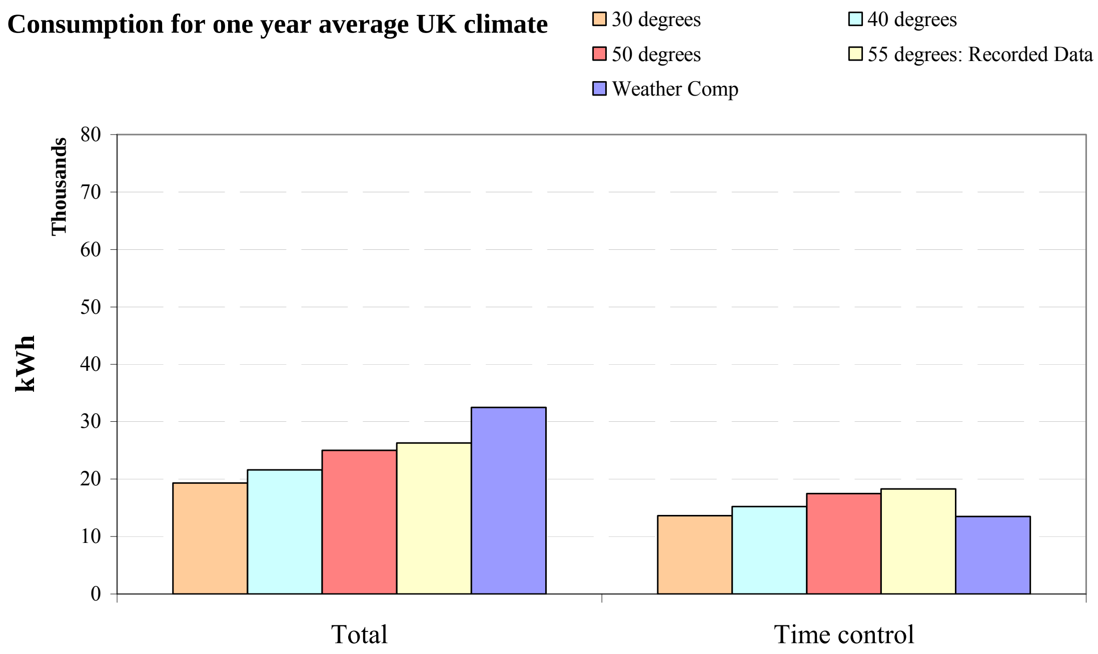


Figure 40. Yearly Consumption with Addition of Weather Compensation

The output which stands out between these two graphs above is the reduction in power consumption when using a wet convective radiator system.

11.1. Matching heat demand

After the compensation was simulated, it was possible display this duty with the heat demand of the house. The graphs below show the heat pump being able to achieve a closer match to the heat demand, thus preventing the heat pump from wasting power that is not required.

In section 10 and 11 it was apparent that there was a large overcapacity during the summer months. The use of compensation should close the gap between supply and demand and therefore increase the energy efficiency of the heat pump.

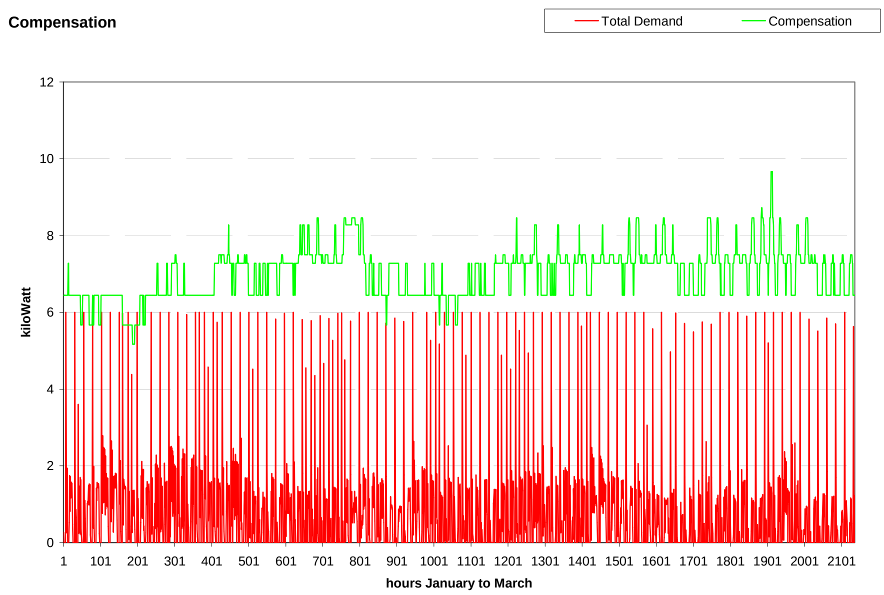


Figure 41. Supply and Demand

The graphs shown here use the heat demand profile for high occupancy, because this gave the largest deficits previously.

Below is the simulation that considers the end of year scenario. Again, the gap between demand and supply appears better matched than previous simulations.

Figure 42. Supply and Demand

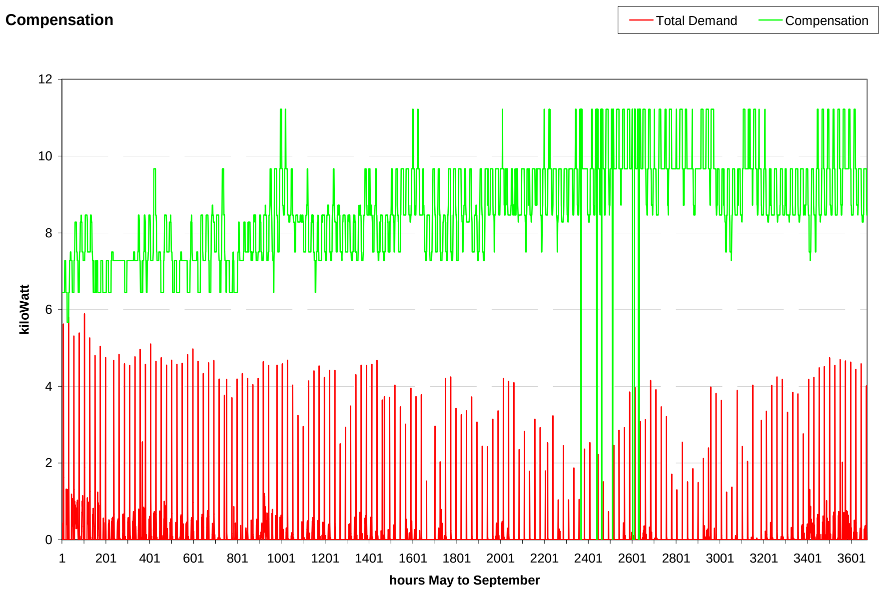


Figure 43. Supply and Demand

Previous summer simulations identified a large gap between demand and supply. The above simulation still shows a large gap between supply and demand, however the heat pump is seen to run for longer at a certain set point, before moving up to the next schedule point. The schedule fluctuations can be seen clearly in figure 40 and 41. In effect, the heat pump delivers energy at a lower level instead of increasing the consumption of the heat pump

12. Conclusions

The aim of this thesis was to carry out a detailed performance review of an air source heat pump, and in addition to this, to determine if ASHP is a viable alternative to other heating methods and the effect of seasonal variance on performance.

Current technology is also considered, and how components of the heat pumps have been developed to obtain better efficiencies.

The content of this thesis therefore facilitates an increased understanding of:

- The technology and processes
- Efforts being made in other countries to develop heat pump technology
- Operational limits

Literature review

Section one provides an explanation of what a heat pump is, and an insight into the technology used to transfer heat from air to water. Heat pump technology in the UK is still not widely understood and this section explains how a heat pump can be used as both a heating and cooling device. It was important to include in this section that the introduction of scroll compressors had greatly increased the performance of heat pumps, by allowing them to operate in temperatures of up to minus fifteen degrees. This is important due to the varied climate that is experience in the UK. This section provides a simple explanation of the components that are used within heat pumps and how they work to utilise the refrigerant to distribute heat.

Section two discusses the benefits of using a heat pump, e.g. energy saved compared to other heating methods. It was also interesting to identify that there are many options available when choosing heating methods. Fuel prices are also considered and show that a volatile market in fossil fuels can favour the use of ASHP.

Section three discusses the main components of performance in heat pumps. The engineering cycles and various stages of the refrigerants process in the ASHP are explained in detail. This gives a greater understanding of the operational limits of the ASHP by understanding the absorption cycle. Also within this section a table is included which breaks down most heating technologies acts as a benchmark to other heat pump technologies. This provides a good appreciation of how ASHP compares to other available heating technologies. Also in this table is a breakdown of CO_2, which shows that ASHP is considerably better than fossil fuel boilers in reducing CO_2 emissions. Government targets in lowering CO_2 emissions favour technologies which are low in carbon.

Section four discusses the main pieces of legislation that impacts ASHP, and that it is important to take a closer look at the SAP (Standard Assessment Procedure) to identify if there are any areas which hinder the development of ASHP. In these procedures it is found that the average value stated is the seasonal performance factor. This is a value of COP averaged over the whole year. A nominal value of 2.5 was given which is used to quantify all ASHP. Upon examining this further it was instantly identified that a large amount of power that the ASHP does produce over the seasons is discounted. Furthermore it was also apparent that ASHP's differing in make and model will not necessarily obtain the same levels of COP. Overall this rating gives ASHP a poor value. This is detrimental to developing ASHP markets in new builds, where all new buildings have to be SAP rated.

