Analysis of Domestic Energy Conversion Systems

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ABSTRACT

What do you associate with the terms: global warming, climate change, atmospheric pollutants, fossil fuels, finite resources, carbon emissions, pollutant rich fuel sources and the Kyoto Protocol? Unfortunately, an energy supply mix that is currently unsustainable.

The solution…

We must act today in order to identify and implement a diverse energy solution that will offer security of supply, help to preserve our future and avert the looming energy crisis. This will require a global effort.

We must drive down and eliminate any unnecessary demand, and we must seek alternative solutions that offer improved energy efficiency and that are sustainable and environmentally friendly.

This is potentially a vast area of research and this thesis therefore focuses on two particular energy aspects: heating and electricity within the domestic sector.

Initially, an investigation into relatively immature technologies such as heat pumps and micro CHP; which offer much improved energy efficiency and make better use of the planets abundant natural resources; has been conducted. Then their merits, limitations and performance are contrasted with the most commonly used existing solution: the gas boiler.

The latter section of the thesis adopts a case study approach, where the performance of a domestic house installed with a heat pump is analysed. This involved running a series of models to determine how varying the occupancy, location and building characteristics would affect the performance and output of the heat pump.

The most significant findings are:

- Heat pumps are a technically viable alternative to the commonly used boiler and air source heat pumps in particular have the greatest potential to be universally installed. They also offer extremely high efficiencies; typically in excess of three units of energy, for every unit expended; and of the technologies considered, they offered the greatest environmental benefits: they have the potential to be fully sustainable, should they be powered by zero carbon content electricity in the future.

- In order to optimise the performance of the heat pump, the consumer should invest in high levels of insulation and put into place measures to control the air infiltration rates, prior to sizing the heat pump: the correct sizing of the heat pump is one of the crucial factors in obtaining optimum performance.

- It was also found that for the particular heat pump tested, carbon dioxide emission savings were realised in almost all of the scenarios, however, at the current prices of gas and electricity, it is still slightly cheaper to meet the domestic heating requirements utilising a condensing gas boiler, where gas in available.

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A. INTRODUCTION

Energy and the environment are two of the biggest problems that mankind face this century. Population levels are increasing globally and energy consumption is rising rapidly as the economies of the developing world industrialise, whilst energy resources are being depleted. As demand increases, costs rise and this drives demand for lower cost forms of energy. Currently, much of this demand; a staggering 82% of today's primary energy requirements [1]; is met utilising non renewable sources of energy and fossil fuels, which are dirty, pollutant rich fuel sources in finite supply and are causing significant damage to the environment. Clearly, the world's current energy mix and heavy dependence on fossil fuel energy is unsustainable: both environmentally and economically.

To ensure a sustainable energy future, it is necessary to identify, develop and establish a variety of alternative energy solutions, some of which should be based on renewable forms of energy. This is a potentially vast area of research and this thesis therefore proposes to focus on two particular energy aspects: heating and electricity within the domestic sector.

Traditionally, domestic heating and electricity requirements have usually been fulfilled by producing heat or generating electricity independently of one another and utilising finite resources such as fossil fuels as the primary fuel source. However, over the past century there have been numerous significant technological developments that have led to new and innovative means of heating and powering the domestic home.

The last century in particular saw significant changes in the way that most domestic British homes were heated. At the start of the century, open fires such as hearths were used, which burned either wood or coal as the primary fuel source. Then there was the development of the enclosed stove; which ensured more efficient burning, over a longer period of time; followed by the development of electric heaters and gas central heating, before more recently the development of renewable technologies, such as ground or air source heat pumps.

The last century also witnessed significant alterations in the way electricity has been generated. At the turn of the 20th century, few people were connected to the electricity network and it wasn't until the 1920's that major cities began to connect more people. Electricity was initially, and has continued to be on the most part, produced utilising some form of electro-mechanical generators. These are driven by steam produced from conventional fuels; for example coal, oil and gas; and the fuel used is usually dependent on resource availability and price. This was followed by the development of nuclear power as an alternative fuel source, before more recent years, where substantial research and development has led to greater use of renewable technologies, such as hydro, wind, wave, biomass and solar to name but a few.

The technologies utilised would originally have been selected and designed based on a combination of the limited engineering and scientific knowledge available at the time, cost and availability of fuel resources. However, later developments focused more towards the search for improved efficiency, followed by safety considerations and security of supply, before more recent years, where developments have largely been driven by the increasing pressure to produce heat and power in a more environmentally and sustainable manner in order to drive down harmful carbon emissions.

As a result, additional new technologies have been developed, such as combined heat and power (CHP); which is capable of achieving exceptionally high efficiency levels; and heat pumps; which seek to make better use of the planets natural resources, whilst also significantly reducing the amount of electricity required to operate. This thesis proposes to investigate the suitability of some of these technologies for use in heating and powering the domestic home.

Therefore, the primary aim of this thesis is to analyse the performance of domestic energy conversion systems.

This will require investigating the performance of different energy conversion technologies and reviewing their performance under varying operating conditions. The outcome is to produce a definitive statement on the performance of the systems analysed under different operating conditions, which will essentially produce a series of recommendations detailing the suitability of the technology for each of the varying operational conditions.

B. METHODOLOGY

The aim of the project is to **analyse the performance of domestic energy conversion systems** and produce a definitive statement on the performance of these systems, making a recommendation as to their suitability under different operating conditions.

To ensure the timely delivery of the dissertation thesis, a comprehensive project plan has been constructed.

1. Literature review

Initially, a literature review was conducted to identify potential technologies that may be analysed in greater detail as the project developed. It is important to ascertain what has been done in the past by others and under what circumstances and conditions, was it successful and if not why? Additionally, the various technologies advantages and limitations were investigated.

2. Define project scope

Having conducted the literature review, the knowledge gained was used to highlight areas of particular interest, as well as focus and narrow the scope of the project. It was important to clearly define the scope of the project as this stage, to ensure the overall project aim was obtainable within the restricted timescale.

3. Devise modelling approach

A modelling approach was then devised, which identified and outlined the criteria that the analysis was based upon at a later date. This was key in ensuring the modelling tool produced suitable outputs and results, which enabled a comprehensive analysis to be conducted based on appropriate criteria.

4. Construct models & run simulations

The models were constructed and modified and then numerous simulations were run. If the desired results were not obtained, the stage was repeated.

5. Results analysis

The outputs from the simulations were used to analyse the results. This included analysing the criteria set earlier, in addition to assessing the economic impact and environmental consequences of the options, which required further calculations. Due to the anticipated amount of simulations, substantial time was set aside to conduct this particular aspect of the project.

6. Conclusions & recommendations

To conclude, conclusions were drawn from the analysis and final recommendations made. This section of the thesis sought to identify any shortcomings in the investigation and suggest any potential areas for future research.

There are several domestic energy conversion system technologies that were initially identified of interest. For example, heat pumps, micro CHP, residential fuel cells and condensing gas boilers. Within each of these technology classifications, there are sub system options that operate using slightly different technology configurations, which could potentially be explored. For example, heat pumps can either be of a ground, water or air source configuration and micro CHP could utilise either Stirling engine technology, internal combustion (IC) engine technology, polymer electrolyte membrane (PEM) fuel cell technology or solid oxide fuel cell technology (SOFC) to name just a few of the options.

There are also several different types of residential dwelling options that have been considered, for example a flat, terrace house, semi-detached house or detached house, and when you combine this with various building options and characteristics, such as old or new build, level of insulation, type of glazing, draught proofing, etc, there are numerous configurations that could potentially be explored.

To add further complexity to the investigation, there are also occupancy characteristics, such as the number of occupants and type of occupant; e.g. student, working professional or elderly; which impact on the length of time the occupant spends in the building, in addition to the various climate conditions that can exist depending on the location of the building.

The potential complexity and scope of the investigation becomes rather daunting given the vast number of potential configurations and the project could easily become larger than the limited time scale the thesis permits. Therefore, in order to narrow the scope of the thesis, it was important to identify and prioritise which of the above configurations should be explored and analysed in greater detail. To achieve this, it was necessary to conduct a literature review, focusing on aspects such as the pro's and con's of each technology, as well as to determine what has actually been investigated in the past.

The initial section focuses on potential domestic energy technologies; such as heat pumps, micro CHP, residential fuel cells and condensing gas boilers; and the later section investigates potential occupancy and building modelling options.

1. Heat Pumps

The theoretical concept of heat pumps has been around for many years: initially using the technology to provide cooling through the use of air conditioning, chillers and refrigerators, which are essentially heat pumps. However, it was not until more recent years that the technology has evolved and we have began to harness it for heating buildings: heat pumps are now a widely used mainstream technology, which provide domestic heating throughout several European countries and the US, and are growing considerably in numbers elsewhere.

This recent growth can mainly be attributed to increasing concerns over global warming and climate change: which has resulted in an increasing number of frequent storms, hail and heavy downpours, in addition to droughts and rising sea levels [2]. The UK, along with many other countries, has committed to the Kyoto Protocol and other legally binding ambitious government legislation targets, in a bid to significantly reduce carbon emissions and other harmful greenhouse gas emissions. To try and meet these targets, a combination of demand reduction measures, improved energy efficiency and a greater proportion of energy generated using renewable technologies will all be required. The ultimate aim is to provide a energy mix for future generations, that is both reliable, favourably priced, environmentally sensitive, but importantly diverse, in order to at least preserve and where possible improve, the standard of living and quality of life that we have become accustomed to today.

"Heat pumps are one of the few developed, reliable and widely available heating technologies that can deliver thermal comfort at either zero or greatly reduced carbon emissions" [3] and if you consider that "the use of fossil fuels to deliver heating in homes and offices is one of the largest sources of carbon dioxide (CO_2) emissions worldwide," [3] at times, where "domestic heating accounts for as much as 40 per cent of our CO_2 emissions in central Europe," [3] heat pumps will play a fundamental and increasingly important role in meeting our future domestic heating requirements. Furthermore, as most heat pumps are electronically driven, there is the potential in the future for heat pumps to be powered by zero carbon content electricity; assuming renewable technologies are used to generate the electricity; making them a truly sustainable technology.

1.1 How a heat pump works

Heat pumps essentially transform thermal energy from a low temperature into thermal energy at a higher temperature. They achieve this by drawing energy from a heat source; which could either be from the air, water or ground; and then transfer the energy, in addition to the input electrical energy required to operate the cycle, to the heat sink, where this can then be used to perform useful heating. For example, to pre heat hot water prior to it entering a conventional boiler or to warm water for radiators or underfloor heating, to provide space heating. The heating heat pumps collect low grade heat and "using a refrigerant circuit, this heat is upgraded by an electrically driven compressor and can be delivered at a useful temperature for heating" [3]. This occurs in a closed cycle process, where the working fluid is constantly undergoing a change of state: evaporation, compression, condensation and expansion.

Figure 1 details the main components of a typical vapour compression refrigeration cycle heat pump: the most common type used to providing domestic heating. An explanation as to the main stages of the refrigerant cycle is provided, but it essentially operates on the basis that the temperature of the gas is raised by compression and then lowered by sudden expansion.

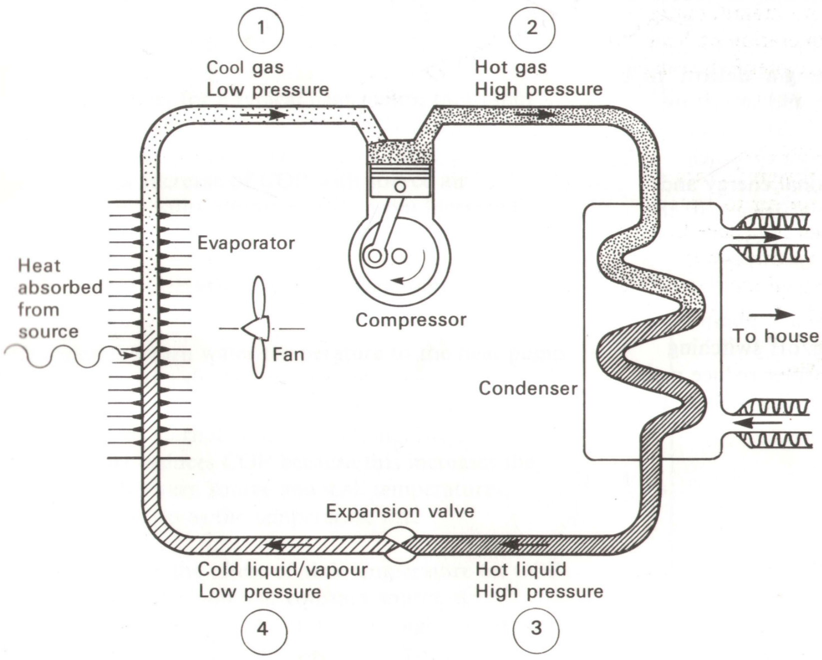

Figure 1: Schematic of heat pump refrigerant circuit [4]

- Between points 1 & 2:
  Cool refrigerant gas is compressed and it emerges from the compressor at high temperature and pressure.

- Between points 2 & 3:
  The hot refrigerant gas is cooled and condenses, which gives up mainly latent heat and raises the temperature of the sink medium. This essentially performs useful heating, e.g. hot water or space heating.

- Between points 3 & 4:
  The refrigerant liquid at high pressure is expanded in order to lower its temperature and pressure, prior to entering the evaporator.

- Between points 4 & 1:
  The liquid refrigerant boils in the evaporator at a low temperature and pressure. Heat is absorbed from the cool source, which provides the necessary latent heat of evaporation. The liquid evaporates and the cool refrigerant gas is returned to the compressor to cycle.

The heat that is absorbed at the evaporator, in addition to the power input to the compressor; which essentially drives the cycle; is released at the condenser. As a result, more useful heat is provided by the heat pump, than is consumed to drive the compressor. This is key in ensuring the heat pump operates efficiently and with the ratio of heat energy released compared to the heat energy consumed being significantly greater than one, heat pumps can be a very efficient means of providing domestic heating. It is not unusual for values to typically fall within the range of 3:1 and up to 5:1 [5].

The efficiency of a heat pump is frequently referred to as the 'co-efficient of performance' (COP) and this is defined as:

$$\frac{\text{Useful heat energy delivered}}{\text{Energy supplied to drive the heat pump}}$$

However, this value is constrained by thermodynamic theory; namely the Carnot cycle; which sets a maximum limit for the COP of any machine. That is:

$$\text{The maximum theoretical COP} = \frac{T_2}{T_2 - T_1}$$

Where T_2 = the higher sink temperature (K) and T_1 = the lower source temperature (K), between which the heat pump is operating.

1.2 Advantages

Having conducted an extensive literature review it is apparent that heat pumps have numerous advantages:

- They collect low grade heat and deliver it at a higher temperature.

- Heat can be delivered at high energy efficiencies and it is common for the COP to fall within the range of 3:1 and 5:1.

- Depending on the fuel source used to produce the electricity, carbon savings can be very significant and heat pumps generally offer excellent CO_2 emissions: even if

100% fossil fuel electricity were to be used to power the generator, this would still result in an overall CO_2 reduction.

- If sized correctly, the total heating load and some, if not all of the hot water load can be met with today's heat pumps.

- The recent upward trend in electricity prices and the predicted continued rise of fossil fuel prices in the future, should ensure heat pumps will continue to offer running cost advantages and this should prove to be even more favourable in the future.

- Depending on the efficiency of the heat pump, it draws typically 75% of its energy from the environment (at no cost), which makes full use of the free abundant renewable energy stored in the air, water and ground. These energy resources are just about unlimited in terms of quantity and availability, and as far as time is concerned.

- Furthermore, because heat pumps use air, water or ground thermal energy, this will help to meet renewable energy heat targets.

- They offer a much reduced dependence on volatile foreign energy fuel supplies, which will help to ensure security of supply for many years to come.

- They can deliver increased fuel price stability and fuel independence.

- Their use can be varied depending on requirements. For example, they can be used to provide space heating in the winter and hot water in the summer months.

- They produce emission free operation on-site: producing no on-site soot or other toxic exhausts.

- No on-site fuel storage is required.

- They can often offer reduced heating costs, however, the extent of this reduction is dependant on the fuel used and its associated cost.

- They generally operate quietly, automatically and are require little maintenance.

- They are very reliable and provide environmentally friendly heating in excess of 20 years.

- When implemented correctly they have very low operation costs.

- As heat pumps operate using a thermodynamic cycle; with no combustion or flames; the chance of any dangerous accident is greatly reduced.

- Heat pumps used for domestic hot water heating can also be used; at no additional investment or operational cost; to ventilate and cool, in addition to dehumidifying at the same time. This can significantly improve the building comfort levels for occupants.

1.3 Limitations

Despite all these numerous advantages, they are not without their limitations and disadvantages:

- The output and efficiency of a heat pump varies considerably with the temperature of the source and is most efficient where the temperature difference between the source and output temperature is minimal. Therefore this is most problematic in the winter when the source temperature is at its lowest and the temperature difference requirement is at a maximum, which can result in the COP being lower at the times of greatest heat requirement.

- Domestic ground source heat pumps gained a poor reputation in the past for poor quality design, installation and equipment in several countries. This reputation must be overcome and heat pumps must be correctly sold, specified, designed, installed and commissioned to ensure a continued wide uptake of this technology in the future.

- Not all buildings are suitable for heat pumps. E.g. in poorly insulated buildings, heat pumps may not be capable of delivering year round comfort levels. They also tend to be "most viable in remote areas where mains gas is not available and are particularly suited to well insulated homes with underfloor heating" [6] installed. Basically they are ideal for low energy homes where only a minimal heating capacity requirement exists. That said, buildings could be improved by implementing measures such as draught proofing and adding further insulation.

- Heat pumps work best with heating systems that are optimised to run at lower water temperature than is commonly used in UK boiler and radiator systems and they can currently only deliver maximum temperatures in the range of 55 to 65 degrees Celsius: which is significantly lower than conventional gas boilers.

1.4 Other considerations

Having conducted an extensive literature review, the following points were apparent and should be given consideration:

- "The maximum annual savings per £ installed is obtained when the heat pump is sized just large enough to meet the house heating requirements at an outside ambient air temperature of around 0^oC to 1^oC" [4]. Designed in this way, the heat pump system would be capable of meeting around 90% of the annual space heating requirements and the other 10% would be met utilising a supplementary heating system.

- Where the heat pump works for as much of the heating season as is possible, but is not fully capable of meeting all of the demand and producing sufficient heat, a secondary source can be installed to meet the demand at these periods: which often occurs on the coolest days. This type of system is known as a hybrid or bi-valent heating system.

- The COP rises as the source and output temperatures converge. Basically, the smaller the required temperature difference between the heat source and the heat sink, the more efficiently and economically the heat pump operates. However, this is not ideal, because in the winter periods the temperature difference will be more extreme and hence the heat pumps will operate with a lower COP and will therefore be less efficient.

- Furthermore, to ensure the heating demand is adequately controlled and comfort levels are maintained, the heat pumps operation must be regulated under thermostatic control. This is achieved by switching the heat pumps output power on and off, however, this has the negative consequence of switching and standing losses, which negatively impact and reduce the mean COP.

Switching looses occur when the heat pump is turned on and off. As a consequence, the overall average performance of the heat pump is lowered and the COP is reduced, the more frequently the heat pump is switched on and off. For space heating with normal cycling frequencies, this is less of a problem and switching losses are not usually significant, however, this is not the case when the heat pump is used for house pre-heating or heating domestic hot water. When used for these applications, the thermostat is likely to demand that heat be continuously supplied, yet the radiator circuit is unlikely able to dissipate a continuous full output power. This results in more frequent cycling in order to operate at the highest attainable output temperature and therefore has a negative effect on the overall COP.

Standing losses occur when the heat pump is not in operation. When it is not running, but is itself still warm, it will continue to loose heat; via the heat pump and the pipe work; to the surrounding environment, whenever the system parts are warmer than the ambient air. This is problematic regardless of the heating source, but is worse when utilising an air source heat pump because these are typically sited outdoors and therefore the heat is lost entirely to the atmosphere. To try and minimise any losses, sufficient quality and quantity of insulation should be fitted.

1.5 Types of heat pumps

In Europe, the most common form of heat distribution system in the domestic sector is water: either via wet radiator systems or wet underfloor (hydronic) heating. Therefore, the predominant heat pumps are **air/ground/water to water** heat pumps.

This following section investigates the differences between the varying types of heat source; which can either be the air, ground (geothermal) or water; as well as reviewing their individual merits and limitations.

1.5.1 Air source

- The traditional difficulty with air source heat pumps is that on the days that most heat is required, the outside air will generally be at its coldest. This therefore makes it very difficult for the heat pump to achieve its highest efficiency and sometimes all of the heating requirement may not be fulfilled. That said, significant progress has been made to try and overcome this limitation, with advances in compressor technology, heat exchanger design and control methods all showing promising signs of improvement.

- Furthermore, of the different types of heat sources, air has the lowest thermal capacity and it is also the most susceptible to seasonal variation, thus adversely affecting the temperature of the source.

- Another problem that is apparent with air source heat pumps is that ambient air contains water vapour and this can condense onto the evaporator. This becomes particularly problematic in lower temperatures, e.g. if the evaporator temperature falls below 1^{o}C, because the condensation forms a layer of frost, which can thicken, forming an insulating layer and blocking the evaporator. This reduces the airflow and can result in significant performance deterioration. To overcome this, the pump must be designed to detect this condition and initiate a defrost, in order to melt the frost. There are various means of achieving de-frosting, however, the most important point to note is they all require additional energy and adversely effect the COP of the heat pump.

- Despite these limitations and disadvantages, air source heat pumps are becoming more attractive. They have gained a reputation for ease of installation and use, as air is available anywhere. The option to install split units has also proven favourable, as these are better able to match demand and are therefore capable of offering an even higher coefficient of performance (COP).

1.5.2 Ground source (geothermal)

- The ground temperature is more consistent all year round, which can result in a lower temperature difference between the ground source and the sink temperature compared to other heat sources; particularly air source. This has the advantage that higher COP can typically be achieved, compared to that of the air source heat pump.

- That said, ground source heat pumps have a higher installation cost compared to that of air and water source heat pumps, because they require underground digging of either wells or trenches to accommodate ground loops. These loops are used to carry a solution of water and anti-freeze and it is this liquid that absorbs heat from the ground. Loops are usually laid flat, however, if space restrictions exist, a vertical loop can be installed to depths in the region of 100m and this accounts for the majority of the additional cost.

- Ground source heat pumps are of a closed loop configuration and are therefore engineered slightly differently to air and water source heat pumps. As a result, they are slightly more "complex in design and operation, because the loop temperatures are engineered to change in order to induce the movement of heat by conduction through the ground" [3]. As a result, this type of system requires more careful and thoughtful planning to ensure long term operating success.

1.5.3 Water source

- Water source heat pumps have a technological advantage over air source heat pumps because the water has a much higher heat carrying capacity than air, better heat transfer characteristics and it can be moved around very effectively with small circulating pumps. However, the major disadvantage is that buildings may not have access to such a resource.

1.6 Used to provide cooling

In some applications a heat pump can also be used to provide cooling; which is achieved through the use of fitting a reversing valve; and using a heat pump in this way actually dominates the global heat pump market. However, for a heat pump to be used for cooling or dual heating and cooling, a slightly different system is required and this usually results in an increased expense due to the additional equipment required.

Furthermore, in countries such as the United Kingdom, where there has previously been little requirement for domestic cooling, there is a fear that if heat pumps are unnecessarily utilised to provide heating *and cooling*, significant amounts of unnecessary electricity will be consumed and any energy conservation gains and carbon reduction achievements may be abolished.

Despite this concern, there is a global trend of increasing temperatures; particularly in the summer months; and if temperatures continue to rise, cooling may become a necessary requirement in new areas: therefore expanding the market potential. However, for the purpose of this thesis, the focus is on heating the domestic home within the UK market and therefore the cooling application of a heat pump has been excluded.

2. Alternative Technologies

There are several other technologies that have been considered, which are capable of meeting or at minimum, partially fulfilling domestic heating and/or power requirements. An overview of these technologies is provided, along with a discussion of their relative merits and limitations.

2.1 Micro CHP (Cogeneration)

Micro CHP is the extension of the idea of cogeneration; simultaneously producing electricity and useful heat; to a domestic home or small office building. Micro CHP has been defined as "applying to systems with an electrical output power of 16A per phase or less, but this implies units up to 3.5kWe for single phase and 11kWe for 3 phase units" [7]. For the purpose of this thesis, micro CHP simply refers to individual units, within individual homes: which would roughly limit the electrical output to approximately 3kWe [7].

"CHP is a highly efficient way to use both fossil and renewable fuels and can therefore make a significant contribution to the UK's sustainable energy goals, bringing environmental, economic, social and energy security benefits" [8]. The potential market for micro CHP has grown considerably in recent years and this can largely be attributed to increasing environmental concerns such as climate change, but it is most likely as a result of escalating fuel prices that have sent household energy bills soaring. This has prompted customers to seek alternative energy generation methods that will both aid energy conservation and provide more efficient energy use.

Micro CHP operates on the basis that a single piece of plant generates electricity near to a location where the 'waste heat' produced can be efficiently utilised and the main advantage over conventional power generation is that the heat produced as a by-product of electricity generation is no longer wasted. As the system uses both forms of energy, this results in an extremely effective CHP scheme, which can realise very high overall efficiencies. The actual value varies considerably depending on the reference source, but lies somewhere in the range of 70% at the point of use [8] up to 90% [9].

The micro CHP unit would typically replace the conventional gas boiler in the home, providing both heat and hot water, but additionally and most importantly, electricity. Micro CHP is driven by the heating demand and the amount of electricity produced is delivered as a by-product: it usually produces enough electricity to meet the large majority of the homes power requirements and on occasions, produces excess electricity. The micro CHP units produce a relatively small amount of electricity; yet enough to fulfil most of the domestic homes demand; however, the true benefits of micro CHP would be realised if it were to be installed throughout the many suitable UK domestic homes: in the region of 12 million [7]. This could potentially produce up to 20% of the UK's electricity generating capacity [10] and it would also be a significant, vital step in moving from centralised power generation towards distributed energy generation, which could help to alleviate predicted future problems with the carrying capacity of the national grids infrastructure, as electricity demand grows and more renewable generation comes online.

There are several different types of CHP systems, with the most common types utilising Stirling engine technology, internal combustion (IC) engine technology, polymer electrolyte membrane (PEM) fuel cell technology and solid oxide fuel cell (SOFC) technology. For small commercial applications, it was found that the majority of systems are based on internal combustion engine technology and for domestic applications, the majority of systems are based on Stirling engine technology. Therefore an explanation as to how a typical domestic micro CHP system operates has been provided.

2.1.1 How micro CHP works: Stirling engine technology

A Stirling engine is an external combustion engine that permits continuous, controlled combustion. It is essentially a heat engine that is capable of converting thermal energy into mechanical energy and it operates on a principal that heated gas expands and cooled gas contracts. In the most basic form, a Stirling engine consists of a cylinder, displacer, piston and regenerator.

