Department of Mechanical and Aerospace Engineering

Viability of river source heat pumps for district heating

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Abstract

This project aims to investigate the viability of implementing a river source heat pump which is capable of driving a district heating network. The heat sources most currently used in the UK are typically the air and the ground. Water is widely available in urban areas of the UK and is capable of delivering large quantities of heat. Using a heat pump, this heat has the potential to be used to drive a district heating network.

A generic methodology was developed to aid the investigation. The value in this tool is its ability to be applied to areas throughout the UK. The methodology covers the core aspects of technical, environmental and economic. The River Clyde running through Glasgow was chosen as the case study for the investigation. The suitability of the river was analysed and a demand/supply matching model was created in an Excel spreadsheet to consider technical aspects of the heat pump. The method for identifying potential areas near to the Clyde was applied to choose a suitable location. Environmental concerns were analysed in terms of impact assessment, CO_2 equivalent emissions and air quality. A financial model was created using a discount cash flow method, allowing for comparisons between different heating configurations. These were gas boilers only, gas boilers and conventional electric heating, CHP only and the river source heat pump and CHP.

The River Clyde was found to be suitable for a large heat delivery, with a proposed heat pump of 6.65 *MW*. The method for identification of a district heating site identified a large part of the Merchant City, which could potentially benefit from district heating. The demand/supply matching model produced a variety of interesting technical results, importantly showing that an annual heat demand of 40 *GWh* is a good match for the proposed heat pump. Environmentally the hybrid system of river source heat pump and CHP provided the lowest CO_2 emissions in the long term, with CHP only having the lowest only for the current year, 2015. A move away from gas heating systems resulted in better air quality, reducing both NO_x and CO emissions. Economically the CHP and river source heat pump provided the lowest payback period of 9.79 years, when upgrading from gas boilers, and 5.36 years, when upgrading from a gas and conventional electric hybrid heating system.

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1. Introduction

Heating currently makes up a large proportion of the energy use worldwide, particularly in countries with milder climates such as the UK. Recently there has been a concentrated effort at increasing the sustainability of the net energy used. This has seen great advances in the installation of large capacities of wind farms and solar power as well as the development of ever maturing technologies such as tidal and wave power devices. This has led to a trend of decarbonisation of the electricity grid, which should continue due to direct governmental intervention, rising fossil fuel costs and cheaper available renewable energy. Despite this, there has not been the same drive towards sustainability in the heating sector.

There have been improvements in energy efficiency standards for buildings, with ever tightening government legislation causing great reductions in energy use for newly constructed buildings. Legislation does however lag for the current building stock so that improvements can still be made in this area, particularly with projections predicting 85% of the current housing stock in the UK will remain by 2050 (Kannan & Strachan, 2009). Even if standards for energy efficient buildings improve there will still be a vast requirement for heating.

Currently the heating demand of the UK is met primarily by gas, supplemented by electricity and oil. Heat pumps have the potential to provide a low-carbon solution for the provision of heat. The sources of heat for heat pumps are low grade and are widely available in urban areas. Currently the greatest uptake of this technology has been with ground and air sourced heat pumps. These utilise the solar heat absorbed by both the earth and the atmosphere. The heat pump provides a way of promoting this low-grade heat up to useful temperatures capable of providing space heating and direct water heating.

Water sourced heat pumps transfer the vast heat available from the abundant sources of water which intertwine with the cities and towns of the UK. From coastal towns on the sea, to inland towns built up alongside lakes, to ex-mining towns sitting above now-abandoned mine shafts, some of which have filled with temperate groundwater, to aquifers underground scattered all over the UK's fractured geological crust, to the fast-flowing rivers so many cities have built up alongside. The potential for heating from these sources of heating is immense. Instead of having to ship gas hundreds of miles from distant countries at large carbon expense, heat pumps provide a means of locally sourcing a low-carbon, sustainable source of heating.

1.1. Aim

Glasgow sandwiches the River Clyde as well as many other smaller rivers such as the River Kelvin. The Clyde splits the city through dense urban and industrial sites, many of which have large heating demands. The aim of this thesis will be to investigate the aspects involved with implementing a large heat pump using the River Clyde, which is capable of providing a substantial amount of heat via a district heating network. The proposed network will draw a large proportion of its heat from the river source heat pump.

1.2. Objectives

The main objectives of the project are outlined below:

- Developing a generic methodology capable of investigating the viability of river source heat pumps driving a district heating network, addressing technical, environmental and economic aspects

- Building an Excel spreadsheet model capable of performing demand/supply calculations for river source heat pumps

- Investigation into the viability of the River Clyde as a heat source

- Analysis of the technical aspects of a river source heat pump on the River Clyde

- Analysis of the various environmental advantages and disadvantages of a river source heat pump with district heating in Glasgow

- Determining the economic viability of a river source heat pump to provide district heating to an area of central Glasgow

1.3. Overview

In section 2, Heat Pumps, the thermodynamic background of heat pumps will be presented along with factors regarding performance. It will discuss various types of heat pumps and include technical information regarding the impact of the choice of refrigerant fluid. This is followed by sub-sections on how heat pumps perform with other heating devices and also where their application is suitable. The section concludes with a case study on the Shettleston Mine-water Heat Pump.

Section 3 introduces the facets of district heating, explaining the principles and what heating systems they use. It ends with the case study of a heat pump driven district heating scheme, Drammen, Norway.

In section 4, Methodology, the generic methodology capable of investigating the viability of river source heat pumps driving a district heating network is presented. It considers analysis of the proposed river as well as the technical details of the heat pump involved. Mapping techniques and technical considerations of district heating are then discussed. The method for developing the demand/supply matching Excel spreadsheet is argued, with the following two sub-sections outlining the environmental and economic considerations which require deliberation.

The Results and Analysis of section 5 applies the methodology outlined to the case of the River Clyde, Glasgow.

Section 6, Conclusions, brings the various discussions and analysis throughout the thesis together, including suggestions for further areas of research.

2. Heat Pumps

Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.

Clausius statement

According to the Clausius statement of the 2nd law of thermodynamics it is impossible for heat to flow from an area of low temperature to an area of high temperature without the aid of an external force. This is obvious from real life experience as when a hand touches a hot object, for example boiling water, the person feels a dramatic (and painful) flow of heat from the higher temperature water to the lower temperature surface of the hand. It is never the case that the heat flows from the hand to the boiling water.

This fundamental law does, however, include the possibility for heat to flow from cold to hot with the aid of an external force. This may seem an odd concept but it is one used by an essential kitchen appliance. Fridges facilitate the flow of heat from a cool body, the food inside, to a warmer body, the room of the kitchen. This is possible due to the electrical work performed by the fridge; the electricity acts as the external force required by the Clausius statement. Essentially the fridge uses electricity to transfer heat from your butter to warm up your kitchen.

The obvious goal of the fridge is for keeping food cool and the fact that the kitchen area is heated up in the process is merely a by-product. Using the same thermodynamic cycle it is possible to provide additional heat to a warmer place from a cooler place, where this time the cooling of the cool place is the by-product. These devices are known as heat pumps and also require an external force to operate. Figure 1 below is a simple schematic outlining the thermodynamic processes of a heat pump. (Cengel, Boles, & Kanoğlu, 2002)

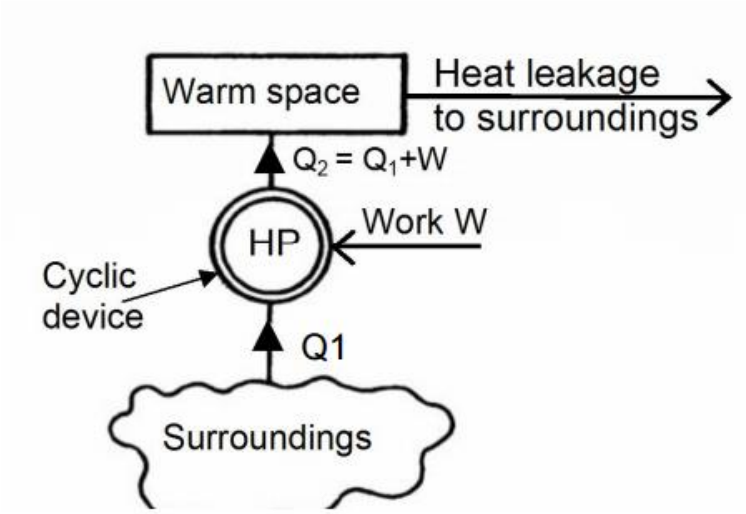

Figure 1: Heat pump schematic (Tuohy, 2008)

2.1. Thermodynamics

Heat pumps use the same thermodynamic cycle as refrigerators: the vapour-compression cycle. The simplest form of this cycle uses 4 basic components: a compressor, an evaporator, an expansion valve and a condenser. The left of figure 2 shows how these connect to form the cycle.

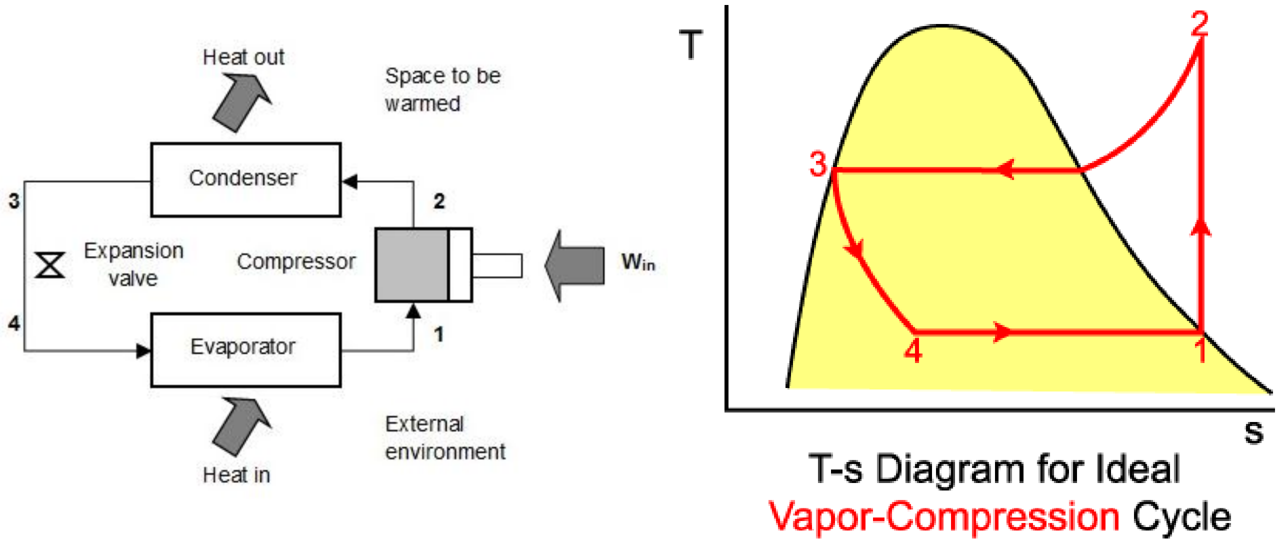

Figure 2: Simple vapour-compression component cycle, T-S diagram for cycle (Tuohy, 2008), (Moran, 2015)

A fluid passes through the 4 points shown on the left figure. The fluid changes from a saturated vapour at point 1 to a superheated vapour at point 2 as it goes through the compressor. Note that it is in the compressor that the electrical work is input. Once the fluid is a superheated vapour it passes through a condenser which cools the fluid to a saturated liquid state at point 3. This is the process by which heat is taken from the cycle and transferred to the area to be warmed. An expansion valve is then used between points 3 and 4 to reduce the pressure of the fluid and change the state to liquid-vapour. Heat is taken into the cycle via the evaporator. Between points 4 and 1 the evaporator uses the heat from a cooler area to change the fluid to a saturated vapour, and thus ready to enter the compressor to restart the cycle.

The cycle outlined is the ideal one and presumes a perfect, reversible compression stage. In a real, practical cycle the compression is irreversible meaning the compressor is required to perform additional work. This can be seen on the P-S diagram, Figure 3, where the entropy of the practical cycle at point 2 is larger than in the ideal case, denoted by the point 2s. Another real characteristic of the cycle is additional sub-cooling of the fluid leaving the condenser as seen by the movement of point 3 on the same figure. While the evaporator can be exposed to various conditions, it is necessary for the compressor to work with solely dry vapour making sub-cooling an essential component. It can be achieved via a heat exchanger between the fluid leaving the condenser and the evaporator. This more realistic process is shown in figure 3, along with the P-S diagram.