Current global development

Whilst researching UK government initiatives in section five, it is identified that funding for ASHP is not as good as other countries. Also identified is that the programs which are found in the UK are superseded frequently by newer ones which offer fewer incentives than previously made available. This indicates that the level of commitment of the UK government in developing heating technologies is low and more could be done to develop this market.

As stated in the introduction, case studies are limited, and it is often difficult to ascertain savings. However, the studies included in this section (Wiltshire Leisure Village etc) give good evidence that the technology is beneficial and fast becoming a realistic alternative to other forms of heating.

It was realised early in the research of development that in other countries a lot has been done to develop heat pump technology. Although the information researched was concentrated on ground source, the same investment and development programs can be used in ASHP. It is fundamentally through the same engineering process that the heat pumps generate heat. In this thesis it has been seen that the advances in technology have made ASHP units run with higher COP's in more challenging climates. All countries researched in this thesis show sizeable increases in heat pump installations rising as a result of their initiatives, development and financial investment.

Performance review

Section eight provides detail about the background of the project description, identifying the type of heat pump used and why the project took place. A detailed explanation of the heat load of the house is included. In order to conduct a thorough and accurate analysis it was important to get a heat demand profile that was close to that of the houses at Bathgate. This was achieved by selecting a model with similar size and construction. This analysis was done by using ESP-r, which allowed the generation of heat demands which differed in occupation and climate. Furthermore this tool made it possible to examine the heat demand over a whole day, and show how the heat pump copes under changing demands in a varying climate. The simulation tool Merit was also used to generate the heat pumps output over the whole year. This gave a clear indication, as seen in the graphs in appendix A, of the effect that external temperature has on the unit and how varied the output can be. This raises awareness in anticipating the performance of an ASHP depending on which climate it is situated.

Section nine and ten provide an extensive breakdown of the ASHP performance. By using Microsoft Excel, the exact deficit in power over the year period could be calculated. In combination with the output graphs, it could be seen where the ASHP output did not meet the demand and for how long. The summary table shows that climate does have an effect on performance. In the colder Dundee climate, the availability of the heat pump to meet demand is lower than that of the UK climate. It is also important to note at this stage, that there was no deficit in power in the simulations which were set at thirty degrees. This shows that using ASHP with underfloor heating is highly desirable due to the low temperatures which are used.

However using the ASHP in a wet convective system is also productive and delivers the desired levels of heat. The benefits of this are that it can be easily fitted to existing radiator systems and the price is lower when compared to that to installing an underfloor system.

After understanding and illustrating the ASHP's performance it was important to look at better ways of controlling the ASHP output. It was seen in sections nine and ten that there are areas on the graphs where there is large over capacity. It is possible to adjust the output of the heat pump to particularly meet the demand of the heat load instead of consuming power that is not needed. Other repercussions of not using this type of control are frequent start up's of the unit which is not desirable due to high start up currents and knock on effects on reliability. Section eleven shows what the output may look like with weather compensation. The units installed at Bathgate did have this capability, but it was not activated until a later date. The outputs shown in this section show a greater increase in efficiency compared to the outputs in the previous section. In these simulations there is negligible deficit, and the over capacity if visibly reduced.

With SAP calculations in mind, it was crucial to see the COP change in the two seasons modelled, and to understand the values achieved. In figure 37 substantial changes in COP are noted. Between winter and summer, there is an increase of the average value from 3 to a COP of 4. If this is added up over the whole season this is a significant figure, which is otherwise disregarded in SAP. It is also noted that the values seen in the simulations are considerably higher than the average value of 2.5 stated on the SAP calculation sheet. In tables nine and ten, a breakdown of the COP and consumption is given. This was included to give an extensive breakdown of the ASHP performance over a range of set points and seasons. Upon reviewing the values explicit to the installation at Bathgate i.e. the 55 degrees set point, and the compensation, it can be seen that the compensation gives increased efficiency in COP and consumption. In the average, maximum and minimum, the value for consumption is around .3 of a kilowatt lower than that of the 55 degrees simulation. This would produce energy and cost savings to the user which in turn reduces the amount of power which is wasted though out its operation.

This is also repeated in the summer simulations where the values are around .5 - .6 of a kilowatt lower. Over the whole year these reductions would produce a considerable reduction in running costs and also reduce demand from the electricity network.

In conclusion, the data presented proves that ASHP is a viable alternative to fossil fuel heating systems and delivers the heat required for a home. The thesis also shows room for growth in the ASHP market and also room for improvement in financial help in installing greener, low carbon technologies in the UK.

12.1. Areas for Further Research

An investigation into the uptake of heat pumps arising from efficiency gains, heat pumps vs. ground pumps would be beneficial and accompany this thesis due to points raised in section seven.

Investigating split heating systems where hot water is generated along with space heating, could further develop the understanding of heat pump potential. In the simulations carried out there were indications that there the extra capacity over the period of a day could be made use of to heat domestic hot water.