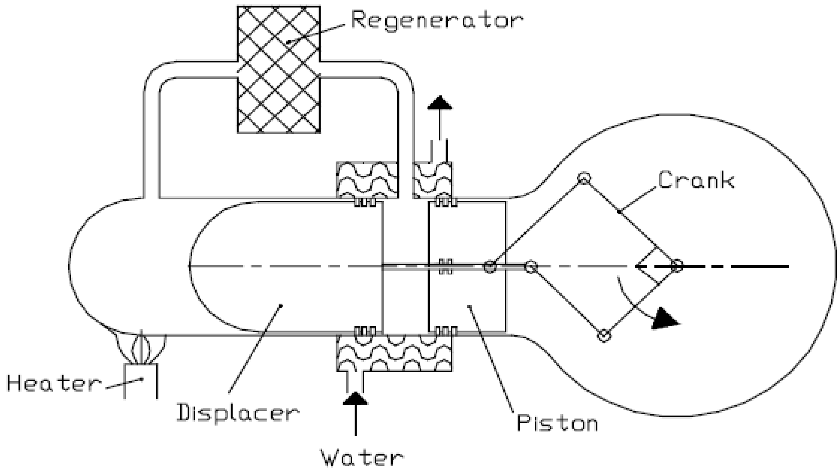

Figure 2: Example of a Stirling engine (kinematic) [7]

Fuel is burned outside the engine; typically natural gas; and this provides the heat to maintain a high temperature at one end of the engine and at the opposite end, water is circulated to provide cooling. A fixed volume of working gas; moved by the displacer and sealed within the engine; is thus alternatively heated and cooled, which forces it back and forth between the two extreme temperature zones via the regenerator. It is the rapid heating and cooling, expansion and contraction of the working gas that results in pressure fluctuations and this acts on the working piston, causing it to move and subsequently generate power.

The crank arrangement is required to convert the reciprocal piston motion to a rotational output, which can then be used to drive a generator and produce electricity, and the circulated cooling water is used to remove heat, with the heat gained via the water being used for domestic water heating or to provide space heating.

Stirling engines have the advantage that they are capable of running without valves or an ignition system; which enables them to operate for longer service intervals and with reduced operational running costs; as well as producing very low pollutant emissions, whilst achieving high combustion efficiency. Furthermore, as the power output is a sinusoidal waveform, this ensures low vibration levels and little noise, and the regenerator also helps to improve the thermal efficiency.

However, Stirling engines are not without there limitations. One of the main problems they encounter is associated with control and there is often a time delay; typically in the magnitude of minutes; between notifying the thermostat demand for heat, the actual availability of heat and then the final output power. Another disadvantage is that prior to being able to shut down the engine at the end of a heating cycle, any stored energy must be passed to the heat distribution system.

2.1.2 Advantages

Having conducted an extensive literature review it is apparent that micro CHP has numerous advantages:

- It increases the total energy utilisation of the primary energy resource.
- It is extremely efficient, with between 15% and 38% of the primary heat being converted to electricity and the majority of the residual heat being utilised to provide space heating or hot water. Furthermore, providing the heat production does not exceed the demand, as much as 90% of the primary energy resource is utilised.
- The overall efficiency is considerably greater than some of the alternatives: 70% at the point of use, compared to coal-fired and gas-fired power stations which dump the excess heat and only realise power station efficiencies in the region of 38% and 48%, respectively [8]. In reality these efficiencies are even lower, due to transmission and distribution losses.
- Micro CHP is a form of decentralised energy technology and as it is installed at the point of consumption, transmission and distribution losses are minimal and transportation costs are avoided.
- Micro CHP is a very effective measure for existing homes. Although it is less effective than loft or wall insulation installed during the construction period, it is substantially more effective compared to cavity wall insulation or installing double glazing windows.
- The average UK domestic home utilises 60% of the total energy for domestic heating and 25% for water heating, giving a total thermal demand of 85% and an electrical demand of only 15% [7]. Micro CHP matches this demand profile particularly well, generating the majority of its energy in the form of heat, whilst managing to meet most of the electrical demand.
- The Stirling engine; the most common micro CHP technology found in the domestic home; uses natural gas as its fuel source. This burns easily, relatively cleanly, is available in most areas and can be easily transported through existing gas pipe infrastructure, which is already present in many UK homes.
- Additionally, whilst most micro CHP units use natural gas, the Stirling engine design is considered fuel flexible. Therefore, there is the potential for alternative fuel sources such as biogas or hydrogen to be used in the future when these become more widely available. This would enhance its environmental benefits even further.

Even more important, are the technologies economics. Economic viability is absolutely fundamental for the uptake of any new technology and micro CHP offers the potential for significant cost savings:

- The total energy efficiency of a micro CHP system is much the same as a conventional boiler, however, micro CHP differs because it produces electricity, which has a much higher value than that of heat. It is the increased value of the electricity that helps to cover the additional investment cost and provide any net savings.

- As fuels are used more efficiently; eg natural gas; less are consumed. This leads to lower energy costs for the consumer, with savings in the region of 15% to 40% compared to imported electricity and on-site boilers [8]. Furthermore, burning less fuel helps to reduce carbon dioxide emissions and in recognition of the significant carbon savings potential associated with micro CHP, the government has set a target within the UK's Climate Change Program of 10,000MW installed capacity by 2010 [8]. At present, CHP represents the most significant individual measure in achieving the European Union's CO_2 reduction targets.

- Micro CHP is driven by the heating demand and produces electricity as a by-product. Operated in this way, it can on occasions generate additional electricity above the required demand. There is the potential for this to be sold to the national grid; sometimes referred to as net-metering; and income can be generated in this way. Similarly, when there is a deficit in electricity, the shortfall can be purchased from the national grid in the conventional way. This system is relatively easy to install and is an extremely efficient means of buying and selling electricity.

2.1.3 Limitations

Despite all these numerous advantages, micro CHP is not without its limitations and disadvantages:

- Micro CHP still has quite a few obstacles to overcome before it can be fully exploited. For example: the maintenance costs and frequency must compare favourably with alternative technologies; the units themselves must be visually and acoustically unobtrusive, as well as being quiet and free from any excessive vibrations; and micro CHP must also be able to match the operating parameters of alternative heating systems, in terms of flow rate, temperatures and ease of installation.

- Due to the way micro CHP generates electricity, the times where there is excess electricity that can be delivered to the national grid results in a delivery that is both haphazard and largely unpredictable. Whilst this is currently not a problem that can not be overcome; with the aid of the national grid balancing mechanism; as more micro CHP schemes come online, this could prove more of a challenge and be problematic when trying to ensure security of supply, balancing the grid and carefully matching demand.

- Micro CHP is not a renewable technology: for example the commonly used Stirling engine design utilises natural gas as the primary fuel source and this therefore produces a net release of carbon dioxide, albeit a smaller release than some of the alternative technologies. Furthermore, where gas is used, the price of the resource has historically been subject to high price volatility and this will influence the extent of any potential savings that could be achieved.

2.1.4 Other considerations

Having conducted an extensive literature review, the following points were apparent and should be given consideration:

- There is also the challenge of obtaining the desired generator energy balance, which will be more problematic at certain times of the year. For example, in the summer months, the electricity demand will still be present, yet there will be a reduced heating demand. As electricity generation is often driven by the heat demand in micro CHP systems, there is likely to be an electricity shortfall in the summer months and an alternative measure must be in place. Alternatively, if it proves more economical to generate in excess of the demand heat to ensure the electrical demand can be met, there must be a suitable means of dumping the excess heat and any financial and environmental implications must be carefully considered.

- To obtain high performance from micro CHP units, the thermal output must be closely matched to the heat demand of the building and the running time of the micro CHP should be maximised. Therefore, the unit should operate for long and consistent periods of time, opposed to intermittently: thus achieving good performance and maximising the carbon savings potential.

- To help bring the micro CHP product to market, a step change technology could be introduced based around existing infrastructure. For example, each year, on average around 1.2 million gas boilers have to be replaced [11] and micro CHP could potentially be installed in their place as a viable alternative.

2.1.5 Other types of CHP: Internal combustion engine & fuel cells

There are two other types of micro CHP: one that utilises internal combustion (IC) engine technology and one that utilises fuel cell technology.

Internal combustion (IC) engine technology is more commonly found in larger CHP applications because there are still problems associated with its suitability for use in micro CHP. Despite this, research and trials are being conducted to try and overcome these problems and design a fully functional micro CHP device.

In an IC engine, the expansion of high temperature and pressure gasses; which have been produced by the combustion of a fuel with an oxidiser; apply a direct force to a movable component of the engine; typically a piston; in order to generate useful mechanical energy that can be used to drive a generator and produce electricity. This process also produces a considerable amount of heat as a by-product and this is fully utilised in CHP applications.

However, there are problems associated with this developing technology. As it is a cyclical process, it can be difficult to control and ensure complete combustion of the fuel. Furthermore, problems with higher emissions, noise levels and the requirement for frequent servicing have all hindered the development of this technology and the measures identified to date that are deemed necessary to overcome these problems have resulted in designs that are too bulky and expensive to merit use in the domestic home. Many have the pessimistic view that "it is unlikely that all the desirable parameters for micro CHP can be achieved with ICE technology" [7].

Fuel cell micro CHP technology is still very much in the early research and development stage, with only a limited number of prototypes having been made.
Fuel cells are capable of converting fuel directly into electricity via an electrochemical process and without the requirement for any mechanical drive or generator. Heat is produced as a by-product and water as a waste product. They theoretically offer very low emissions, high efficiency and low noise levels. However, this does require some

additional work, which comes at a price and these advantages have yet to be fully realised in any practical domestic product [7] [12]:

- They require hydrogen, which involves reforming natural gas. This requires energy itself, as well as additional components and their associated expense.
- To ensure the process produces very few emissions, the gas supply may have to be treated prior to use in order to eliminate sulphur and the exhaust gas may also have to be treated to remove carbon monoxide.
- The DC output must be converted to AC, which requires power electronics. This has an associated cost implication and power losses may occur.

Fuel cell technology for use in micro CHP; namely polymer electrolyte membrane (PEM) fuel cell technology and solid oxide fuel cell (SOFC) technology; are still in the relatively early design stages, but have showed promising signs of becoming a viable, alternative CHP technology in the relatively near future. For this to materialise, continued research and development will be fundamental in making this product commercially viable and ensuring adequate performance, lifetime and cost targets are met.

Therefore, at present, the only realistic and viable micro CHP system choice on the market is that of the Stirling engine configuration.

2.2 Condensing Gas Boilers

Historically, the gas boiler would have been the most obvious water-heating appliance of choice used to meet a homes domestic space heating requirement and to provide hot water: via radiators and a hot water cylinder. However, as has been demonstrated earlier, technological advancements are expanding this choice and offering very viable alternative options such as micro CHP and heat pumps.

However, at the same time, key developments also continued to enhance the gas boiler design: making them much more energy efficient compared to older traditional models and therefore significantly reducing the greenhouse gas emissions associated with their use. To ensure these environmental benefits were realised and under pressure to meet ambitious Kyoto targets and ease global warming, in early April 2005, the government decided to implement a switch over, making it a legal requirement that all new gas boiler instillations must have a SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) rating of A or B and therefore a minimum efficiency of 86% [13]. Currently, the new-style condensing gas boiler is the only type of boiler that can achieve this.

Furthermore, given that a staggering 20% of the UK's carbon dioxide emissions are generated by domestic heating systems, this is a key area that is being targeted with alternative, more sustainable solutions. Assuming that every household in the UK were to embrace the governments step change policy and install a condensing gas boiler, a carbon dioxide reduction in the region of 17.5 million tonnes per year could be achieved, as well as a combined saving of £1.3 billion on energy bills per annum [14]. This would be a significant step towards reducing the impact of climate change, the much improved efficiency would help to drive down the total energy demand and consumers would also benefit from reduced energy bills: basically a win-win situation for all.

Government backing, in addition to consumer's familiarity with gas boilers has ensured that the majority of consumers are still opting to replace conventional boilers with the most up to date boiler technology; the condensing gas boiler; despite the numerous advantages associated with newer, alternative technologies. Perhaps, this choice may very well be due to people's aversion to the fear of the unknown getting in the way of them making a truly informed choice, but none the less, there is a very healthy future market for condensing gas boilers.

The condensing gas boiler is the most efficient gas boiler to date, achieving efficiencies in the region of 85% when operating in normal mode and rising to well above 90% when operating in condensing mode [14]. This high efficiency can largely be attributed to two key design features: periodically operating in condensing mode and using either a larger or duel heat exchanger.

2.2.1 How condensing gas boilers work

A condensing boiler "uses very high efficiency heat exchangers designed to capture virtually all the available sensible heat from the fuel as well as some of the latent heat of vaporisation" [15]. Figure 3 clearly demonstrates how energy efficient this process can be:

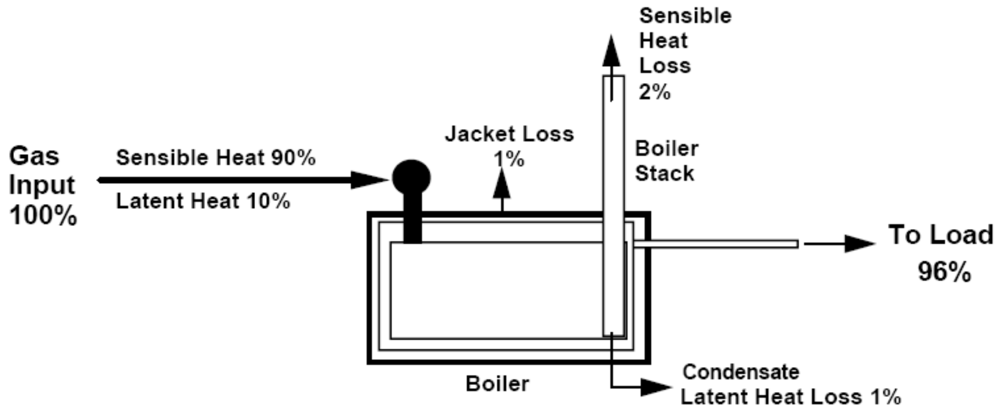

Figure 3: Efficiency of condensing boiler [15]

It achieves this exceptionally high efficiency by recovering the heat that would normally be wasted in a conventional gas boiler and by utilising a larger or duel heat exchanger to maximise the heat transferred from the burner. The low water return temperature is also crucial in obtaining high condensing efficiencies: where the flue gas temperature would previously have been in the region of 120°C to 180°C in a conventional boiler, the condensing boiler reclaims most of the heat and the flue gas temperature is much reduced, at between 50°C and 60°C [14] [16]. Basically the lower the return water temperature, the greater the boiler efficiency.

There are several different types of condensing boiler designs, some of which are shown in figure 4.

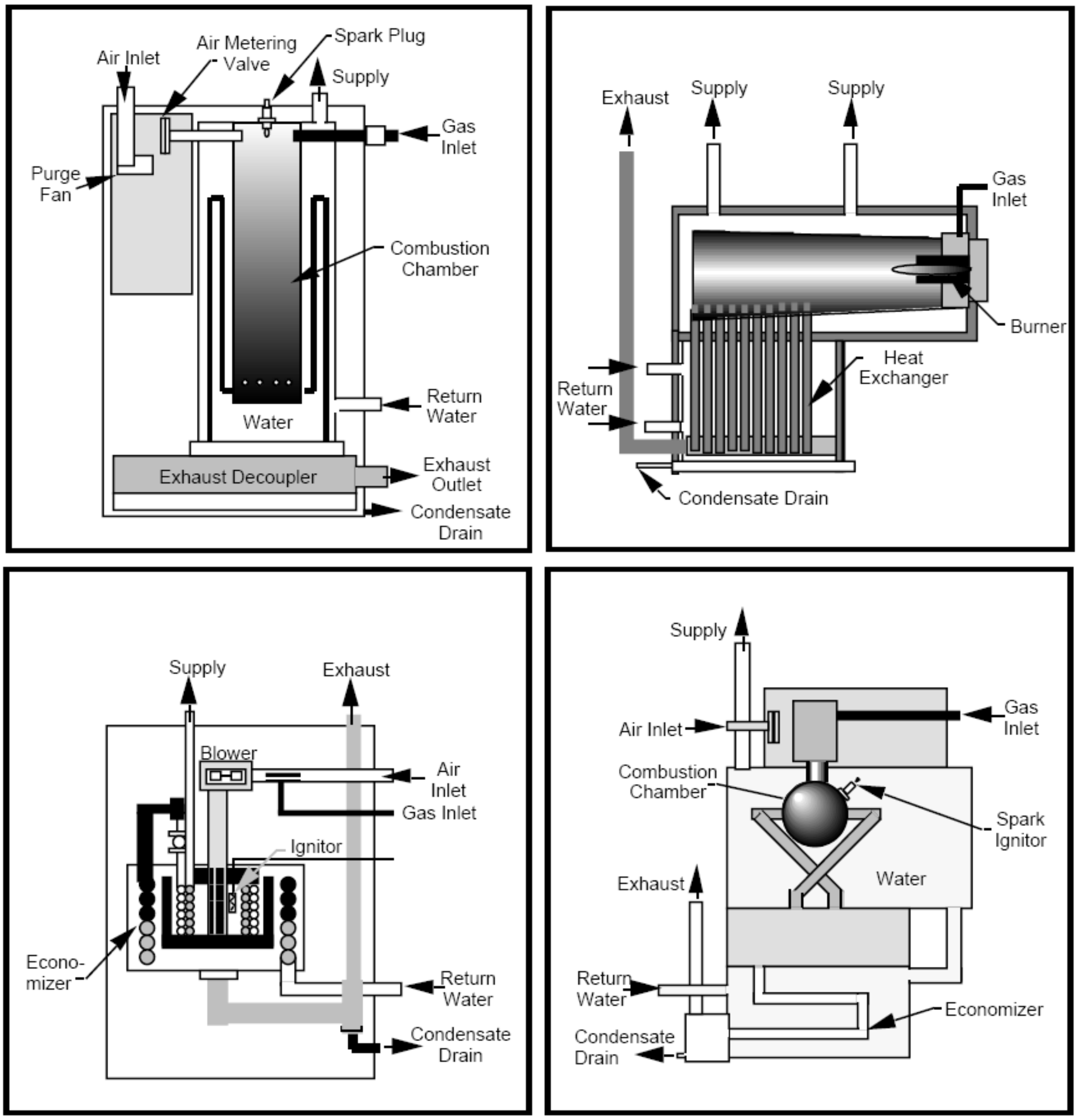

Figure 4: Types of condensing boilers [15]

Despite the number of design variations, each design only varies slightly and they principally operate in a very similar way [15]:

When the thermostat demands space heating or hot water, a signal is sent from an external air temperature sensor to the burner modulation controller. At the same time, the combustion chamber is purged; which essentially removes any gas; prior to combustion air being drawn through the inlet pipe, where it mixes with natural gas; that has been piped through the gas inlet; in the combustion chamber. A spark is then used to ignite this gas/air mixture and the combustion process generates a substantial amount of heat, which is transferred to the water via contact with the combustion chambers walls. The resultant hot exhaust gasses are then forced through very high efficiency heat exchangers within an insulated boiler enclosure, where further heat is transferred to the supply water, prior to it being distributed to the building load.

Condensation typically occurs at the base of the heat exchanger; which discharges more heat to the supply water; and any cooling in the stack results in further condensation. The process is complete when the condensation is drained.

2.2.2 Advantages

Having conducted an extensive literature review it is apparent that condensing gas boilers have numerous advantages:

- They are much more efficient than conventional gas boilers: 85% efficiency rising to well above 90% compared to between just 55% and 65% for old boilers and 78% at the most, for a brand new conventional gas boiler [14]. The government has claimed that they are 37% more efficient than traditional boilers [13].

- Due to the improved efficiency, they capture much more useable heat from the fuel compared to a non-condensing boiler and they therefore require less fuel, which drives down emissions in addition to saving the consumer money.

- Although they are initially more expensive to purchase and install, they benefit from reduced fuel bills and over the lifetime of the boiler, significant savings will be achieved.

- Furthermore, as the main fuel source is gas and gas prices have been rising above inflation, the payback period may be even shorter in the future.

- They are more compact in design and therefore occupy less space compared to conventional gas boilers.

- They are just as reliable as conventional boilers, when properly fitted by a registered installer. However, in the earlier years, they gained a poor reputation and to some extent, this has persisted despite the technology having been developed further and these earlier problems being overcome.

2.2.3 Limitations

Despite all these numerous advantages, condensing gas boilers are not without their limitations and disadvantages:

- They are still a relatively new technology and have been subject to several improvements over recent years.

- Condensing gas boilers are more expensive to purchase and install compared to conventional gas boilers. However, the actual amount varies quite considerably depending on different sources: with most suggesting they are anything between £100 and £300 more expensive [14], but can be up to £500 [13] more expensive.

- Gas boilers produce harmful emissions, although they do produce fewer compared to conventional gas boilers. They can produce total oxides of nitrogen; nitric oxide (NO) and nitrogen oxide (NO_2); carbon monoxide (CO) and particulates, which have adverse environmental consequences and can lead to detrimental health problems.

- They are technically more complex in design, which makes the installation process more of a challenge and there are therefore potentially more problems that can occur.

- They have gained a reputation for an expensive and troublesome switchover, which must now be overcome to accelerate progress and a more rapid uptake of the technology.

- Earlier design problems; such as corrosion of the heat exchanger due to the acidic condensate; resulted in condensing gas boilers gaining a reputation for having a shorter working life compared to conventional boilers. However, technological advancements have overcome earlier problems and with replacement parts available, condensing gas boilers in theory have an unlimited life, although this could come at a significant price!

- Critics have argued that they require more frequent servicing, are less reliable, more prone to malfunctioning and can cost hundreds of pounds per annum to maintain.

2.2.4 Other considerations

Having conducted an extensive literature review, the following points were apparent and should be given consideration:

- To get the most out of a condensing boiler and achieve peak efficiency, a good control system must also be installed.

  This should also ideally comprise of an outdoor weather sensor, which will run the central heating at a temperature that takes into consideration the external conditions, e.g. a particularly hot or cold day. Likewise, when hot water is required, the controls will ensure just enough hot water to meet the demand is produced. Operating in this manner, the water returning to the boiler will be roughly 55^{o}C; within the ideal range required for it to condense; and the boiler will therefore mainly operate in condensing mode, thus maximising the efficiency of the system for the majority of the time.

  There should also be a control system in place that helps to modulate the capacity and minimise any losses due to cycling at less that full load. Where the requirement for a particularly large capacity exists, it may be better to meet this by installing several smaller capacity boilers, in place of one large boiler, as this facilitates: better control, higher overall efficiency, greater reliability, usually lower capital costs, in addition to reducing the chance of complete system failure because multiple units are installed.

- The boiler should also be correctly sized, because if it is too large it will operate at a lower efficiency and if it is too small, it will not be capable of meeting all of the demand, which is particularly problematic at periods of peak demand. It is also important to maximise the efficiency of the home prior to purchasing a new condensing gas boiler, as this will enable a smaller boiler to be used. All efficiency measurements must be calculated; eg insulation, windows, etc; and then the boiler should be sized based on the remaining heat demand.

- Earlier condensing boiler designs had issues with corrosion as a result of the flue gasses condensing within a ferrous metal heat exchanger. To overcome this problem, heat exchangers made from a non-ferrous material such as stainless steal should be selected and this is commonly found in just about all new boiler designs.

- In a condensing boiler, flue gasses leave at a lower temperature and they therefore tend to condense as they exit the flue, which can be both unsightly and inconvenient. To overcome this, boilers should ideally be fitted with an external flue; where sufficient outdoor space exists; or alternatively, an internal vertical flue, which will enable the flue gasses to exit near or through the roof.

- Servicing the boiler in accordance with the manufacturers instructions should ensure its continued efficient operation and help to maximise the life span and reliability of the appliance.

2.2.5 Types of condensing boilers

There are two different types of condensing boilers: regular condensing boilers and combination condensing boilers; commonly referred to as combi-boilers. The main difference between them is that **regular** condensing boilers heat hot water using a hot water cylinder, where as **combination** condensing boilers are capable of generating hot water on demand, without the requirement for any storage facility such as a hot water cylinder. It should be noted that not all homes are suitable for instillation of a combination boiler and the decision must be based on the existing home heating system.

3. Building Modelling Options

Following a technology investigation, an extensive brainstorm was conducted to identify the various building modelling configurations that could potentially be modelled and analysed. This revealed numerous characteristics and these have been separated into two sub categories: occupancy characteristics and building characteristics.

3.1 Occupancy Characteristics

From the occupancy characteristics brainstorm; figure 5; it was identified that the building use could vary considerably depending on the type of occupant. For example:

- Professionals / working people are unlikely to occupy the building during normal working hours of 9am to 5pm.
- Students are likely to have a more sporadic and intermittent use pattern, as a result of varying course timetables and staying up late, and
- The elderly / retired are likely to live a more sedentary lifestyle and will therefore continuously occupy the building for most of the time.

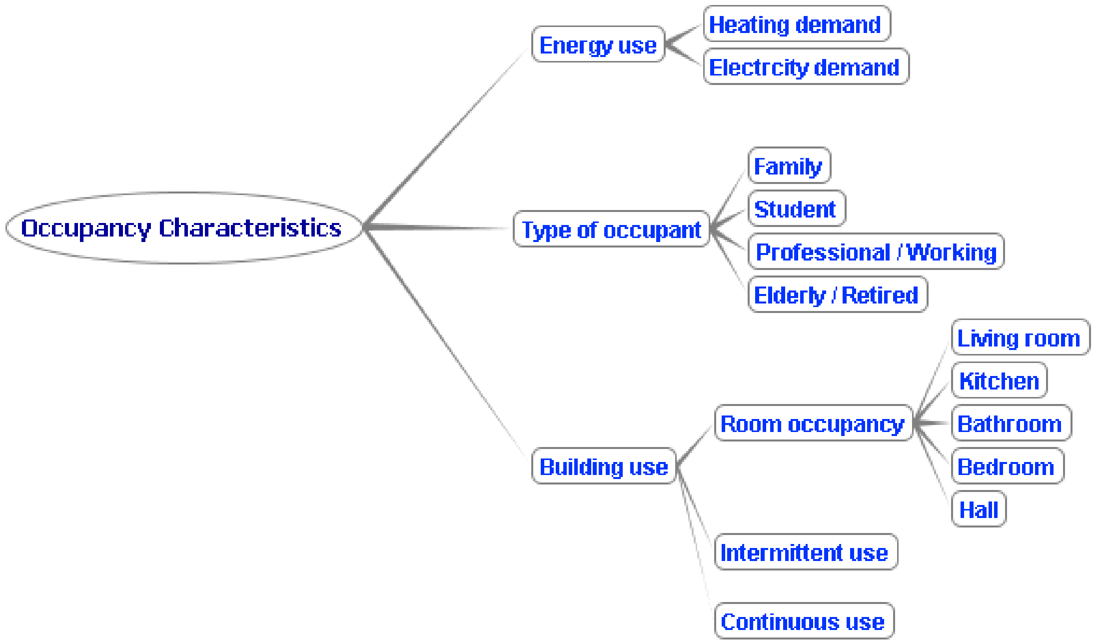

Figure 5: Building modelling options – occupancy characteristics

These different occupants and associated use patterns have a considerable influence on the heating and electricity demand, and this was identified as one of the criteria that should be investigated during modelling.

3.2 Building Characteristics

From the building characteristics brainstorm; figure 6; there are several important characteristics that could have an influence on the heating and electricity demand.

Firstly, the levels of insulation within the building will have a significant impact on the heating demand and this includes both the wall and loft insulation levels, in addition to the type of window glazing installed.

Furthermore, the amount of draught proofing within the building will also have a significant impact on the heating demand. For example, if the building is older and not well sealed, large quantities of external cold air may enter the building and increase the heating requirement.

The location of the building and the associated climate also have an influence on the heating demand of the building. For example:

- Scotland is generally a few degrees cooler than England,
- Inland the temperatures are usually warmer compared to that of coastal areas, and
- The east coast is generally slightly cooler in the winter than the west coast.