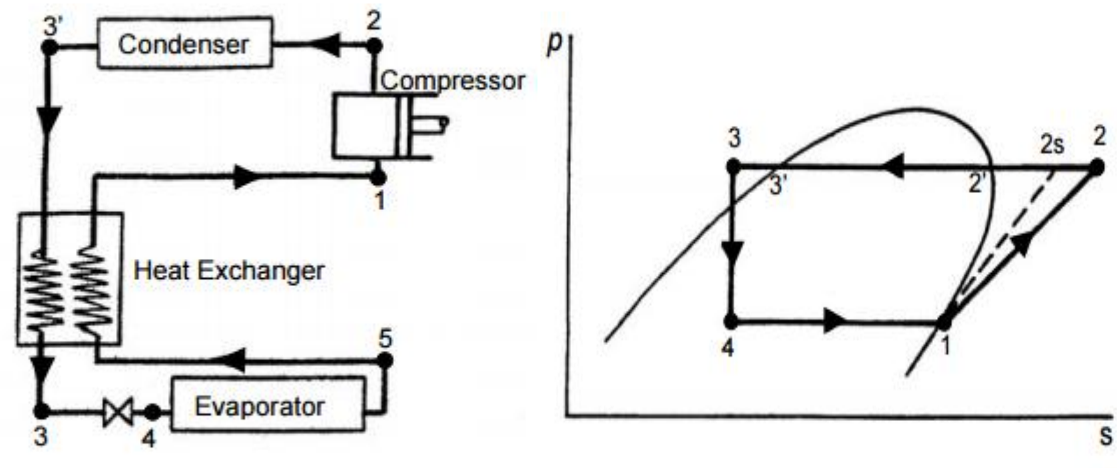

Figure 3: Realistic vapour-compression cycle, with heat exchanger (Tuohy, 2008)

There are many further considerations to be made with regards to maximising the performance for a vapour-compression cycle. A flooded or liquid overfeed evaporator arrangement can improve the heat transfer ability, as opposed to a dry expansion evaporator. The work input required by the compressor can also be reduced by using a multi-stage compression scheme. This introduces a lower, intermediate pressure which means a reduced pressure ratio across the compressor. This in turn reduces the work required by the compressor, leading to an increased level of performance. (Tuohy, 2008)

2.2. Performance

The level of performance for a heat pump is measured by its *Coefficient of Performance (COP)*. It is defined as the ratio of the useful heating provided to the electrical input. Note that this is the COP specifically for a heat pump, for a refrigerator the COP is the ratio of the cooling provided to the electrical input. As explained earlier, it is simply the desired goal which sets these devices apart. The previous sub-section ended with a discussion of improvements for the vapour-compression cycle. The successes of such modifications are explicitly quantified by whether they increase or decrease the COP of the system. This is an important measure of the viability of a heat pump system. The UK government is currently running the Renewable Heat Incentive (RHI), a subsidy for which water source heat pumps qualify. A requirement to qualify for this is a COP of 2.9, conveying the importance set against COP. (OFGEM, 2015b)

However, one of the most fundamental factors affecting the COP is the temperature difference between the environments where heat is being transferred from and where the heat is going to. For illustration, the COP for a heat pump using the ideal Carnot cycle can be expressed as

$$COP = \frac{T_{Cold}}{T_{Hot} - T_{Cold}}$$

Where T_{Cold} is the temperature of the cold area where heat is being extracted from and T_{Hot} is the temperature of the hot area heat is being transferred to. It can be seen that minimising the difference between the hot area and cold area will result in an improved COP. (Sonntag, Borgnakke, Van Wylen, & Van Wyk, 1998)

Another useful measure of the performance of a heat pump can be found by calculating the *Seasonal Performance Factor (SPF)*. This is defined as the ratio of the total useful heating provided over a year to the total electrical consumption. This is useful because the COP of a heat pump is not a temporally static figure. Various conditions depending on an individual heat pump can affect the day-to-day and season-to-season COP. The SPF provides a more insightful measure of how a heat pump is performing under different conditions. (Herold, Radermacher, & Klein, 1996)

An important characteristic for the COP of a heat pump is its variation with respect to the outlet temperature from the heat pump. Figure 4 illustrates this inverse linear relationship as well as the reduction of COP in relation to the ambient air temperature (this is a generic relationship which is relevant for the temperature of any source, i.e. applicable to water source heat pumps). Note in the graph the term ‘Entering Water Temperature’ is equivalent to outlet temperature.

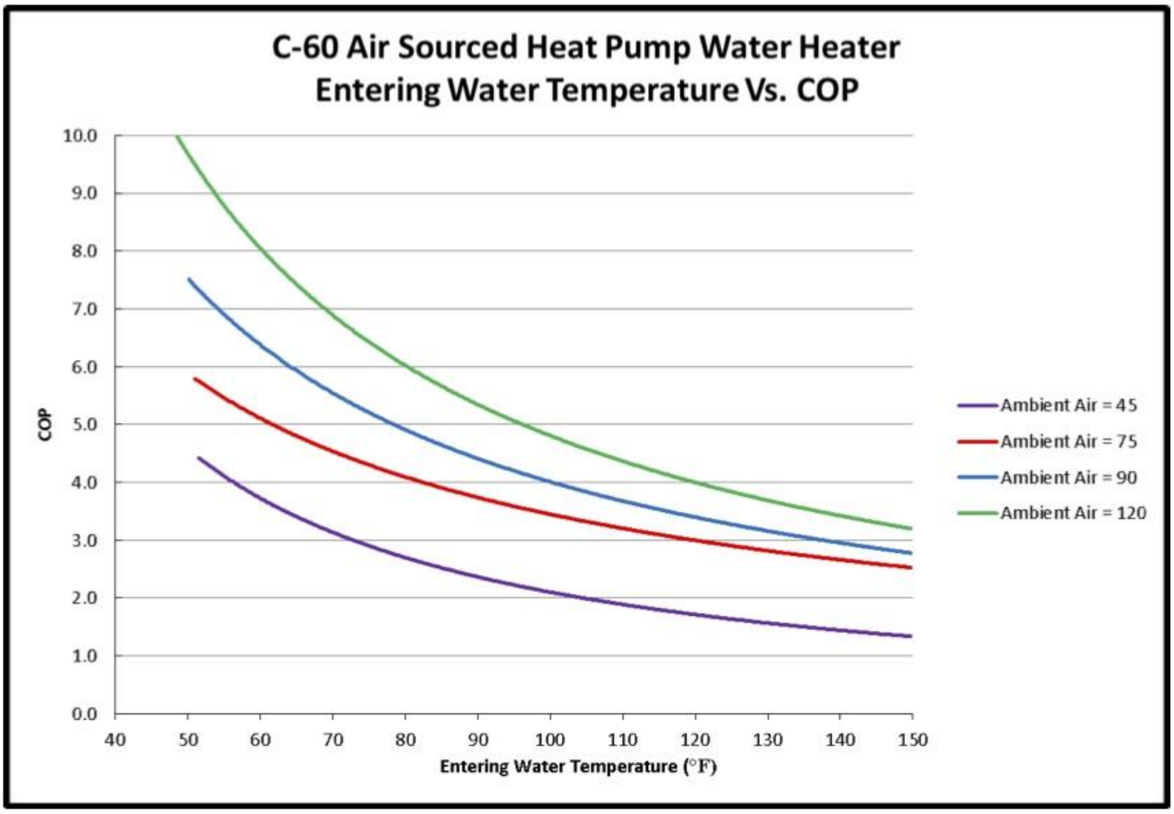

Figure 4: Relationship between COP and outlet temperature (Mathissen, 2011)

This is important because it shows how useful it is to have a heating scheme which can work with low temperatures so that the heat pump can perform even more efficiently. (Mathissen, 2011)

2.3. Types of heat pump

The sources of heat for heat pumps are most commonly air, ground and water. Air-source heat pumps have heat exchangers exposed to the outside environment and transfer the heat from the air. Ground-source heat pumps consist of heat exchangers buried in the earth and transfer the heat from there. This thesis concentrates on the potential of water sourced heat pumps, where the heat exchangers transfer the heat from a body of water.

In literature water source heat pumps are often referred to as surface water GSHPs (ground-sourced heat pumps) due to their similarity in function to common GSHPs, and typically air-sourced heat pumps are abbreviated to ASHP. For clarity this thesis will refer to water source heat pumps as WSHPs to differentiate them from GSHPs.

The distinct value of a WSHP is in the heat transfer coefficients. Water has a particularly high convective heat transfer coefficient of 1200 W/m^2K, which is for water flowing in a tube (EngineersEdge, 2015). Compare this to air with a convective heat transfer coefficient of 100 W/m^2K, which is for air travelling at a moderate speed over a surface (EngineersEdge, 2015), and to the ground conduction heat transfer coefficient of 1 W/mK, for a moist area (EngineeringToolbox, 2015). Note that air and water transfer heat by convection, radiation and conduction while the ground does not transfer heat via the convection process. Water source heat pumps can therefore have a heat transfer coefficient a factor of up to 10 times larger than those of air or ground source heat pumps.

Heat transfers more quickly through a wet surface than a dry one. This is why it is generally desirable to place GSHPs in places with abundant water such to increase their efficiency. Some of the comparative pros and cons of ground and air source heat pumps are outlined in table 1.

Table 1: Comparison of GSHP and ASHP. Help from (Wu, 2009)

GSHP		ASHP	
Pros	**Cons**	**Pros**	**Cons**
More efficient, stable temperatures underground	More upfront cost, need for drilling and heat exchanger underground	More flexible, system can easily provide heating in winter and cooling in summer	Less efficient, large seasonal air temperature variations
Better visually, out of sight and silent	Large disruption, lots of construction work needed	Easier construction, no groundwork necessary	More maintenance needs, possibility of freezing in winter
Possibility for using ground as thermal store		Less upfront cost, no need for drilling	More visual impact, visible and occasional noise problems
Less maintenance, heat pump protected from elements underground			More possibility for vandalism

WSHPs utilise the low-grade heat of ground water or surface water. Surface water sources can be rivers, lakes, streams or seawater. Ground water is found beneath the Earth's surface in fractured rock spaces (aquifers) or in soil pockets. Reaching aquifers can require expensive drilling. However, during large construction projects, in certain geographical areas, these are often exposed. Another possible source is mine-water. (David Banks, 2012)

2.3.1. Open-loop systems

Open-loop heat pumps involve the physical abstraction of water from the source and directly passing it through the heat exchanger where the heat is extracted. When using a groundwater source, a suitable aquifer is required such that there is a reliable and usable flux of water so that an extraction well can be built. In reality, to have sufficient knowledge of the suitability of an underground aquifer requires a specialist hydrogeologist. The design component of the extraction well requires planning for the depth of the well as depths of aquifers range from a few metres to 100s of metres, the diameter of the well which constrains the size of the pump which can be inserted, the yield of the well which will be dictated by the heat pump size, and the physical properties of what needs to be drilled which greatly effects the economics. The water is then either returned to the aquifer or disposed of. For heat pumps utilising surface water, naturally, there is no need for an extraction well. Water is pumped directly from the source to the heat exchanger and then returned to source at a lowered temperature.

These offer high efficiencies as they do not require an intermediate heat transfer carrier, the heat is transferred directly from the water. The lack of requirement for this intermediate stage reduces the capital cost of the system and the simplicity of the system provides a lower risk of damage to the piping. Care must be taken depending on the conditions of the water that is being pumped into the heat exchanger. A filtration system may be needed to protect the heat exchanger from damaging debris. This increases the required maintenance and power consumption. Therefore an added design consideration in a preliminary feasibility study would be the water cleanliness quality. There is also additional power consumption arising from the necessary pumping of the water. Environmentally open-loop systems can have a direct impact, this is because the water is being physically moved meaning that living creatures can be drawn into the pump. (David Banks, 2012)

2.3.2. Closed-loop systems

The other system which can be used for WSHPs are closed-loop systems. They consist of big plates or lattices which are submerged in the water. These use an intermediate heat transfer stage to transfer heat directly from the water source, requiring no pumping. This involves an intermediate fluid which is commonly an antifreeze solution, although it can be a variety of chemicals including ammonia and glycol.

Figure 5: Closed-loop water source heat pump graphic (KensaHeatPumps, 2015)

They are generally installed as either horizontal or vertical loops, and due to this their environmental interaction is limited to the water being exposed to these loops. However, the intermediate fluid if leaked can have potentially damaging effects. Their design is primarily specified by the properties of the body of water they are to be used in, with the design generally requiring less maintenance than an open-loop system. They are more susceptible to damage in rivers than open-loop systems as the submerged components are liable to float away with high flow rates. In rivers which are used for shipping the plates are exposed to damage from passing boats. (Russo & Civita, 2009)

2.4. Refrigerant fluids

Refrigerants are one of the most important parts of a heat pump and the choice of which one to use has both significant technical and environmental impacts. In the function of a heat pump it is the refrigerant which takes the energy from the heat sources and delivers it to the heat exchanger to be used. Common refrigerants used in heat pumps, and fridges, also have a high possible global warming impact. Making the right choice of refrigerant is vital in determining the feasibility of any heat pump system.

The condensation pressure of refrigerants varies with temperature and this variation is unique for different refrigerants. Some refrigerants will stop working at too very high temperatures because the pressure becomes excessive, which can cause damage to the heat pump’s components. Contrastingly low pressure can also cause risks as the volume which needs to be swept increases which means that larger, more expensive heat pump components are needed. Figure 6 graphically shows the relationship between pressure and temperature for an array of refrigerants. When a refrigerant’s line on the graph stops, this means that it has reached its supercritical stage. Beyond the pressure and temperature at this point there is a transition from the liquid to the gaseous state. This means that only some refrigerants will work for large heat pumps which require high operating temperatures. Different refrigerants will result in different COP, and the heat pump system must be designed with this in mind to achieve optimal results.