13. Appendix A

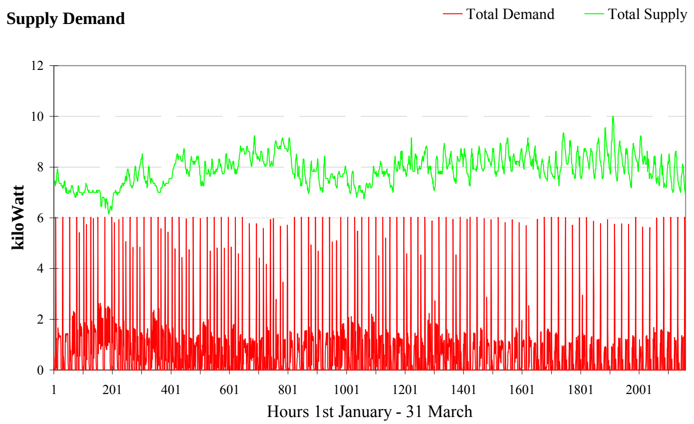


Figure 44. Supply and Demand Start of Year Set Point 30

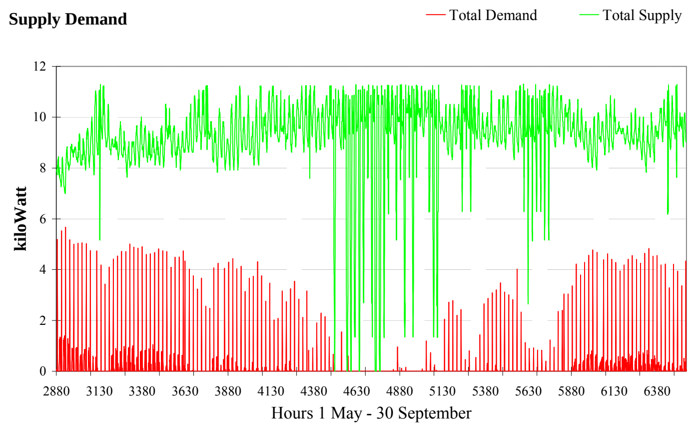


Figure 45. Supply and Demand Summer Set Point 30

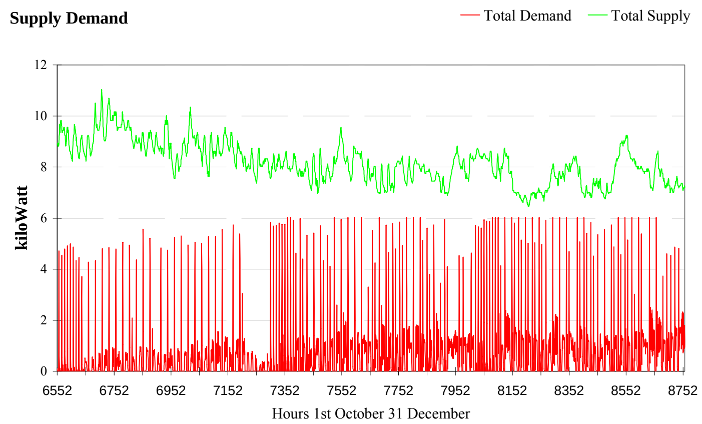


Figure 46. Supply and Demand End of Year Set Point 30

Set point 30deg low occupancy

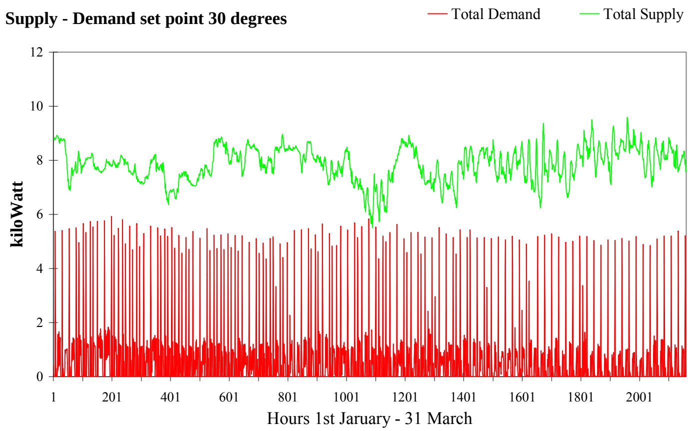


Figure 47. Supply and Demand Start of Year Set Point 30

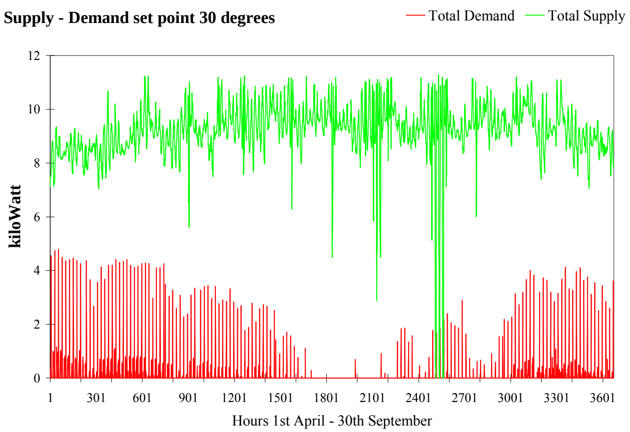


Figure 48. Supply and Demand Summer Set Point 30

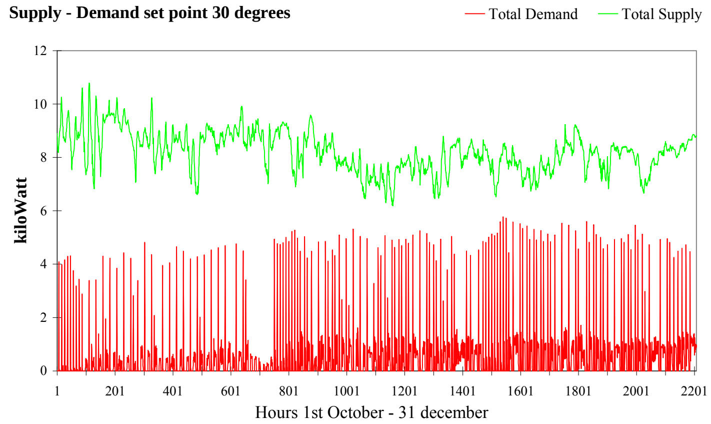


Figure 49. Supply and Demand End of Year Set Point 30

Set point 55deg high occupancy

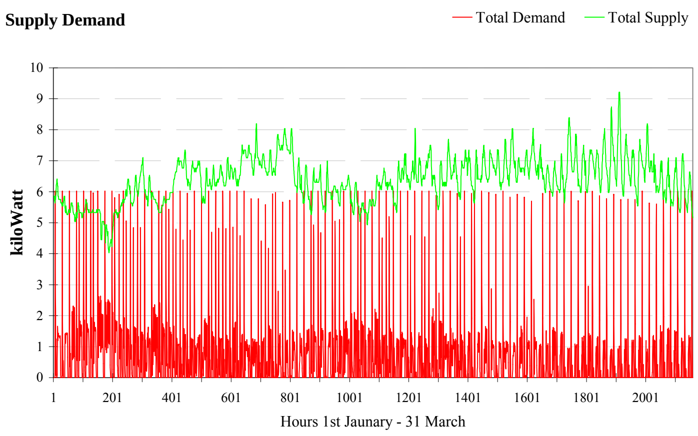


Figure 50. Supply and Demand Start of Year Set Point 55

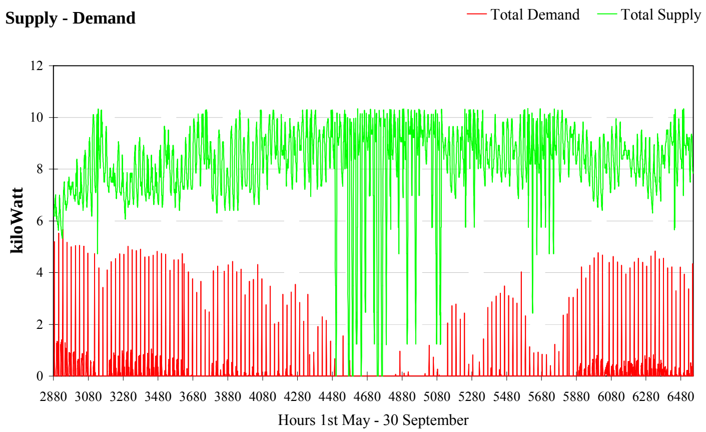


Figure 51. Supply and Demand Summer Set Point 55

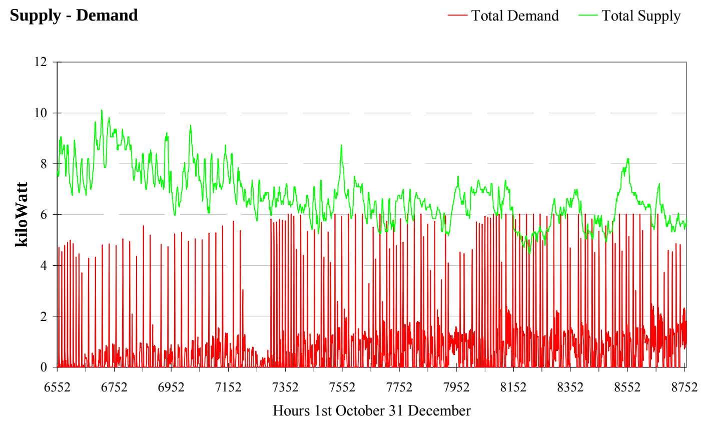


Figure 52. Supply and Demand End of Year Set Point 55

Set point 55 deg low occupancy