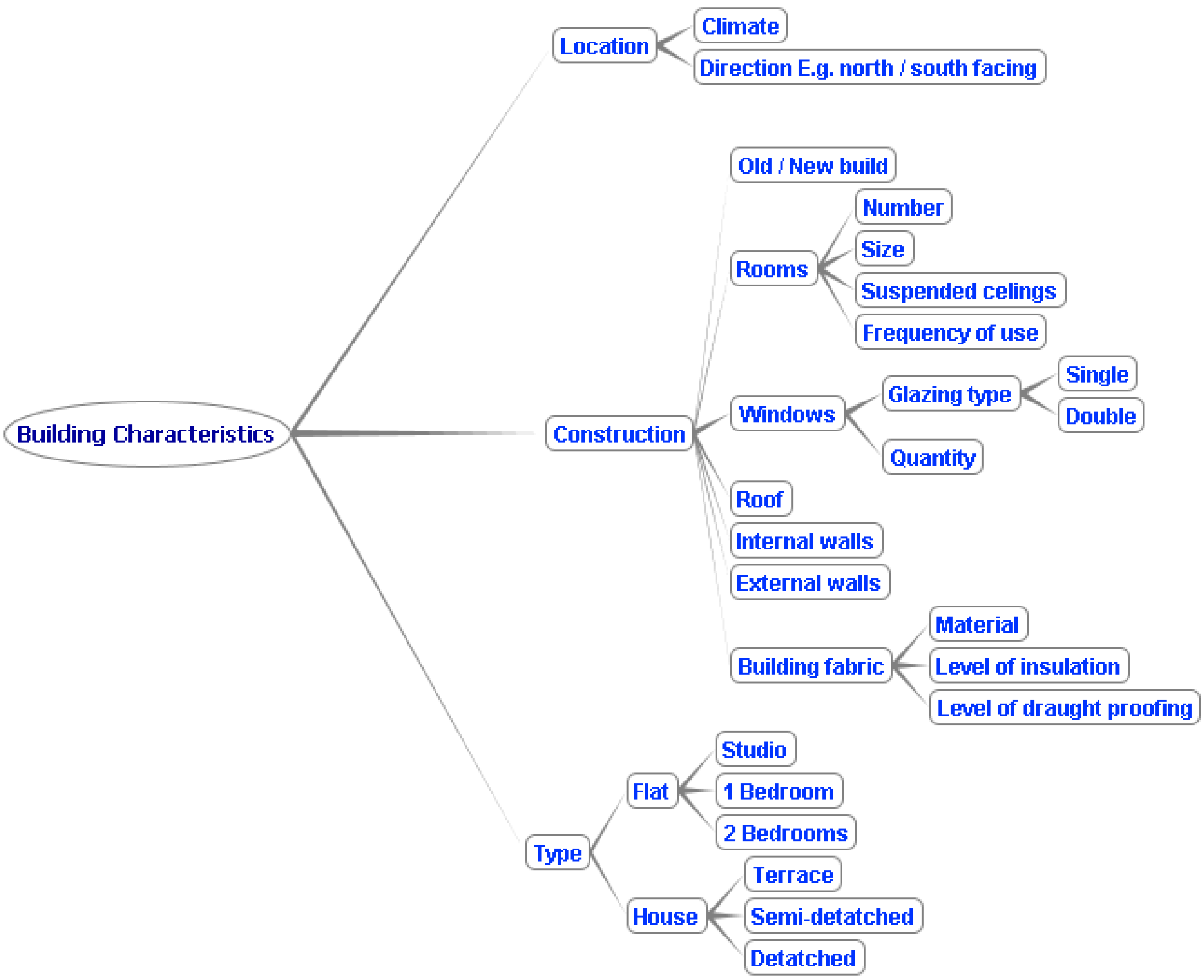

Figure 6: Building modelling options – building characteristics

The extent of the effect of the variables described above were investigated with the aid of a modelling tool. This involved modelling slight variations of the configurations identified above and this process is explained in greater detail in the section, Modelling & Results Analysis: Modelling Approach & Analysis Criteria.

4. Literature Review: Summary & Key Learning Points

To summarise the main findings of the initial research and the literature review, the technological section of the literature review revealed three technologies that offer alternative, potentially viable heating solutions for the domestic home:

- Heat pump technology,
- Micro combined heat and power (Micro CHP), &
- Condensing gas boilers.

All of these technologies offer several benefits over existing methods of fulfilling a homes heating demand, however, the two main advantages that they share in common are:

- They benefit from improved, higher levels of efficiency, and
- They offer a more sustainable and environmentally friendly solution, because they produce significantly fewer emissions compared to the commonly used conventional gas boiler or electric heaters.

With respect to the **heat pumps**, these use the planets abundant low-grade heat resource and utilising a small amount of electricity, they are capable of delivering temperatures suitable for heating the home; both space and water heating. With high energy efficiency (COP) commonly falling within the range of 3:1 and 5:1, not only is the home's heating demand fulfilled using essentially a 'free' resource; heat contained in the air, ground or water; but the amount of electricity required to achieve this compared to conventional methods is much reduced. Furthermore, heat pump technology also has the potential in the future to be a 100% sustainable source, providing the electricity required is generated using purely renewable sources.

With respect to **micro CHP**, this is used to heat *and power* the domestic home, with electricity being generated and the typically 'waste' heat being put to use: therefore improving the overall efficiency of the process. Not only does this fulfil the majority of the home's heating requirements, but it can also potentially generate additional quantities of electricity in excess of the home's demand, which can then be sold to the national grid to generate an income. This process offers improved efficiency over conventional methods of producing electricity; for example power stations; thus reducing harmful emissions; but additionally, it will also facilitate the transition towards more reliable, distributed energy generation.

With respect to **condensing gas boilers**, these offer much improved heating solutions compared to existing home heating methods because of the very high overall efficiency. Not only does this technology make better use of the fuel and therefore requires less, but it also produces fewer emissions. That said, of the three technologies investigated, condensing gas boilers are the only solution that does not offer any electricity benefit.

Another factor that is important when seeking a viable alternative technology is consumers awareness and confidence in these more unfamiliar, alternative heating solutions and if this does not exist, the uptake of these technologies will be slow. This is where the new style condensing gas boiler has an advantage, because it is simply a more efficient version of a technology that consumers are already familiar with and therefore have a degree of confidence in. Therefore, trying to overcome consumers 'fear of the unknown' to ensure this does not prevent them making a truly informed choice as to which technology offers the best heating solution poses a real challenge and this must be addressed early in the product's launch to market, to ensure the future success of technologies such as heat pumps and micro CHP.

However, despite this concern, considering and weighing up all of the advantages and limitations of each technology, it is apparent that heat pumps are the only technology that can potentially deliver a fully sustainable heating resource in the future and they are capable of realising a significant electricity consumption reduction within the home. As a result of this dual benefit, this technology has been selected to be investigated in the following case study section of the thesis and from this point forward, the scope of the investigation has been narrowed to heat pump technology.

With respect to the modelling options aspect of early research, it is apparent that four different characteristics were highlighted of particular interest and these form the testing scenarios to be investigated in the following case study section of the thesis. These characteristics are:

- Occupancy,
- Insulation (including window glazing, roof and wall insulation),
- Draught proofing, &
- Location and climate.

1. Modelling approach

To ensure the desired results were obtained, two types of software were identified and utilised. ESP-r; a university modelling tool, which tries to closely simulate the real world and enables an in-depth assessment of the factors that influence the energy and environmental performance of buildings; was used to model the building and the heat pump system. In addition, an operating system known as Ubuntu was used and this facilitated the use of a script to run the model and associated simulations.

Firstly, the university provided a domestic dwelling model that had been constructed using ESP-r. The model had previously been designed and constructed for a similar project in the past and already had heat pump technology built into the model. Using, but adapting an existing model saved a considerable amount of time and to ensure the model was suitable for investigating the parameters within this thesis, the model details; primarily the buildings construction; were checked. This revealed that a few alterations had to be made, mainly changing the roof and wall constructions to ensure they were consistent throughout the model and this completed the construction of the base case model. A detailed explanation of the most important construction and operational details is provided in the following section. It was crucial that this model was correct prior to proceeding and running any simulations, as all future modifications and testing parameters would be made and compared based on this model.

The model within ESP-r was then used in collaboration with an Ubuntu script, to run an annual simulation of the base case model. The simulations themselves could have been run using ESP-r alone, however, this would have generated a significant amount of very detailed results, which would have been very time consuming, memory intensive and unnecessary. By using an Ubuntu script, this focused the results output to the key parameters that were of interest, which were: actual COP, ideal COP, system COP, electrical (kWh), ASHP heat out (kWh), system heat loss (kWh), total system heat out (kWh), useful system heat out (kWh) and the number of on/off cycles. These results were provided in monthly intervals, for a year.

Having generated the base case results, Microsoft excel was then used to post process the results. This involved plotting three graphs, to identify how the performance of the heat pump varied throughout the year. Each graph investigated different key performance areas of the heat pump:

- The COP,
- The energy performance, and
- The cycling frequency.

The main analysis objective was to identify any patterns and to try to provide an explanation as to the cause of what was occurring.

In addition to analysing the heat pump's performance, the financial impact and environmental consequences also had to be investigated. This was achieved by comparing these criteria to the most commonly used alternative: the condensing gas boiler; and this research focused on two aspects: the running cost (electricity equivalent) to operate the technology, as well as the carbon emissions associated with its use.

Having run and analysed the base case model, an investigation into the effect of altering some of the operational and building characteristics identified earlier also had to be conducted to ascertain what, if any impact they had on the performance of the heat pump. This was achieved by copying the base case model and altering it to test each characteristic, one at a time. The simulation and analysis procedure described above was then conducted for each alteration.

2. Model description

The ESP-r base case model is a Westfield house installed with an air source heat pump. The heat pump has been configured to fulfil the home's space heating requirement, however, it does not model the home's hot water requirement. The model is a one bedroom, detached dwelling with a total base/floor area of $57.9m^2$: comprising of a living room ($21.5m^2$), kitchen ($8.12m^2$), bedroom ($11.7m^2$), bathroom ($5.52m^2$) hallway ($6.18m^2$) and an additional partition area.

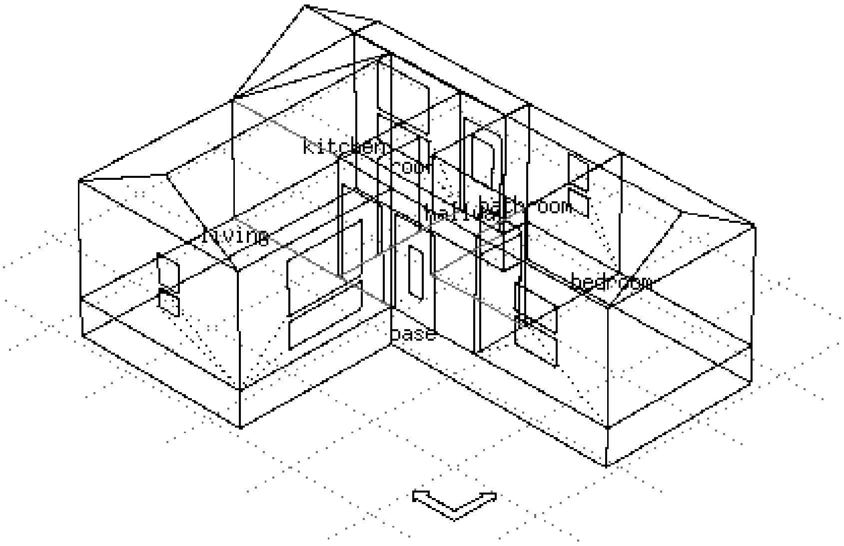

Figure 7: Perspective view of base case model

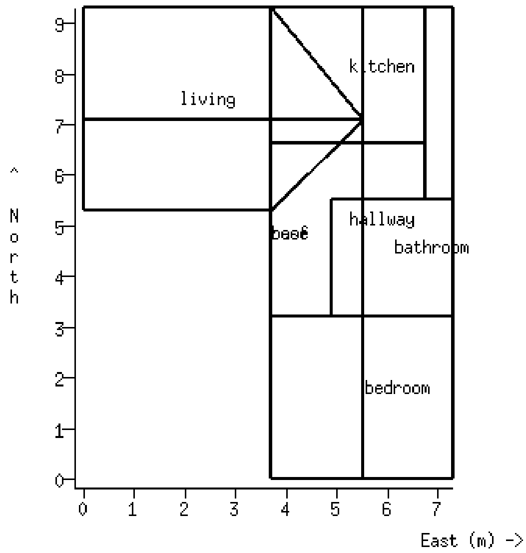

Figure 8: Plan view of base case model

There are numerous building construction and operational details that could be discussed, however, the ones of greatest importance in terms of the characteristics that will be altered in the modelling scenarios have been highlighted below:

- The building is located in Dundee, on the east coast of Scotland: 56.5N 3.0W of local meridian.

- The dwelling has 5 windows: two of which are in the living room and one in each of the other rooms, excluding the hall. They are all double glazed, constructed with 'dbl_glz' and surrounded by 'win_frame'. The double glazing consists of 6mm glass plate, 12mm air and 6mm glass plate and this is surrounded by a frame, consisting of 25mm softwood.

Material: Dbl_glz								
Material Description	Thickness (mm)	Conductivity	Density	Specific heat	IR emissivity	Solar Absorption	Diffuse resistance	R (m^2 K/W
Plate glass	6	0.760	2710	837	0.83	0.05	19200	0.01
Air	12	0.000	0	0	0.99	0.99	1	0.17
Plate glass	6	0.760	2710	837	0.83	0.05	19200	0.01
ISO 6946 U values (horiz/upward/downward heat flow)= 2.811 3.069 2.527 (partition) 2.243								

Table 1: Material properties – dbl_glz

Material: Win_frame								
Material Description	Thickness (mm)	Conductivity	Density	Specific heat	IR emissivity	Solar Absorption	Diffuse resistance	R (m^2 K/W
Softwood	25	0.130	630	2760	0.90	0.65	12	0.19
ISO 6946 U values (horiz/upward/downward heat flow)= 2.760 3.009 2.486 (partition) 2.211								

Table 2: Material properties – win_frame

- The ESP-r software represents draught proofing by the scheduled airflows. Within the base case model, all of the rooms; the living room, kitchen, bedroom, bathroom and hallway; and the roof have been configured to have an infiltration level in excess of 2 air changes per hour (ac/h) to represent an extremely leaky house. The base of the building is the only exception and it has an infiltration level of 3ac/h.

- The external walls are constructed from 'ext_wall2'; which consists of 100mm brick, 120mm UF foam, 100mm brick and 10mm plasterboard.

Material: Ext_wall2								
Material Description	Thickness (mm)	Conductivity	Density	Specific heat	IR emissivity	Solar Absorption	Diffuse resistance	R (m^2 K/W
Brick	100	0.840	1700	800	0.90	0.70	25	0.12
UF foam	120	0.030	30	1764	0.90	0.50	5	4.00
Brick	100	0.840	1700	800	0.90	0.70	25	0.12
Plasterboard	10	0.210	900	1000	0.91	0.70	11	0.05
ISO 6946 U values (horiz/upward/downward heat flow)= 0.224 0.226 0.222 (partition) 0.220								

Table 3: Material properties – ext_wall2

- The internal patrician walls are constructed from 'int_wall' which consists of 10mm plasterboard, 80mm brick and 10mm plasterboard.

Material: Int_wall								
Material Description	Thickness (mm)	Conductivity	Density	Specific heat	IR emissivity	Solar Absorption	Diffuse resistance	R (m^2 K/W
Plasterboard	10	0.210	900	1000	0.91	0.70	11	0.05
Brick	80	0.770	1700	1000	0.90	0.70	22	0.10
Plasterboard	10	0.210	900	1000	0.91	0.70	11	0.05
ISO 6946 U values (horiz/upward/downward heat flow)= 2.709 2.949 2.444 (partition) 2.178								

Table 4: Material properties – int_wall

- The roof is constructed from 'roof_2' which consists of 15mm clay tile, 5mm roof felt and 12mm plywood (700 density).

Material: Roof_2								
Material Description	Thickness (mm)	Conductivity	Density	Specific heat	IR emissivity	Solar Absorption	Diffuse resistance	R (m^2 K/W
Clay tile	15	0.850	1900	837	0.90	0.60	52	0.02
Roof felt	5	0.190	960	837	0.90	0.90	15	0.03
Plywood	12	0.150	700	1420	0.90	0.65	576	0.08
ISO 6946 U values (horiz/upward/downward heat flow)= 3.402 3.788 2.994 (partition) 2.604								

Table 5: Material properties – roof_2

- The ceiling is constructed from 'ceiling_2' and 'ceiling2_inv' which consists of 200mm glass fibre quilt and 10mm plasterboard.

Material: Ceiling_2 & Ceiling2_inv								
Material Description	Thickness (mm)	Conductivity	Density	Specific heat	IR emissivity	Solar Absorption	Diffuse resistance	R (m^2 K/W
Glass fibre quilt	200	0.040	12	840	0.90	0.65	30	5.00
Plasterboard	10	0.210	900	1000	0.91	0.70	11	0.05
ISO 6946 U values (horiz/upward/downward heat flow)= 0.192 0.193 0.190 (partition) 0.188								

Table 6: Material properties - ceiling_2 & ceiling2_inv

- The floor is constructed from 'floor_2' and 'floor2_inv' which consists of 5mm synthetic carpet, 5mm wool felt underlay and 15mm flooring.

Material: Floor_2 & floor2_inv								
Material Description	Thickness (mm)	Conductivity	Density	Specific heat	IR emissivity	Solar Absorption	Diffuse resistance	R (m^2 K/W
Synthetic carpet	5	0.060	160	2500	0.90	0.65	10	0.08
Wool felt underlay	5	0.040	160	1360	0.90	0.65	10	0.12
Flooring	15	0.140	600	1210	0.91	0.65	14	0.11
ISO 6946 U values (horiz/upward/downward heat flow)= 2.060 2.196 1.903 (partition) 1.738								

Table 7: Material properties - floor_2 & floor2_inv

- The default occupancy schedule is as follows:

Bedroom	Type of Gain	Time Period	Sensible Gain (W)	Latent Gain (W)
Weekday, Saturday & Sunday				
	Occupant (W)	0 - 8	60	30
	Occupant (W)	8 - 24	0	0
	Lights (W)	0 - 24	0	0
	Equipment (W)	0 - 8	0	0
	Equipment (W)	8 - 10	1500	0
	Equipment (W)	10 - 19	0	0
	Equipment (W)	19 - 21	1500	0
	Equipment (W)	21 - 24	0	0

Table 8: Base case default occupancy schedule - bedroom

Bathroom	Type of Gain	Time Period	Sensible Gain (W)	Latent Gain (W)
Weekday, Saturday & Sunday				
	Occupant (W)	0 - 24	0	0
	Lights (W)	0 - 24	0	0
	Equipment (W)	0 - 24	0	0

Table 9: Base case default occupancy schedule - bathroom

Kitchen	Type of Gain	Time Period	Sensible Gain (W)	Latent Gain (W)
Weekdays				
	Occupant (W)	0 - 8	0	0
	Occupant (W)	8 - 9	30	15
	Occupant (W)	9 - 11	0	0
	Occupant (W)	11 - 13	30	15
	Occupant (W)	13 - 18	0	0
	Occupant (W)	18 – 20	30	15
	Occupant (W)	20 - 24	0	0
	Lights (W)	0 - 24	0	0
	Equipment (W)	0 - 8	0	0
	Equipment (W)	8 - 9	2400	0
	Equipment (W)	9 - 11	0	0
	Equipment (W)	11 - 13	2400	0
	Equipment (W)	13 - 18	0	0
	Equipment (W)	18 - 20	2400	0
	Equipment (W)	20 - 24	0	0

Table 10: Base case default occupancy schedule – kitchen (weekdays)

Kitchen	Type of Gain	Time Period	Sensible Gain (W)	Latent Gain (W)
Saturday & Sunday				
	Occupant (W)	0 - 8	0	0
	Occupant (W)	8 - 9	30	15
	Occupant (W)	9 - 11	0	0
	Occupant (W)	11 - 12	30	15
	Occupant (W)	12 - 18	0	0
	Occupant (W)	18 - 19	30	15
	Occupant (W)	19 - 24	0	0
	Lights (W)	0 - 24	0	0
	Equipment (W)	0 - 8	0	0
	Equipment (W)	8 - 9	2400	0
	Equipment (W)	9 - 11	0	0
	Equipment (W)	11 - 13	2400	0
	Equipment (W)	13 - 18	0	0
	Equipment (W)	18 - 20	2400	0
	Equipment (W)	20 - 24	0	0

Table 11: Base case default occupancy schedule – kitchen (weekend)

Living Room	Type of Gain	Time Period	Sensible Gain (W)	Latent Gain (W)
Weekdays				
	Occupant (W)	0 - 9	0	0
	Occupant (W)	9 - 11	30	15
	Occupant (W)	11 - 13	0	0
	Occupant (W)	13 - 18	30	15
	Occupant (W)	18 - 20	0	0
	Occupant (W)	20 - 24	60	30
	Lights (W)	0 - 24	0	0
	Equipment (W)	0 - 9	0	0
	Equipment (W)	9 - 12	725	0
	Equipment (W)	12 - 13	0	0
	Equipment (W)	13 - 18	725	0
	Equipment (W)	18 - 20	0	0
	Equipment (W)	20 - 24	725	0

Table 12: Base case default occupancy schedule – living room (weekdays)

Living Room	Type of Gain	Time Period	Sensible Gain (W)	Latent Gain (W)
Saturday & Sunday				
	Occupant (W)	0 - 9	0	0
	Occupant (W)	9 - 11	30	15
	Occupant (W)	11 - 12	0	0
	Occupant (W)	12 - 18	30	15
	Occupant (W)	18 - 19	0	0
	Occupant (W)	19 - 24	60	30
	Lights (W)	0 - 24	0	0
	Equipment (W)	0 - 9	0	0
	Equipment (W)	9 - 12	725	0
	Equipment (W)	12 - 13	0	0
	Equipment (W)	13 - 18	725	0
	Equipment (W)	18 - 20	0	0
	Equipment (W)	20 - 24	725	0

Table 13: Base case default occupancy schedule – living room (weekend)

Hall	Type of Gain	Time Period	Sensible Gain (W)	Latent Gain (W)
Weekday, Saturday & Sunday				
	Occupant (W)	0 - 24	0	0
	Lights (W)	0 - 24	0	0
	Equipment (W)	0 - 24	0	0

Table 14: Base case default occupancy schedule – hall

As you can see, the base case model has no provision build in for occupancy in the bathroom or hall. It was assumed that this would be acceptably representative of a real life situation, given that in real life, occupants would spend very little time in these areas. Furthermore, very short periods of sometimes frequent intermittency would be difficult to model using the ESP-r software; due to the amount of detail required and ESP-r only being configured to hourly time periods; and this would likely have a minimal impact on the performance of the heat pump, compared to the scale of all of the other influencing factors. This was therefore deemed unnecessary and left to the default of zero occupancy in both of these rooms.

3. Analysis criteria

It was important to consider and select the analysis criteria prior to commencing any modelling or running of the simulations to ensure the modelling tool selected would generate appropriate outputs to permit a comprehensive and methodical analysis. The parameters that were identified of greatest importance were:

- The coefficient of performance (COP),
- The energy performance,
- The cycling frequency,
- The economics of running a heat pump, and
- The environmental impact.

3.1 Coefficient of performance

From the literature review is was apparent that the efficiency of a heat pump is frequently measured by the coefficient of performance (COP) and this commonly fell within the range of 3:1 to 5:1.

Basically, the higher the COP, the better the efficiency and performance of the heat pump.

3.2 Energy performance

There are several energy performance parameters that can be investigated: electrical consumption, ASHP heat out, system heat loss, total system heat out and useful system heat out.

In terms of the performance of the heat pump, a lower electrical consumption would be advantageous because this would make the heat pump cheaper to run due to minimal electricity purchase and obviously the system heat loss should ideally be minimised. Where this is the case, the disparity between the ASHP heat out and the total system heat out and the useful system heat out should be minimal.

3.3 Cycling frequency

From the literature review it was also apparent that the no. of on/off cycles of the heat pump would have an impact on the starting losses and standing losses.

In an ideal situation, these losses should be minimised, however there must be a trade off between operating the heat pump for the necessary amount of time to meet the demand and incurring starting and standing losses. It would clearly not be beneficial to run the heat pump continuously and produce excess heat, just to avoid starting or standing losses.

3.4 Economics

The cost of running the heat pump must be compared to that of the most commonly used alternative, the condensing gas boiler and this will be achieved by performing the following back calculation for each scenario:

Referring to figure 9, $\mathbf{Q_{in} = Q_h / \eta_T}$

Where:

- Q_h = the total system heat out value from the heat pump, and
- η_T = total efficiency

The following assumptions were made:
- The condensing gas boiler efficiency = 0.94, and
- The system heat efficiency (see appendix 1) = total system heat out / ASHP heat out.

Therefore, η_T = boiler efficiency (η_B) * system heat efficiency (η_S)

As both Q_h and η_T are known, Q_{in} (the equivalent energy content of a condensing gas boiler) can be found.

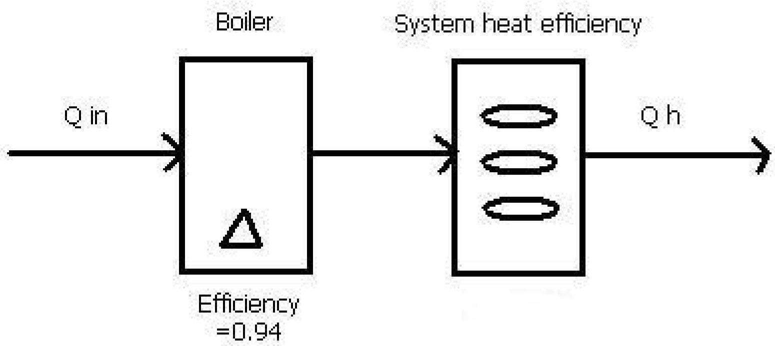

Figure 9: Calculating the equivalent energy content of a condensing gas boiler

Reviewing the heat pump scenario, the electricity required to generate Q_h is known, so the electrical consumption can be multiplied by the cost of electricity.

Having calculated the condensing gas boiler energy equivalent (Q_{in}), this can be multiplied by the cost of gas.

On the 20th of August 2009, USwitch recommended EOn as the cheapest supplier of both gas and electricity. The prices were as follows:

Gas:
- 6.525p per kWh
- 3.407p per kWh for consumption greater than 2680kWh per annum.

Electricity:
- 24.18p per kWh
- 9.67p per kWh for consumption greater than 900kWh per annum.

3.5 Environmental impact

The environmental impact of the heat pump technology must also be compared to that of the most commonly used alternative, the condensing gas boiler. This will primarily focus on the carbon dioxide (CO_2) emissions and will be assessed utilising the electricity consumption and equivalent gas consumption values as calculated above.

The Carbon Trust, Energy and Carbon Conversations fact sheet – 2008 update; refer to appendix 2; quoted the following CO_2 emission values [18]:
- 0.537kg of CO_2 emissions per kWh unit of grid electricity, and
- 0.185kg of CO_2 emissions per kWh unit of natural gas.

These will be used to compare the environmental impact of utilising the different technologies.

4. Base case results

Having outlined the modelling approach, analysis criteria and investigated in detail the models base case configuration, the base case simulation was run. This generated a result set that was post processed with the aid of Microsoft Excel and the findings are summarised below.