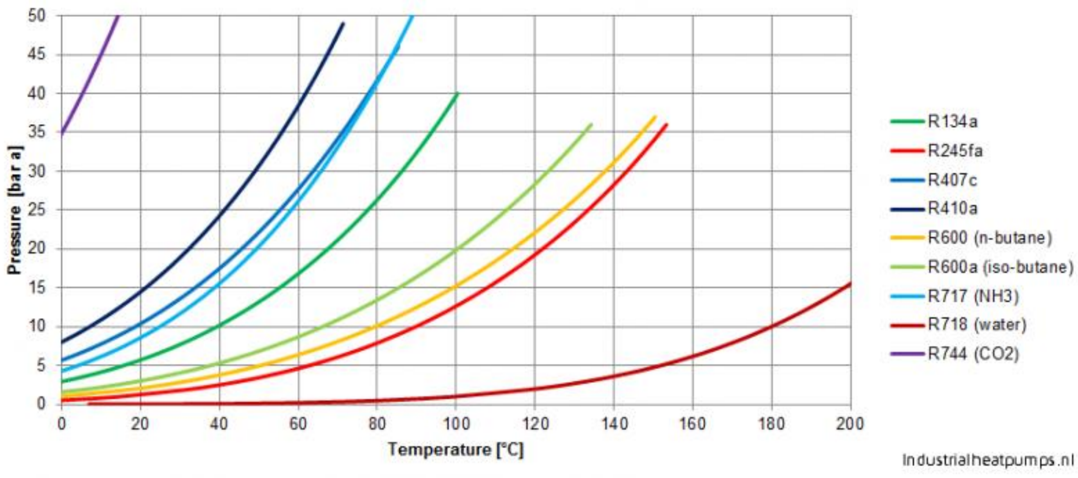

Figure 6: Comparison of refrigerants (IndustrialHeatPumps, 2012)

Refrigerants are also prone to leaking into the environment from the heat pump. They each leak with their own characteristics and, importantly, have varying impacts on global warming. The leakage occurs during the operation of the heat pump while there is another risk of escaping refrigerant during disposal after the lifetime of the heat pump. The impact on the climate due to refrigerant leakage is not negligible compared with the electricity use. It is estimated 25-30% of total impact is due to refrigerant leakage for a 56 *kWe* system which assumes 40-50 percent of the refrigerant is recovered. (Meacock, 2013)

Two widely used working fluids are CFCs and HFCFs, and they historically offer the potential for the highest operational COP. These are particularly harmful to the climate and there is ongoing research into the replacement of the use of these. Balance is needed between optimising the heat pump via the choice of an effective refrigerant which raises the COP of the system and the negative climatic impacts these refrigerants have. There are a number of natural refrigerants which can be, and have been, used in modern heat pump systems.

CO_2, perhaps surprisingly, offers a climate friendly alternative to CFCs and HFCFs as its climatic impact is in the order of thousands of times lower. It is easy to use with other substances and technology has advanced such that the high pressures necessary for CO_2 to be used in heat pumps is readily available. Heat pumps which use CO_2 should be designed carefully to take into account its specific thermodynamic characteristics. If this is done then the COP reduction normally associated with using non-CFCs or non-HFCFs can be minimised. CO2 offers a real technically suitable alternative while vastly reducing the climatic impact.

Hydrocarbons have similar properties to HCFCs and therefore offer a potential alternative. However, often hydrocarbons, such as propane, are highly flammable and require a secondary loop for safety reasons to be implemented in the heat pump. This has the unappealing result of reducing the COP by about 20%. Hydrocarbons are commonly used in domestic refrigeration.

Water as a refrigerant is very desirable in terms of its climatic impact. It is one of the oldest used chemicals in refrigeration. Technical problems associated with the heat pump design do arise due to high specific volume at low temperatures. Ammonia is another abundant substance capable of acting as the working fluid. It is environmentally friendly and capable of achieving comparable COPs. The main issue is that ammonia is highly flammable. Therefore there needs to be a lot of safety precautions taken in order to design a heat pump which will operate safely. Ammonia is also a toxic substance. (Stoecker, 1998)

The factors of climate impact, system performance and cost need to be weighed up to ultimately decide which working fluid should be used in the heat pump. This is a part of what will ultimately result in the final design of a heat pump and should be taken early on such that the heat pump is optimised to work with a specific refrigerant.

2.5. Hybrid systems

Heating demands vary seasonally and as such any potential heat pump needs to be sized appropriately to obtain the highest possible SPF. Figure 7 shows an example heating demand over a year. This U-shape trend can be found in a wide variety of demand profiles and is therefore a useful starting point when sizing a base load provider such as a heat pump. The easiest solution is to size the heat pump to the minimum heating demand such that the heat pump provides the entire heating requirement when the heating load is lowest. This solution requires the need for external provision of heat.

Figure 7: Monthly variations of gas and electricity demands (Harrison, 2011)

The purpose of this discussion has been to introduce the important notion of heat pump hybrid systems. To ensure that the peak heating demand is met throughout the year devices capable of dispatchable heat production is required. It is also possible to use renewable heating devices which require no fuel. This means that efficient use of their output is less important.

The common devices capable of delivering dispatchable heat are commonly gas boilers, biomass boilers, diesel generators and electrical heating. Gas boilers are the most commonly used as the systems are cheap to install, expertise is widespread and the fuel is easily obtained through the gas network. Due to the desire to switch to sustainable options increasingly common dispatchable heating devices are bio boilers. These are designed to burn bio materials such as wood chips, biogases or industrial waste. These fuels are seen as more sustainable than using fossil fuels like oil or gas. Electrical heating is one of the most costly ways of heating but remains widespread, particularly in older buildings. More modern hybrid systems involve solar heating and desalination processes. (Chua, Chou, & Yang, 2010)

2.6. Applications

Heat pumps can be used to provide heating for individual homes. In the UK GSHPs and ASHPs are slowly growing in popularity with people looking for alternatives to conventional fossil fuel boilers to heat their individual homes. The trend is most common for homes which are off the gas network (Caird, Roy, & Potter, 2012). This is because it is much easier for the economics of heat pumps to beat those of electrical heating. At the domestic level gas boilers are still seen as the economical choice of heating. One of the main reasons for this is that for a heat pump to perform at a high COP the outlet temperature should be as low as possible. Current housing stock is poor at maximising the space heating provided and as such radiators need to be provided with very high temperatures (around 75 degrees) to heat a home comfortably. Heat pumps work better with large radiators or ideally underfloor heating. These types of systems can provide comfortably heated homes at low operating temperatures. For new build homes it is easier to install these heating systems and therefore often heat pumps are economically, as well as environmentally, the best choice. For providing direct hot water high temperatures are necessary. This is because of the risk of legionella bacteria thriving in water tanks between 20 and 45 degrees. The bacteria do not survive above 60 degrees so for these health reasons hot water should be raised above this temperature (Borella et al., 2004). Heat pumps can provide the temperatures required, but at the cost of a lowered COP.

High temperature heat pumps are becoming more common. This is despite the thermodynamic relationship that a higher required temperature delivery results in a less efficient heat pump, and that it is always important to keep this temperature at a minimum. Industrial sites generally require high temperature delivery and therefore heat pumps are not seen as the obvious solution. However, in hybrid schemes it is possible for heat pumps to provide a base heating load and then to use biomass or gas boilers to top up the temperature. This helps reduce the emissions associated with the heat being delivered.

2.7. Case study: Shettleston Mine-water Heat Pump

There are numerous examples of working water source heat pumps in the UK. In Glasgow a successful example is the heat pump at the social housing scheme Shettleston, in the East End. The housing scheme, consisting of 16 flats and houses, was built with sustainability as an overarching aim and features a number of ‘green’ innovations. Of particular interest is the heating scheme used. The heat pump which utilises the water from an abandoned mineshaft provides low-temperature heating, with the heating systems in the flats and houses incorporating low-temperature radiators and underfloor heating to accommodate this.

An open-loop heat pump is used to draw water from the disused mine 90m below the surface. Due to the abundance of connected mines which replenish the water between them the extracted water keeps a steady temperature of 12°C. The heat pumps upgrade the water to higher temperatures, which is stored in a thermal tank from which the water is then pumped to the individual domestic heating systems. It is a hybrid system where solar heating panels further increase the temperature to 55 degrees and there is a backup 90 kW electric heater (though this has only been used twice in 5 years).

Economically the novel heating system has been successful with average heating bills of £440 per annum. Compare this to the average of £700 for a Scottish family. The main difficulty that has been experienced pertains to the filtering of the mine-water. The filtration system had to be replaced with a more sophisticated one soon after installation, and water filters need to be serviced weekly to avoid blocking with iron oxide. This project has been accepted as a success and governmental reports cite it as a positive example of a water source heat pump.

The Shettleston case study shows how water source heat pumps can viably be used to provide heating to a group of homes, more commonly known as a district heating scheme. (D Banks, Pumar, & Watson, 2009) ("Glenalmond Street Housing Shettleston, Glasgow, Case Study," 2015)

3. District Heating

Two distinct visions of the future of heating and cooling for buildings exist, with both of them focussing on improving the sustainability and efficiency of current methods. One focusses on buildings themselves, particularly a move to low-energy buildings. These could be passive houses where no heating or cooling is required. A possible future situation could be that through heat generating devices incorporated into buildings, such as solar thermal collectors, houses have a surplus of heat. The buildings would generate more heat than they require. A problem with this vision is the prediction of the future housing stock. It is estimated that 85% of the current housing stock will remain in the UK by 2050 (Kannan & Strachan, 2009). It is easier to build a passive house from scratch than to add retrofit improvements to an old building so it becomes passive. Therefore, while this vision may prove possible in the long-term, in the medium-term it is essential to find solutions to the heating problem. The second vision consists of widespread district heating schemes offering a method of bringing together sustainable, low carbon heat. Renewable systems such as large-scale heat pumps, as is the focus here, geothermal energy and large-scale solar thermal collectors can be combined with heat from places which are currently rarely taken advantage of: power plants, waste facilities, distilleries, and a whole assortment of industries. (Harvey, 2006)

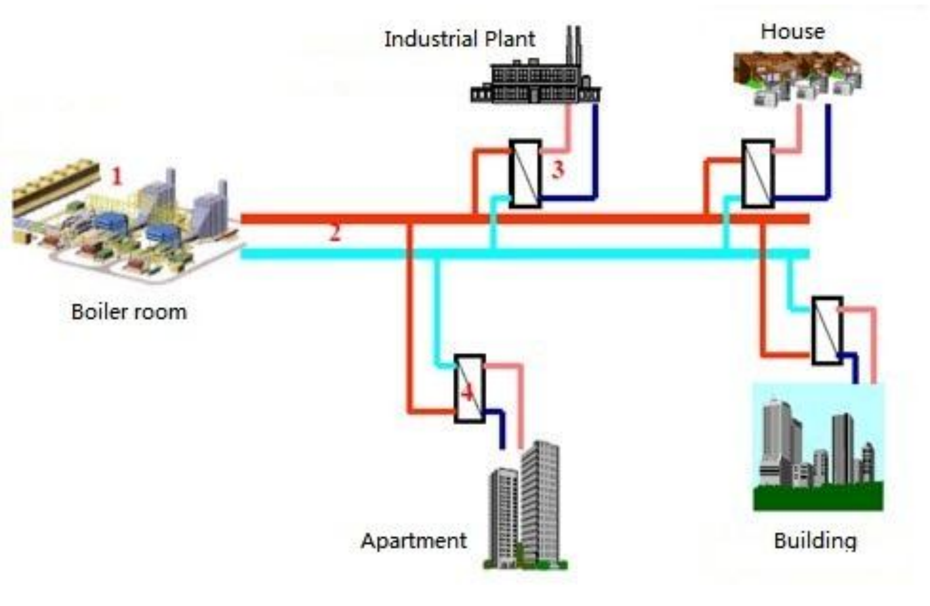

Figure 8: Simple schematic of district heating (SmartHeat, 2012)

3.1. Principles

District heating is the method of providing centralised heating to a group of buildings, industrial and/or domestic. Pipes carry hot water which has been heated using a centralised heating source, in a network to the buildings. Such schemes are currently scarce in the UK but are more prevalent in European countries; in Denmark 60% of heating comes from district heating (Lund, Möller, Mathiesen, & Dyrelund, 2010). In the UK it is more common to have gas piped to individual buildings which then use boilers to provide hot water.

District heating networks consist of three principle components. The first is the district heating plant, which is the source of the heat. This heat is then transported around the district through the second component which is a series of twin pipes; one pipe delivering the heated water and the other returning cooled water. The third component is the buildings themselves which provide the heating demand of the system.