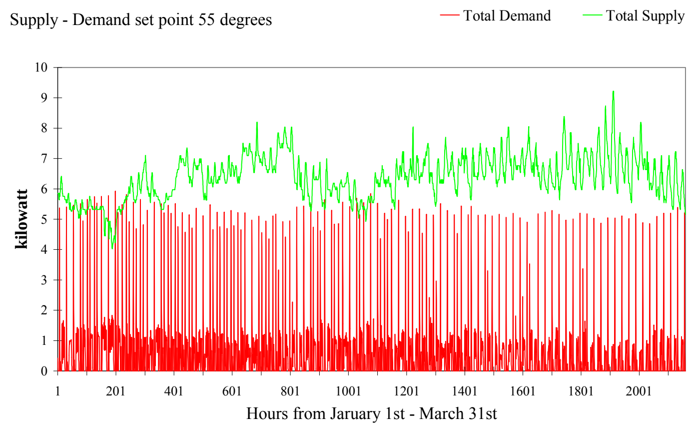


Figure 53. Supply and Demand Start Of Year Set Point 55

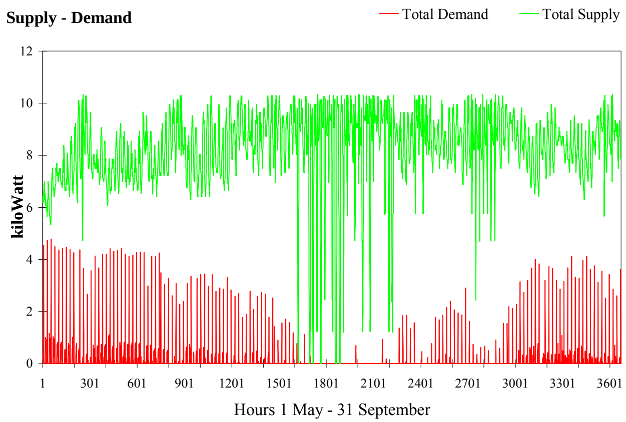


Figure 54. Supply and Demand Summer Set Point 55

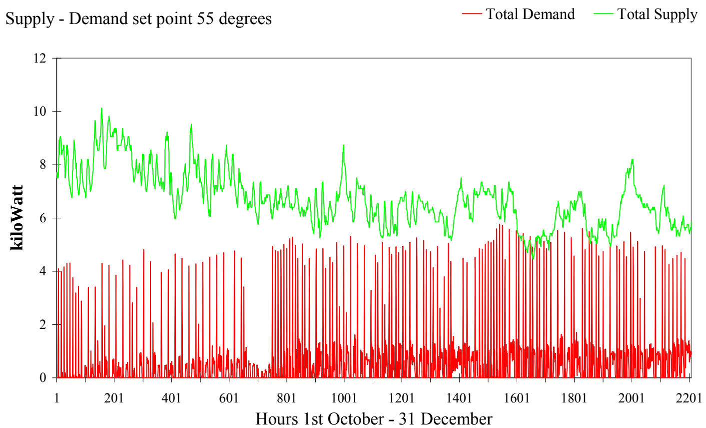


Figure 55. Supply and Demand End of Year Set Point 55

Set point 30deg high occupancy Dundee

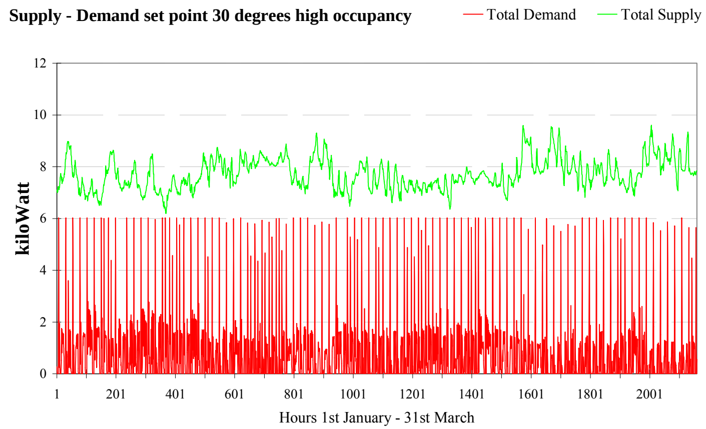


Figure 56. Supply and Demand Start of Year Set Point 30

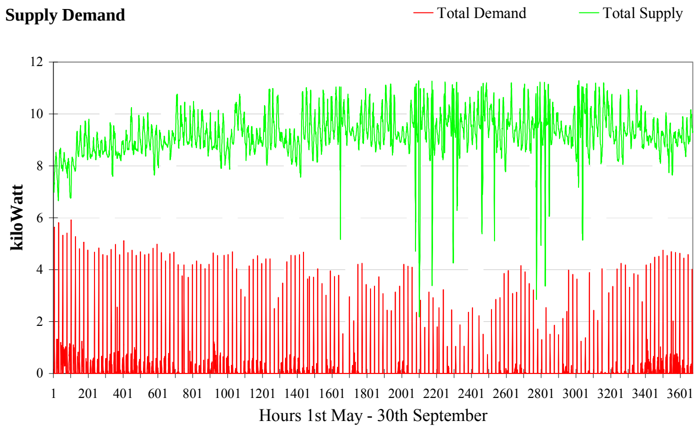


Figure 57. Supply and Demand Summer Set Point 30

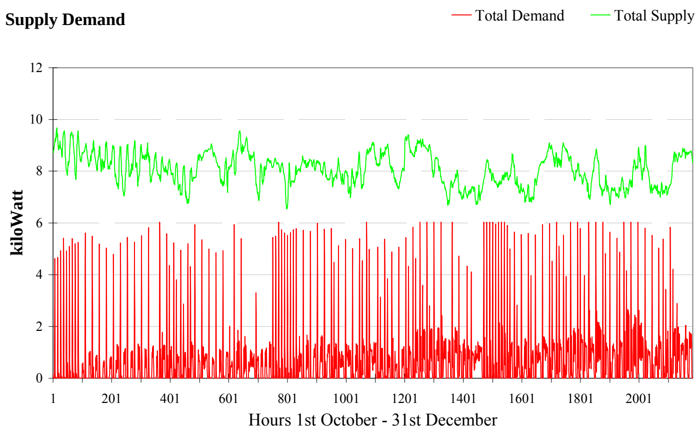


Figure 58. Supply and Demand End of Year Set Point 30

Set point 30deg low occupancy Dundee

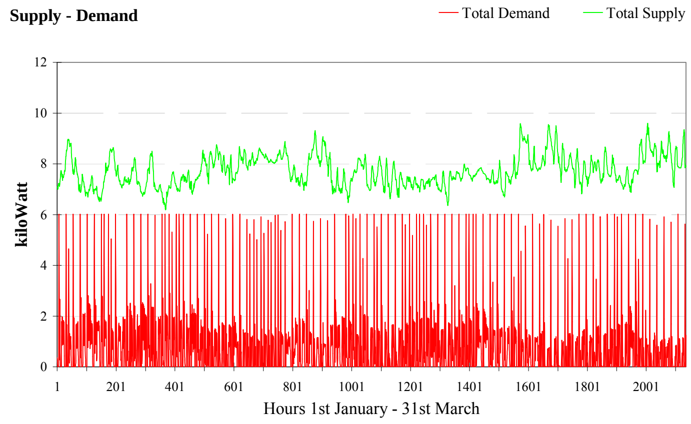


Figure 59. Supply and Demand Start of Year Set Point 30

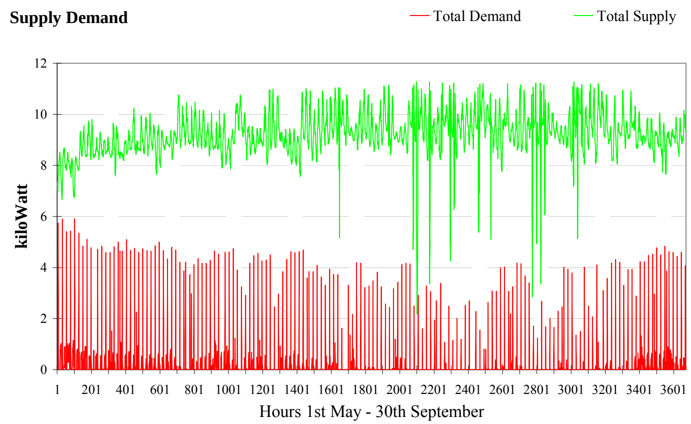


Figure 60. Supply and Demand Summer Set Point 30

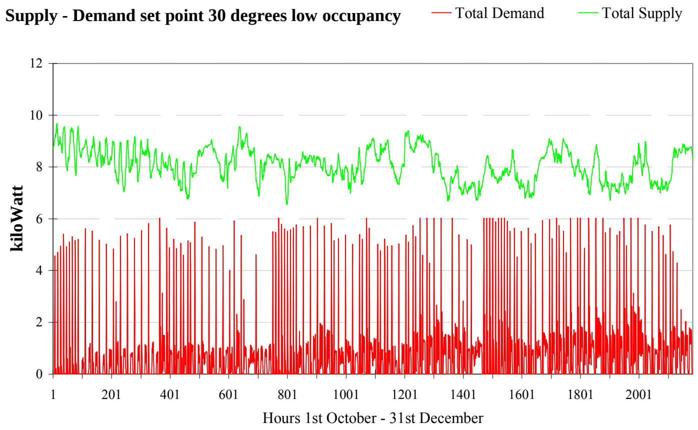


Figure 61. Supply and Demand End of Year Set Point 30