4.1 Comparison of COP

The script utilised highlighted three key pieces of information regarding the efficiency of the heat pump:

- Actual COP (which is the performance of the heat pump alone, excluding the rest of the system)
- Ideal COP (which is the heat pumps performance obtained under laboratory conditions) and
- System COP (which is the performance of the entire heat pump system, taking account of system losses, such as losses due to pipe work, radiators, etc)

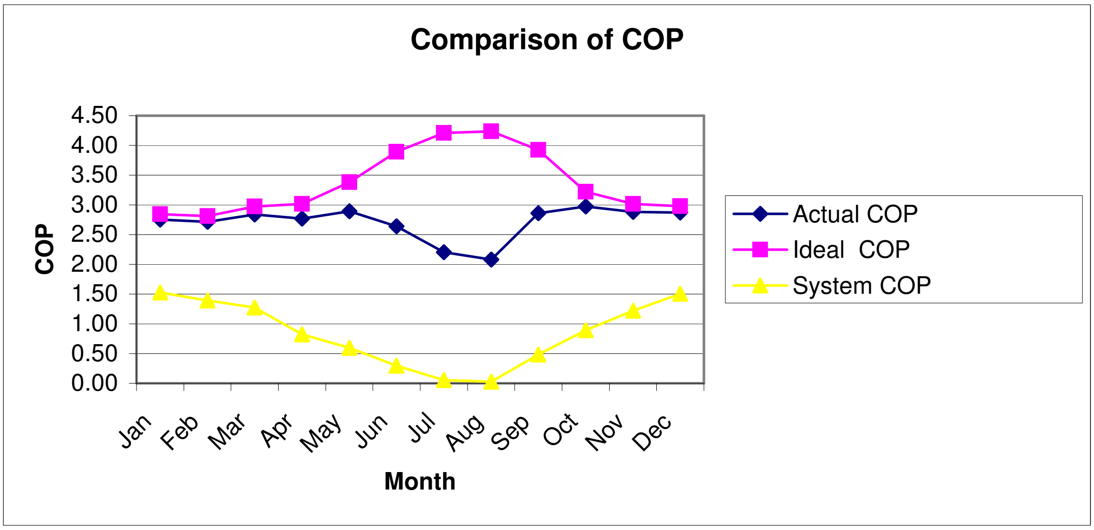

Figure 10: Base case – comparison of COP

Figure 10 reveals that the performance of the heat pump appears to be inline with theory and this therefore suggests that a satisfactory model has been built, which is representative of a realistic heat pump installed within a dwelling. The following trends provide an indication of this.

The Ideal COP falls within an acceptable range of 2.810 in February and 4.237 in August. It also peaks during the summer months; July and August; which occurs because the COP should theoretically be at a maximum when the temperature between the source and the sink is at a minimum. For example, in a typical year, the source temperature would be greatest during the summer and therefore the difference between the increase in temperature required to meet the desired heating demand temperature would be at a minimum.

However, in reality, the actual COP is lower than the ideal COP and is at its poorest during the summer months. This can be explained if the heat pump were to have been correctly sized; for example, to meet the demand which would be greatest in the winter; and therefore during the summer period, the heating demand is significantly less, which would result in too large a heat pump system for this period of operation and hence an overall reduced efficiency.

That said, there are a couple of measures that can be implemented to help alleviate this problem. Firstly, the heat pump can be designed to provide both space heating and domestic hot water, altering the use depending on demand. For example, in the winter it would be used to provide space heating and during the summer when the space heating demand is almost negligible, the heat pump can be used to provide hot water. Alternatively, multiple heat pump units could be installed and the level of demand would dictate how many units would be required to operate. However, it is likely that a sufficiently large demand would have to exist to merit this and a cost benefit analysis would have to be conducted to ascertain if this option would actually be financially beneficial or if it would be better to run a single unit with a slightly lower COP.

Additionally, the system COP also complies with theory, in that it follows a similar trend to the actual COP, but has lower COP values as a result of all of the system losses, as was expected. However, there is another noticeable trend: the difference between the actual COP and the system COP appears to be proportionally greatest during the summer months, when the heating demand is at it's lowest. This period of poor performance is experienced and worse at this particular time of year because the heat pump has again been sized for a much larger demand, i.e. winter demand. Again, this has a detrimental impact on the overall efficiency, which is much reduced and proportionally worse at the height of the summer.

There are clearly three different COP results that can be used to assess the performance of the heat pump. However, from this point forward, only the actual COP will be used to assess any changes, as this relates to the installed and operational performance of the actual heat pump, but excludes any system losses resulting from other equipment such as the pipe work, radiators, etc.

Therefore, the key results from the base case scenario in terms of COP are as follows:

- The maximum actual COP occurred in October at a value of 2.974,
- The minimum actual COP occurred in August at a value of 2.082, and
- The monthly average actual COP was 2.707.

4.2 Energy Performance

The script utilised highlighted several pieces of information regarding the energy performance, outputs and losses of the heat pump:

- Electrical (which is the energy consumed by the heat pump)
- ASHP Heat Out (which is the energy supplied by the heat pump)
- System Heat Loss (which is the heat lost from the system, for example, pipe work)
- Total System Heat Out (which is the 'useful' heat to the radiators = ASHP heat out minus system heat loss. It is also worth noting that some of the heat loss may end up in the zone)
- Useful System Heat Out (which is the heat out during the occupied period. It is also worth recognising that the heat stored in the system that is lost on switch off is wasted)

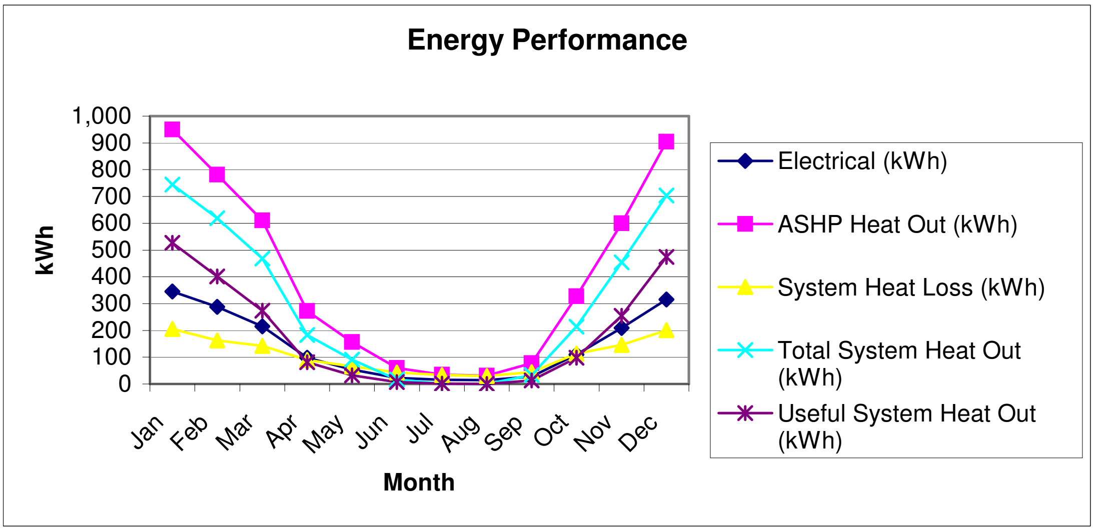

Figure 11: Base case - energy performance

Figure 11 reveals the anticipated annual trend, in that the heating demand and therefore the amount of heat generated follows that of the external climate temperature conditions throughout the year. For example, during the summer the dwelling will benefit from direct and diffuse solar radiation gains; reducing the heating demand; as well as the source temperature of the air being typically greater. This means that for the heap pump to satisfy the pre-set comfort conditions, this can be achieved by generating less heat and performing less work in order to achieve this; because the source temperature is closer to the desired sink temperature; and this therefore utilises less electricity to meet the already reduced heating demand.

Furthermore, with regards to numerical calculations, as you would expect, the ASHP Heat Out energy is the largest figure. This is followed by the Total System Heat Out, which is calculated by subtracting the System Heat Loss from the ASHP Heat Out and the Useful System heat out is lower than the Total System Heat Out, because this figure only takes into consideration the heat out during the occupied period, which means that further losses are incurred during periods of switch off.

There are clearly different energy performance results that could be used to measure the energy performance of the heat pump, however, the most important results that will be used for future analysis are:

- The electricity required to operate the heat pump; Electrical: and
- The Total System Heat Out = ASHP Heat Out – System Heat Loss.

Therefore, the key results from the base case scenario in terms of electrical consumption are as follows:

- The maximum electricity requirement occurred in January at a value of 344.96kWh,
- The minimum electricity requirement occurred in August at a value of 14.68kWh,
- The monthly average electricity requirement was 142.82kWh, and
- The total electricity requirement for a year was 1713.86kWh.

The key results from the base case scenario in terms of total system heat out are as follows:

- The maximum total system heat out occurred in January at a value of 744.34kWh,
- The minimum total system heat out occurred in August at a value of 0.35kWh,
- The monthly average total system heat out was 294.10kWh, and

- The total system heat out for a year was 3529.17kWh.

4.3 No. of on/off cycles

The script utilised generated one key piece of information regarding the cycling frequency of the heat pump, basically the number of on/off cycles.

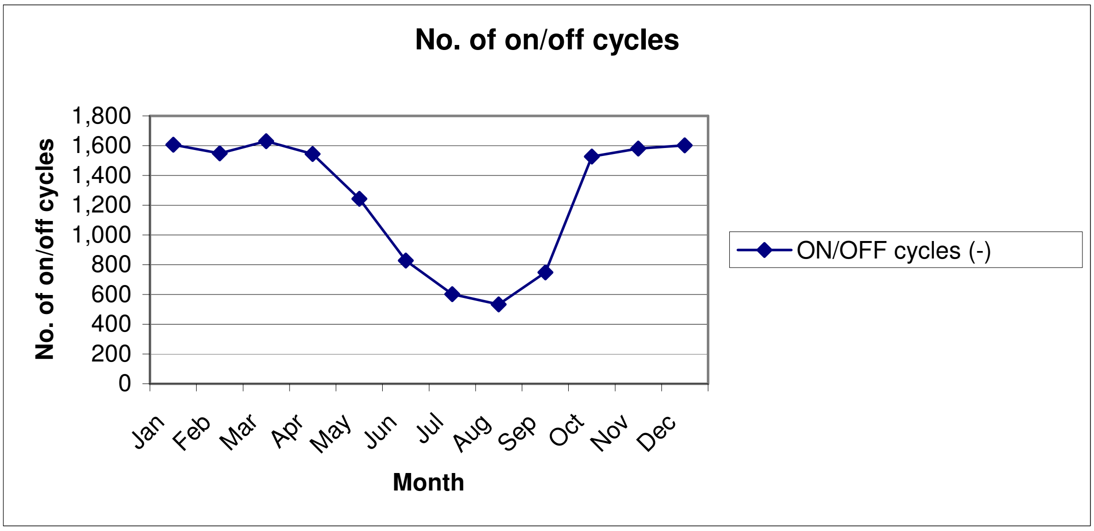

Figure 12: Base case – no. of on/off cycles

Figure 12 revels that as you might expect, the cycling frequency appears to be influenced by the external climate. For example, the number of on/off cycles is less during the summer, when the demand is lower, compared to a higher number of on/off cycles during the winter, when the demand is higher.

However, comparing the number of on/off cycles to the actual COP, it is also apparent that the performance of the heat pump follows a similar trend to the frequency of switching on/off of the heat pump. For example, the actual COP declines in the summer, when the number of on/off cycles is less frequent. As explained in the literature review section, losses such as switching and standing losses should be minimised in order to maximise the performance of the heat pump and the COP is reduced the more frequently the heat pump is switched on and off. However, it would not be beneficial for the heat pump to operate and produce in excess of the required heating demand just to avoid these losses, so a compromise must be reached between the frequency of cycling and the standing losses incurred.

Therefore, the key results from the base case scenario in terms of cycling frequency are as follows:

- The maximum number of on/off cycles occurred in March at a value of 1631,
- The minimum number of on/off cycles occurred in August at a value of 533,
- The monthly average number of on/off cycles was 1249, and
- The total number of on/off cycles in a year was 14993.

4.4 Electricity consumption & running cost

To ascertain which technology was cheaper to operate, the energy cost associated with running each technology was calculated.

The heat pump is capable of generating a total system heat out (Q_h) of 3,529.17kWh per annum and this requires an electricity consumption of 1,713.86kWh per annum.
Utilising the method explained in the Analysis Criteria, section 3.4 Economics, the cost of running the heat pump is:

= (900 * 0.2418) +((1,713.86 - 900) * 0.0967)
= 217.62 + 78.7003
= £296.32 per annum.

To generate the same quantity of heat utilising a condensing gas boiler requires the following gas energy content, where the total efficiency =

$\boldsymbol{\eta_T = \eta_B * \eta_S}$
= 0.94 * 0.73
= 0.6862

Therefore:

$\boldsymbol{Q_{in} = Q_h / \eta_T}$
= 3529.17 / 0.6862
= 5143.06kWh of gas.

Therefore, the cost of running the condensing gas boiler:

= (2680 * 0.06525) + ((5143.06 – 2680) * (0.03407))
= 174.87 + 83.92
= £258.79

In this particular scenario, it would be £37.53 cheaper to meet the heating requirement of the dwelling using a condensing gas boiler than a heat pump. This is likely as a result of the relatively poor efficiency of the heat pump system: the ideal COP obtained a maximum value of 4.237, yet the actual COP maximum only obtained a maximum value of 2.974. Should the theoretical ideal maximum have been obtainable, this would have significantly improved the performance of the heat pump.

Furthermore, there is currently a large disparity between the price of gas and electricity. If this price difference were to converge; and both electricity and gas prices have experienced high price volatility before; it is likely that the heat pump could be cheaper and therefore more economical to run in the future.

4.5 Carbon emissions & savings

To ascertain which technology has the environmental advantage, the carbon emissions associated with each technology were calculated.

To generate the same quantity of heat requires:

- 1713.86kWh of electricity to run the heat pump, or
- 5143.06kWh of gas to run the condensing gas boiler.

Therefore the carbon emissions associated with the heat pump are:

= 1713.86 * 0.537kg/kWh
= 920.34kg of CO_2 per annum.

The carbon emissions associated with the condensing gas boiler are:

= 5143.06 * 0.185kg/kWh
= 951.47kg of CO_2 per annum.

In this particular scenario, there is a slight environmental benefit in generating the dwellings heating requirement utilising a heat pump over a condensing gas boiler, as this would save 31.13kg of CO_2 per annum. Although this saving is relatively small, if heat pumps were to be installed in every domestic home throughout the UK, the total carbon savings would be substantial.

From this point forward, the base case scenarios actual COP, electrical requirement, total system heat out, number of on/off cycle data, running costs and carbon emissions will all be used to compare the performance of the heat pump with future model changes.

5. Scenarios

5.1 Scenario 1: Occupancy

5.1.1 Model changes explained

To ascertain the effects of varying types of occupants and their associated use of the building on the heat pumps performance, the following occupancy schedules have been configured. These are shown in tables 15 to 19 and any changes to the base case model are highlighted in blue. It has also been assumed that for each of the three occupancy types, that there are 2 occupants living in the dwelling.

- The bedroom occupancy schedule for weekdays, Saturday & Sunday is the same and is as follows:

Type of Gain	Time Period	Base Case		Elderly		Students		Working	
		SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)
Occupant (W)	0 - 8	60	30	120	60	120	60	120	60
Occupant (W)	8 - 24	0	0	0	0	0	0	0	0
Lights (W)	0 - 24	0	0	0	0	0	0	0	0
Equipment (W)	0 - 8	0	0	0	0	0	0	0	0
Equipment (W)	8 - 10	1500	0	1500	0	1500	0	1500	0
Equipment (W)	10 - 19	0	0	0	0	0	0	0	0
Equipment (W)	19 - 21	1500	0	1500	0	1500	0	1500	0
Equipment (W)	21 - 24	0	0	0	0	0	0	0	0

Table 15: Bedroom occupancy schedules – all days

This occupancy schedule assumes that the occupants spend very little time in the bedroom, other than to sleep and get ready first thing in the morning.

- The kitchen occupancy schedule for weekdays is as follows:

Type of Gain	Time Period	Base Case		Elderly		Students		Working	
		SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)
Occupant (W)	0 - 8	0	0	0	0	0	0	0	0
Occupant (W)	8 - 9	30	15	120	60	60	30	60	30
Occupant (W)	9 - 11	0	0	0	0	0	0	0	0
Occupant (W)	11 - 13	30	15	120	60	60	30	0	0
Occupant (W)	13 - 18	0	0	0	0	0	0	0	0
Occupant (W)	18 - 20	30	15	120	60	120	60	120	60
Occupant (W)	20 - 24	0	0	0	0	0	0	0	0
Lights (W)	0 - 24	0	0	0	0	0	0	0	0
Equipment (W)	0 - 8	0	0	0	0	0	0	0	0
Equipment (W)	8 - 9	2400	0	2400	0	2400	0	2400	0
Equipment (W)	9 - 11	0	0	0	0	0	0	0	0
Equipment (W)	11 - 13	2400	0	2400	0	1200	0	0	0
Equipment (W)	13 - 18	0	0	0	0	0	0	0	0
Equipment (W)	18 - 20	2400	0	2400	0	2400	0	2400	0
Equipment (W)	20 - 24	0	0	0	0	0	0	0	0

Table 16: Kitchen occupancy schedules - weekdays

The occupancy schedule assumes:

- The elderly couple spend equal amounts of time in the kitchen during breakfast, lunch and dinner and they use the kitchen more than the other occupants because they would generally have more time and would therefore tend to be in less of a rush.

- The students only spend half of the time in the kitchen at breakfast and lunch compared to the elderly and the working professionals again spend only half the time in the kitchen at breakfast and have no occupancy during the day due to an assumed 9am to 5pm working day.
- Each of the occupant types spend an equal amount of time in the kitchen for evening meals, however, this figure has been scaled up compared to the base case scenario to account for two occupants living in the dwelling.

- The kitchen occupancy schedule for Saturday & Sunday is as follows:

Type of Gain	Time Period	Base Case		Elderly		Students		Working	
		SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)
Occupant (W)	0 - 8	0	0	0	0	0	0	0	0
Occupant (W)	8 - 9	30	15	120	60	0	0	120	60
Occupant (W)	9 - 11	0	0	0	0	0	0	0	0
Occupant (W)	11 - 12	30	15	120	60	120	60	120	60
Occupant (W)	12 - 18	0	0	0	0	0	0	0	0
Occupant (W)	18 - 19	30	15	120	60	120	60	120	60
Occupant (W)	19 - 24	0	0	0	0	0	0	0	0
Lights (W)	0 - 24	0	0	0	0	0	0	0	0
Equipment (W)	0 - 8	0	0	0	0	0	0	0	0
Equipment (W)	8 - 9	2400	0	2400	0	0	0	2400	0
Equipment (W)	9 - 11	0	0	0	0	0	0	0	0
Equipment (W)	11 - 13	2400	0	2400	0	2400	0	2400	0
Equipment (W)	13 - 18	0	0	0	0	0	0	0	0
Equipment (W)	18 - 20	2400	0	2400	0	2400	0	2400	0
Equipment (W)	20 - 24	0	0	0	0	0	0	0	0

Table 17: Kitchen occupancy schedules - weekends

All of the occupant types spend roughly the same amount of time in the kitchen at the weekend, with the exception of students because it has been assumed that they do not have breakfast following a night out and there is therefore no equipment demand at this time.

- The living room occupancy schedule for weekdays is as follows:

Type of Gain	Time Period	Base Case		Elderly		Students		Working	
		SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)
Occupant (W)	0 - 9	0	0	0	0	0	0	0	0
Occupant (W)	9 - 11	30	15	120	60	60	30	0	0
Occupant (W)	11 - 13	0	0	0	0	60	30	0	0
Occupant (W)	13 - 18	30	15	120	60	0	0	0	0
Occupant (W)	18 - 20	0	0	0	0	0	0	0	0
Occupant (W)	20 - 24	60	30	120	60	120	60	120	60
Lights (W)	0 - 24	0	0	0	0	0	0	0	0
Equipment (W)	0 - 9	0	0	0	0	0	0	0	0
Equipment (W)	9 - 12	725	0	725	0	725	0	0	0
Equipment (W)	12 - 13	0	0	0	0	0	0	0	0
Equipment (W)	13 - 18	725	0	725	0	0	0	0	0
Equipment (W)	18 - 20	0	0	0	0	0	0	0	0
Equipment (W)	20 - 24	725	0	725	0	725	0	725	0

Table 18: Living room occupancy Schedules - weekdays

The occupancy schedule assumes:

- The elderly couple lead a relatively sedentary lifestyle and therefore spend the majority of there time at home in the living room.
- The students spend more of their time in the living room in the morning and the premises are vacant during the afternoon when they are attending lectures or studying in the library.
- The working professionals lead a hectic lifestyle and therefore only spend time in the evenings relaxing in the living room. To reflect this, equipment and occupancy demand only occurs in the evenings.

- The living room occupancy schedule for Saturday & Sunday is as follows:

Type of Gain	Time Period	Base Case		Elderly		Students		Working	
		SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)	SG (W)	LG (W)
Occupant (W)	0 - 9	0	0	0	0	0	0	0	0
Occupant (W)	9 - 11	30	15	120	60	60	30	120	60
Occupant (W)	11 - 2	0	0	0	0	60	30	0	0
Occupant (W)	12 - 18	30	15	120	60	120	60	120	60
Occupant (W)	18 - 19	0	0	0	0	0	0	0	0
Occupant (W)	19 - 24	60	30	120	60	720	360	120	60
Lights (W)	0 - 24	0	0	0	0	0	0	0	0
Equipment (W)	0 - 9	0	0	0	0	0	0	0	0
Equipment (W)	9 - 12	725	0	725	0	725	0	725	0
Equipment (W)	12 - 13	0	0	0	0	0	0	0	0
Equipment (W)	13 - 18	725	0	725	0	725	0	725	0
Equipment (W)	18 - 20	0	0	0	0	725	0	0	0
Equipment (W)	20 - 24	725	0	725	0	725	0	725	0

Table 19: Living room occupancy schedules - weekends

It has been assumed that the occupancy schedule at the weekend is very similar for all three types of occupants, with them spending most of their time in the living room. However, it has been assumed that the students spend the greatest amount of time in the living room studying during the day and then the occupancy level is particularly high in the evening to account for when they have friends over prior to going on a night out. The very high occupancy and demand during 7pm and midnight reflects approximately 12 people occupying the living room and the associated electrical demand.

- The bathroom occupancy schedule remains unchanged from the base case scenario.

- The hall occupancy schedule remains unchanged from the base case scenario.

5.1.2 Comparison of COP

Figure 13 reveals that the COP trend is roughly the same for each of the different occupancy schedules: with the base case scenario being the only scenario that has been designed around one occupant and all of the others being designed based on two people living in the property, but inhabiting it in different ways. However, this change of use appears to have only a small effect. This may be as a result of the equipment usage not having being scaled up, however, this was deemed unnecessary, because regardless of one or two occupants, they would utilise much the same equipment; e.g. watch the same television; and cook using the same equipment. Any increase in equipment or lighting demand would only be minimal.

The main difference that is apparent is that the actual COP of the heat pump is slightly better throughout the year in the working couple scenario. In this particular instance, there are little or no casual gains during the weekday hours of 9am to 5pm to account for the couples working pattern and as a result, the heat pump is required to generate more heat in order to maintain the desired preset comfort temperature. There is therefore an increased heating demand, which could be responsible for the improved COP, because due to the greater demand, this could require more consistent and sustained periods of operation, which could potentially reduce the cycling frequency and minimise any standing losses: thus improving the actual COP.

Furthermore, it is also worthwhile noticing that the student scenario performs slightly better compared to that of the elderly couple scenario. Again, this re-enforces the idea above, in that the students have less of a 'routine' casual gains emitting pattern than the elderly, making the casual gains more intermittent and increasing the total heating demand. This could suggest that the heat pump performs with higher efficiency when meeting greater demands than when trying to operate at a minimal but constant level in order to maintain heating comfort levels. Or, alternatively it may be that the heat pump's size is more appropriate for meeting this particular level of demand, thus achieving a higher actual COP. Further investigation into different heat pump sizes would be required to ascertain if this was the case.

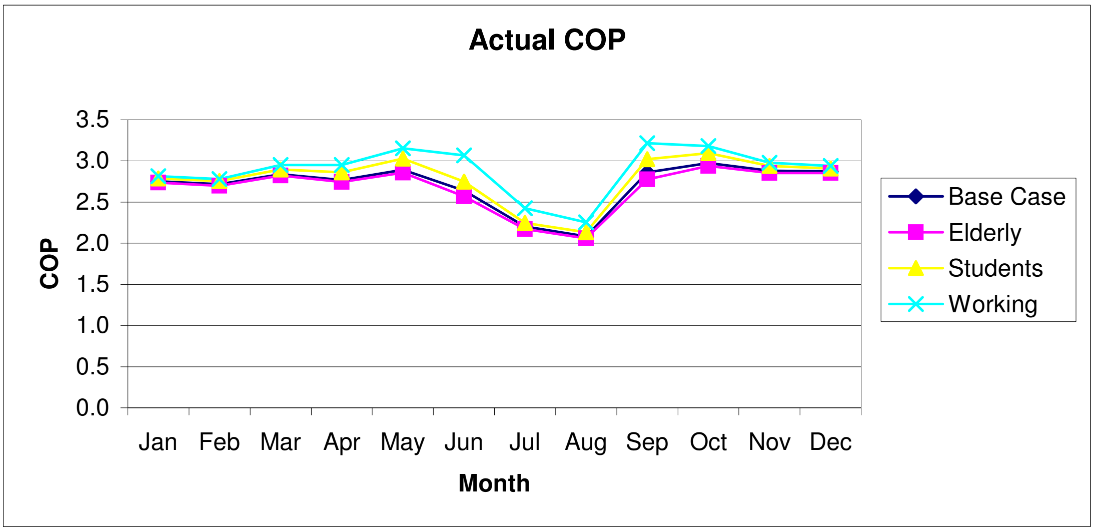

Figure 13: Occupancy – comparison of COP

The summary statistics in table 20 re-enforce the idea that a change in occupancy and the associated usage of a property only has a relatively small, however noticeable effect on the COP: the variation between the average best and worse case scenario was only 0.185. Never the less, the working couple scenario had the highest maximum and minimum actual COP: at 3.214 and 2.254 respectively.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**
Base Case	2.974	Oct	2.082	Aug	2.707
Elderly	2.940	Oct	2.060	Aug	2.674
Students	3.094	Oct	2.134	Aug	2.785
Working	3.214	Sep	2.254	Aug	2.892

Table 20: Occupancy statistics - actual COP

5.1.3 Energy Performance

Figure 14 reveals that the electricity requirement also varies only very slightly between the different occupancy models and the difference in electrical demand is almost negligible during the summer months: June through to August.

There is however, a noticeable trend that the working couple scenario, which has the smallest casual gains, has the highest electricity consumption and this is most apparent during the colder seasons of the year. This was the anticipated result, because fewer casual gains from the occupants would result in an increased overall heating demand. The electrical consumption was therefore greatest for the periods of least occupancy, with the working couple scenario having the highest electrical consumption, followed by the students, base case and elderly scenarios.

This electrical consumption appears to be linked to that of the COP trend: the greater the electrical consumption, the higher the actual COP.

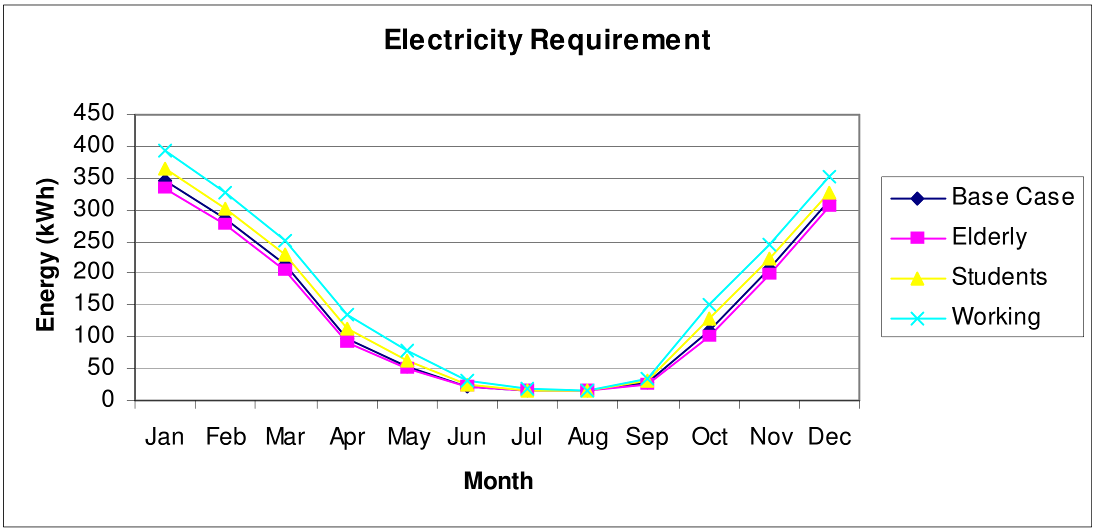

Figure 14: Occupancy – electricity requirement

The summary statistics in table 21 show that the total electricity consumption associated with more permanent occupancy; e.g. the elderly; is considerably reduced over the period of a year, compared to that of less frequent occupancy; e.g. working professionals; due to the impact of casual gains (both people and equipment) reducing the overall heating demand. This amounted to a significant difference, in the region of 400kWh.