3.2. Methods of heating

Conventional district heating systems use CO_2 emitting fossil fuels such as gas boilers. More novel solutions involve an assortment of heating sources. Many cities contain industrial sites which produce excess heat, which is most commonly disposed of through cooling towers and reservoirs. This could be used essentially as free heat. District heating provides a way for this heat to be delivered to homes. It also allows for the implementation of renewable heating solutions. Biomass boilers are becoming increasingly popular as a form of providing industrial scale heat and power. In cities there is often an abundance of waste biomass material to be burned, providing a sustainable heating option. It is difficult to follow the traditional model of buildings having individual boilers when using biomass as this would require the delivery or collection of large amounts of biomass every day. It is simpler to provide a centralised boiler which burns the biomass and provides heating to the district.

The options discussed such as biomass boilers and gas boilers provide the scheme with the possibility for not only heating but power too. Combined heat and power

(CHP) increases the efficiency of using boilers. In stand-alone power plants (essentially large boilers) there is a large amount of heat generated along with the production of power. By taking the boilers to a smaller scale, or taking the waste heat directly, into district heating schemes the efficiency of the boilers is increased. This is a distinct advantage of using CHP over large power plants where the excess heat is disposed of. (Harvey, 2006)

3.3. Distribution systems

District heating distribute heat either via water or steam. Older systems have tended to use steam whereas modern systems use water, therefore the focus will be on water distribution systems. The reason for this shift is down to improved efficiency. Distribution systems for district heating usually consist of two concurrent pipes delivering and returning heated and cooled water. An imposing technical problem for using heat pumps is that they work less efficiently when the required water temperature delivered in the network is high. Therefore the choice of temperature has a dramatic effect on the suitability of a water source heat pump. Two primary choices are available. One is to use a high temperature heating network such that the heat delivered to each load of the network is immediately useable. This is the network in use at Drammen, where the heat pump delivers high temperature water. The heat pump there has been designed to sufficiently to still have a high COP, showing that it is possible to deliver high temperatures along with high performance. The alternative is for the network to deliver low temperature water, and then for the individual loads to have their own heat pump or alternative to increase the temperature to meet their requirements. This has the advantage of being able to cater for a larger variety of unique thermal demands, while maintaining a high COP for the heat pump. It is particularly advantageous where the buildings use heating delivery systems suited to low temperature water delivery such as underfloor heating. Most of the current housing stock do not have such heating delivery systems installed and usually require high temperature water to satisfy their heating delivery systems. In simplistic terms it is beneficial to employ a high temperature district heating network for areas where the current building stock is expected to remain and to use a low temperature district heating network for new build schemes.

A novel idea slowly gaining recognition in literature is the idea of combining heating and cooling in one integrated thermal network. The cooled return water would act as the cooling delivery pipe. This provides the opportunity to gain more heat into the network as cooling can be thought of as simply taking heat from another source. This would add another layer of complexity and as the methodology presented is quite UK-centric, where cooling needs are smaller than most countries, it is deemed to be outside the scope for this thesis. This, however, may be a short-lived assumption as current trends suggest that cooling is the fastest growing energy intensive process in the UK, primarily due to the growth of computing facilities such as datacentres which require huge levels of energy for cooling.

3.4. Case study: Drammen, Norway

Drammen is a town around 50km from the capital of Norway, Oslo and has a population of over 60,000 people. In recent years the town has undergone redevelopment with a new hospital, housing, hotels, shopping centre and ice rink having been built. To further renovate the town the district heating system powered by biomass boilers was upgraded to a heat pump district heating system.

In 2011 Star Refrigeration built the heat pump consisting of three systems which combine to deliver 15 *MW* of thermal heat. In addition there are two 30 *MW* gas boilers to provide back up. The heat pump provides 85% of the hot water required by the town.

Figure 9 shows a typical daily variation of the heating demand profile of the town. The blue block shows the heating provided by the heat pump, with the remainder of the load supplemented by the gas boiler. The heat pump provides a steady power output up to its 15 *MW* capacity. The temperature of the water supplied is proportional to the heat demand. In the summer when there is the minimum heat demand the supply temperature is 75°C and in the winter when there is the peak heat demand the supply temperature is as high as 120°C. The temperature of the return water is more consistent, around 60°C for the entire year.

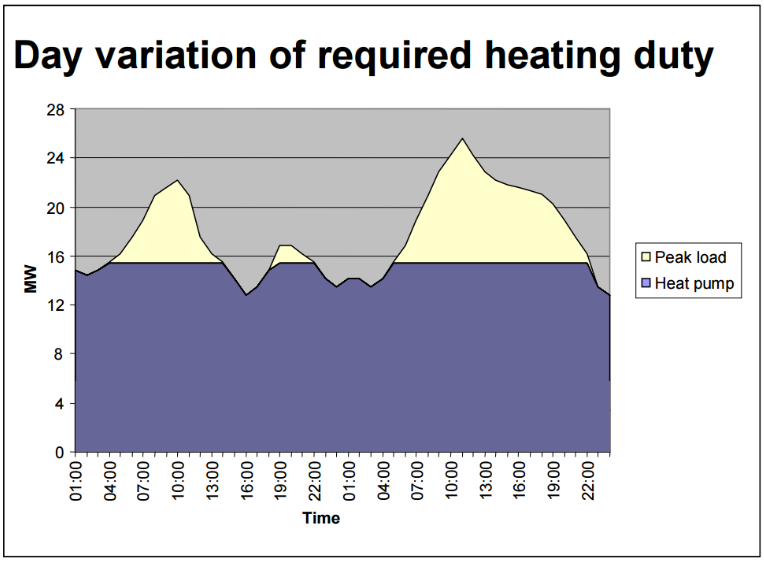

Figure 9: Drammen typical day heating demand profile (Hoffman, 2011)

The source of the heat for the heat pump is sea water. A unique characteristic of the fjord which Drammen sits upon is the steep gradient at which the sea level drops from the coastline. At the depths of around 40m the water has a steady temperature and is independent of the air temperature which can fluctuate between +20 degrees Celsius and -20 degrees Celsius.

The expectation of the heat pump was a SPF of 2.85 but, unusually for new technologies, the operating SPF is 3.15, exceeding expectations. Star Refrigeration estimates that using heat pumps as the base load in the district heating scheme, as opposed to conventional gas, provides savings of £1,042,289 annually. These technical and economic results outline the strong performance of utilising water source heat pumps in a district heating scheme. It suggests that the UK can also benefit from the widespread introduction of such schemes using the vast natural water resources available near to the countries' dense urban areas. (Hoffman, 2011), (Ayub, 2015)

4. Methodology

The methodology will outline the steps necessary to perform an investigation into the viability of a generic river source heat pump driven district heating scheme. It will focus on the core features: technical, environmental and economic. A flow diagram will be developed to provide a visual aid which brings together the different considerations required. Each section ends with the appropriate flow diagram. This methodology will be applied to an area of central Glasgow utilising a water source heat pump on the River Clyde to drive a district heating network.

4.1. River properties

Technically when looking at the feasibility of implementing a heat pump into a specific river the two most important characteristics are the water temperature and the river flow rates. This data can be obtained from local environmental government organisations where available. However, this data is usually gathered in data centres away from the prospective location of the heat pump on the river. River flow rates depend on the topology of the river bed but with large volume rivers this difference may be negligible. The water temperature is dependent on the depth at which the probe measures, with the temperature more steady (less dependent on air temperatures) at lower depths. This makes heat pumps which use water at lower depths more feasible. Independent measurements should be taken to improve the accuracy of the analysis. Both flow rates and water temperature is dependent on tidal influences. This thesis will not discuss this in detail as the dependency is taken to be inherent to the methods of data acquisition described. There will also be environmental impacts on the river as a result of installing a heat pump. These will be discussed in detail in “Section 4.5.2 Construction”.

4.1.1. Flow rate

A typical flow rate graph showing the daily flow rates of the river Don at Parkhill is Figure 10. There are large variations in the flow rates, probably due to heavy rainfall. There is also a general trend of higher flow rates in winter than in summer, which is to be expected due to higher temperatures causing higher evaporation. These are general trends to be found in rivers in the UK.

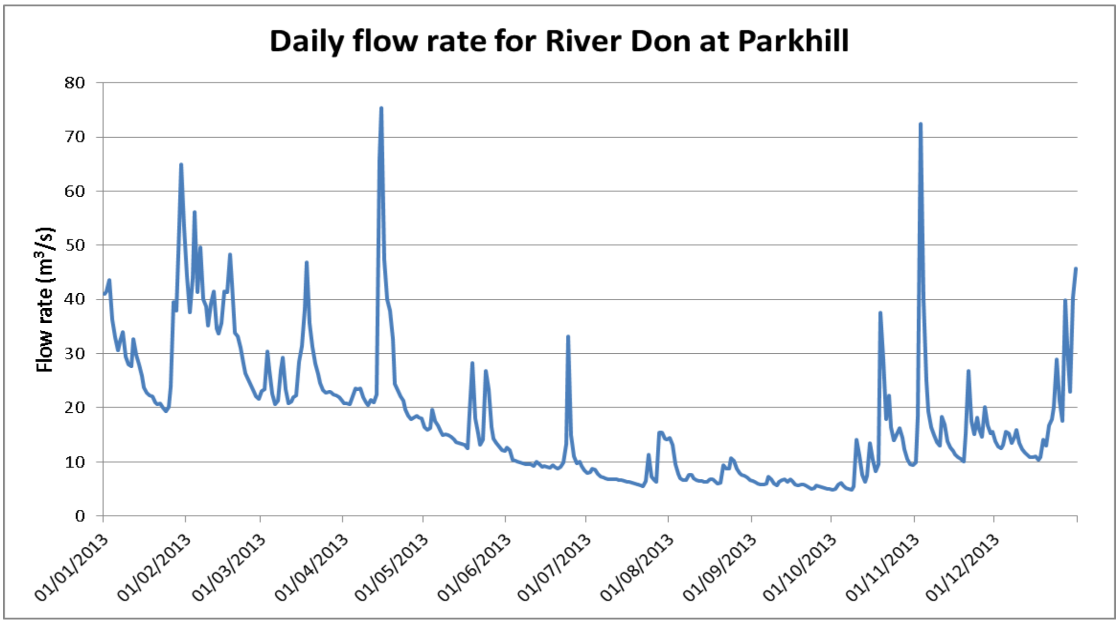

Figure 10: River flow rate, River Don

It is more useful to display the data in accordance with the percentage of time that a certain flow rate is exceeded. This provides a method of analysing suitable extraction levels for a heat pump and can be seen in figure 11. The flow rate required by the heat pump can be used to check for what percentage of the time that flow rate is exceeded. This gives the percentage of time that the heat pump can produce heat and what restrain the river flow rate has on the output of the heat pump.

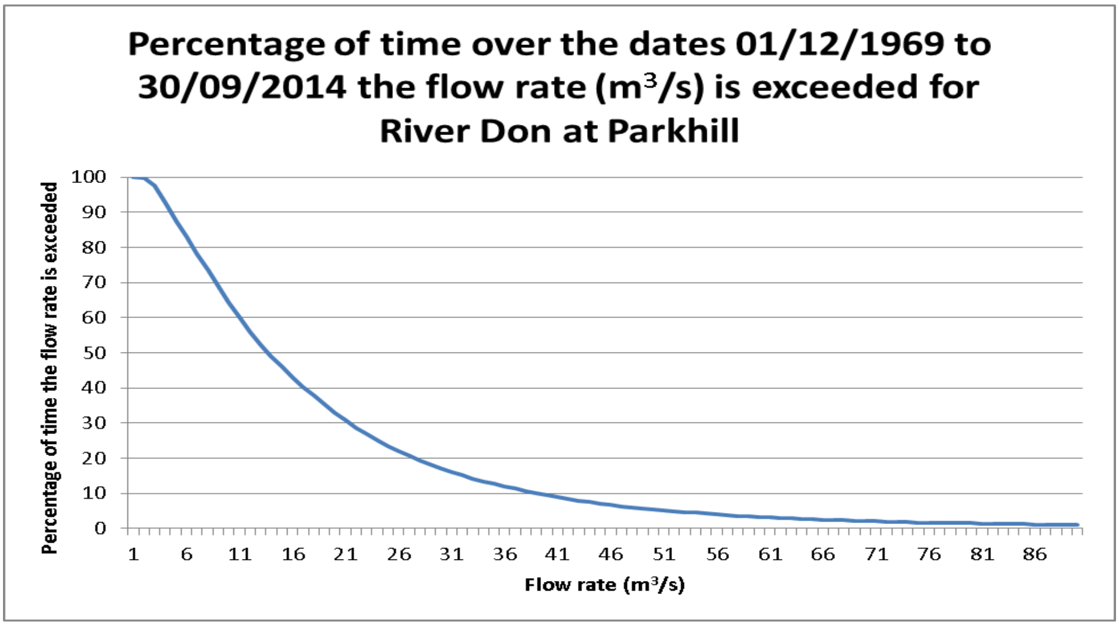

Figure 11: Flow rate exceedance curve, River Don

Data provided over longer periods of time provide a more reliable curve. The data in this example is from a 45 year period, and this is typically what is available from the National River Flow Archive (NRFA) for flow rates (NRFA, 2015). This is a robust period of time to extrapolate future flow rate availability. The above analysis method does not account for the seasonal variation of heat pump use. In reality in summer months the heat pump will be less in use while concurrently the flow rate will be lower. This means that the exceedance curve obtained from the entire year will be artificially lower than the exceedance curve which accounts for the winter months when the heat pump will be more in use.