Set point 55deg high occupancy Dundee

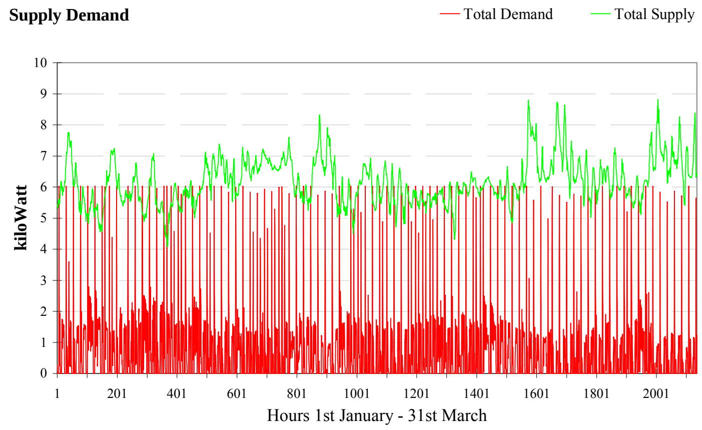


Figure 62. Supply and Demand Start Of Year Set Point 55

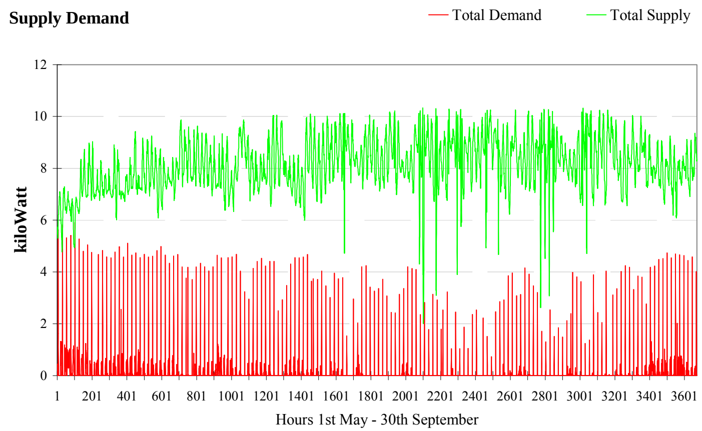


Figure 63. Supply and Demand Summer Set Point 55

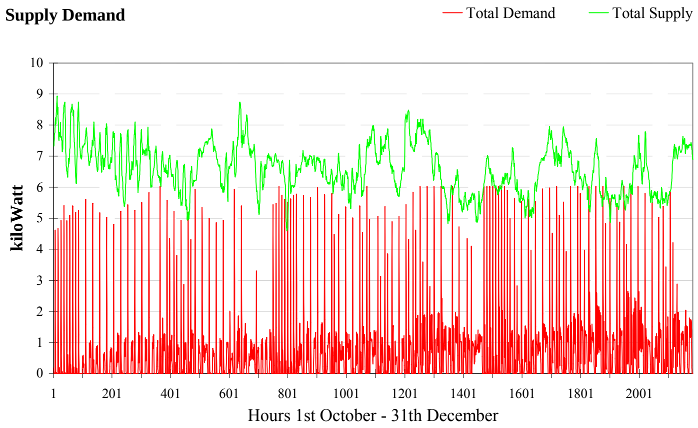


Figure 64. Supply and Demand End of Year Set Point 55

Set point 55deg low occupancy Dundee

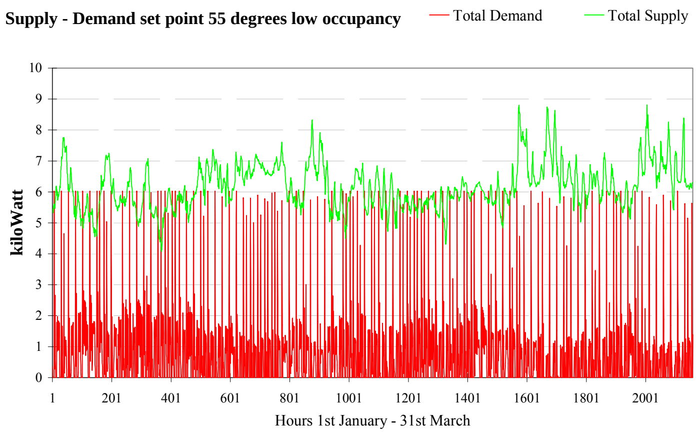


Figure 65. Supply and Demand Start of Year Set Point 55

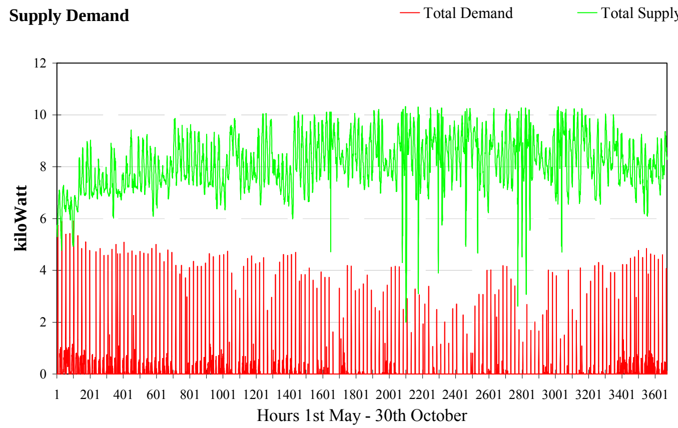


Figure 66. Supply and Demand Summer Set Point 55

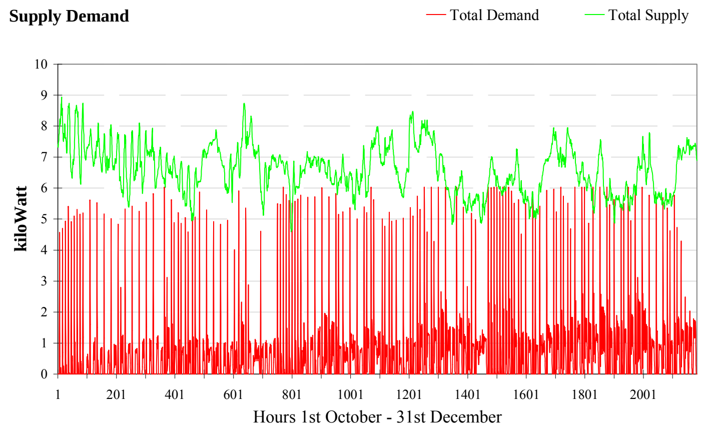


Figure 67. Supply and Demand End of Year Set Point 55

14. Appendix B

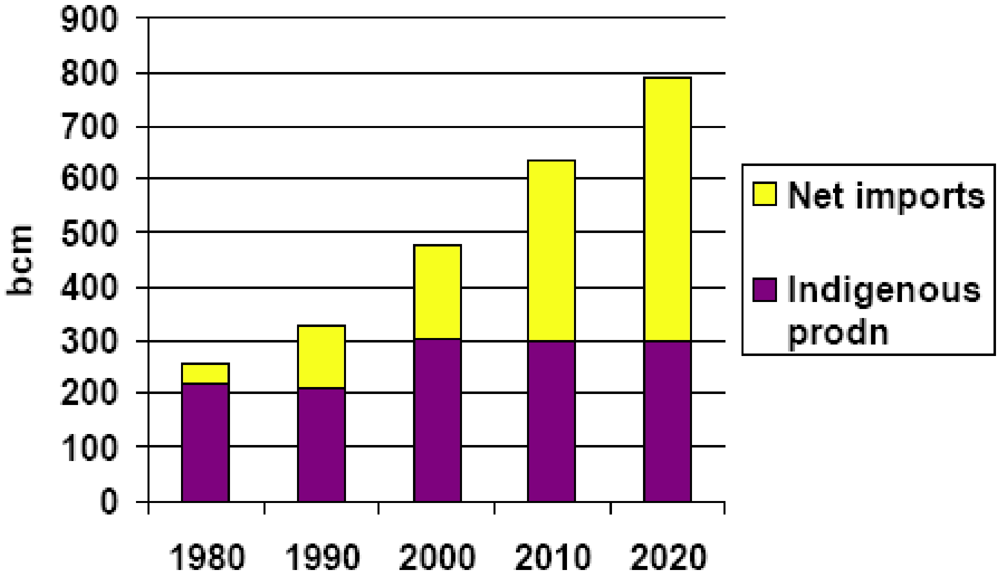


Figure 68. OECD[9] Europe Gas Balance [72]

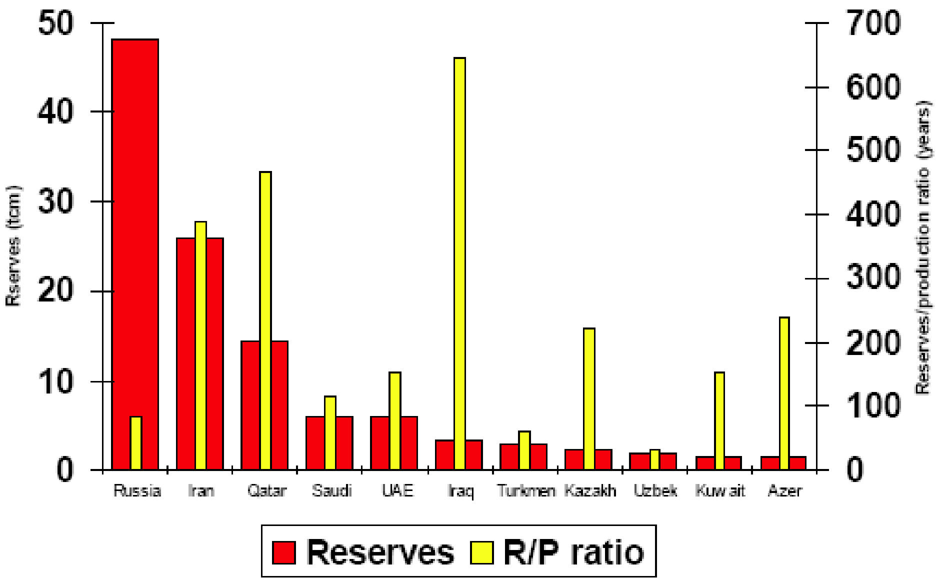


Figure 69. Proven Gas Reserves [73]

[9] Organization for Economic Co-operation and Development

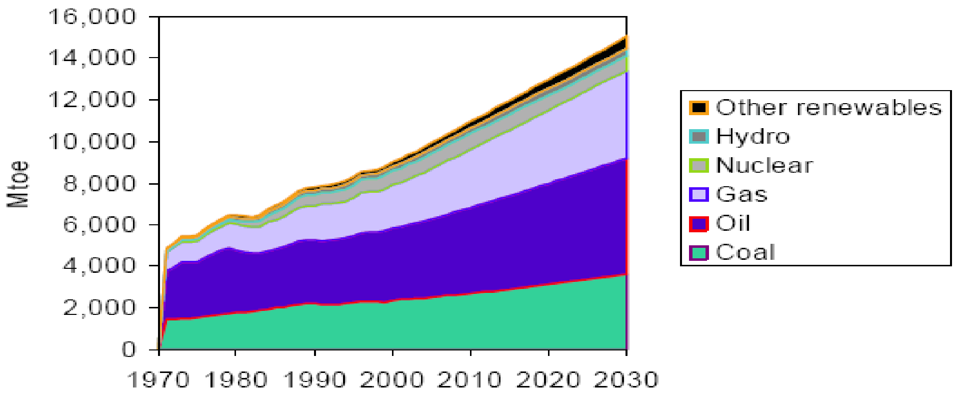


Figure 70. World Primary Energy Demand [74]