Scenario	Max	Month	Min	Month	Average	Total
Base Case	344.96	Jan	14.68	Aug	142.82	1,713.86
Elderly	334.10	Jan	14.52	Aug	136.54	1,638.54
Students	363.50	Jan	15.07	Aug	153.48	1,841.76
Working	391.81	Jan	15.97	Aug	169.78	2,037.33

Table 21: Occupancy statistics – electricity requirement

Figure 15 reveals that the total system heat out trend is almost identical to that of the electricity requirement, shown in figure 14 and it is simply a scaled up version of the electricity consumption according to the heat pumps efficiency. This is the pattern you would expect: with the working professional scenario producing the least casual gains, the heating requirement and therefore the system heat out should be the greatest and this is also in accordance with the electricity required to meet this demand.

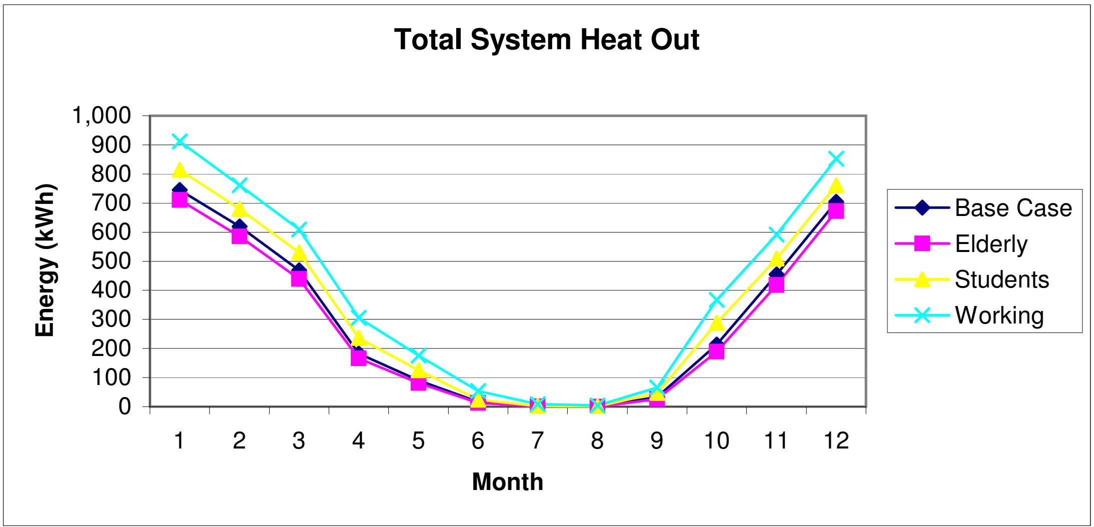

Figure 15: Occupancy – total system heat out

The summary statistics in table 22 highlight that there is a fairly substantial difference in the heating requirement the heat pump system must produce for a property that is almost continuously occupied; e.g. elderly; compared to more intermittent and overall less occupancy; e.g. working professionals. This amounted to a substantial difference in the region of 1400kWh over the course of a year.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
Base Case	744.34	Jan	0.35	Aug	294.10	3,529.17
Elderly	710.63	Jan	0.13	Aug	275.21	3,302.49
Students	814.35	Jan	1.46	Aug	335.30	4,023.60
Working	911.85	Jan	4.33	Aug	392.51	4,710.17

Table 22: Occupancy statistics – total system heat out

5.1.4 Cycling frequency

Figure 16 reveals that the cycling frequency of the heat pump is only marginally affected by differing number of occupants and varying the occupancy use.

The cycling frequency within the summer months is almost identical for all of the scenarios and there is only a slight, yet noticeable difference in the winter months, with the elderly and the base case scenarios cycling slightly more frequently, followed by the students and working professional scenarios. However, this is an important finding. In the case of the working professionals and students, these two scenarios had the highest overall heating demand due to fewer casual gains from the occupants and as a result of the increased demand placed on the heat pump, this actually had the effect of causing the heat pump to cycle less, which in turn would have reducing standing and switching losses: thus improving the COP of the heat pump.

Additionally, what is worthwhile noticing is that the working professional scenario; which has the least casual gains; cycles least frequently during the winter months and most frequently during the summer months. It also produces the maximum total system heat out, consumes the largest quantity of electricity compared to all of the scenarios, yet it is the most efficient scenario with the highest actual COP.

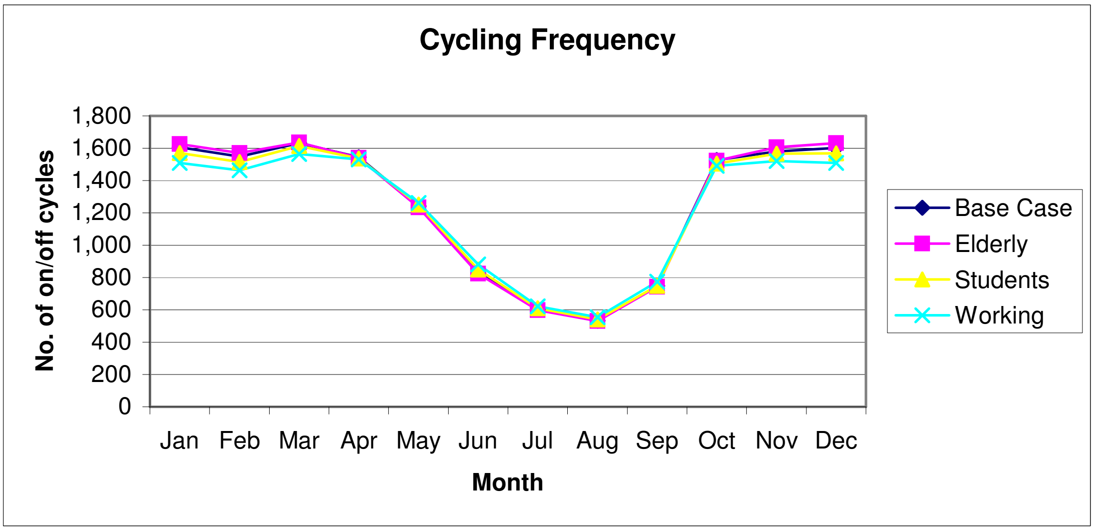

Figure 16: Occupancy – cycling frequency

This suggests that a correctly sized heat pump is very important and the size of the heat pump remained unchanged throughout all of the scenarios. In the working professional scenario, it is likely that the heat pump is more appropriately and correctly sized to meet the winter demand and therefore in the summer, its performance is adversely affected the most. Table 23 provides an indication of this, because in this particular scenario the working professional incurs the lowest maximum number of on/off cycles and the highest minimum number of on/off cycles.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
Base Case	1,631	Mar	533	Aug	1,249	14,993
Elderly	1,635	Mar	531	Aug	1,255	15,061
Students	1,614	Mar	541	Aug	1,240	14,877
Working	1,565	Mar	555	Aug	1,223	14,680

Table 23: Occupancy statistics – no. of on/off cycles

The occupancy results would definitely suggest that it is beneficial to use this particular size of heat pump to meet a larger heating demand and that there is also an advantageous relationship between cycling less frequently and improving the actual COP. However, further investigation would be required to confirm this and ascertain the full impact, including any associated standing losses.

5.1.5 Electricity consumption & running cost

To ascertain which technology and scenario was the cheapest to operate, the energy cost associated with running each technology was calculated.

Figure 17 details the total annual electricity consumption of each of the heat pump scenarios, which revealed that the working professional scenario; which has least occupancy and therefore fewest occupancy gains; required the largest quantity of heating and electricity per year. The heating requirement is clearly linked to the occupancy gains and the quantity of electricity required: with all of the scenarios following this trend.

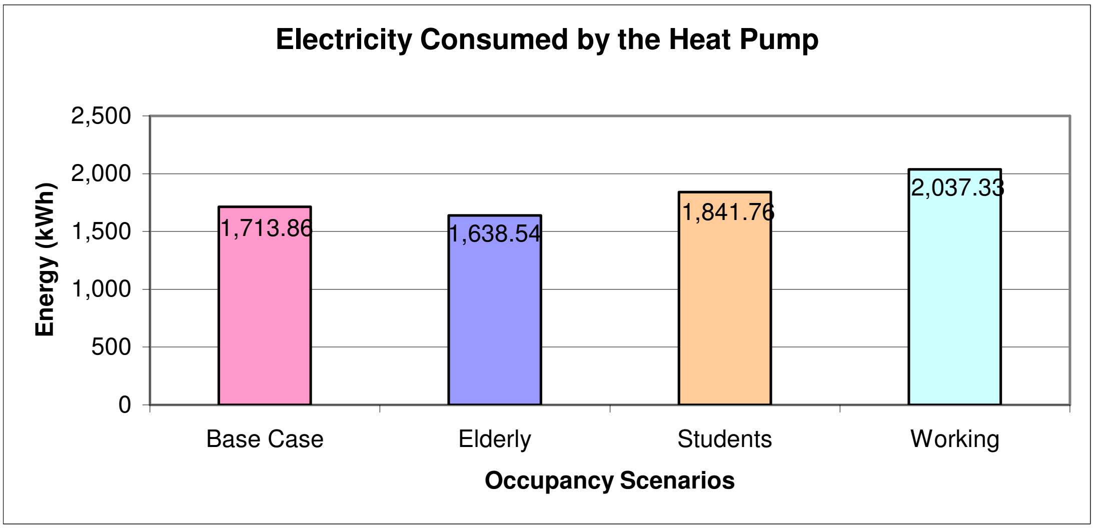

Figure 17: Occupancy – electricity consumed by the heat pump

As explained previously, the total system heat out of the heat pump was used to back calculate and ascertain the equivalent quantity of gas required to operate a condensing gas boiler. This revealed that for all four scenarios, it would in fact be cheaper to meet the heating requirement of the dwelling using a condensing gas boiler, compared to that of this particular heat pump. Evidence of this is provided in table 24.

In this particular model, the highest actual COP only reached 3.214 in the working couple scenario and this efficiency was not sufficiently high enough to warrant the additional cost of installing and running a heat pump: with a higher annual electricity bill compared to that of the condensing gas boiler; with a difference of £28.41 more expensive. Therefore, the heat pump system could never economically pay for its self, unless the price disparity between electricity and gas were to converge in the future, or higher heat pump efficiencies could be realised.

Scenario	**Electric Consumption (kWh)**	**Qh: Total System Heat Out (kWh)**	**Qin: Gas Consumption (kWh)**	**Cost**	
				Electricity	**Gas**
Base Case	1,713.86	3,529.17	5,112.43	£296.32	£257.74
Elderly	1,638.54	3,302.49	4,846.84	£289.04	£248.69
Students	1,841.76	4,023.60	5,611.87	£308.69	£274.76
Working	2,037.33	4,710.17	6,328.96	£327.60	£299.19

Table 24: Occupancy statistics – technology & scenario cost comparison

5.1.6 Carbon emissions & savings

To ascertain which technology has the environmental advantage, the carbon emissions associated with each technology were calculated.

Figure 18 reveals that in all four scenarios tested, it would be more environmentally friendly to use heat pump technology compared to that of a condensing gas boiler as the heat pump produced fewer net CO_2 emissions. The greatest CO_2 emissions saving was seen in the working professional scenario, with a difference of 76.81kg between the two technologies, however, this scenario also produced the greatest emissions; regardless of technology; compared to all of the other occupancy scenarios tested.

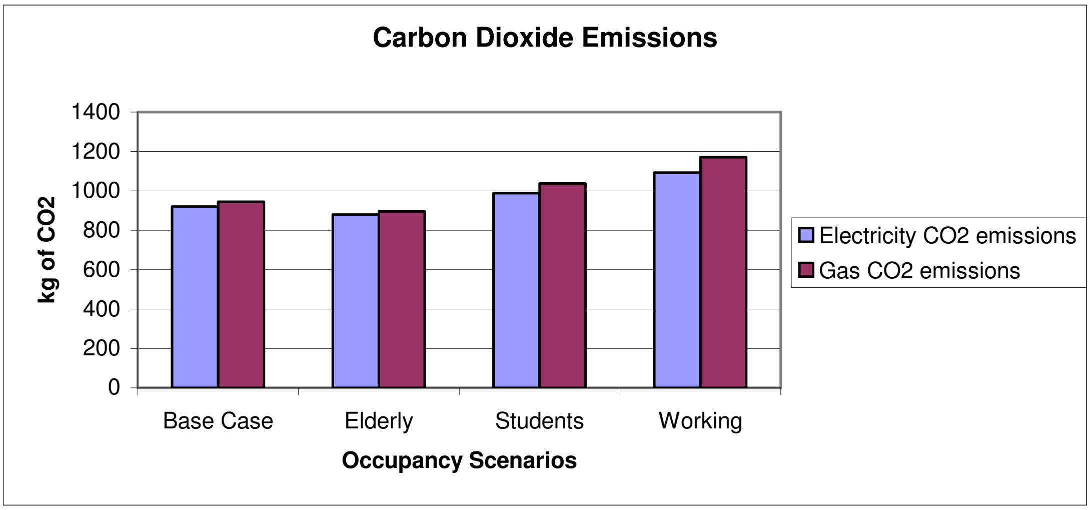

Figure 18: Occupancy – carbon dioxide emissions

Scenario	CO2 emissions	
	Electricity (kg of CO2)	**Gas (kg of CO2)**
Base Case	920.34	945.80
Elderly	879.89	896.66
Students	989.03	1,038.20
Working	1,094.05	1,170.86

Table 25: Occupancy statistics – technology & scenario emissions comparison

Given that for all of the occupancy schedules tested, there was no economic benefit of utilising a heat pump and there was only a relatively small environmental benefit, it would be unlikely that consumers would choose to install a more expensive technology to make a relatively small carbon emissions savings. However, should a means of improving the efficiency of the heat pump materialise, or the price of gas and electricity converge, heat pumps may be capable of generating economic benefits in the future, which would significantly improve the uptake prospects of such a technology.

5.2 Scenario 2: Insulation

5.2.1 Model changes explained

To ascertain the effect of varying levels of building insulation on the performance of the heat pump, the construction materials type or thickness can be altered. However, the decision was made to focus on only varying the insulation thickness of the construction materials, to ensure the modelling aspect was not overcomplicated by introducing too many variables.

The three building properties that were initially identified of interest were the roof and wall levels of insulation, in addition to the window glazing installed.

However, upon closer investigation of the base case model, this revealed that due to the roof's construction being made of clay tile, roof felt and plywood, it would actually be better to alter the ceilings construction, which was made of glass fibre quilt and plasterboard, as this actually contained the insulating material.

Furthermore, when reviewing the potential glazing constructions contained within the constructions database, this revealed that there was no option to select single or triple glazing, only double-glazing. Due to this limitation of the ESP-r database and one of the major benefits of double glazing over single glazing actually resulting from the much improved window seals, the decision was made to investigate this aspect through the dwellings draught proofing and subsequent infiltration levels.

Therefore the glazing was left unchanged as double glazing and the two properties chosen to be investigated and analysed were the ceiling and wall constructions, with the focus on the materials insulation thickness. This involved configuring three additional models, in order to represent building constructions from the 1950's through to the present date.

The base case model had the following material constructions and insulation values:

- A wall insulating layer consisting of 120mm of UF foam, with corresponding U-values (horiz/upward/downward heat flow) of 0.224 0.226 0.222 (partition) 0.220, and

- A ceiling insulating layer consisting of 200mm of glass fibre quilt, with corresponding U-values (horiz/upward/downward heat flow) of 0.192 0.193 0.190 (partition) 0.188.

The model was then altered to represent the following 'typical' building constructions:

- In the **1950's**, it was common for buildings to be constructed without insulation and consequently a UF foam thickness of 1mm and a glass fibre quilt thickness of 1mm was utilised. This resulted in the following corresponding U-values (horiz/upward/downward heat flow) 2.045 2.178 1.890 (partition) 1.727 and U-values (horiz/upward/downward heat flow) 4.122 4.703 3.538 (partition) 3.006, respectively.

- In the **1980's**, due to a large increase in the price of oil, homes were constructed or retrofitted with insulation in order to drive down energy consumption. Consequently a UF foam thickness of 50mm and a glass fibre quilt thickness of 100mm was utilised and this resulted in the following corresponding U-values (horiz/upward/downward heat flow) 0.471 0.478 0.462 (partition) 0.452 and U-values (horiz/upward/downward heat flow) 0.368 0.372 0.363 (partition) 0.356, respectively.

- In **2009**, again in a bid to reduce energy consumption and with increasing pressure to act in an environmentally friendly manor, building regulations became more stringent and stipulated lower minimum U-values: which can be viewing in appendix 3. Consequently a UF foam thickness of 150mm and a glass fibre quilt thickness of 250mm was utilised and this resulted in the following corresponding U-values (horiz/upward/downward heat flow) 0.183 0.184 0.182 (partition) 0.180 and U-values (horiz/upward/downward heat flow) 0.155 0.155 0.154 (partition) 0.152, respectively.

The May 2009 Scottish building regulations stipulate that there must be a minimum area-weighted average U-value of 0.3W/m^{2}K for the walls and 0.2W/m^{2}K for the roof. Reviewing the above scenarios, the constructions built in the 1950's and 1980's would not pass these regulations, however, the 2009 scenario would considerably surpass this minimum requirement, including an allowance for windows.

5.2.2 Comparison of COP

Figure 19 reveals that the 1950's scenario; with almost 0mm insulation; has a substantially higher actual COP compared to the other three scenarios, which perform very similarly. This can be explained because due to the poor levels of insulation installed, more heat escapes the dwelling via the walls and roof to the outside of the building and as a result, the heat pump must generate more heat, consuming more electricity, to maintain the preset temperature comfort conditions. It will therefore operate for more sustained periods of time to meet this greater demand and is thus capable of achieving a higher efficiency rating, improving the actual COP.

This trend is apparent throughout the year, but is exacerbated during the spring and summer seasons because where the demand would typically be much lower, a relatively high demand still exists in the situation of poor insulation, due to the continued high level of heat loss.

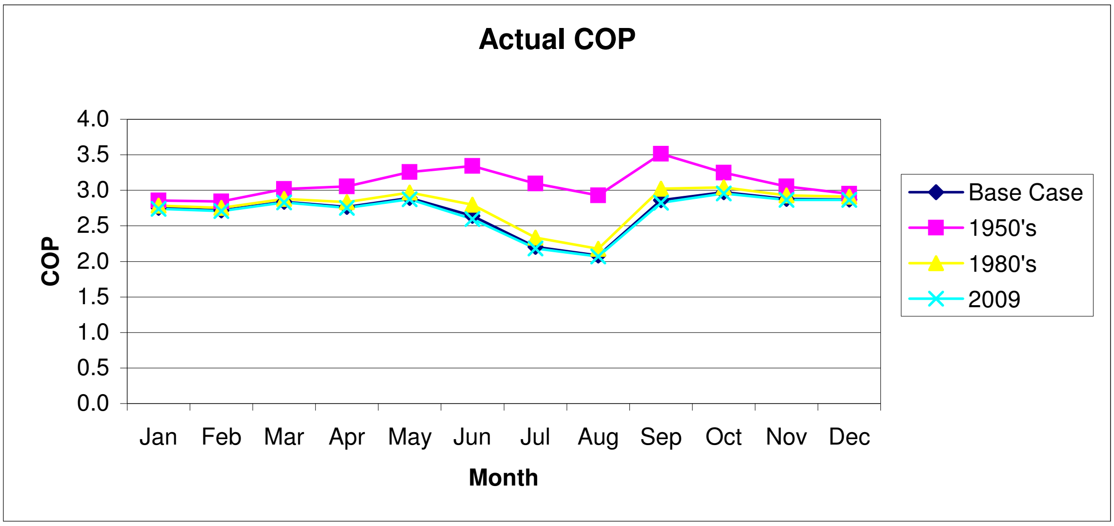

Figure 19: Insulation – comparison of COP

The summary statistics in table 26 reveal that the maximum and minimum COP obtained is significantly larger for the 1950's scenario, at 3.516 and 2.843, respectively, compared to all of the other scenarios and the average COP is also somewhat greater than the next closest scenario; the base case; with a COP of 3.098 compared to 2.707.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**
Base Case	2.974	Oct	2.082	Aug	2.707
1950's	3.516	Sep	2.843	Feb	3.098
1980's	3.041	Oct	2.178	Aug	2.787
2009	2.958	Oct	2.068	Aug	2.689

Table 26: Insulation statistics – comparison of COP

In this particular instance and for the size of heat pump tested, a greater demand results in an improved actual COP. However, this benefit should be viewed with caution, because to obtain the higher COP, greater quantities of electricity must be consumed which has both a financial and environmental penalty. It would therefore be my recommendation that the COP should be maximised only in situations where this is not to the determent of electricity consumption and the environment, and it would most likely be most beneficial to correctly size the heat pump to the buildings thermal demand in order to achieve this.

5.2.3 Energy Performance

Figure 20 reveals that the greatest benefit from insulating a building is realised when a dwelling with zero insulation is upgraded to have insulation: basically the biggest step change is the initial installation of insulation, which can been seen by comparing the 1950's and 1980's scenarios. There is however still a benefit from further insulating the building, but comparatively this is much smaller, e.g. comparing the 1980's to 2009 scenarios.

The largest benefit of insulating the building is that the dwelling suffers from less heat loss to the external environment and therefore the total heating demand and electricity consumption is much reduced.

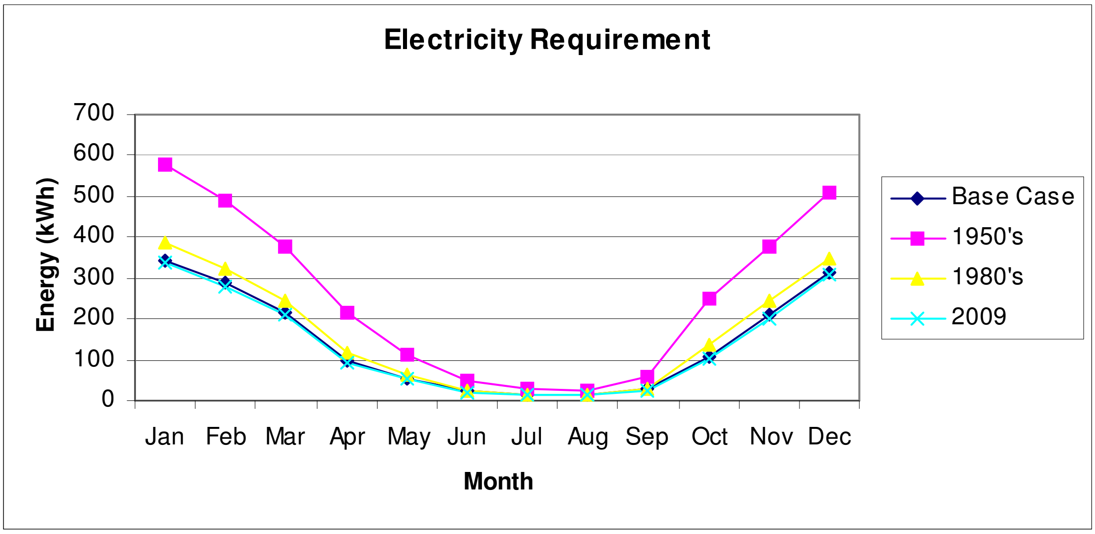

Figure 20: Insulation – electricity requirement

The summary statistics in table 27 clearly demonstrate than over the course of a year, installing insulation in a building that has previously had almost none; 1950's scenario compared with 1980's; reduces the electricity consumption by 1,114.23kWh and then installing further insulation; 1980's scenario compared to 2009; reduces the electricity consumption by a further 282.07kWh per year. That is a 36.39% decrease followed by a 14.48% decrease in electrical consumption.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
Base Case	344.96	Jan	14.68	Aug	142.82	1,713.86
1950's	575.42	Jan	24.28	Aug	255.20	3,062.35
1980's	384.30	Jan	15.39	Aug	162.34	1,948.12
2009	336.96	Jan	14.58	Aug	138.84	1,666.05

Table 27: Insulation statistics – electricity requirement

Figure 21 details the total system heat out is simply a scaled up version of the electricity consumption, dictated by the efficiency of the heat pump. It therefore has similar trends to the electricity consumption, as expected.

What is worthwhile noticing is that because the actual COP of the 1950's scenario was the highest, the percentage increase comparing the electricity requirement to total system heat out is greatest for this scenario, would at first appear to be beneficial. However, when you consider that this scenario also has the highest electricity consumption due to its poor levels of insulation, it therefore suffers from the highest running costs and the greatest CO_2 emissions, resulting in large heating losses to the external environment.

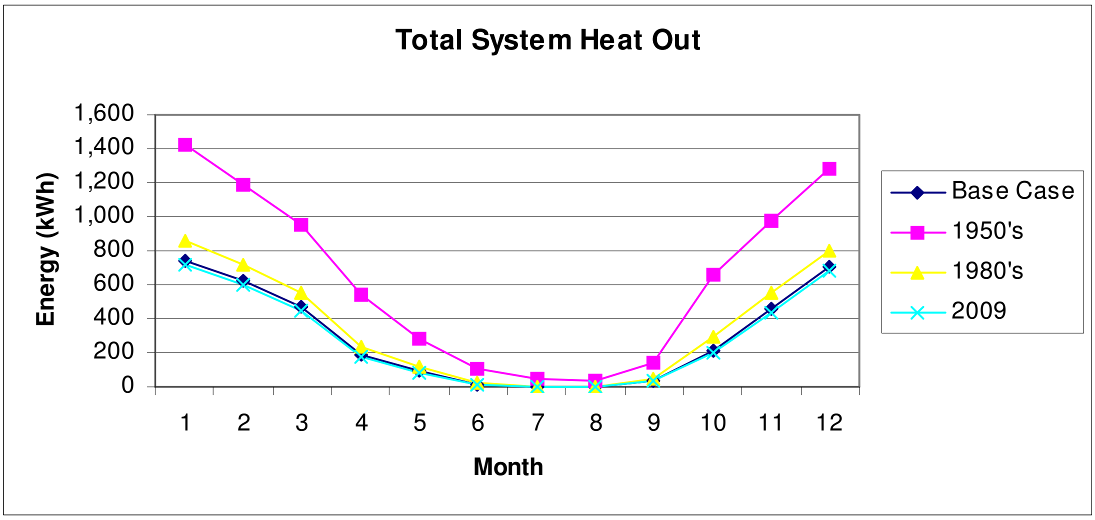

Figure 21: Insulation – total system heat out

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
Base Case	744.34	Jan	0.35	Aug	294.10	3,529.17
1950's	1,419.90	Jan	34.30	Aug	636.69	7,640.33
1980's	857.11	Jan	2.30	Aug	351.80	4,221.55
2009	719.61	Jan	0.17	Aug	282.19	3,386.24

Table 28: Insulation statistics – total system heat out

5.2.4 Cycling frequency

Figure 22 details the cycling frequency, where it is apparent that the 1950's scenario; which has the largest heating requirement due to the poorest levels of insulation; actually cycles the least frequently. This trend was also experienced previously in the working couple occupancy scenario and as a result of higher demand, the scenario had the best actual COP. This occurs because the heat pump is operating for more prolonged periods of time to meet the larger heating demand, compared to that of the other three scenarios, which all have a lower, similar heating requirement. In the case of the 1950's scenario, as a result of cycling less frequently and the heat pump being in operation for longer sustained periods, the heat pump suffers from fewer standing losses and starting losses, thus contributing to a higher actual COP.