4.1.2. Water temperature

Water temperature data from a prospective river source is required to determine the change in temperature which is possible. This is limited by the need to avoid freezing conditions. If the heat pump reduces the temperature of the water to 0°C or below then freezing of the water will occur. To avoid this it is necessary to ensure that historical temperature data is obtained and analysed to identify by what temperature it is possible to reduce the water by before freezing occurs. Another important reason is that the river temperature determines the temperature at which the refrigerant evaporates, which has a large effect on the possible COP of the system. It is desirable to achieve this at a high a temperature as possible. Higher river temperatures lead to higher COP heat pumps.

This data is not as easily obtained from environmental agencies as with river flow rates. Taking temperature readings from places further way can provide at least an intuitive guide as to river suitability. As with flow rates the suggested method is to take readings at the particular location of the potential heat pump. It is also ideal to take temperature readings from different locations on the river to identify trends and finally the location on the river with the highest temperature. The readings should be taken at as low a level in the river as possible, because this is where the heat pump should be situated to give as steady temperatures as possible.

Figure 12 is an example of the data which can be used to analyse river temperatures over a year period. The generic trend of seasonal variations is explicit, with summer temperatures exceeding those in winter. This variation should be minimised at lower depths in the river, making high temperature, deep rivers a prudent choice for heat pumps.

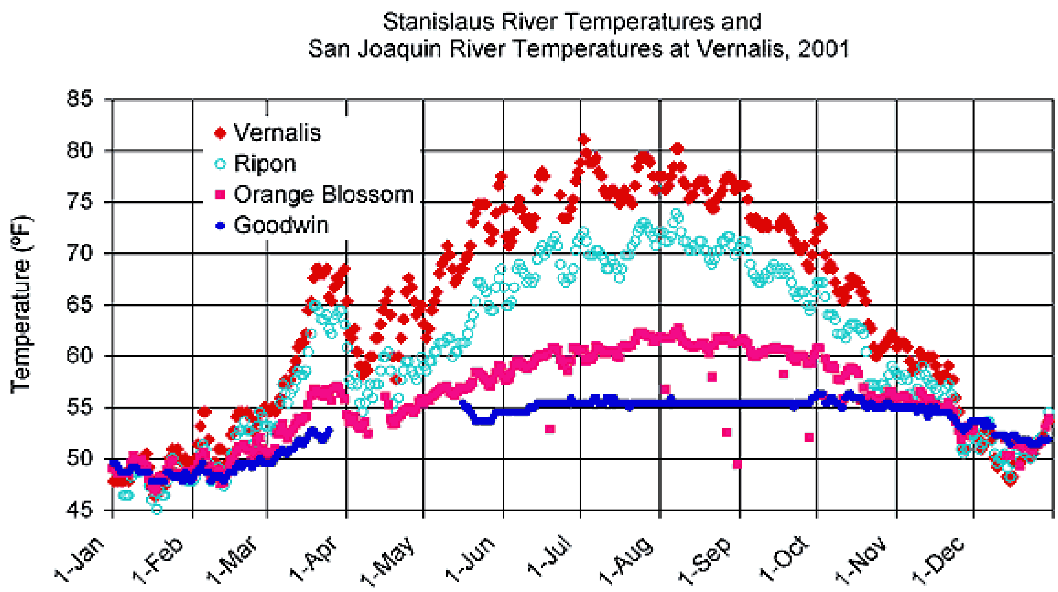

Figure 12: Example river temperature plot

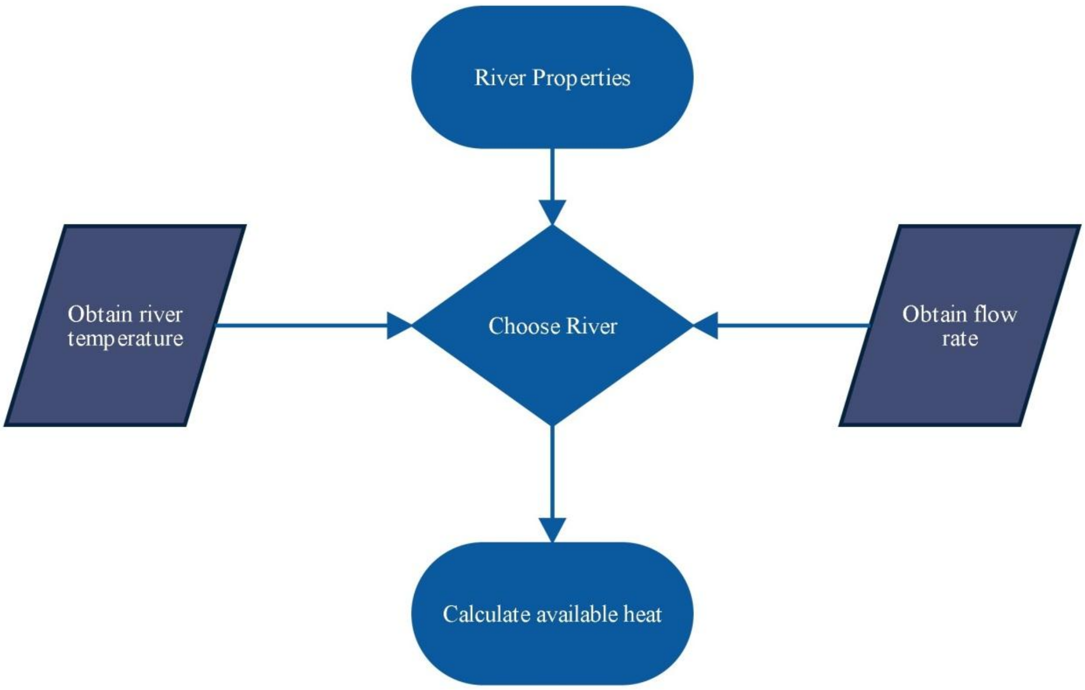

Figure 13: River properties flow diagram

4.2. River source heat pump

The heat which can be drawn from a river is determined by one of the fundamental equations of thermodynamics.

$$Q_{in} = \dot{m}\, \rho\, C_p\, \Delta T$$

Here Q_{in} refers to the heat which is drawn into the heat pump, *J*, $\dot{m}$ is the mass flow of water, *m^3/s*, ρ is the density of the fluid water, *kg/m^3*, C_p is the heat capacity of the water, *J/K*, and ΔT is the temperature difference between the water entering and exiting the heat pump, °C.

The mass flow is determined by the flow rates outlined in the previous river properties section. This equation emphasises the point that fast flowing rivers have greater potential because they can deliver higher quantities of heat. The equation also raises the importance of being able to lower the temperature of the river water by as much as possible. This again returns to the river properties, as the lowest river temperatures in winter will negate attempts to have a large temperature differential.

In a feasibility study the next step is to design the heat pump to fit both the demand profile of the heating and the quantity of heat available from the river. This thesis will look at implementing the heat pump which delivers the most heat to a thermal network. That means that this section looks at how to install the heat pump which delivers the most heat. This avoids the need to integrate a pre-defined thermal network at this stage. The district heating network will later be identified to fit the heat pump.

4.2.1. Heat pump sizing

It is important to optimise the size of the heat pump based on the energy available from the river. In reality to minimise cost it is important to consider various ways of minimising the size of the heat pump to increase the efficiency with which it can use the energy from the river. The capital cost of heat pumps generally outweighs conventional heating with the savings coming from reduced energy use. Carefully sizing a heat pump can reduce capital cost. The performance of certain components or the design of how they go together is beyond the scope of this thesis but is an area which is being researched extensively. Instead, this thesis will examine a limited number of potential options to help with reducing the size, and hence the capital cost, of a heat pump.

Diurnal thermal energy storage

Heat pumps can provide a more steady heating output at a smaller size if they are coupled with a thermal energy storage device. This is because they do not need to boost or reduce heat production to the same degree due to fluctuations in the heat demand profile. These fluctuations can be as simple as seasonal or night time variations. Thermal energy storage can be utilised to “fill the gap” during peaks or to be filled during periods of low demand; the heat pump can work at a much more constant level. Importantly this level can be lower than the peak heating load because of the thermal storage’s ability to “fill the gap”. Thermal energy storage need not simply be a conventional water tank. Thermal mass can be added to buildings in walls or floors such that the heating demand of the homes themselves can be more stable. It is also possible to use rock beds or phase change materials as an alternative to water tanks. However water tanks do offer a tried and tested method of storing heat and is likely to be the most appealing option. If the storage device is carefully controlled such that it is regularly emptied, it can negate much of the losses which arise from problems such as heat leakage. Another benefit to be gained is that the timing of heat production is further under user control. Often it is profitable to take advantage of cheaper night time tariffs to use electricity, meaning using heat pumps at night would lead to cheaper heat production. (Zalba, Marín, Cabeza, & Mehling, 2003) (Hasnain, 1998)

Seasonal underground storage

It is possible to engineer heat pumps such that they are reversible. This means that it is possible for them to provide heating and cooling. This opens the possibility for a novel method of storing heat. In a typical UK climate heating is required in winter and cooling in the summer, therefore it is seasonally dependent. When providing cooling in the summer, the heat pump must move the heat to somewhere. This could be underground. This is a particularly useful method for storage with GSHPs as the boreholes are already there to dump heat underground. It could be useful for water source heat pumps too if there is sufficient need for cooling in the summer. It does require the extra capital cost for digging underground, and essentially adding a GSHP to assist the WSHP. Another problem is that heat pumps are usually optimised in design to provide either heating or cooling, by including a reversibility function the efficiency, and therefore COP, of the heat pump is lowered for both, and consequently overall. Additional analysis is required to compare these economic and technical advantages and disadvantages to determine whether seasonal underground storage is a worthwhile additional feature to help with minimising the size of the heat pump. (Reuss, Beck, & Müller, 1997)

Technology-assisted heat pumps

Heat pumps can be designed to meet the entire heating load required. Due to the capital intensive nature of heat pumps it is better to use them to provide a part of the heating demand and install additional heating technologies to meet the variations that come from hourly, daily and seasonal differences. As has been discussed there are storage options which allow for the heat pump to overcome these fluctuations without additional heat producing technology. Installed systems are often hybrid systems which provide a top up to the heat pump's base load. A more extensive discussion is included in "Section 2.5 Hybrid Systems". This section is included to ensure that as part of any methodology for heat pump sizing that care is taken to analyse what technologies are paired with the heat pump. This is important particularly in all the three core sections of economical, technical and environmental. Economically it is useful to optimise the size of the heat pump and therefore savings can be made from how well the additional technologies can meet fluctuations, negating the need for an oversized heat pump to compensate. The choice of fuel from the additional heating device impacts on the overall environmental impact of the hybrid heating system too. Some heating technologies have a much higher CO_2 emission rate than others and therefore care is needed. (Ben-Yaacov, Wiener, & Lampert, 2013)

4.2.2. Case studies: Large-scale water source heat pumps

The purpose of this section is to look at more specific examples which utilise rivers, or similar seawater, as their source of water and which can apply for use on a generic river. The previous case studies gave a general overview of how heat pumps and district heating can be used in tandem to provide a novel heating solution. The case studies presented in this section focus on the heat pump technology currently in use, and how they can be applied to future projects. The focus will be on the technical aspects of the design of the heat pumps, such that they can be used to provide realistic technical details for later modelling. In a real-life feasibility study it would require an in depth design process to decide the technical details of a heat pump which is optimised to suit the specific situation.

Duindorp open loop seawater heating plant, Hague, Holland

In the district of Duindorp in the city of Hague, Holland there is a district heating system which is driven by an open-loop seawater heat pump maintaining a flow temperature of 11°C in the distribution network. Then in each individual household there is a heat pump which increases the temperature to around 65°C for hot water and 45°C for space heating. The system delivers 2.7MW and uses ammonia as the working fluid. Capital cost was around £6 million with operating costs of around £300k per year. Both energy and carbon dioxide emissions are estimated to have been halved as compared to having high efficiency gas boilers. (Stoelinga, 2009)

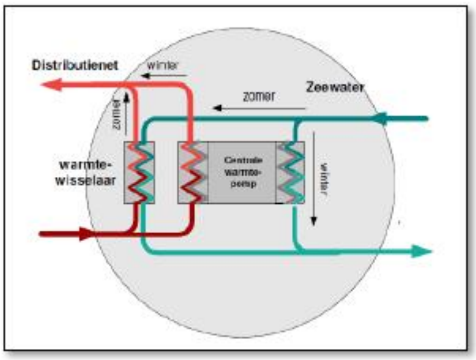

Figure 14: Duindorp, with heat pump arrangement (Stoelinga, 2009)

Kingston Heights open loop water source heat pump system

Kingston Heights is a housing development with an emphasis on eco-friendly living. They employ a heat pump which extracts water from the nearby River Thames and in combination with the whole system provides 2.3 *MW* of heat to 137 apartments and a 142 bedroom hotel.