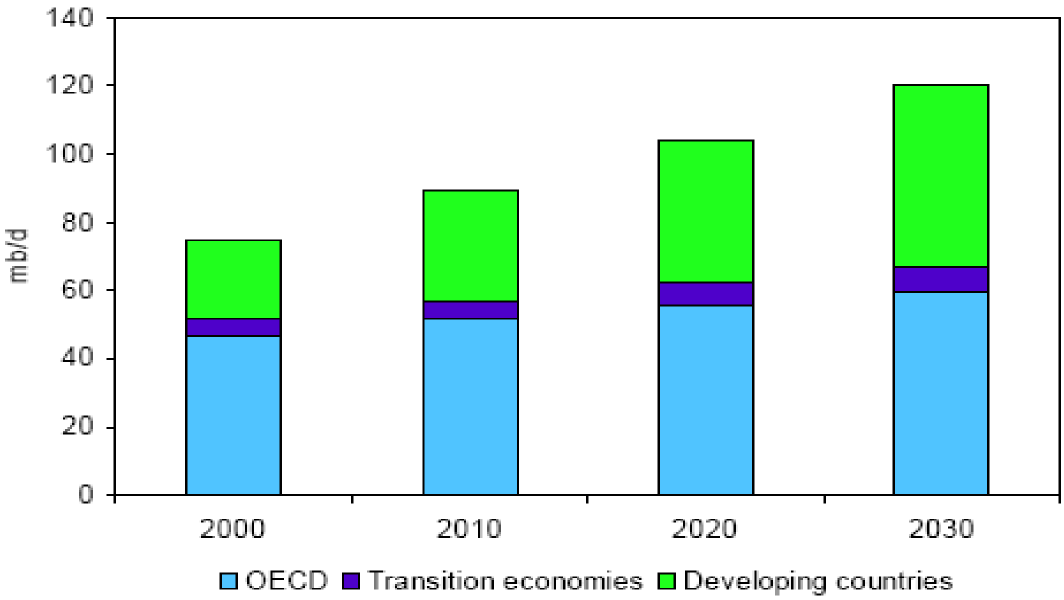
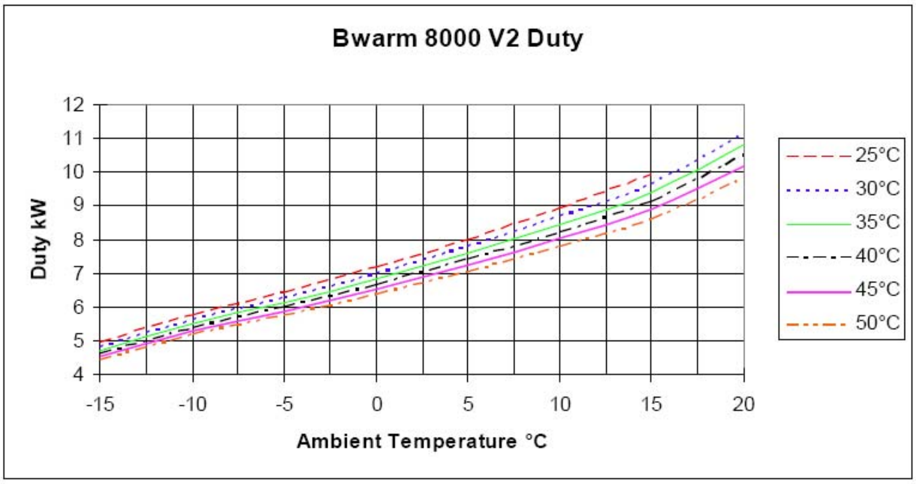


Figure 71. World Oil Demand [75]

15. Appendix C



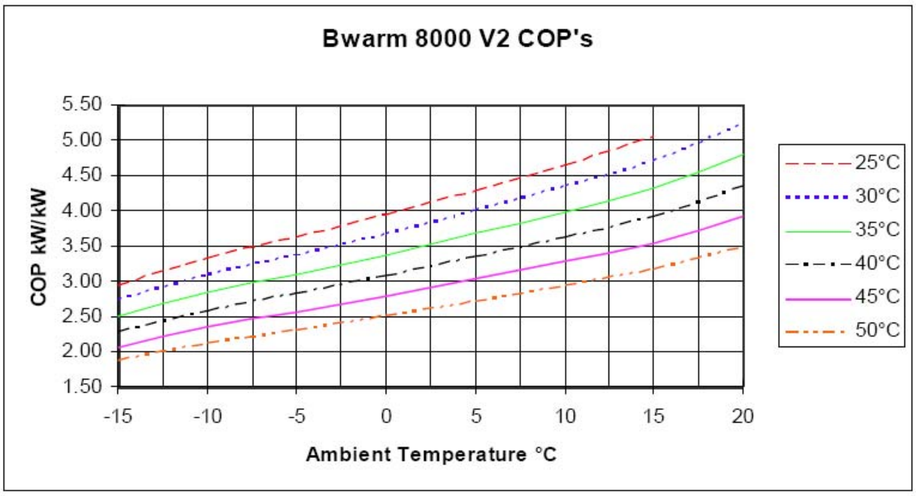


Figure 72. Manufacturer Performance Data

		COP						
	WATER SET POINT	25	30	35	40	45	50	55
OUTSIDE TEMPERATURE	-20	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-15	2.944	2.750	2.500	2.306	2.083	1.861	1.000
	-10	3.333	3.111	2.861	2.583	2.361	2.139	1.333
	-5	3.639	3.388	3.111	2.833	2.555	2.306	1.667
	0	3.940	3.694	3.389	3.083	2.805	2.500	2.000
	5	4.277	4.000	3.694	3.361	3.055	2.722	2.333

Table 11. Example 2D Array

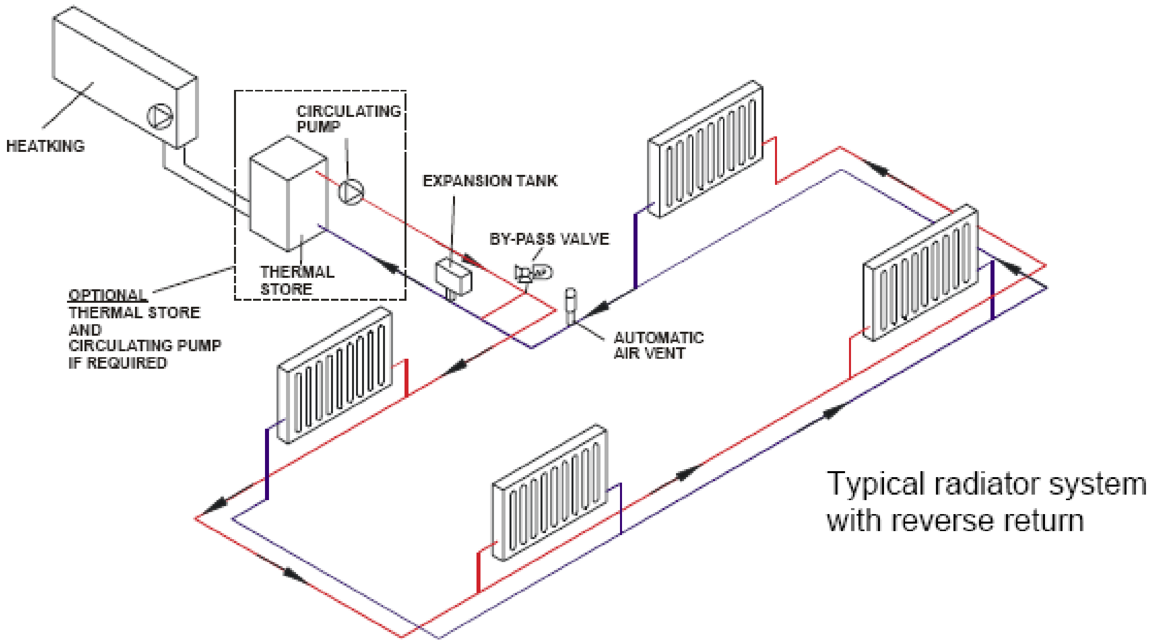


Figure 73. Radiator System Diagram[76]

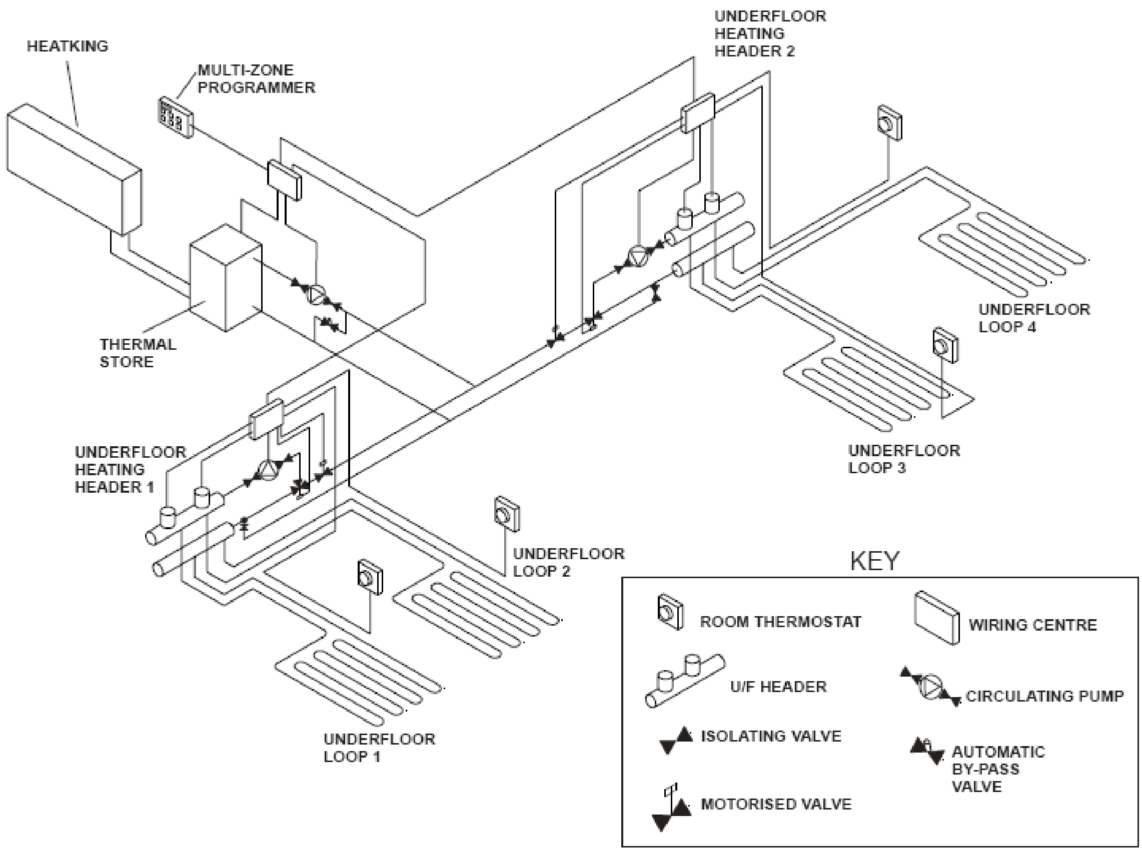


Figure 74. Underfloor Heating Diagram[77]