As a general observation, it is also apparent that the cycling frequency on the whole is greater during the colder periods of the year; e.g. in the winter; as the heat pump will be required to operate for more sustained and frequent time periods, to enable it to meet the greater heating demand which occurs at this time of year.

However, there is an unusual trend experienced at the beginning of the year; less cycling in February; and this occurs because within the base case climate of Dundee, the month of February is in fact slightly cooler for this particular climate year compared to the months on either side. Where the external climate is cooler, it would appear that the heat pump must operate for a more consistent, sustained time period to meet the greater demand and it therefore cycles less frequently, compared to the months of January and March, where the external temperature is warmer and therefore the demand is less. Furthermore, the air source temperature is lowest in February at only 3.3 degrees Celsius, which would require more energy to raise the source temperature to that of the desired sink temperature and meet the preset thermal comfort conditions.

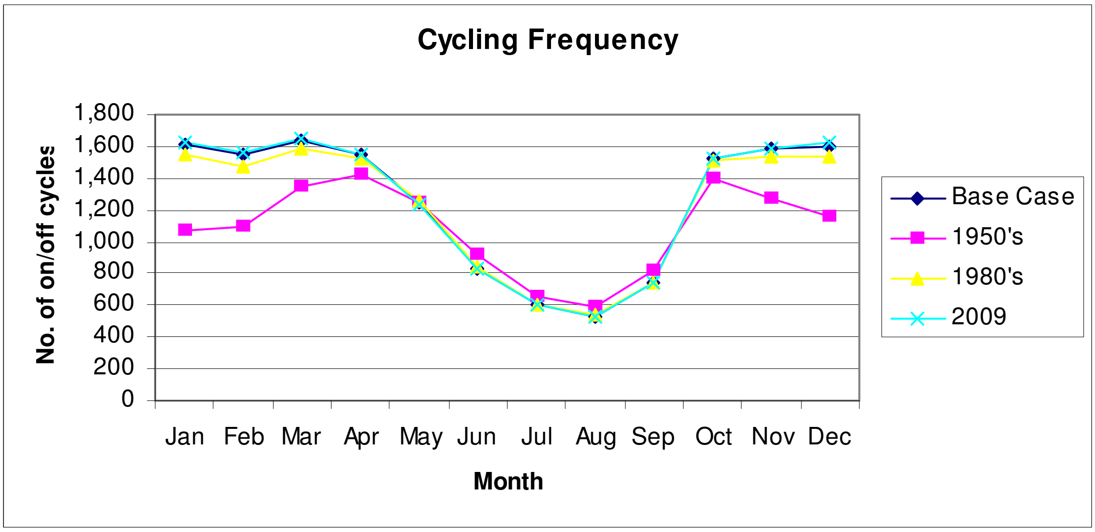

Figure 22: Insulation – cycling frequency

The summary statistics in table 29 reinforce that for the scenario which requires the greatest heating demand; the 1950's scenario with least insulation; the heat pump operates for more consistent, sustained time periods, thus operating with fewer on/off cycles, minimising the starting and standing losses, which in turn beneficially raises the actual COP of the heat pump. Over the course of a year, the 1950's scenario had fewer on/off cycles compared to the 2009 scenario, with 12,992 compared to 15,066, respectively.

Scenario	Max	Month	Min	Month	Average	Total
Base Case	1,631	Mar	533	Aug	1,249	14,993
1950's	1,421	Apr	586	Aug	1,083	12,992
1980's	1,588	Mar	541	Aug	1,226	14,712
2009	1,643	Mar	534	Aug	1,256	15,066

Table 29: Insulation statistics – no. of on/off cycles

5.2.5 Electricity consumption & running cost

To ascertain which technology and scenario was the cheapest to operate, the energy cost associated with running each technology was calculated.

Figure 23 details the total annual electricity consumption of the heat pump for each of the insulation scenarios, which revealed that the 1950's scenario; which has the poorest levels of insulation; required the largest quantity of heating and electricity per year. The heating requirement is clearly linked to the insulation level installed in the dwelling and the quantity of electricity required to maintain heating comfort levels.

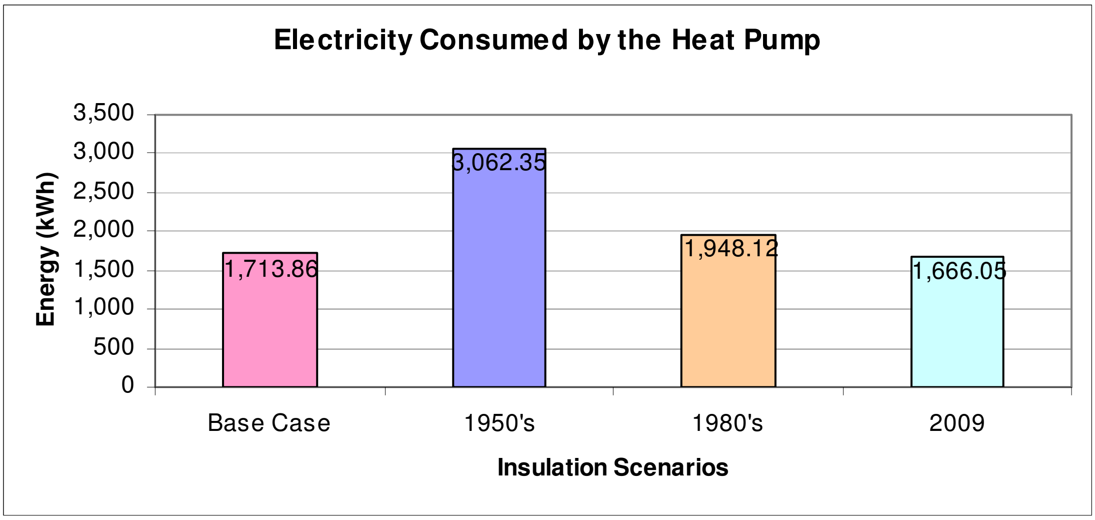

Figure 23: Insulation – energy consumed by the heat pump

As explained previously, the total system heat out of the heat pump was used to back calculate and ascertain the equivalent quantity of gas required to operate a condensing gas boiler. The summary statistics provided in table 30 reveal that for all of the scenarios, it would in fact be cheaper to meet the heating requirement of the dwelling using a condensing gas boiler, compared to that of this particular heat pump and the annual savings ranged from £10.32 for the 1950's scenario up to £39.62 for the 2009 scenario.

Furthermore, the 2009 scenario; which has the highest level of insulation proved to be the cheapest scenario to run, regardless of the technology. This confirms that if the dwelling is installed with high levels of insulation, it reduces the total heating demand from the heat pump and is consequently cheaper to run.

However, the most important finding is that it is the first installation of insulation that provides the largest benefits.

Scenario	Electric Consumption (kWh)	Qh: Total System Heat Out (kWh)	Qin: Gas Consumption (kWh)	Cost	
				Electricity	**Gas**
Base Case	1,713.86	3,529.17	5,112.43	£296.32	£257.74
1950's	2,062.35	7,640.33	9,769.31	£426.72	£416.40
1980's	1,948.12	4,221.55	5,914.86	£318.97	£285.08
2009	1,666.05	3,386.24	4,948.99	£291.70	£252.08

Table 30: Insulation statistics – technology & scenario cost comparison

5.2.6 Carbon emissions & savings

To ascertain which technology has the environmental advantage, the carbon emissions associated with each technology were calculated. Figure 24, reveals that for all four scenarios, the heat pump produced a lesser quantity of net CO_2 emissions compared to using a condensing gas boiler. The greatest savings were achieved in the 1950's scenario followed by the 1980's, base case then 2009.

However, it was also the 1950's scenario that produced the highest level of emissions of the four scenarios, regardless of the technology. This is due to the high levels of heat loss from the dwelling and the associated larger heating demand placed on the heat pump.

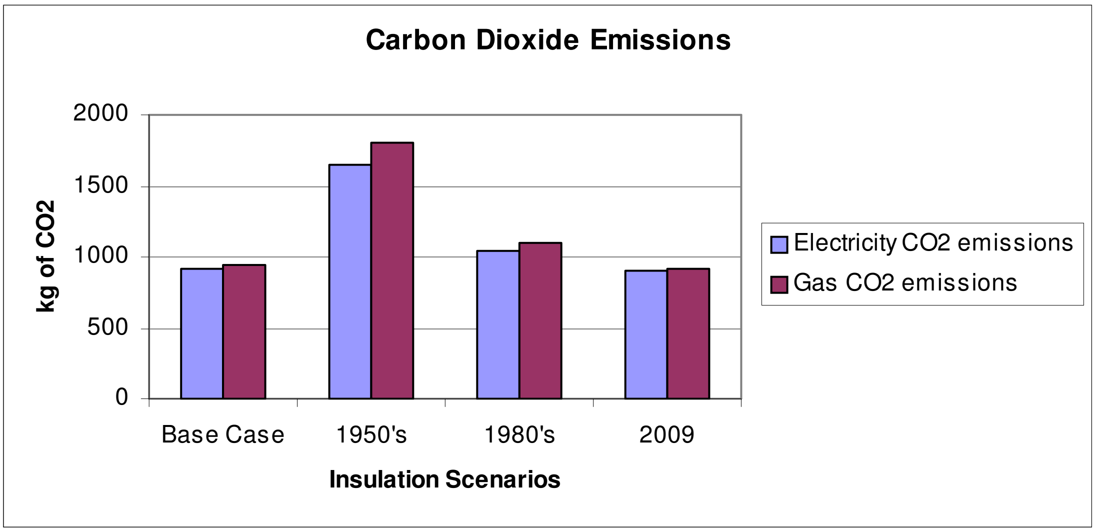

Figure 24: Insulation – carbon dioxide emissions

The amount of emissions produced is clearly related to the level of insulation installed within a dwelling. Where the highest level of insulation was installed; driving down the construction materials U-value; the emissions were fewest. Where there was almost negligible insulation, the dwelling suffered from high levels of heat loss to the external environment, hence the heat pump had to meet a larger heating demand, thus consuming the greatest quantity of electricity and generating the greatest quantity of carbon dioxide emissions.

Furthermore, referring to the summary statistics in table 31, as the amount of insulation increased; e.g. 1950's compared to 1980's levels and 1980's compared to 2009 levels; the dwelling had fewer associated CO_2 emissions and became more environmentally friendly. Basically, as the system heating demand declined with greater quantities of insulation, the environmental situation became increasingly favourable.

Scenario	**CO2 emissions**	
	Electricity (kg of CO2)	**Gas (kg of CO2)**
Base Case	920.34	945.80
1950's	1,644.48	1,807.32
1980's	1,046.14	1,094.25
2009	894.67	915.56

Table 31: Insulation statistics – technology & scenario emissions comparison

Given that for all of the insulation schedules tested, there was no economic benefit of utilising a heat pump and there was only a relatively small environmental benefit, it would be unlikely that consumers would choose to install a more expensive technology to make a relatively small carbon emissions savings. However, should a means of improving the efficiency of the heat pump materialise, or the price of gas and electricity converge, heat pumps may be capable of generating economic benefits in the future, which would significantly improve the uptake prospects of such a technology.

5.3 Scenario 3: Draught proofing

5.3.1 Model changes explained

The ESP-r software represents draught proofing; which is uncontrolled air leakage across the building envelope; within the model by the scheduled airflows within the building, e.g. the air infiltration rate. "Air infiltration is a function of the leakiness of the building, and the different pressures across the envelope, which are caused by indoor-outdoor temperature differences and forces exerted by the wind" [17].

Having conducted some initial research, it was apparent that the infiltration rates of a building could alter quite considerably depending on factors such as:

- Weather conditions: e.g. wind speed, temperature and pressure, and
- The buildings construction: e.g. a tight, typical or leaky house; window and door cracks/openings; level of natural or forced ventilation, etc.

From the heating perspective of a building, it would be advantageous to have as low an infiltration rate as possible, however, consideration must be given to the comfort levels of the building; eg thermal comfort, air quality, air velocity, humidity levels, low pollutants; and there must be an adequate but not excessive supply of fresh air to ensure the air quality is maintained.

Depending on the weather conditions and buildings construction, it was found that air infiltration levels in the region of 0.1ac/h for a tight house under mild weather conditions, to 1.5ac/h for a leaky house under severe weather conditions, were common.

Therefore, the base case model which had an infiltration level in excess of 2ac/h for all of the rooms and the roof was adapted to test varying air infiltration levels of: 0.1ac/h, 0.5ac/h, 1ac/h and 1.5ac/h, which would appear to be more realistic values. The floor of the dwelling remained unchanged for all of the scenarios, at the base case level of 3ac/h.

5.3.2 Comparison of COP

Figure 25 reveals that the less draught proofing a dwelling has; the higher the rate of air changes and hence a higher air infiltration level; the higher the actual COP. This observation is apparent throughout the year and occurs because when a building suffers from greater levels of air changes; warm air exits the dwelling and cool air enters the dwelling; it increases the total heating demand and as a result, the heat pump must generate more heat, consuming more electricity, to maintain the preset temperature comfort conditions. It will therefore operate for greater, sustained periods of time to meet this increased demand; minimising any starting and standing losses; and is thus capable of achieving a higher efficiency rating, improving the actual COP.

Additionally, it may be that the higher level of demand is better suited to this particular size of heat pump, which would also beneficially affect the performance and the actual COP of the heat pump.

Therefore, in this particular instance, the base case scenario with the least draught proofing and an infiltration rate in excess of 2ac/h performed with the greatest actual COP. Basically, the better the buildings draught proofing, the lower the infiltration, however, this also reduces the dwellings heating requirement, which adversely affects the actual COP.

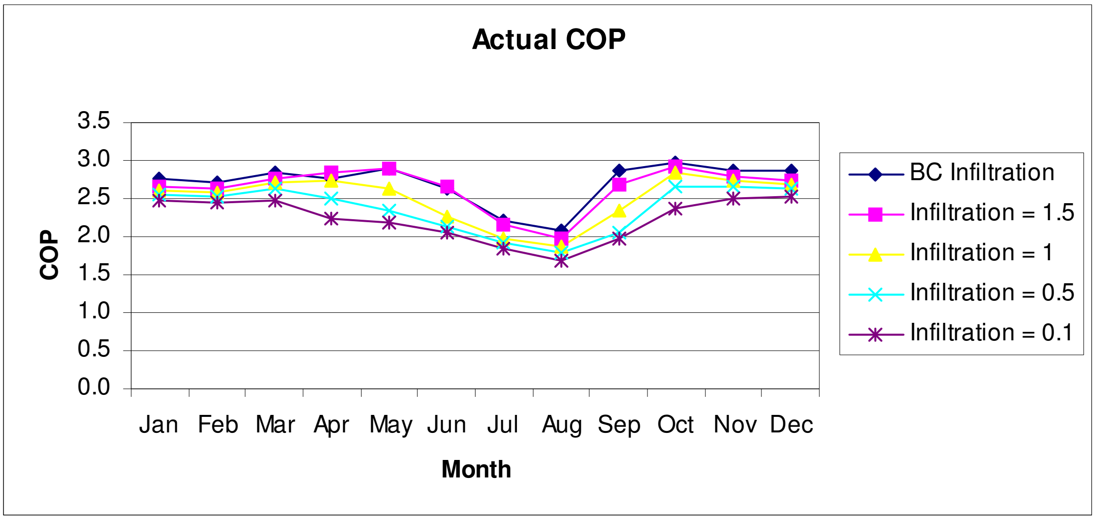

Figure 25: Draught proofing – comparison of COP

The summary statistics in table 32 reinforce the idea that the worse the draught proofing, the greater the air changes per hour, the higher the COP. For instance, comparing the 1.5ac/h scenario with the next closest scenario; the 1ac/h; the average improvement in actual average COP between the two scenarios is 0.142 and this is similar to the improvement between the other scenarios, where in both instances, the average actual COP increased by 0.136. Therefore, there is a proportionally improving trend, in the region of a 0.14 increase in average actual COP, per 0.5ac/h increase and this is apparent for each of the different scenarios.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**
Base Case	2.974	Oct	2.082	Aug	2.707
1.5 ac/h	2.927	Oct	1.983	Aug	2.644
1 ac/h	2.832	Oct	1.879	Aug	2.502
0.5 ac/h	2.647	Oct	1.797	Aug	2.366
0.1 ac/h	2.538	Dec	1.688	Aug	2.230

Table 32: Draught proofing statistics – comparison of COP

5.3.3 Energy Performance

Figure 26 reveals that with a higher rate of infiltration; the dwelling suffers from more heat loss and a greater penetration of cool air; which increases the heating demand and therefore the dwellings electricity requirement.

Furthermore, reviewing the electricity requirement for each of the scenarios, it is apparent that there is a consistent proportional increase in electricity consumption per 0.5ac/h increase, comparing the 0.1ac/h to 1.5ac/h. This trend would therefore indicate that the initial base case model has an air infiltration level in the region of 2.2ac/h and at this level, the literature would suggest that this is not particularly representative of a typical UK dwelling, as the value exceeds the maximum realistic 1.5ac/h.

Therefore, from this point forward, the analysis mainly focuses on the more realistic infiltration levels, falling within the range of 0.1ac/h to 1.5ac/h.

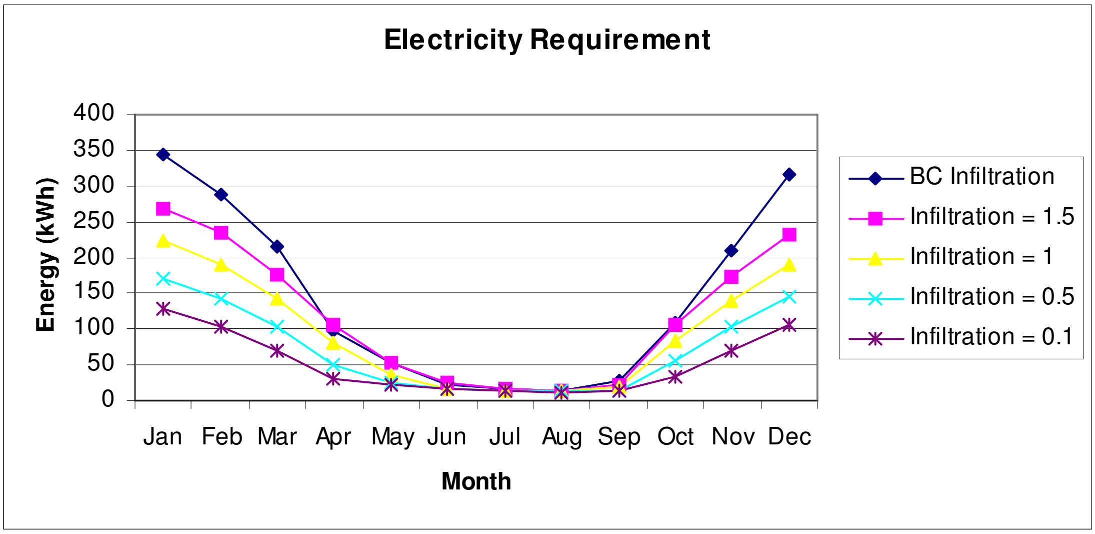

Figure 26: Draught proofing – electricity requirement

The summary statistics in table 33 reveal that the electricity requirement varies substantially according to the varying levels of infiltration. It would therefore be beneficial for a dwelling to have a high level of draught proofing; to the extent that it is considered 'tight'; and with this lower infiltration rate, it would consume less electricity to maintain the same heating comfort conditions. For example, comparing two extreme scenarios: the 1.5ac/h with the 0.1ac/h; a 'tight' property would require less than half the electricity to maintain the same heating demand compared to a 'leaky' property, resulting in a saving in excess of 800kWh over the course of one year.

However, draught proofing a building to the extent that it is considered very 'tight' should not be carried out to the detriment of other building comfort conditions. It must be realised that an adequate supply of fresh air; natural or forced; will have to be permitted, to ensure air quality is maintained and the build up of pollutants or excessive moisture is avoided.

Furthermore, using less electricity to maintain the same heating comfort conditions will also have a beneficial impact on the cost of running the heat pump, in addition to reducing the associated atmospheric emissions. However, this will be quantified and discussed in the following sections.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
Base Case	344.96	Jan	14.68	Aug	142.82	1,713.86
1.5 ac/h	269.90	Jan	14.09	Aug	118.82	1,425.78
1 ac/h	222.47	Jan	13.43	Aug	95.79	1,149.50
0.5 ac/h	171.44	Jan	13.02	Aug	71.35	856.22
0.1 ac/h	127.53	Jan	12.53	Aug	51.77	621.29

Table 33: Draught proofing statistics – electricity requirement

Figure 27 reveals the total system heat out, which is simply the electricity requirement for each scenario proportionally increased by the COP. It details the same trends as highlighted in the electricity consumption, but as the base case infiltration has the highest actual COP, the total system heat out is proportionally the greatest.

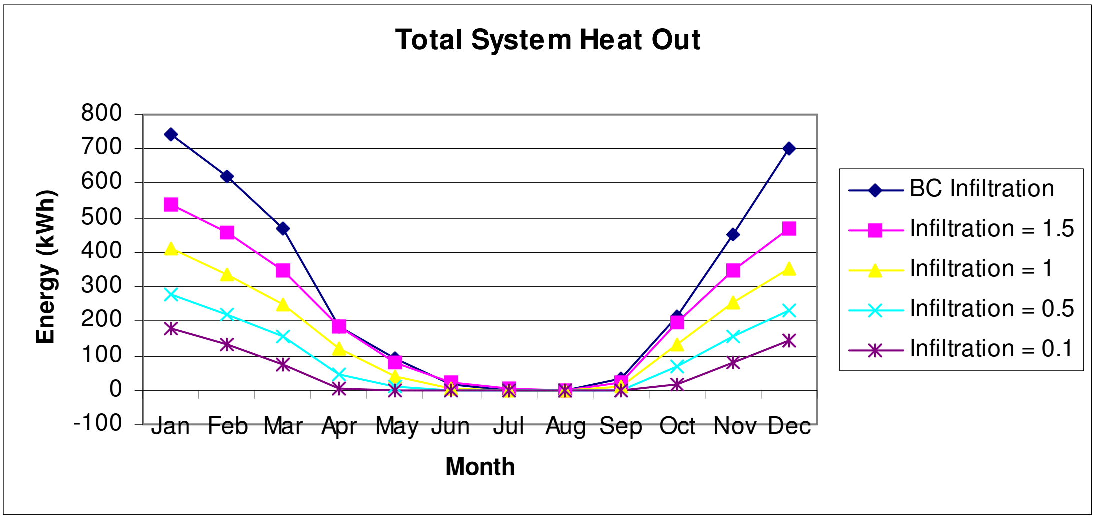

Figure 27: Draught proofing – total system heat out

The summary statistics in table 34 re-enforce the idea that the poorer the draught proofing, the higher the infiltration, the greater the number of air changes, and hence a higher heating demand, which must be met by the heat pump. For example, the total heating demand over the course of a year for the 'leaky' dwelling; 1.5ac/h scenario; is 4 times greater than that of a 'tight' dwelling; 1.5ac/h scenario.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
Base Case	744.34	Jan	0.35	Aug	294.10	3,529.17
1.5 ac/h	541.21	Jan	1.13	Aug	221.76	2,661.09
1 ac/h	409.59	Jan	0.05	Aug	157.74	1,892.89
0.5 ac/h	277.65	Jan	-0.04	Jul	96.34	1,156.14
0.1 ac/h	176.18	Jan	-0.05	Jul	52.61	631.30

Table 34:Draught proofing statistics – total system heat out

5.3.4 Cycling frequency

Excluding the base case scenario for the reasons explained earlier, figure 28 and table 35 reveal that over the course of one working year, the heat pump cycles marginally more frequently with the poorly draught proofed dwelling; the 1.5ac/h scenario; which has the greatest number of air changes per hour. However, in this situation, the heating demand is vastly increased; more than four times greater that the 0.1ac/h scenario; yet the same scale of difference does not apply to the number of on/off cycles of the heat pump. When you review the annual total number of on/off cycles for each of the scenarios, the values are much the same. Therefore, for a 'leaky' house, which has a greater demand, this demand must be met by the heat pump operating for more sustained periods of time and not with more frequent cycling of the heat pump.

As a general observation, the performance of the heat pump is affected with varying climatic seasons, as is the number of on/off cycles. In the winter months, the 'leaky' house with higher infiltration; 1.5ac/h; has the fewest on/off cycles because the demand is much greater, the heat pump therefore has to operates for more prolonged periods of time in order to generate the necessary heating demand. However, in the summer months, the 'leaky' house with higher infiltration; 1.5ac/h;

cycles the most, because comparatively, the heating demand is much greater, which requires more frequent on and off operations in order to match the pre-set temperature comfort conditions.

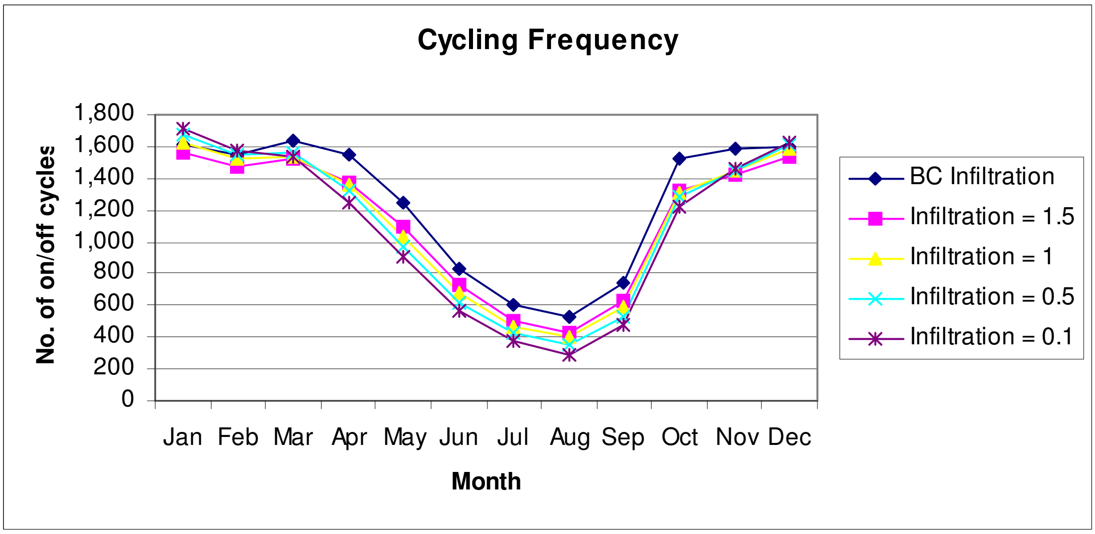

Figure 28: Draught proofing – cycling frequency

The summary statistic shown in table 35 re-enforce the previously mentioned points. In the cooler months, the least maximum number of on/off cycles is apparent in the highest infiltration scenario; 1.5ac/h; and occurs in January with 1,562 cycles, yet it is also this scenario that obtains the highest minimum number of on/off cycles during the warmer time of the year, which occurs in August with 432 cycles.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
Base Case	1,631	Mar	533	Aug	1,249	14,993
1.5 ac/h	1,562	Jan	432	Aug	1,133	13,592
1 ac/h	1,620	Jan	401	Aug	1,129	13,548
0.5 ac/h	1,670	Jan	354	Aug	1,112	13,340
0.1 ac/h	1,711	Jan	293	Aug	1,085	13,015

Table 35: Draught proofing statistics – no. of on/off cycles

5.3.5 Electricity consumption & running cost

To ascertain which technology and scenario was the cheapest to operate, the energy cost associated with running each technology was calculated.