Figure 15: Kingston Heights heat pump system (Smith, 2014)

The capital cost of the system was £2.5 million but the developers are confident that incentives, reduced operating costs and reduced energy use ensure that the project is economically viable and not simply part of an environmental agenda. Water is raised to a temperature of around 45°C through a series of stages. The complexity of this system gives a disadvantage of potential efficiency losses. (Smith, 2014)

Värtan Ropsten, Stockholm

Largest water source heat pump in the world with a capacity of 180 *MW*, this is a seawater heat pump which was completed in 1988. It uses 8 separate heat pump units which each use the refrigerant R134a haloalkane. This refrigerant is very harmful to the environment, being hazardous and having a global warming impact 1,410 times larger than CO_2. The system is highly capable of providing a variable output. Each unit has a 30MW capacity and an ability to downgrade output to 10% of capacity. The heat is fed into the Stockholm district heating scheme with water return and supply temperatures being around 57°C and 80°C. (Nowacki, 2014)

Figure 16: Largest water heat pump in the world, Värtan Ropsten (Nowacki, 2014)

4.2.3. COP seasonal variation model

The seasonal variation in river temperature causes changes in the COP of the heat pump. A simple model in Excel was created to simulate this variation. It was assumed that the heat pump is designed to provide the mean COP at the mean river temperature, and then the COP varies linearly with respect to the variations in temperature. The variation is taken to be 5% of designed COP per degree variation. This means that an increase in water temperature by one degree results in a 5% increase in COP and similarly a one degree decrease results in a 5% decrease in COP. Figure 17 displays the variation of the COP against the difference between the water temperature and the annual mean water temperature. Taking the average of this seasonally varying COP over the entire year gives the SPF. The heat pump design ultimately dictates the COP variation and instead of modelling this tests could be performed by the manufacturer to determine sensitivity.

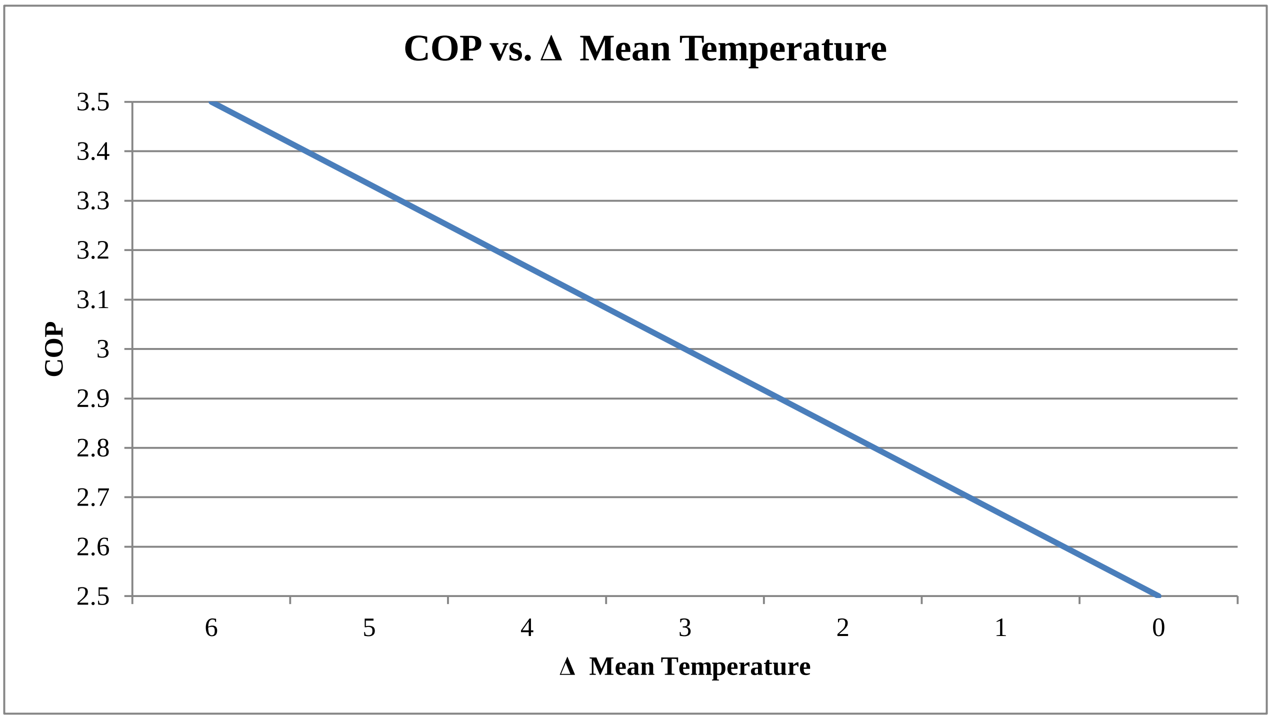

Figure 17: Seasonal variation of COP, River Clyde

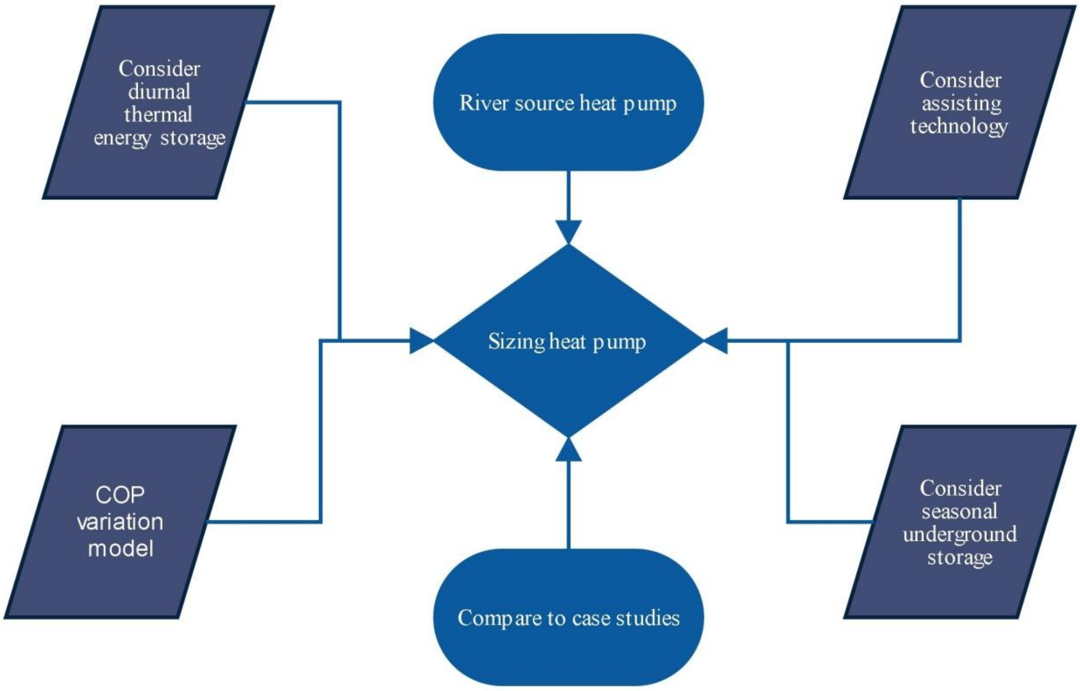

Figure 18: River source heat pump flow diagram

4.3. District heating

In the previous sections some technical aspects of a WSHP have been detailed as well as a look at a few case studies which detail some characteristics of water source heat pumps in various parts of the world. The design process also depends on the demand profile the heat pump is accommodating for. Heat pumps can be used to heat an assortment of needs: individual homes, large tenement blocks, distilleries, government/council buildings, universities, etc. District heating can be used to provide a method of connecting the thermal requirements of all of these. This results in a collective demand profile which needs to be met. As has been discussed, the best heating system for district heating is likely to be a hybrid system, consisting of different heating devices. This means that along with the river source heat pump there will be additional devices covering variability in the load and to provide back up. Modelling is required to investigate the best fit for a variety of heating configurations and will be performed by developing an Excel spreadsheet. This will primarily be used as an exercise in demand/supply matching to examine the various benefits of different heating supply options.

Determining the demand profile for a district heating scheme can be complicated and in the following sections a methodology for identifying a potential area suitable for district heating and producing a basic demand profile for that area will be outlined. The methodology presented here is not for an accurate prediction of the actual future, past or present demand profile, but for providing a demand profile realistic enough to provide useful insight. This section concludes with the relevant flow diagram.

4.3.1. Heat map site identification

In an effort to promote the implementation of low-carbon heating solutions the Scottish Government developed an interactive heat map "to visualise and assess who needs heat, where sources of heat might come from and how these can be connected in an efficient way to reduce the cost of heat supply and the carbon intensity of heat generation." (HeatMap, 2015) It is a Geographical Information Systems (GIS) tool, containing large datasets capable of providing greater understanding of the potential for alternative heating. It is a map of Scotland with tools for overlaying information regarding heat demand, current heat supplies, geothermal opportunities, social property ownership percentage and current district heating schemes. The underlying motivation is to provide a tool capable of highlighting the socio-economic benefits, which are widely available, of transforming away from traditional methods of heating to modern, low-carbon ways of heating.

It is most useful for identifying where concentrated areas of heat demand exist. These are areas which have the greatest potential for installation of district heating. In the context of river source heat pumps it should be used for identifying the areas along rivers which suit the capabilities of a heat pump driven district heating scheme.

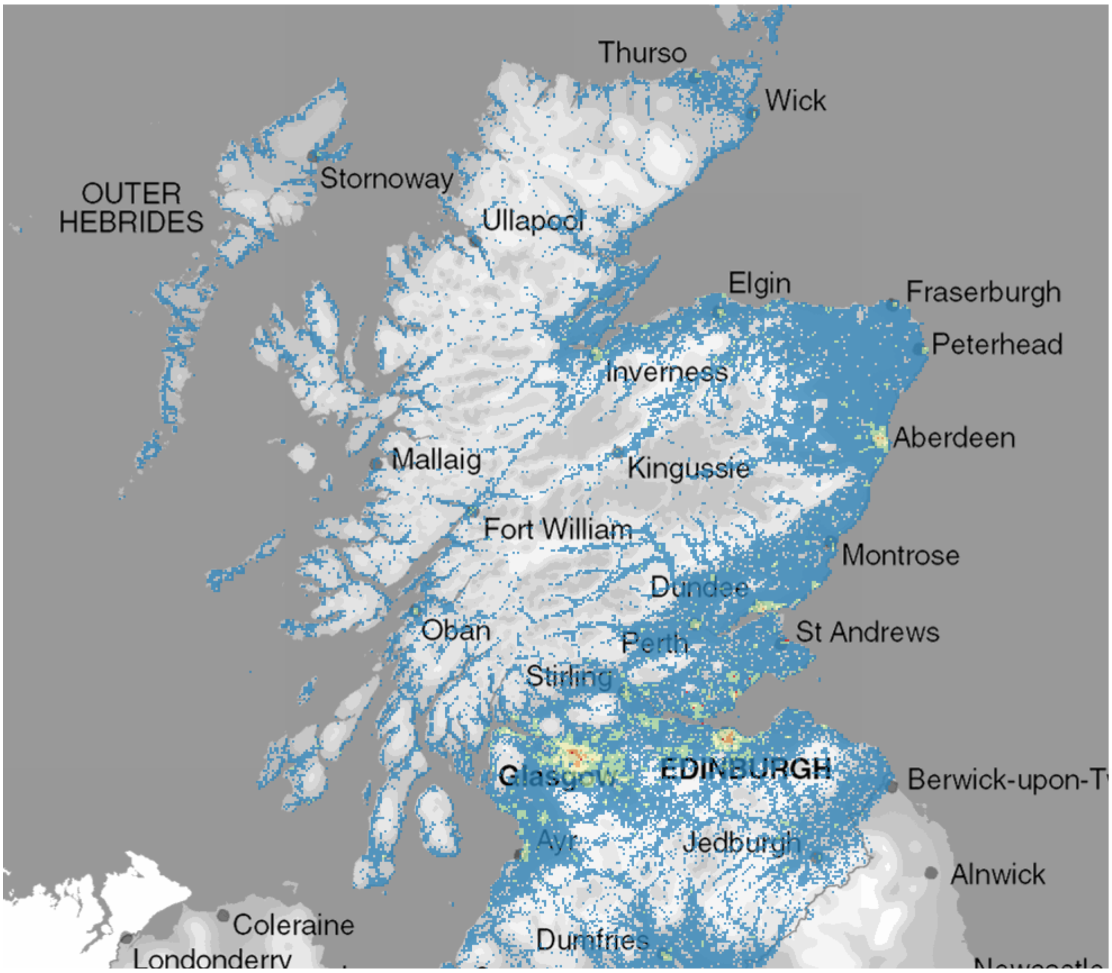

Figure 19: Heat Map Scotland: Overview of Scotland

Figure 19 is a snapshot from the heat map providing an overview of the heating demands spread across the entire country. The scale runs from grey to blue to red, with red and grey corresponding to a large heating requirement and virtually non-existent heating demand respectively. It is immediately obvious that the central belt and east coast regions of Scotland, where most of the population resides, have the highest density of heating demand.