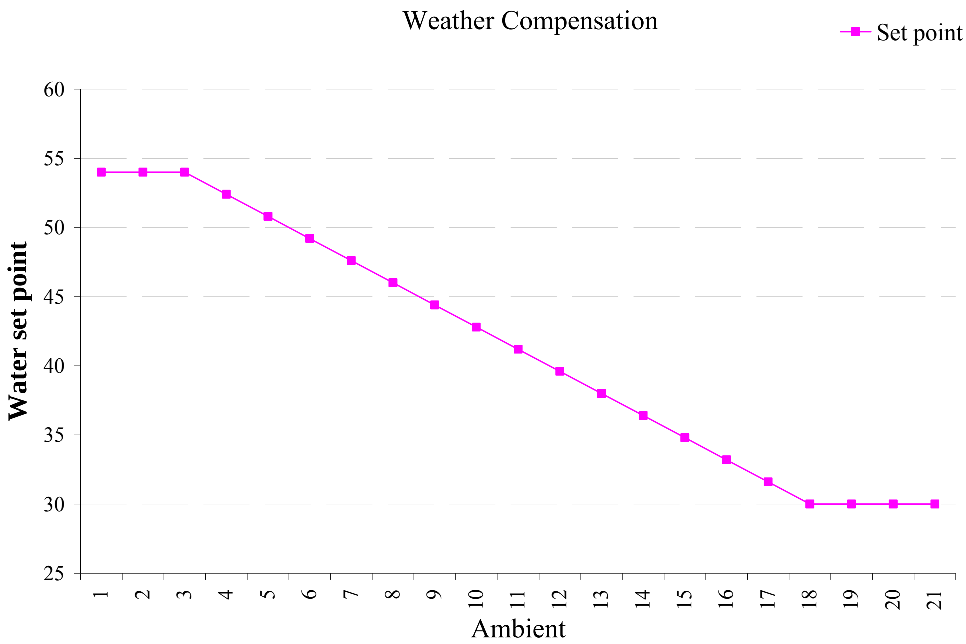


Figure75. Weather Compensation Schedule[78]

Figure 76 Position of Westfield and Relation to Dundee[79]

Figure 77 UK Climate File Position [80]

Model Thermal Properties

Surface Layer	Thick (Mm)	Conductivity W/Mk	Density Kg/M	Specific Heat Cp	IR Emis	Solar Abs W/Mk	Description
Surf-1 Is Composed Of Exterior Wall And Is Opaque:							
1	100	0.84	1700	800	0.9	0.7	Brick (Milton Keyns)
2	50	0	0	0			Air Gap (R= 0.180
3	50	0.05	12	840			Glass Fibre Quilt
4	140	1.06	1950	1000			Concrete Block (Milton Keynes)
5	25	0	0	0			Air Gap (R= 0.180)
6	55	0.025	25	1000			Eps
7	15	0.16	950	840	0.84	0.55	Gypsum Plasterboard
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Exterior Wall Is 0.245 0.247 0.243 0.240							
Surf-4 Is Composed Of Exterior Wall And Is Opaque:							
1	100	0.84	1700	800	0.9	0.7	Brick (Milton Keyns)
2	50	0	0	0			Air Gap (R= 0.180)
3	50	0.05	12	840			Glass Fibre Quilt
4	140	1.06	1950	10			Concrete Block (Milton Keynes)
5	25	0	0	0			Air Gap (R= 0.180)
6	55	0.025	25	1000			Eps
7	15	0.16	950	840	0.84	0.55	Gypsum Plasterboard
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Exterior Wall Is 0.245 0.247 0.243 0.240							
Surf-1 Is Composed Of Exterior Wall And Is Opaque:							
1	22	0.15	800	2093	0.84	0.7	Chipboard
2	100	0	0	0			Air Gap (R= 0.180)
3	100	1.06	1950	1000			Concrete Block (Milton Keynes)
4	100	0	0	0			Air Gap (R= 0.180)
5	12.5	0.16	950	840	0.84	0.55	Gypsum Plasterboard
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Interior Ceiling Is 1.178 1.221 1.125 1.065							
Surf-6 Is Composed Of Interior Floor And Is Opaque:							
1	12.5	0.16	950	840	0.84	0.55	Gypsum Plasterboard
2	100	0	0	0			Air Gap (R= 0.180)
3	100	1.06	1950	1000			Concrete Block (Milton Keynes)
4	100	0	0	0			Air Gap (R= 0.180)

5	22	0.15	800	2093	0.84	0.7	Chipboard
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Interior Floor Is 1.178 1.221 1.125 1.065							
Sth2 Is Composed Of Exterior Wall And Is Opaque:							
1	100	0.84	1700	800	0.9	0.7	Brick (Milton Keyns)
2	50	0	0	0			Air Gap (R= 0.180)
3	50	0.05	12	840			Glass Fibre Quilt
4	140	1.06	1950	1000			Concrete Block (Milton Keynes)
5	25	0	0	0			Air Gap (R= 0.180)
6	55	0.025	25	1000			Eps
7	15	0.16	950	840	0.84	0.55	Gypsum Plasterboard
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Exterior Wall Is 0.245 0.247 0.243 0.240							
Glz_Doorsth Is Composed Of Windows & Optics SBSADG_CIBSE							
1	6	1.05	2500	750	0.05	0.06	6mm CF Low E
2	18	0	0	0			Air Gap (R= 0.380)
3	6	1.05	2500	750	0.05	0.06	6mm CF Low E
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Windows Is 1.781 1.882 1.663 1.535							
Wind_Sth Is Composed Of Windows & Optics SBSADG_CIBSE							
1	6	1.05	2500	750	0.05	0.06	6mm CF Low E
2	18	0	0	0			Air Gap (R= 0.380)
3	6	1.05	2500	750	0.05	0.06	6mm CF Low E
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Windows Is 1.781 1.882 1.663 1.535							
Surf-11 Is Composed Of PART And Is Opaque:							
1	3	0.42	1200	837	0.91	0.5	Gypsum Plaster
2	13	0.16	950	840			Gypsum Plasterboard
3	75	0	0	0			Air Gap (R= 0.170)
4	13	0.16	950	840			Gypsum Plasterboard
5	3	0.42	1200	837	0.91	0.5	Gypsum Plaster
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For PART Is 1.935 2.054 1.796 1.648							
Surf-10 Is Composed Of PART And Is Opaque:							
1	3	0.42	1200	837	0.91	0.5	Gypsum Plaster
2	13	0.16	950	840			Gypsum Plasterboard
3	75	0	0	0			Air Gap (R= 0.170)
4	13	0.16	950	840			Gypsum Plasterboard
5	3	0.42	1200	837	0.91	0.5	Gypsum Plaster
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For PART Is 1.935 2.054 1.796 1.648							
East1 Is Composed Of Exterior Wall And Is Opaque:							

1	100	0.84	1700	800	0.9	0.7	Brick (Milton Keyns)
2	50	0	0	0			Air Gap (R= 0.180)
3	50	0.05	12	840			Glass Fibre Quilt
4	140	1.06	1950	1000			Concrete Block (Milton Keynes)
5	25	0	0	0			Air Gap (R= 0.180)
6	55	0.025	25	1000			Eps
7	15	0.16	950	840	0.84	0.55	Gypsum Plasterboard
ISO 6946 U Values (Horizontal/Up/Down Heat Flow) For Exterior Wall Is 0.245 0.247 0.243 0.240							

Table 12 Model properties breakdown

A summary of the surfaces in living area follows:

Outside walls are 135.81% of floor area, with an average U-value of 0.4 and UA (found by multiplying the U-Value by the area of the surface) value of 10.290. Flat roof is 100.00% of floor area, with an average U-value of 1.2 and UA value of 23.555. Glazing is 27.566% of floor and 16.872% of facade, with an average U-value of 1.8 and UA value of 9.4734. Infiltration rate is 0.65 air changes per hour