Figure 29 details the total annual electricity consumption of the heat pump for each of the infiltration scenarios, which revealed that the base case and 1.5ac/h scenarios; which has the poorest levels of draught proofing; required the largest quantity of heating and electricity per year. The heating requirement is clearly linked to the infiltration level penetrating the dwelling and the quantity of electricity required to maintain heating comfort levels.

As explained previously, the total system heat out of the heat pump was used to back calculate and ascertain the equivalent quantity of gas required to operate a condensing gas boiler. The summary statistics provided in table 36 revealed that for all of the scenarios, it would in fact be cheaper to meet the heating requirement of the dwelling using a condensing gas boiler, compared to that of this heat pump and the annual savings ranged from £38.58 for the base case scenario up to £55.80 for the 0.5ac/h scenario.

Basically, the higher the draught proofing, the smaller the infiltration and consequently the less electricity required to meet the smaller heating demand.

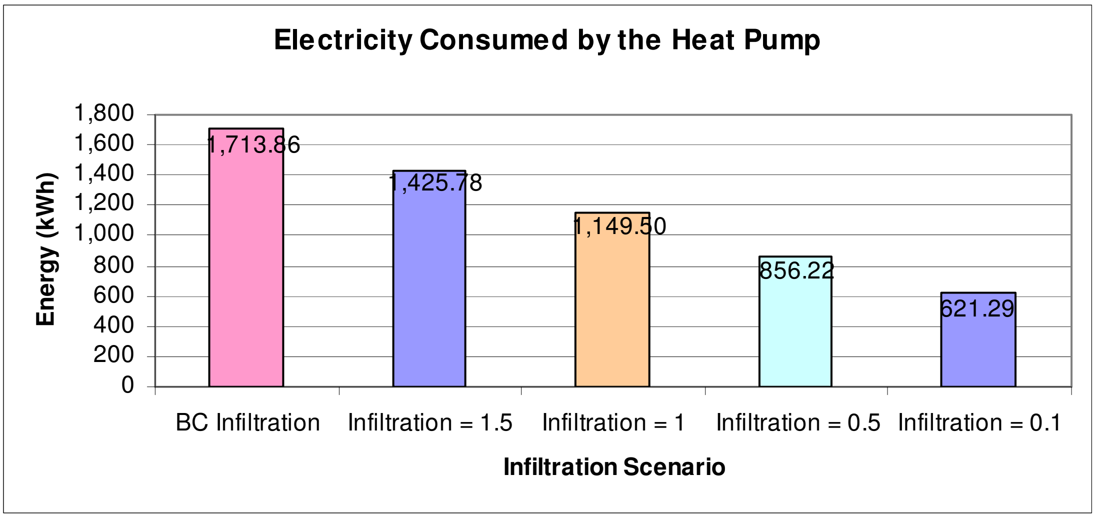

Figure 29: Draught proofing – electricity consumed by the heat pump

However, an interesting observation was that with a higher rate of infiltration the system heat efficiency was also improved; refer to appendix 1. As a result, the potential savings of using a gas boiler was greatest for the 0.5ac/h scenario with a saving of £55.80 compared to £43.98 for the 1.5ac/h scenario, despite the 1.5ac/h scenario requiring a greater quantity of fuel; either gas or electricity; to meet the increased demand.

Scenario	**Electric Consumption (kWh)**	**Qh: Total System Heat Out (kWh)**	**Qin: Gas Consumption (kWh)**	**Cost**	
				Electricity	**Gas**
Base Case	1,713.86	3,529.17	5,112.43	£296.32	£257.74
1.5 ac/h	1,425.78	2,661.09	4,136.09	£268.46	£224.48
1 ac/h	1,149.50	1,892.89	3,241.24	£241.75	£193.99
0.5 ac/h	856.22	1,156.14	2,317.77	£207.03	£151.23
0.1 ac/h	621.29	631.30	1,587.79	£150.23	£103.60

Table 36:Draught proofing statistics – technology & scenario cost comparison

Therefore, the 0.1ac/h scenario; which has the highest level of draught proofing; proved to be the cheapest scenario to run, regardless of the technology. This confirms that if the dwelling is 'tight' and well draught proofed, it suffers fewer air changes, and thus reduces the total heating demand from the heat pump, which is consequently cheaper to run.

5.3.6 Carbon emissions & savings

To ascertain which technology has the environmental advantage, the carbon emissions associated with each technology were calculated. Figure 30 revealed some interesting results:

- The base case scenario was the only scenario that could be operated using a heat pump to provide a CO_2 saving over that of a condensing gas boiler.
- For the 1.5ac/h infiltration scenario, the emission associated with the use of a heat pump and condensing gas boiler were the same.
- For the 1ac/h, 0.5ac/h and 0.1ac/h scenarios, it would be environmentally beneficial to use a condensing gas boiler to generate the demand as this produced fewer emissions.

It was also the base case scenario with the least draught proofing and highest level of infiltration that produced the highest level of emissions of the five scenarios, regardless of the technology. This is due to the high levels of heat loss to the external environment and external cooler air penetrating the dwelling, which results in a larger heating demand being placed on the heat pump.

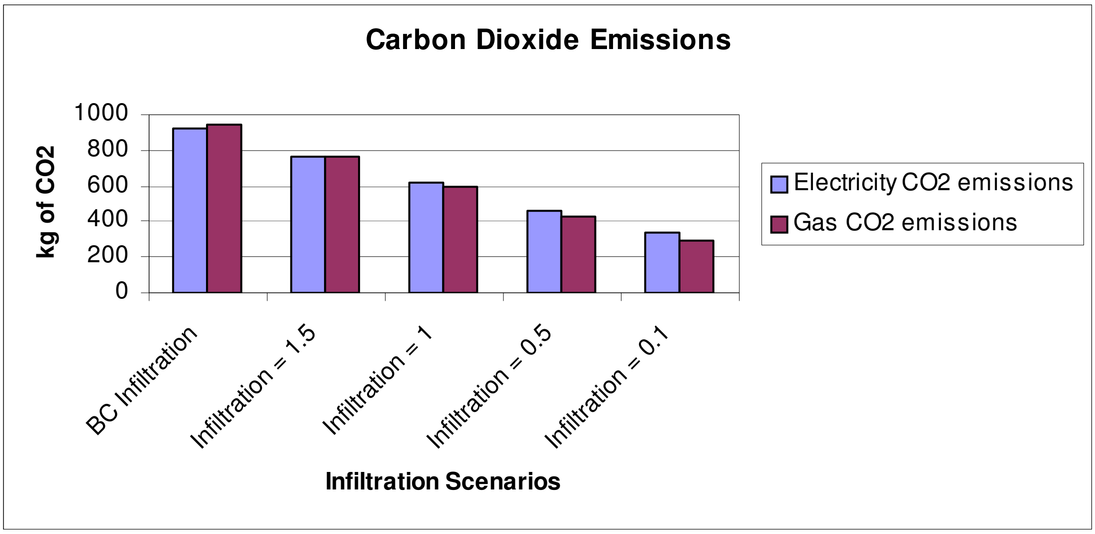

Figure 30: Draught proofing – carbon dioxide emissions

The summary statistics in table 37 detail the emissions associated with the use of the heat pump and a condensing gas boiler. The amount of emissions produced is clearly related to the heating demand of the dwelling, which can be influenced by varying levels of draught proofing. There is clearly a break even point at the 1.5ac/h: where above this level it is environmentally beneficial to use a heat pump, but below this level, it is advantageous to use a condensing gas boiler. That said, as more renewable technologies are used to generate the UK's electricity, the carbon emissions associated with electricity use should decline: resulting in more favourable conditions for heat pumps in the future.

Scenario	**CO2 emissions**	
	Electricity (kg of CO2)	**Gas (kg of CO2)**
Base Case	920.34	945.80
1.5 ac/h	765.64	765.18
1 ac/h	617.28	599.63
0.5 ac/h	459.79	428.79
0.1 ac/h	333.63	293.74

Table 37: Draught proofing statistics - technology & scenario emissions comparison

Given that for all of the draught proofing schedules tested, there was no economic benefit of utilising a heat pump and in most instances, with the exception of one, it would actually be detrimental to the environment to use a heat pump, it is very unlikely that consumers would opt to install this more expensive technology. That said, should a means of improving the efficiency of the heat pump materialise, the price of gas and electricity converge or the emissions associated with electrical usage decline, heat pumps may be capable of generating economic and environmental benefits in the future, which would significantly improve the uptake prospects of such a technology.

5.4 Scenario 4: Location & climate

5.4.1 Model changes explained

The model was modified to investigate the impact of varying UK climate conditions on the performance of the heat pump. The initial base case model used a Scottish Eastern climate file; Dundee, which has a typically cold and windy climate, but is drier than the west.

The model was later modified to represent two other UK locations:

- A Scottish west coast climate; Oban; which is typically slightly warmer than the east coast, but wetter, and
- A Southern England climate; Gatwick; which is typically quite a few degrees warmer compared to that of the north of the UK.

One of the limitations of this study was that unfortunately the climate data files available were not for the same year: Dundee refers to 1980, Oban to 1994 and Gatwick to 1991. As a result, the 'ideal' like for like year comparison cannot be made and the varying climate years and unusual temperature patterns; explained in greater depth below; will have to be taken into consideration when conducting the analysis of the heat pumps performance.

To provide an indication of the weather conditions present, an investigation into the temperature and wind speeds in the varying locations was conducted. The ESP-r software is capable of generating annual temperature and wind speed profiles, however, due to the frequency of the plots; 52 weeks; it was difficult to ascertain patterns and identify what was actually 'typical' for the specific location.

Therefore, the decision was made to compare the monthly average dry bulb temperature and the monthly average wind speed for each location; shown in figures 31 & 32; as this provided a better indication of the trends experienced in these particular climate years.

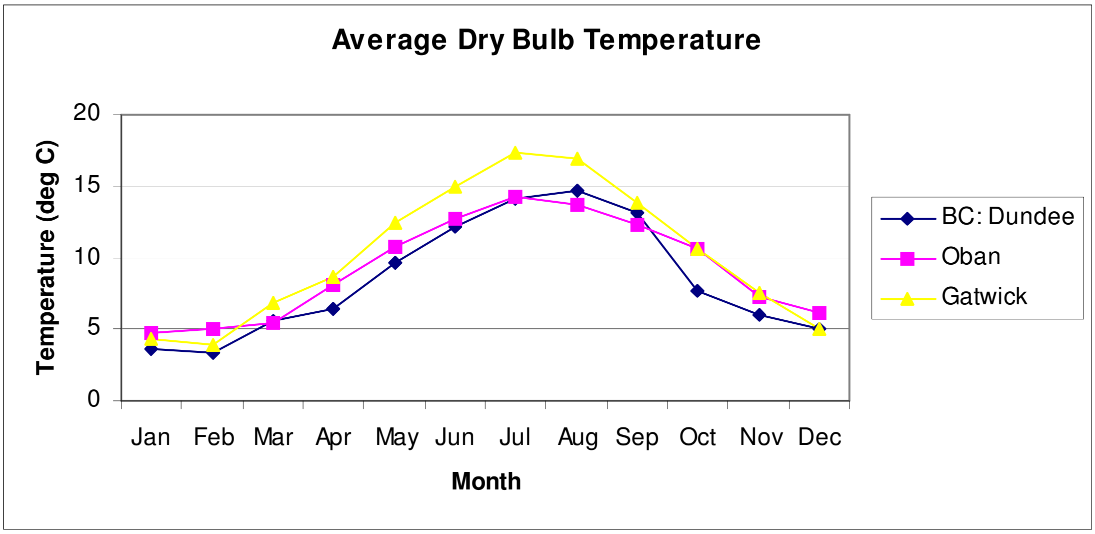

Figure 31: Climate – average monthly dry bulb temperature

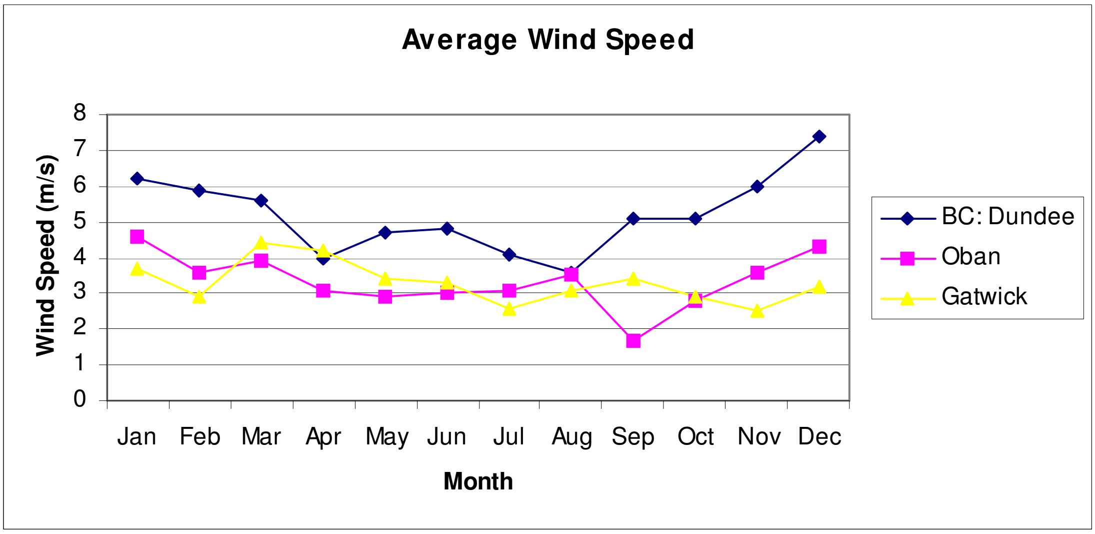

Figure 32: Climate – average monthly wind speed

The Gatwick climate follows the expected trend in that it is generally warmer, with an average temperature of 10.3 degrees Celsius.

In general, the Dundee climate is the coolest of the three climates; with an average temperature of 8.5 degrees Celsius; although it did experience months that were warmer than Oban; for example, August and September. Dundee was also the windiest location; which would contribute to the lower temperatures experienced; with an annual average wind speed of 5.2m/s compared to 3.3m/s for both Oban and Gatwick.

It was also apparent that the average temperature for Oban in the months of January and February were warmer than Gatwick; possibly due to the Gulf Stream; however, on the most part Oban did have the 2nd highest average temperature, as expected, at 9.3 degrees Celsius.

These climate trends will be used to conduct the analysis and to try and provide an explanation as to why the heat pumps performance varies under differing climate conditions.

5.4.2 Comparison of COP

As you can see in figure 33, the actual COP for each of the scenarios reveals a pretty sporadic pattern, however, during the period of January to April and October to December, the variance between the actual COP for all of the scenarios is relatively minimal.

On initial inspection, the actual COP doesn't appear to follow the previously experienced consistent trend, where by the actual COP follows the same trend as that of the seasons and associated temperatures. If this were to be the case, you would have expected the COP of the Dundee heat pump to be the highest; due to the highest demand; followed by Oban and then Gatwick.

However, on closer inspection and referring to the temperature and wind profiles in figures 31 and 32, the actual COP does follow the climate trends, because the climates experienced in the different locations were also different to what may have been considered 'the norm' for these areas:

The performance of the heat pump was best during the cooler winter months, however, the reason for this differed according to the scenario location and associated climate.

> For example, at the start of the year, during January and February, for the climate years used, Oban actually unexpectedly had the highest ambient air temperature. This had two main consequences with respect to the COP: with a hotter climate, the heating demand is reduced, which adversely effects the COP, but due to the hotter ambient air temperature, the source temperature is increased, which reduces and minimises the temperature difference between the sink and source, thus improving the COP. In this particular scenario, the increased source temperature experienced in the winter has proven most advantageous; as there would still be a high heating demand due to the winter climate; and this has enhanced the performance of the heat pump. This result was unexpected, because you would have anticipated that in a 'typical' year, Gatwick would have experienced the hottest climate, with its location being in the South of England.
>
> Furthermore, as expected, Dundee was the coolest and windiest location during January and February, which could have resulted in higher levels of infiltration and consequently an increased heating demand. Therefore, in order to achieve and maintain the dwelling's heating comfort levels, this particular scenario would have required the largest heating demand, ensuring the heat pump operated for longer, sustained periods, thus reducing starting and standing losses. For these reasons, the performance of the heat pump in this scenario was also comparatively good during these months.

The trend of the heat pump performing with the highest actual COP, relative to the highest temperature is apparent from January through to April and again in December, which are obviously the colder months of the year. However, in the months in between, the trend is somewhat different. During May to October when the dry bulb temperature is somewhat greater, the reverse begins to happen and the actual COP performs the poorest with the higher temperature, e.g. the Gatwick scenario. This is likely due to the dwelling benefiting from the external ambient temperature as well as direct and diffuse solar radiation gains, which reduces the overall heating requirement, hence the heat pump is sized too large to meet the demand during this period, thus operating with lower efficiency and also suffering from greater standing losses.

The dry bulb temperature and the effect the wind speed has on the temperature clearly has an influence on the actual COP. It would appear that during the colder seasons of the year; e.g. autumn and winter; there are two distinct trends:

- With a colder climate (as experienced in winter) there is also an increased heating requirement and therefore demand. As a heat pump is generally sized based on the maximum heating demand, it operates with greatest efficiency during this time period, which enhances the actual COP.
- Furthermore, the higher the dry bulb temperature experienced in the colder climates, the better the actual COP, because there is a reduction between source and sink temperature, which also improves the efficiency.

Reviewing the warmer seasons of the year; e.g. spring and summer; the heat pumps size appears to have a greater influence over the actual COP, with a cooler ambient air temperature requiring a greater heating demand from the heat pump, thus the heat pump operating more frequently and minimising standing losses.

This would also re-enforce the idea that the efficiency of the heat pump is much improved when it is appropriately sized to meet the demand and although the heat pump would still be too large in the summer for the Dundee climate, it does perform with the best overall average actual COP, of all three scenarios.

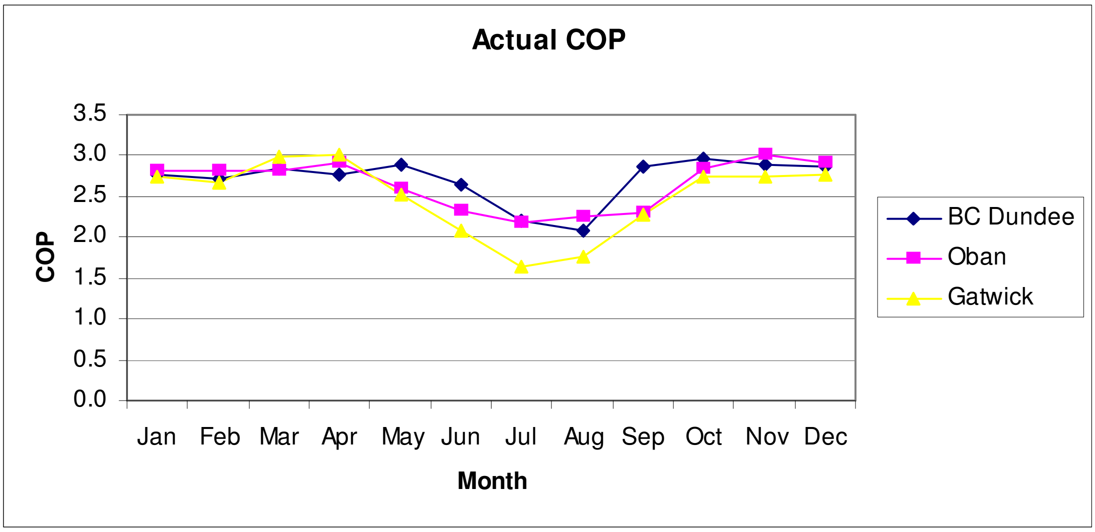

Figure 33: Climate – comparison of COP

Reviewing the average statistics over the year for all three locations, the heat pumps actual COP performance appears to be most effected by a hotter external climate, as opposed to a cooler climate.

The summary statistics in table 38 re-enforce this, with the warmer Gatwick climate experiencing the poorest annual average actual COP of 2.495, and the cooler base case Dundee climate experiencing the best annual average actual COP of 2.707.

Furthermore, comparing the maximum and minimum actual COP values, the heat pump generally achieves the maximum COP in the cooler periods of the year; e.g. winter; and the minimum COP during the warmest time of the year; e.g. summer; which would suggest the heat pump performs best when the demand is greater and the heat pump is operating with a higher capacity.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**
BC: Dundee	2.974	Oct	2.082	Aug	2.707
Oban	3.000	Nov	2.170	Jul	2.647
Gatwick	3.000	Apr	1.640	Jul	2.495

Table 38: Climate statistics – actual COP

5.4.3 Energy Performance

Figure 34 reveals that the location that requires the greatest heating requirement over the course of a year; Dundee; also consumes the greatest quantity of electricity to operate the heat pump.

However, there does appear to be only a very minimal difference in the electricity consumption between the Gatwick and Oban climate scenarios, which is surprising given the perception that they have noticeably different climate conditions. That said, on further inspection of the temperatures over the course of the simulated year, there was actually only a very small temperature difference; on average just 1 degrees Celsius; which is therefore inline with the electricity requirement and would appear to be correct.

Reviewing the electricity requirement for different seasons of the year, the electricity consumption during the summer is almost negligible for all three scenarios, with the greatest difference in electricity consumption being apparent in the winter, during the more extreme, colder climate.

The unusual trend that occurs in February with respect to Oban and Gatwick, where by Gatwick consumes more electricity than Oban materialised, because Oban had a warmer ambient air temperature than Gatwick: at 5.1 degrees Celsius compared to 3.9 degrees Celsius, respectively. As a result of the difference between the source and sink temperatures being smaller, Oban would have benefited from a higher COP as well as Oban also having a reduced demand, because it would have benefited from the warmer ambient air temperature and solar gains, thus reducing the total demand. This improved COP combined with a reduced demand resulted in Oban having a smaller electricity consumption compared to that of Gatwick.

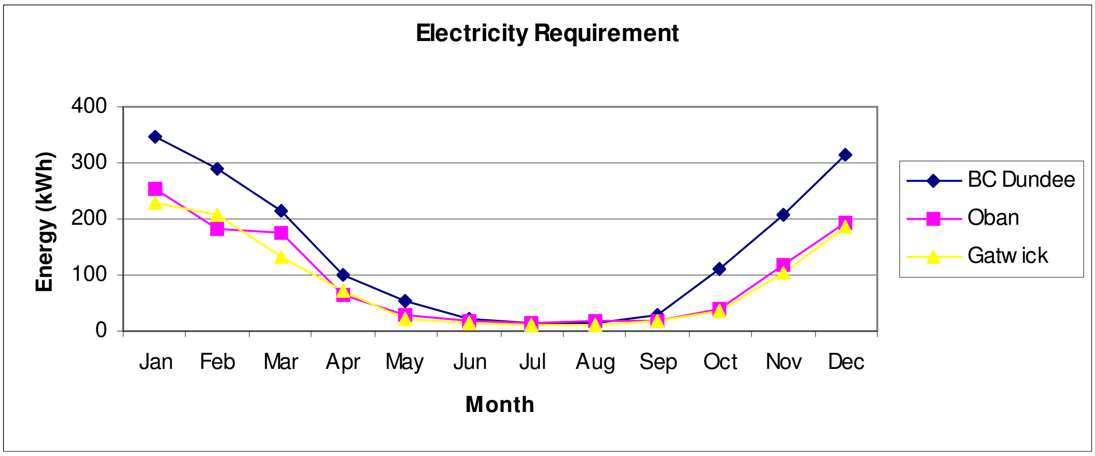

Figure 34: Climate – electricity requirement

The summary statistics in table 39 reinforce the link between a cooler climate; e.g. Dundee; and an increased heating demand and hence electrical consumption: with Dundee requiring a much greater average electrical consumption of 142.82kWh per month, compared to 86.83kWh and 92.79kWh for Gatwick and Oban, respectively.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
BC: Dundee	344.96	Jan	14.68	Aug	142.82	1,713.86
Oban	253.55	Jan	15.20	Jul	92.79	1,113.46
Gatwick	228.98	Jan	11.47	Jul	86.83	1,041.90

Table 39: Climate statistics - electricity requirement

The total system heat out; figure 35; shows much the same trend as the electrical consumption and it is basically just a scaled up version of the electricity consumption, according to the heat pumps actual COP. As the Dundee scenario had the highest average actual COP, the total system heat out would be comparatively greatest.

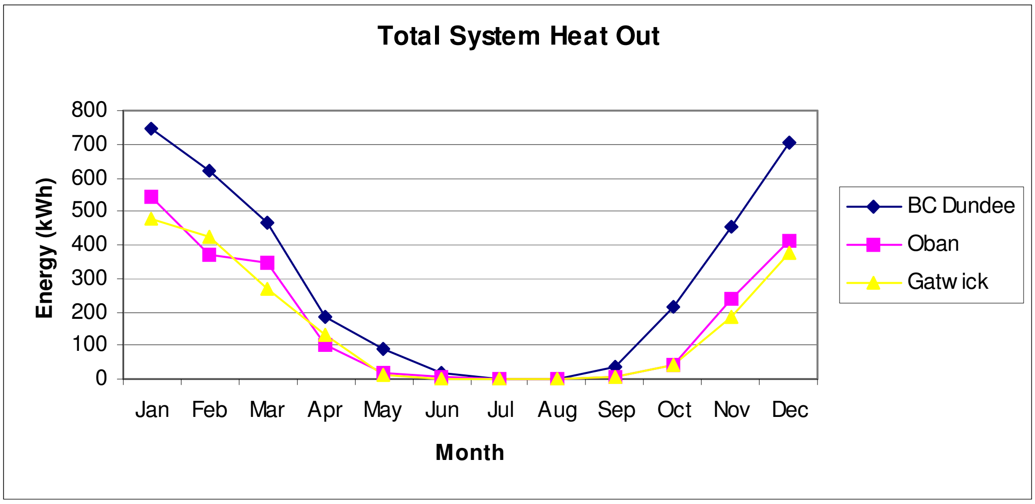

Figure 35: Climate – total system heat out

Table 40 reinforces this: the Dundee scenario has the highest average actual COP of 2.707 and viewing the electricity consumption and the subsequent total system heat out, this scenario was the most efficient, where 1,713.86kWh of electricity was converted by the heat pump into 3,529.17kWh of system heat out over the course of one year.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
BC: Dundee	744.34	Jan	0.35	Aug	294.10	3,529.17
Oban	542.98	Jan	1.29	Jul	172.99	2,075.86
Gatwick	477.52	Jan	0.02	Aug	160.06	1,920.74

Table 40: Climate statistics - total system heat out

5.4.4 Cycling frequency

Figure 36 reveals that the heat pump appears to have a higher total number of on/off cycles with the lowest temperature scenario Dundee. During the winter periods, the heat pump appears to be cycling with much the same frequency for all three scenarios, however during the summer in particular there is more of a noticeable change. Gatwick cycles the least frequently during the summer, as expected, because the heating requirement from the heat pump would be least due to a smaller demand. However, this would also cause the heat pump to incur more standing losses, which would explain why during the summer period the actual COP for the Gatwick scenario is the poorest of the three scenarios.