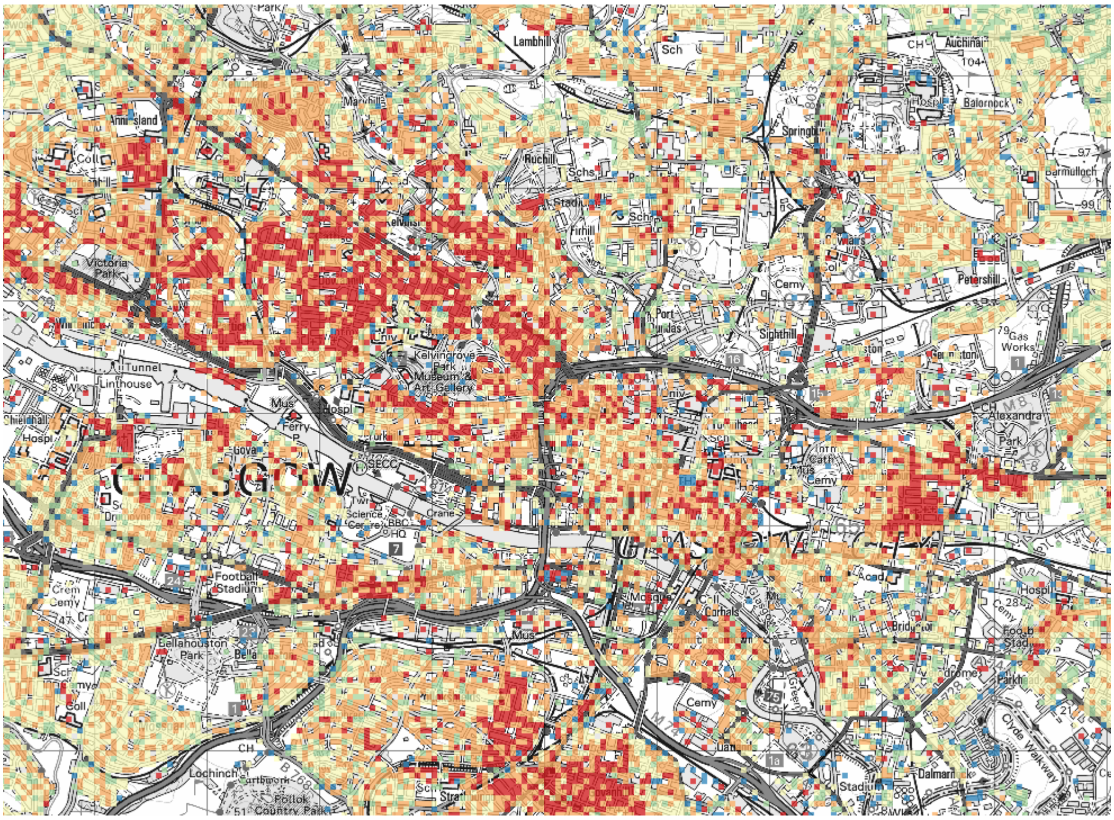

Figure 20: Glasgow heating demand map

Figure 20 zooms up on central Glasgow showing the heating demand at the lowest possible scale of 50 m^2. This conveys then resolution power of the heat map. It is possible to, with a reasonable degree of accuracy, map out areas near to the River Clyde which are most suitable for district heating. There is a zone selection function which calculates the total annual heating demand in a user defined area. This allows selection of a suitable area with a heating demand which a river source heat pump can drive a district heating scheme for.

The map also contains other valuable tools. It can show where there are installed low-carbon energy supplies, as shown in figure 21. Another tool displays the operational (pink) and in development (green) district heating schemes, with the size of the icon denoting the relative size of the scheme. The percentage of social housing in an area is shown in the same figure, 22, and is useful because generally district heating is easier to be agreed upon in these areas.

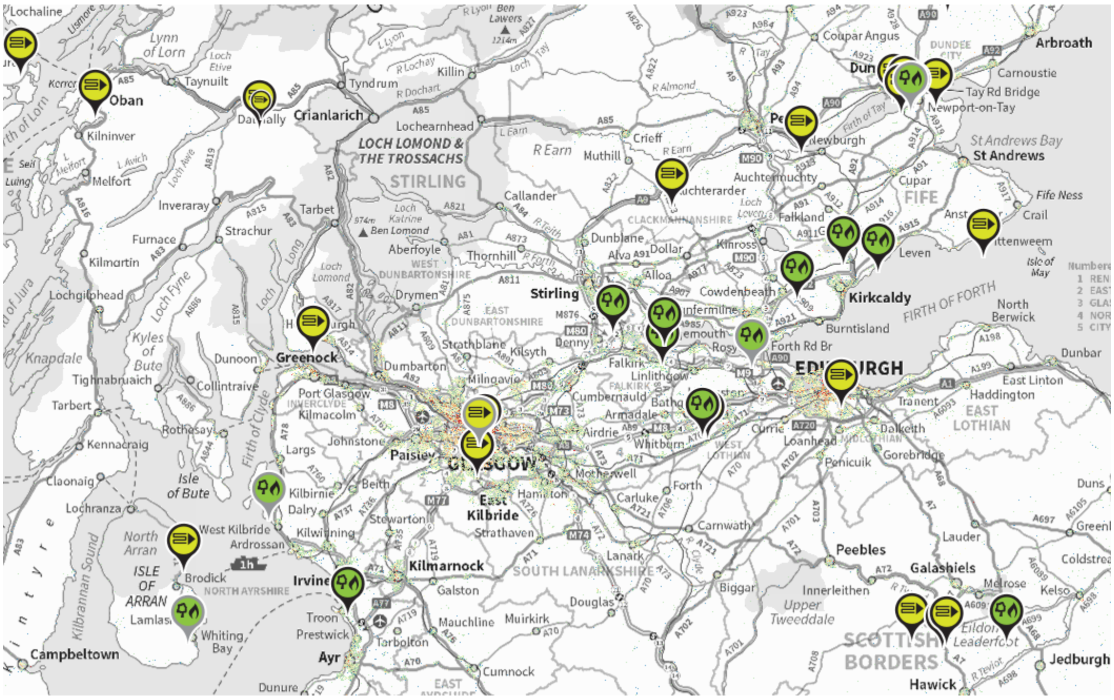

Figure 21: Heat map, low-carbon technologies, yellow: ASHP, green: Biomass

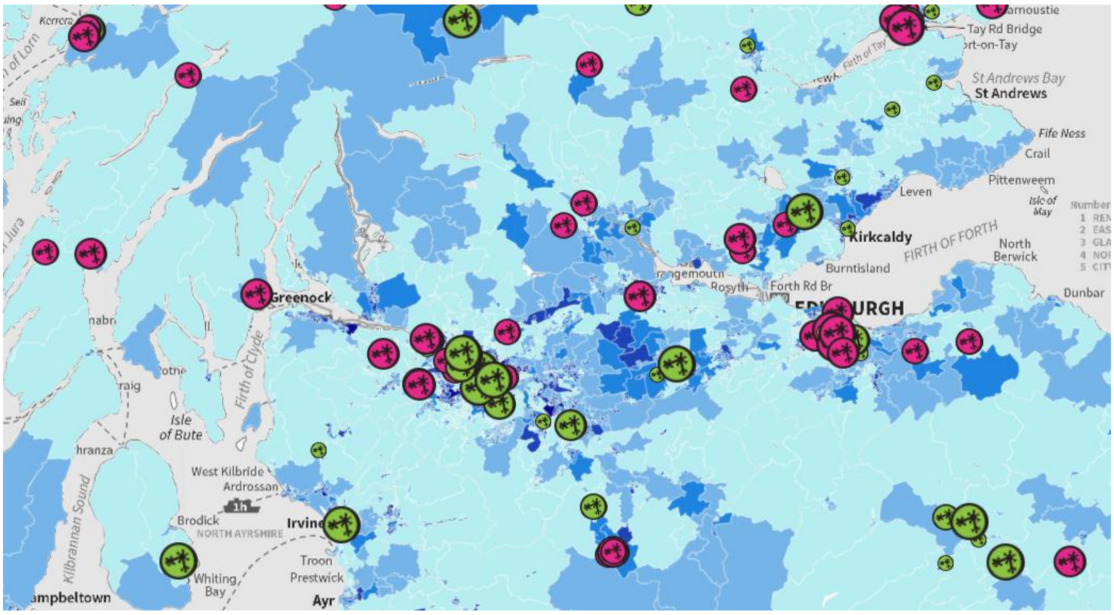

Figure 22: Heat map, social housing and district heating icons

4.3.2. Demand profile

Once an area has been selected from the heat map the next step is to produce a demand profile over a year. The heat map only provides an annual heating requirement, which is useful to give a very basic notion of the size of heat pump which is required. However, it is necessary to consider the seasonal, daily and hourly fluctuations which will characterise the heating demand profile. This is done by attempting to distinguish different classes of heating demands in the selected zone. The chosen classes were domestic dwelling, offices, and retail. Some buildings are unique so should be treated as an individual class. For a real feasibility study it would be necessary to attempt to contact the relevant authorities and businesses to obtain a more accurate heating profile. The heating demand is usually separated between hot water and space heating. This analysis aims to provide an overview of total heating requirements, so shall combine the two indiscriminately. Table 2 outlines the various characteristics of the classes of building.

Table 2: Thermal demand characteristics of building class

Residential	Commercial	Office
Heating demand zero during night: 00:00 → 06:00	Heating demand zero during evening and night: 19:00 → 08:00	Heating demand zero during evening, afternoon and night: 12:00 → 07:30
Fairly constant demand: 06:00 → 00:00	Reducing demand from: 08:00 → 19:00	Sharp rise and fall to peak at 09:30 from 07:30 → 12:00
Gradual seasonal variation	Gradual seasonal variation	Distinct seasonal variation

The following graphs show a typical day demand for each of the building classes, illustrating further the characteristics outlined in Table 2. Note that the residential profile is based on a three bedroom house. The demands were obtained from the Merit demand/matching software with half hourly time-steps over a whole year.