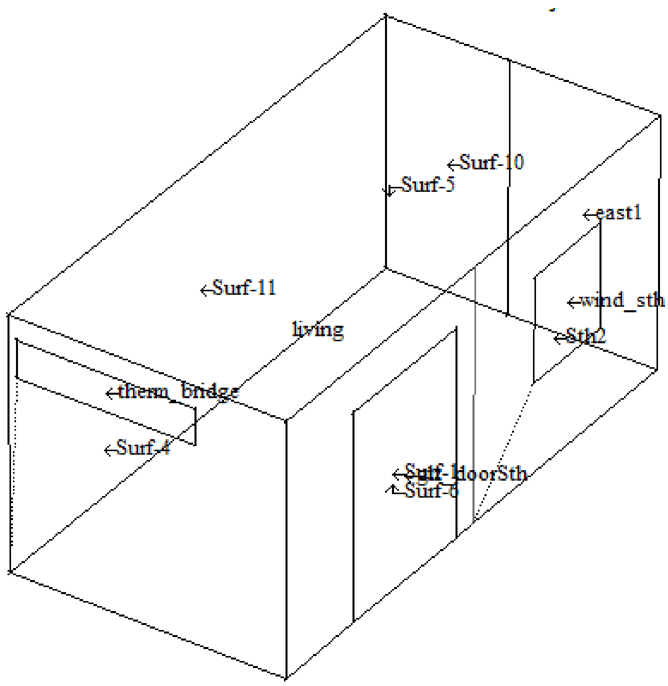


Figure 78 Model of Living Area

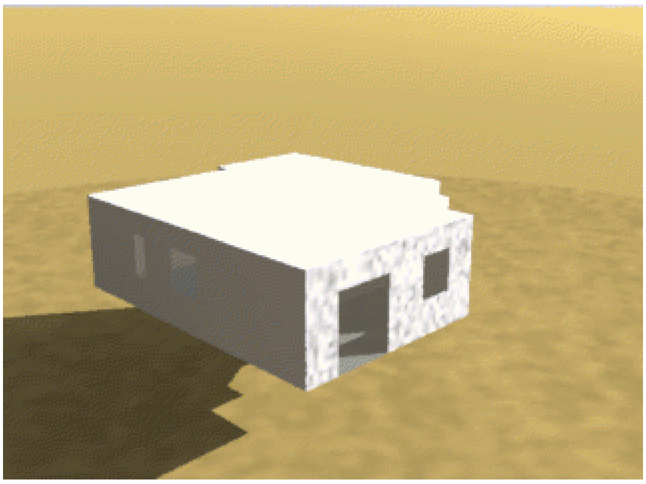


Figure 79 Full Model of the Dwelling

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

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

[3] Software and background available at http://www.esru.strath.ac.uk/

[4] http://www.heatpumps.org.uk/TypesOfHeatPumpSystems.htm

[5] http://www.heatpumps.org.uk/TypesOfHeatPumpSystems.htm

[6] McLean, R., 2008, *Energy Systems Analysis*, in *Course Notes*., Strathclyde University

[7] C.Ross, e., *Refrigeration.png heat flow*. 2008

[8] www.mge.com, *heating mode heat pump system diagram*

[9] The Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP Ozone Secretariat United Nations Environment Programme,1990-200

[10] Gao Tieyu, Yuan Xiuling, Huang Dong Gong Jianying, November 2007, Effects of air flow maldistribution on refrigeration system dynamics of an air source heat pump chiller under frosting conditions, Energy Conversion and Management 49 (2008) 1645–1651, p 1

11 Liu Zhiqiang, Li Xiaolin, Wang Hanqing, Peng Wangming, June 2007, Performance comparison of air source heat pump with R407C and R22 under frosting and defrosting, Energy Conversion and Management 49 (2008) 232–239, p 7

[12] The Air-Conditioning Heating and Refrigeration Institute, http://www.ahrinet.org/Content/ReplacingYourIndoorComfortSystem_295.aspx

[13] Low Carbon Buildings Programme, http://www.lowcarbonbuildings.org.uk/micro/air/

[14] Low Carbon Buildings Programme, http://www.lowcarbonbuildings.org.uk/micro/air/

[15] Heat Pump Association, Heat pump news: Saving energy, 2006 http://www.heatpumps.org.uk/PdfFiles/HeatPumpNewsNo.5.pdf

[16] McLean, R., 2008, Energy Systems Analysis, in Course Notes, , Strathclyde University

[17] McLean, R., 2008, Energy Systems Analysis, in Course Notes, , Strathclyde University

[18] IEA Heat Pump CENTRE NEWSLETTER, 2005, Volume 23 No. 1/

[19] McLean, R., 2008, Energy Systems Analysis, in Course Notes, Strathclyde University.

[20] Ma Guoyuan, Chai Qinhu, Jiang Yi, July 2002Experimental investigation of air-source heat pump for cold regions, Applied Energy 77 (2004) 235–247, pp 1 -13 ,

21 Yanjun Ding, Qinhu Chai, Guoyuan Ma, Yi Jiang, January 2004, Experimental study of an improved air source heat pump, Applied Energy 77 235–247, p 3

22 Low Carbon Buildings Programme, http://www.lowcarbonbuildings.org.uk/micro/air/

23 Energy saving trust: http://www.energysavingtrust.org.uk/Generate-your-own-energy/Types-of-renewables/Air-source-heat-pumps

[24] Heat pump association, http://www.heatpumps.org.uk/GlossaryOfTechnicalTerms.htm

[25] BRE, http://projects.bre.co.uk/sap2005/

[26] Published on behalf of DEFRA by: BRE, 2005 edition , The Government's Standard Assessment Procedure for Energy Rating of Dwellings, SAP 2005, revision 2, , p 135

[27] Scottish Community and Householder Renewables Initiative (SCHRI) http://www.energysavingtrust.org.uk/scotland/Scotland/Scottish-Community-and-Householder-Renewables-Initiative-SCHRI

[28] Low Carbon Buildings Programme, http://www.lowcarbonbuildings.org.uk/micro/air/

[29] Heat Pump Association, http://www.heatpumps.org.uk/CaseStudies.htm

[30] Heat Pump Association, http://www.heatpumps.org.uk/CaseStudies.htm

[31] Heat Pump Association, http://www.heatpumps.org.uk/CaseStudies.htm

[32] Heat Pump Association, http://www.heatpumps.org.uk/CaseStudies.htm

[33] On the topic of the Altherma air-to-water heat pumps, quote from space air, http://www.heatpumps.org.uk/CaseStudies.htm

[34] Heat Pump Association, http://www.heatpumps.org.uk/CaseStudies.htm

[35] The International Energy Agency, http://www.iea.org/about/index.asp

[36] The International Energy Agency, http://www.iea.org/about/index.asp

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

[38] International Energy Agency, 2006, Renewables For Heating And Cooling GIA, P 52

[39] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[40] International Energy Agency, Renewables For Heating And Cooling Adapted from Signorelli et al., 2004, P 87

[41] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[42] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 85

[43] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[44] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[45] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[46] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[47] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[48] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[49] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 86

[50] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 190

[51] International Energy Agency, 2007, Renewables For Heating And Cooling, , P 190

[52] International Energy Agency, 2007, Renewables For Heating And Cooling EGEC,., P 193

[53] International Energy Agency, 2007, Renewables For Heating And Cooling, P 192

[54] International Energy Agency, 2003, Renewables For Heating And Cooling, Karlsson et al., , p 99

[55] Heat pump systems ion Sweden- country report for IEA annex 28, 2003, Fredrik Karlsson, , p 12

[56] IEA Heat Pump Centre Newsletter, 2005 , Volume 23 - No. 3, p18, www.heatpumpcentre.org

[57] IEA Heat Pump Centre Newsletter, 2005 , Volume 23 - No. 3, p25, www.heatpumpcentre.org

[58] International Energy Agency, Renewables For Heating And Cooling, 2004 HPC, p 181

[59] International Energy Agency, Renewables For Heating And Cooling, 2004, HPC, p 181

[60] International Energy Agency, Renewables For Heating And Cooling, 2004, HPC, p 184

[61] International Energy Agency, Renewables For Heating And Cooling, 2004, HPC, p 184

[62] International Energy Agency, Renewables For Heating And Cooling, 2004, HPC, p 142

[63] International Energy Agency, Renewables For Heating And Cooling, 2004, HPC, p 142

[64] International Energy Agency, Renewables For Heating And Cooling, Lund et al., 2001; Lund et al., 2005, p 142

[65] International Energy Agency, Renewables For Heating And Cooling, HPC, 2004, p149

[66] International Energy Agency, Renewables For Heating And Cooling, HPC, 2004, p176

67 IEA Heat Pump CENTRE NEWSLETTER, Volume 22, No. 3/2004, p8

[68] IEA Heat Pump CENTRE NEWSLETTER, Volume 22, No. 3/2004, p8

[69] Heat King, Air Source Heat Pumps BWarm & BCool2 units, 2005Technical Manual, , p 15

[70] Heat King, Air Source Heat Pumps BWarm & BCool2 units, 2005Technical Manual, , p 28

[71] Heat King, Air Source Heat Pumps BWarm & BCool2 units, 2005Technical Manual, , p 28

[72] Dr. Fatih Birol, June 2002, IEA Conference On Natural Gas Transit And Storage In Southest Europe, , 31 May - 1

[73] Dr. Fatih Birol, June 2002, IEA Conference On Natural Gas Transit And Storage In Southest Europe, 31 May - 1

[74] IEA Oil and Gas Outlook, April 2004, 5th International Oil Summit, Claude Mandil, , p 2

[75] IEA Oil and Gas Outlook, April 2004, 5th International Oil Summit, Claude Mandil, , p 3

[76] Heat King, 2005, Air Source Heat Pumps BWarm & BCool2 units, Technical Manual, , p 15

[77] Heat King, 2005, Air Source Heat Pumps BWarm & BCool2 units, Technical Manual, , p 17

[78] TEV Limited, Armytage Road, Brighouse, West Yorkshire

[79] Google earth

[80] Google earth