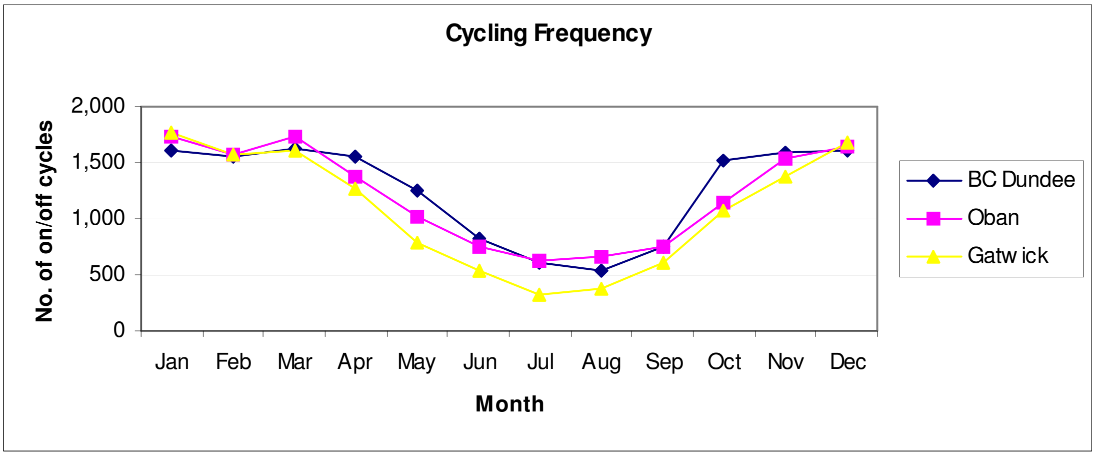

Figure 36: Climate – cycling frequency

The summary statistics in table 41 reveal that over the course of a year, there is only a relatively small difference between the maximum number of on/off cycles; with there being the greatest difference between the Dundee scenario compared to the Oban and Gatwick scenarios. Annually, Gatwick has fewer on/off cycles because it generally has a smaller heating requirement due to a favourable, year round warmer climate.

This idea is reinforced with the minimum number of on/off cycles, where the Gatwick scenario is as low as 320 in the month of July compared to almost double for that of Oban in the same month.

Scenario	**Max**	**Month**	**Min**	**Month**	**Average**	**Total**
BC: Dundee	1,631	Mar	533	Aug	1,249	14,993
Oban	1,738	Jan	623	Jul	1,210	14,552
Gatwick	1,764	Jan	320	Jul	1,081	12,972

Table 41: Climate statistics – no. of on/off cycles

5.4.5 Electricity consumption & running cost

To ascertain which technology and scenario was the cheapest to operate, the energy cost associated with running each technology was calculated.

Figure 37 details the total annual electricity consumption of the heat pump for each of the location scenarios, which revealed that the Dundee scenario; which has the coolest and windiest climate; required the largest quantity of heating and electricity per year. The heating requirement is clearly largely effected by the external weather conditions and this also impacts on the quantity of electricity required.

As explained previously, the total system heat out of the heat pump was used to back calculate and ascertain the equivalent quantity of gas required to operate a condensing gas boiler. This revealed that for all three scenarios, it would in fact be cheaper to meet the heating requirement of the dwelling using a condensing gas boiler, compared to that of this heat pump and evidence of this is provided in table 42.

Furthermore, the summary statistics table exposed that the Gatwick scenario was the cheapest to run, regardless of the technology, followed by the Oban and Dundee scenarios. This confirms that if the dwelling is located in a warmer climate, it benefits from the warmer ambient air temperature, as well as direct and diffuse solar gains, thus reducing the total heating demand from the heat pump.

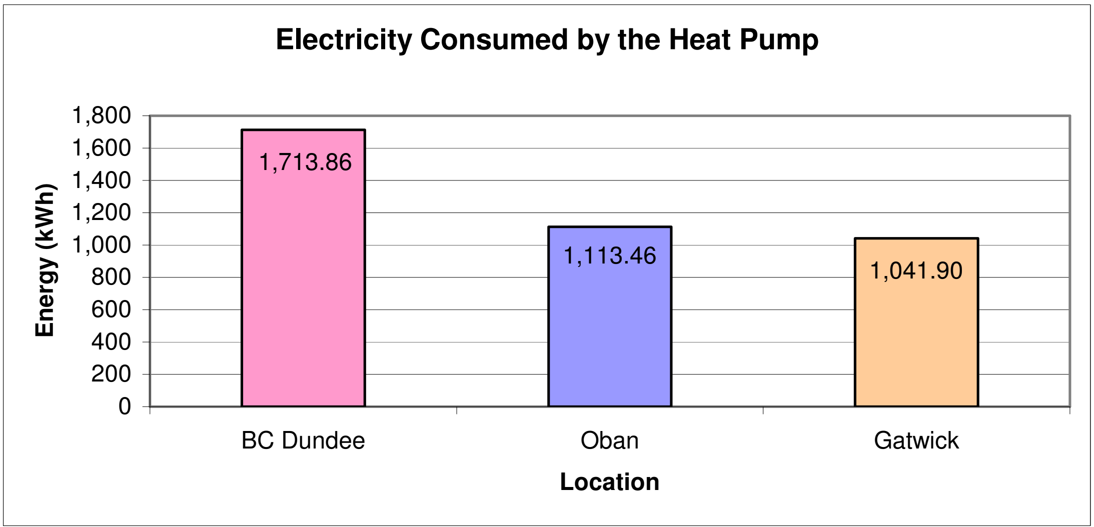

Figure 37: Climate – electricity consumed by the heat pump

Scenario	Electric Consumption (kWh)	Qh: Total System Heat Out (kWh)	Qin: Gas Consumption (kWh)	Cost	
				Electricity	**Gas**
BC: Dundee	1,713.86	3,529.17	5,112.43	£296.32	£257.74
Oban	1,113.46	2,075.86	3,339.61	£238.26	£197.34
Gatwick	1,041.90	1,920.74	3,032.41	£231.34	£186.88

Table 42: Climate statistics - technology & scenario cost comparison

In the climate scenarios, the highest actual COP only reached 3 in both the Oban and Gatwick scenarios and at this level of efficiency, the additional cost of installing and running a heat pump compared to the condensing gas boiler could not be justified. Therefore, the heat pump system will never economically pay for its self, unless the price disparity between electricity and gas were to converge in the future or the efficiency of the heat pump could be substantially improved.

5.4.6 Carbon emissions & savings

To ascertain which technology has the environmental advantage, the carbon emissions associated with each technology were calculated. Figure 38 revealed that in all three locations tested, the heat pump produced a slightly smaller quantity of CO_2 emissions compared to using a condensing gas boiler, providing a net CO_2 saving.

However, the amount of emissions produced is clearly related to the dwellings location and subsequent climate experienced. In the coldest of the three scenarios; Dundee; the heat pump had to meet the largest heating demand, hence consuming the greatest quantity of electricity and this generated the greatest quantity of carbon dioxide emissions.

Furthermore, referring to the summary statistics in table 43, the scenario which had the highest system heating demand produced the greatest difference of carbon emissions between the two technologies with a difference of 25.46kg, and as the system heating demand declined, the environmental situation improved between the technologies, with an decreasing difference of 19.90kg for Oban and 1.50kg for Gatwick.

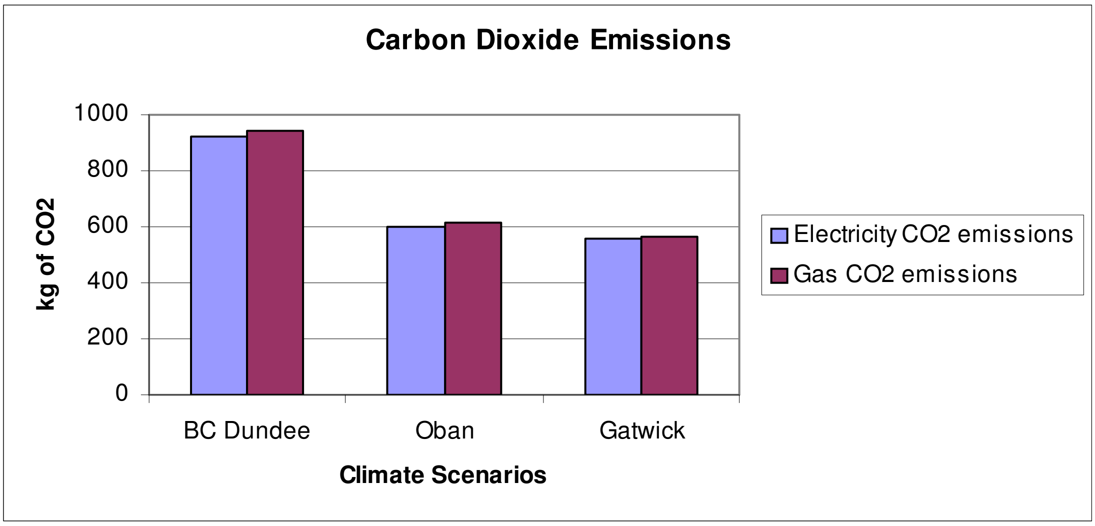

Figure 38: Climate – carbon dioxide emissions

Scenario	CO2 emissions	
	Electricity (kg of CO2)	**Gas (kg of CO2)**
BC: Dundee	920.34	945.80
Oban	597.93	617.83
Gatwick	559.50	561.00

Table 43: Climate statistics – technology & scenario emissions comparison

Given that for all of the location and associated climate scenarios tested, there is no economic benefit and only a very minor environmental benefit of utilising a heat pump, it would be unlikely that consumers would choose to install a more expensive technology to make a relatively small carbon emissions saving. However, should a means of improving the efficiency of the heat pump materialise, or the price of electricity and gas converge, heat pumps may be capable of generating economic benefits in the future, which would significantly improve the uptake prospects of such a technology.

5.5 Environmental sensitivity analysis

In the majority of the case studies and scenarios investigated, it was apparent that there was only a relatively small environmental advantage of using a heat pump over a condensing gas boiler, if any at all. However, this comparison was made using the current levels of CO_2 emissions associated with grid electricity usage; of 0.537kg of CO_2 per kWh; and this value will be subject to change in the future as the UK's electricity supply mix inevitably alters.

Almost everyone is in agreement that the current energy mix is unsustainable and we must act quickly to identify and implement a more diverse energy solution in order to ensure security of supply, drive down harmful emissions and try to avert the looming energy crisis. However, the actual future energy supply mix remains somewhat uncertain and there are many conflicting ideas as to how the UK should try to achieve this. There are numerous options:

A greater uptake of renewable technologies would certainly drive down the carbon emissions, but at what financial penalty and would consumers really be prepared to invest in more expensive, immature technologies to realise only environmental benefits?

A greater uptake in nuclear power; as backed by the British Government; would certainly result in fewer net carbon emissions, yet the Scottish Parliament remain stubborn and refuse to commit to such measures.

In many ways, it would be easier to stick to the tried and tested conventional methods of coal, gas and oil power generation. However, they are responsible for the climate change and global warming problems that we are experiencing today and a continued or accelerated use would only further exacerbate the problems, not to mention that these resources are diminishing in supply and sooner or later an alternative must be sought.

That said, the UK Government have committed to numerous targets and legally binding legislation, which should see more environmentally friendly methods of electricity generation in the future: forcing an increase in both nuclear power generation and renewables. When these alternative methods of electricity generation materialise, this should reduce the carbon emissions per unit of electricity; as both nuclear and renewables are almost carbon free; and this will beneficially reduce the CO_2 emissions associated with the electrical use required to operate the heat pump.

However, this solution will take time to implement and in the shorter term, to avoid the situation of 'blackouts', it may be the case that there is a slight increase in conventional methods, which could see the level of CO_2 emissions rise, prior to declining.

Therefore to ascertain what effect this would have on the environmental viability of the heat pump, a sensitivity analysis has been conducted on the base case scenario, testing varying levels of kg/KWh of CO_2 emitted, with respect to the electricity content.

According to the carbon trust, the most recent literature states that there is currently 0.537kg of CO_2 emitted per kWh of grid electricity. It was therefore decided to investigate increases and reductions from the current level, in increments of 2.5% of the existing level, up to 25%. This will help to ascertain how the heat pumps environmental performance could compare to the condensing gas boiler in the future.

Furthermore, it is also worth recalling that the CO_2 emissions associated with the use of a heat pump can be improved by utilising more renewable or nuclear sources of electricity generation, however, the same cannot be said for the condensing gas boiler, which can only use natural gas: with a fixed emission value of 0.185kg CO_2 per kWh of gas.

The findings of the sensitivity analysis are provided in figure 39, which reveals that if the kg of CO_2 per kWh electric were to increase by 2.5% to 0.550, the amount of emissions associated with using a heat pump or a condensing gas boiler would be identical. Therefore, if the level of CO_2 were to rise in excess of 0.550kg of CO_2 per kWh electric, the heat pump would produce more carbon emissions and it would therefore be advisable to utilise a condensing gas boiler. On the other hand, if the level of CO_2 were to fall below 0.550kg of CO_2 per kWh electric, the heat pump would produce a net carbon saving and it would therefore be beneficial to install a heat pump over a condensing gas boiler.

Additionally, in many instances only a relatively small carbon dioxide emissions saving is achieved, however, if you consider the number of UK homes that must be heated, even a small saving in each will result in a very significant overall saving, should everyone embrace a step change to heat pump technology.

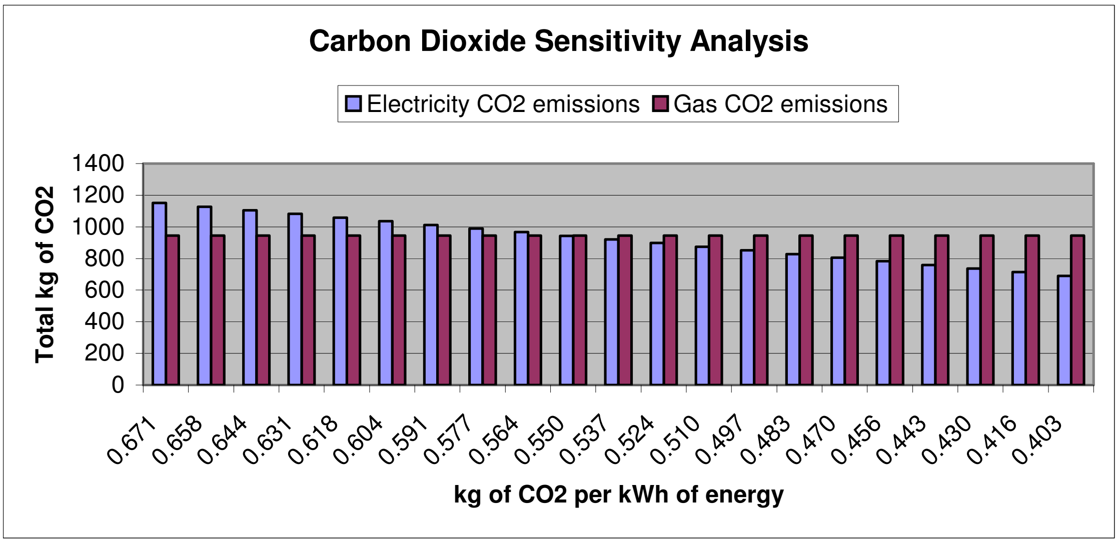

Figure 39: Carbon dioxide sensitivity analysis

Considering all of the measures that have been put into place to try to reduce carbon emissions; Kyoto Protocol, legislation, government targets to name but a few; it is most unlikely that the carbon emissions per kWh of electricity will rise in the future. For this reason, the heat pumps environmental emissions are only likely to improve and become increasingly favourable in the future as the CO_2 emissions per kWh of electricity decline.

E. CONCLUSIONS & RECOMMENDATIONS

1. Conclusions

As a global community it is recognised that that the current energy supply mix, the way in which we meet the heating and power demands of the domestic home and the amount of energy we consume is unsustainable. In order to preserve our future and to in an effort to try and avert the looming energy crisis, a combination of demand reduction measures, improved energy efficiency and a greater proportion of renewables and nuclear generation will all be required. Furthermore, we should also seek an energy supply mix that is reliable and diverse to ensure security of supply, in addition to being favourably priced and environmentally sensitive.

As a result, this has led to the development of new and alternative technologies; such as heat pumps, micro CHP and condensing gas boilers; which realise improved efficiencies and make better use of the planets abundant natural resources.

1.1 Literature Review

- The literature review identified that of the options examined, heat pumps were the most likely viable alternative to the commonly used gas boiler.
- Of the heat pump types considered; air, ground and water; air source heat pumps were selected because they had the greatest potential to be universally installed; both ease of installation and cost; whilst recognising that they may not be the best technology in every situation, due to their greater susceptibility to seasonal temperature variation.
- The most obvious significant factor is the promise of gaining typically three units of energy, for every unit expended.
- Secondly, being electrically operated, there is the potential for them to be powered by zero carbon content electricity.

1.2 Base Case Scenario

The base case analysis considered the coefficient of performance (COP), energy performance, cycling frequency, economics and environmental impact and contrasted the latter two parameters with the performance of the currently used alternative: a high efficiency condensing gas boiler.

COP:

- The actual COP is always greater than the system COP due to system losses.
- The difference between the actual COP and system COP is proportionally greatest during the summer period and this is most likely as a result of reduced demand for heating, because the heat pump is sized for maximum winter load.

- The COP should theoretically be greatest, as the source and sink temperatures converge; i.e. in the summer; however, as the point above illustrates, in practical application this is not the case.

Energy performance:

- Unsurprisingly, energy consumption is greater in the winter than the summer, but due to the COP being greater in the winter, the ASHP heat out is proportionally greater, i.e. the largest gains are achieved in the winter.

Cycling frequency:

- The number of on/off cycles are greater in the winter than the summer, because of the substantial difference in heating requirement.

- Cycling frequency contributes to system losses and it would therefore be advantageous to minimise this by correctly matching the size of the heat pump to demand.

Economics:

- Based on the current cost of gas and electricity, it would be 12.67% cheaper to meet the heating demand of the dwelling using a condensing gas boiler compared to a heat pump.

- In the absence of the availability of gas, using a heat pump would result in a saving of 63.06%; based on the average COP of 2.707; using electricity alone.

Environmental impact:

- Based on the current carbon emissions associated with using each of the fuel types, the heat pump produces 3.27% fewer CO_2 emissions compared to that of the condensing gas boiler.

- If the carbon emissions associated with using electricity reduce as a result of the increased generation from renewable and/or nuclear, the environmental benefits would prove even more favourable for the heat pump, as the emissions from gas are fixed.

1.3 Scenarios

The literature review revealed numerous characteristics that could influence the heating demand of the dwelling and the associated performance of the heat pump. The options chosen to be explored in greater detail in the case study section of the thesis included: occupancy, insulation (including window glazing, roof and wall insulation), draught proofing and location & climate.

1.3.1 Occupancy

The greatest time spent in the house was the elderly couple, followed by the students then the working couple. Higher occupancy levels result in greater sensible and latent heat gains from the occupants and equipment, which are a function of lifestyle and affect the heating requirement from the heat pump.

- Of the four case studies investigated, a change in occupant type and their associated use of the dwelling had the least impact on the performance of the heat pump.

- The actual COP was slightly higher throughout the simulated year in the case of least occupancy.

- On initial inspection, a higher COP would appear to be advantageous, however, when you consider that in order to obtain this higher efficiency, perversely this is achieved whilst the occupants are not in residence.

- Furthermore, as the occupants contribute to the heating requirement of the dwelling (through sensible and latent heat gains and equipment usage), this gain is not costed in the model.

- In the situation where there is least occupancy, the heat pump must operate more to meet the heating demand, thus consuming more electricity and emitting greater quantities of CO_2.

- In all three occupancy types, the condensing gas boiler was the cheaper option.

- In all three occupancy types, the heat pump produced a net CO_2 emission saving.

1.3.2 Insulation

The model was designed to investigate how varying the dwellings insulation levels affected the performance of the heat pump, based on typical construction methods in the 1950's, 1980's and 2009.

- Of the four case studies investigated, the level of insulation had the greatest effect on the COP, giving the highest values of COP for an un-insulated house. This was also accompanied by the highest demand for heating load.

- The COP was significantly higher throughout the simulated year in the case of least insulation, compared to a modern insulated house complying with today's building regulations. This persisted throughout the year, but was particularly significant in the summer months.

- To achieve a higher COP, a greater energy demand was required, which is again detrimental to the running cost and the environment.

- The greatest energy reduction was realised in the initial installation of insulation; e.g. the difference between the 1950's and 1980's scenarios; when insulation was installed in a previously un-insulated building.

- That said, there are also continued benefits from insulating the dwelling further, but comparatively, these are much smaller.

- For all insulation levels, the condensing gas boiler was the cheaper option.

- For all insulation levels, the heat pump produced a net CO_2 emission saving, but only just in the 2009 scenario.

1.3.3 Draught proofing

The model was designed to investigate how varying levels of air infiltration ranging between 0.1 and 1.5 air changes per hour (ac/h), affected the performance of the heat pump.

- Of the four case studies investigated, the level of infiltration had the second greatest effect on the COP.
- The COP was greatest throughout the year for the 1.5ac/h scenario, which represented a draughty house. This was also accompanied by the highest demand for heating load.
- To achieve a higher COP, a greater energy demand was required, which is again detrimental to the running cost and the environment.
- The greatest energy reduction was realised by minimising air leakage; i.e. install draught proofing; and it was the dwelling with an air infiltration rate of 0.1ac/h that had the smallest heating load of all of the case studies and scenarios.
- For all infiltration levels, the condensing gas boiler was the cheaper option.
- For the infiltration levels, 1.5ac/h has the equivalent CO_2 emissions regardless of the technology used and where the infiltration was 1ac/h or less, the condensing gas boiler actually produced a net CO_2 emission saving.

1.3.4 Location & climate:

The model was designed to investigate how varying the buildings location and associated climate affected the performance of the heat pump. The analysis was conducted based on buildings located in Dundee, Oban and Gatwick.

- The COP obtained was much the same for all of the scenarios during the colder periods of the year, however, the warmer of the climates (Gatwick) did experience a marginally higher COP.
- Conversely, during the warmer periods of the year, the cooler of the climates (Dundee) had the highest COP, associated with greatest demand.
- It was found that for a colder and windier location, the overall ambient air temperature would be reduced, thus there would be an increased heating requirement, which would be detrimental to the running cost and the environment.
- For all climate and location scenarios, the condensing gas boiler was the cheaper option.
- For all climate and location scenarios, the heat pump produced a marginal CO_2 emission saving.

2. Recommendations

Having summarised the most pertinent learning points from the case studies and thesis, the following recommendations have been made:

- In areas not served by mains gas, choosing a heat pump for domestic heat purposes will provide substantial operating cost savings compared to that of electric heaters.

- To minimise environmental damage caused by carbon dioxide emissions, choosing a heat pump for domestic heating purposes is the most environmentally friendly option.

- Closely matching the capacity of the heat pump to the heating demand of the dwelling is absolutely crucial, as it substantially influences the performance of the heat pump system.

- The cycling frequency should be minimised; reducing starting and standing losses; which should maximise the performance of the heat pump. Correctly matching the heat pumps capacity to the heating demand will help to achieve this.

- Balancing the load throughout the year, by finding an alternative heating requirement; e.g. hot water in the summer; or by installing and operating multiple heat pump units as required, will help to better match the demand.

- Invest in insulation to reduce the heating demand prior to sizing the heat pump, to ensure the smallest capacity heat pump can be installed. This will also contribute significantly to environmental benefits.

- Controlling the air infiltration by investing in efficient draught proofing prior to sizing the heat pump will again ensure the smallest capacity heat pump can be installed. If greater air changes are required, installation of a heat recovery system (regenerator) should be considered.

3. Suggested areas for future work

Due to the limited time scale allocated to conduct the thesis, the scope of the project was relatively tight. However, during the course of the thesis, it became apparent that there were several additional areas that were of interest and would merit further investigation. Therefore, potential areas for future research have been suggested:

- One of the most important findings was that the correct sizing of the heat pump, relative to the heating demand is absolutely crucial, as it substantially influences the performance of the heat pump. This thesis only investigated one size of heat pump, and it would be interesting to model varying sizes of heat pumps to ascertain to what extent this influences the heat pumps performance.

- The heat pump system investigated was only configured to provide domestic space heating, however, it could be designed to provide both domestic space heating and hot water, altering the use depending on the demand. For example, it could be used for space heating during the winter when the greatest requirement exists and then in the summer when the space heating demand is minimal, the heat pump system could be configured to produce hot water. By configuring the heat pump in this way, a consistent annual demand could be maintainable, which could potentially result in a higher actual COP throughout the year and more favourable running costs, however, the extent of these benefits would have to be investigated.

- It would also be worthwhile investigating utilising multiple heat pump units to try and better match the demand; particularly during the summer; and ascertain if this would improve the COP and to what extent. However, a cost-benefit analysis would also have to be conducted to ascertain whether this would make economic sense and whether it would be better to operate with a slightly lower COP, than incur the cost of installing multiple units and the associated control system.

- The heat pump system was configured to utilise air as the source, however, air heat pumps are most susceptible to seasonal variation and it would therefore be interesting to model the heat pump using either the water or the ground as the source. However, this would incur additional equipment costs and if this were to result in any performance improvements, a financial cost benefit analysis would also have to be conducted.

- Furthermore, at present it is slightly more expensive to operate the heat pump system for the case studies and scenarios tested, compared to that of a condensing gas boiler. Therefore, a sensitivity analysis should be conducted on the price of electricity and gas, in order to ascertain what price conditions would make the heat pump system economically viable in the future.

- Additionally, the heat pump system investigated only realised a relatively poor actual COP, given that theory suggested it could be as high as 5:1. It would therefore be advisable to investigate other models; e.g. different heat pump sizes to ascertain the effect on the COP; or to simply conduct a sensitivity analysis on the actual COP obtained with this model, to determine how an 'optimised' model could effect the economical viability of the heat pump system in the future.

- Finally, the building and occupancy characteristics brainstorm conducted earlier revealed several potential scenarios that could have been explored, but it was not feasible to conduct them all in the limited time scale. It would be interesting to review the performance of the heat pump under different conditions, for example dwelling type; a flat or larger house; or altering: the number of occupants to a greater extent, the direction the building faces, the insulating material type, the type of glazing, to name a few.

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1. Appendix 1: System heat efficiencies

Scenario	System Heat Efficiency
Base case	0.73
Occupancy	
Elderly	0.72
Students	0.76
Working professionals	0.79
Infiltration	
> 2 ac/h	0.73
1.5 ac/h	0.68
1 ac/h	0.62
0.5 ac/h	0.53
0.1 ac/h	0.42
Insulation	
1950's	0.83
1980's	0.76
2009	0.73
Climate	
Dundee	0.73
Oban	0.66
Gatwick	0.67

2. Appendix 2: Energy conversion factors

	Conversion to CO_2 (gross CV basis[2])	
Fuel	**Units**	**kg CO_2/unit**
Grid electricity[3]	kWh	0.537
Renewable electricity	kWh	See footnotes 4 & 5
Natural gas	kWh	0.185
	therms	5.421
LPG	kWh	0.214
	therms	6.277
	litres	1.495
Gas oil	tonnes	3,190
	kWh	0.252
	litres	2.674
Fuel oil	tonnes	3,223
	kWh	0.268
Burning oil[6]	tonnes	3,150
	kWh	0.245
Diesel	tonnes	3,164
	kWh	0.250
	litres	2.630
Petrol	tonnes	3,135
	kWh	0.240
	litres	2.315
Industrial coal	tonnes	2,457
	kWh	0.330
Wood pellets[7]	tonnes	132
	kWh	0.025

Carbon Trust, Energy and Carbon Conversions (fact sheet CTL018)– 2008 update [18]

3. Appendix 3: Scottish building regulations – minimum U values

Maximum U-values for building elements of the insulation envelope

Type of element	**(a) Area-weighted average U-value (W/m^2K) for all elements of the same type**	**(b) Individual element U-value (W/m^2K)**
Wall [1]	0.30	0.70
Floor [1]	0.25	0.70
Roof	0.20	0.35
Windows, doors, rooflights	2.2	3.3

Notes:

1. Excluding separating walls and separating floors where thermal transmittance should be ignored.

Scottish Building regulations – May 2009 update [19]