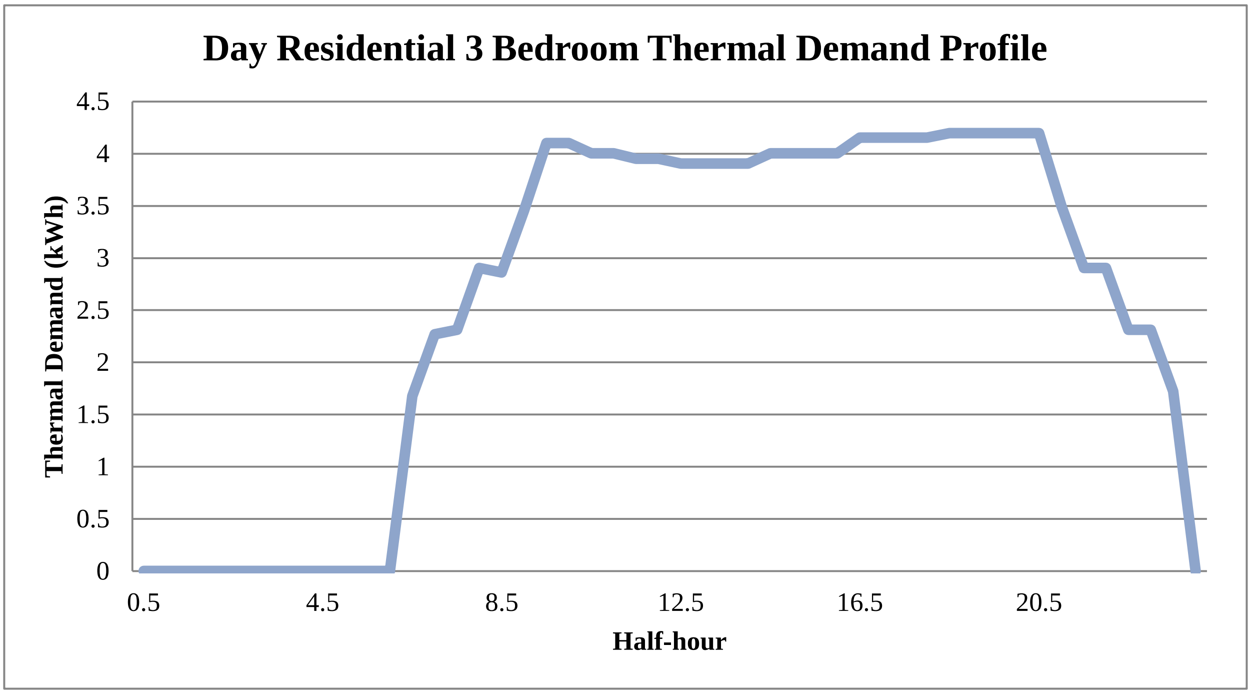

Figure 23: Residential thermal demand profile

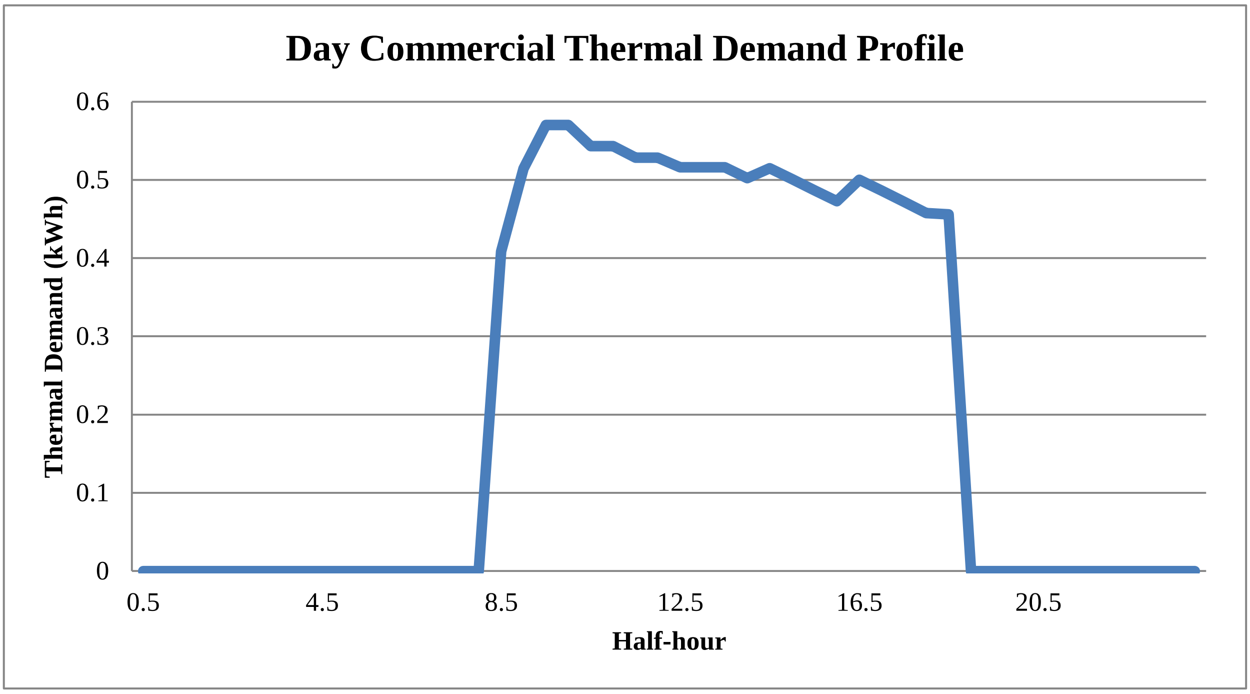

Figure 24: Commercial thermal demand profile

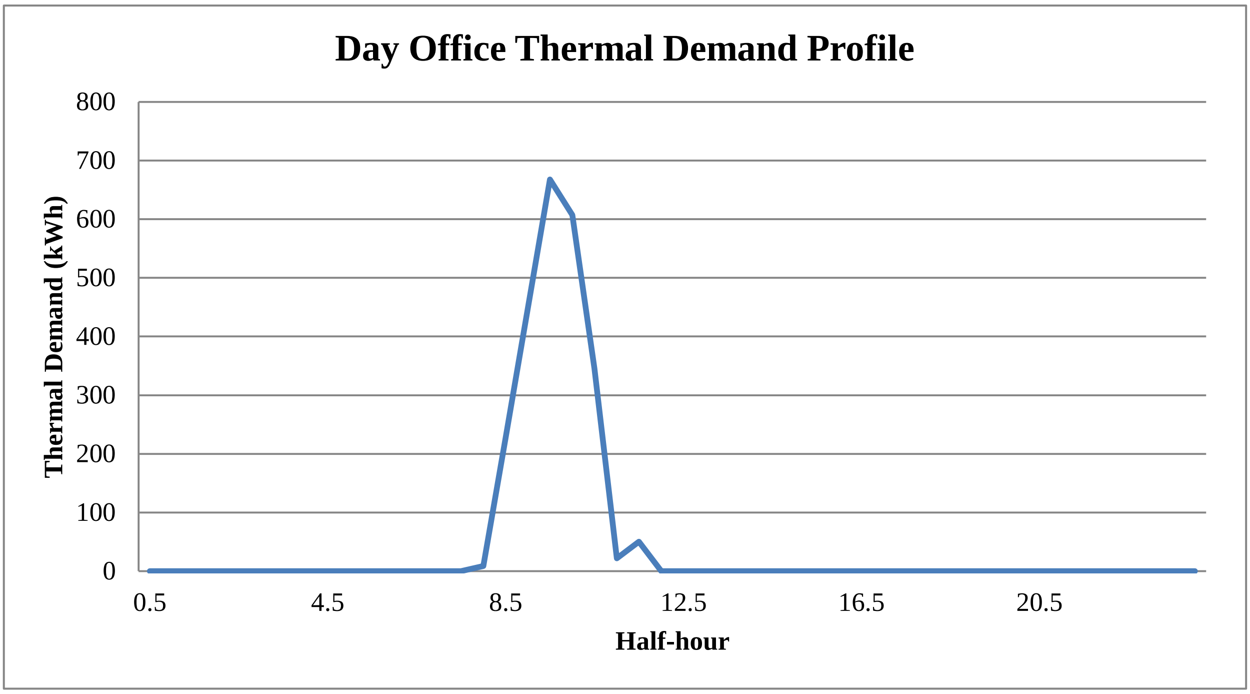

Figure 25: Office thermal demand profile

These demand profiles then need to be accumulated to provide a representation of the district heating network. The first step is to find the total annual demand of the proposed area. The heating demands should then be normalised to each other based on their individual total annual demand. This is because in their original format they all have different individual total annual demands. The relative ratios of the building classes should then be estimated based on any information regarding the proposed area that can be obtained. For example if it is estimated that there is equal proportion of the three classes then there is a 33.33 : 33.33 : 33.33 relative ratio. The normalised building classes can then be scaled up such that they account for the total annual demand of the proposed district scheme. The problem here is that it assumes that each house will use heat at the exact same time and they will all use a peak heat load at the same time. In reality the accumulation of thermal demands causes a smoothing of the demand profile. This is because individual buildings will have slightly different demand profiles and the differences combine to result in a smoothing effect. To simulate this, a moving average over 36 half-hour data points is taken. This provides a demand profile which maintains the characteristics of the individual profiles, while accounting for the inherent reduced variability of scaling the demand up to the district scheme level.

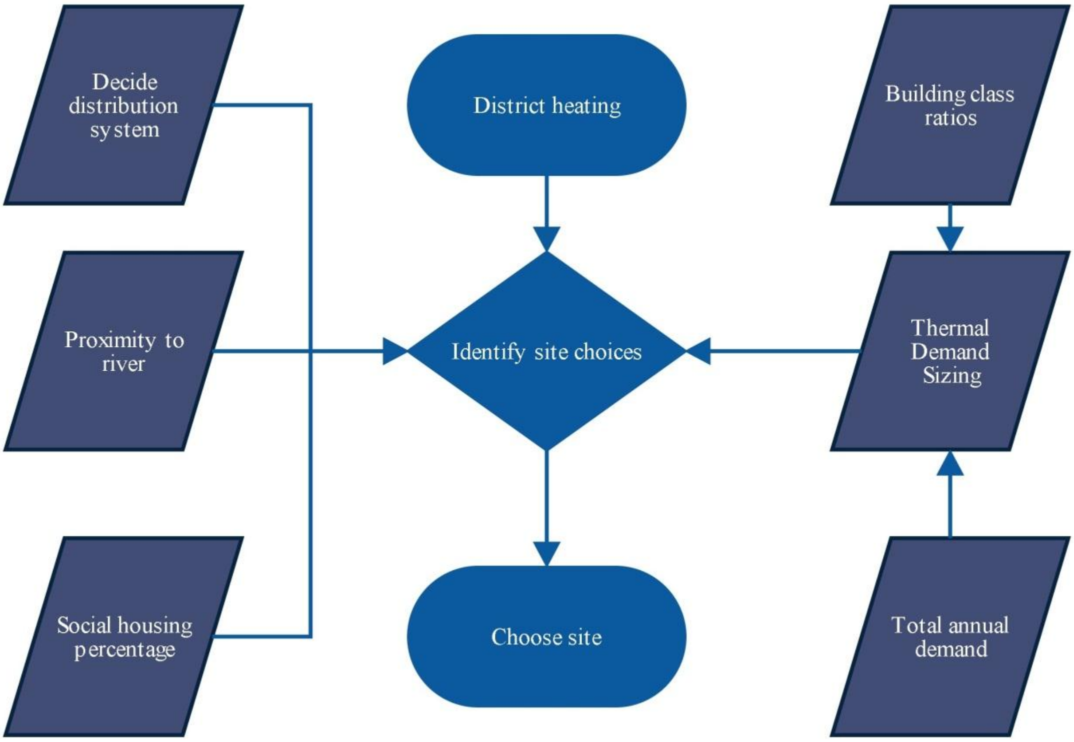

Figure 26: District heating flow diagram

4.4. Demand/Supply matching

In order to suitably combine the heat pump and the district heating demand it is necessary to perform demand/supply matching. This was done through the development of an Excel spreadsheet which essentially compares the supply, the heating system, and the demand, the district heating. The methodologies for developing profiles for the district heating demand and the supply profile of the heat pump have been described earlier. The purpose of the Excel is to bring these two profiles together. The heating system configuration will be set up in the spreadsheet and are defined in the following section. A number of technical outcomes are used to help with sizing a demand to fit the heat pump.

4.4.1. Heating system configuration

Four heating system configurations were used in the analysis to provide comparisons. The first two cases do not employ a district heating scheme, individual buildings provide their own heating through individual heating systems. The other two cases do have district heating. These incur 2.5% losses due to the piping systems involved.

The base case uses gas boilers to provide all the heating needs. This is taken as the base case because it is the most common heating setup in the UK. It is easy to set up as it is presumed that all of the heating needs are met by the individual boilers. They are high efficiency boilers with $\eta = 80\%$. (Sun, Wang, & Sun, 2004)

The second base case is a 50:50 mix of individual boilers and electrical heating. Electrical heating is still prevalent in many outdated homes and therefore needs to be considered. It is taken that electrical heaters are 100% efficient. This neglects the inefficient methods by which electrical heaters are employed in homes.

The third case employs solely gas-powered CHP devices. It is assumed that they have sufficient output variability to meet any change in demand. The heat leads the power meaning that the power produced by the plants is the by-product and does not try and match actual electrical demands. It is assumed that all the power produced by the CHP can be used. The ratio of heat to power was 2:1. This means that for every 2 *kWh* of heat produced, 1 *kWh* of power is also produced. The efficiency of the CHP is taken to be 75%. (CarbonTrust, 2010)

The fourth case is made up of a river source heat pump and CHP. The CHP has the same characteristics as the third case. The technical parameters of the WSHP is determined by following the methodology given in section ‘4.2 River source heat pumps’, and is dictated by the specifics of the river, technical limitations, and the district heating scheme demand needs. Table 3 outlines the technical characteristics of all four configurations.

Table 3: Heating system configurations of the four cases

	Base Case 1	**Base Case 2**	**Case 1**	**Case 2**
Configuration	Indiv. Gas Boilers	Indiv. Gas Boilers + Elect. Heating	CHP Only	WSHP + CHP
Efficiency	80%	80% + 100%	75%	N/A% + 75%
Piping Losses	0%	0%	2.5%	2.5%

To model the effect of choosing between high or low temperature distribution systems, two different COPs were used in the following demand/supply matching analysis. For a high temperature distribution system a COP of 3.0 was used and for the low temperature one a COP of 3.5 was used. These are based on comparative COPs from case studies and the requirement to qualify for the Renewable Heat Incentive (RHI) which requires a COP of at least 2.9.

4.4.2. Technical outcomes

A number of technical outcomes are produced from the Excel spreadsheet to aid the sizing of the demand to fit the heating system configuration. A simple technical outcome will be the net electricity consumed by the heating configuration including the heat pump.

The average percentage of the capacity of the heat pump utilised (*A.C.F.)* provides an insight into whether the heat pump is the correct size to fit various demands. This is calculated using the following equation.

$$A.C.F.(\%) = \frac{(Heat\ pump\ provision/Heat\ pump\ capacity\ output)\ \times 100}{17520\ (= number\ of\ half - hours\ in\ a\ year)}$$

The percentage of the annual demand provided by the heat pump *(P.H.P)* gives another insight into the utilisation of the heat pump device itself. It is calculated using this equation.

$$P.H.P.\ (\%) = \frac{(Heat\ pump\ provision/Demand)\ \times 100}{17520\ (= number\ of\ half - hours\ in\ a\ year)}$$

The heating system configuration with the heat pump also includes CHP. It is important to keep track of what size of CHP is required to compliment the heat pump. This is done by evaluating the size of CHP unit required by examining the peak load over the year and including a safety 10% to ensure that the heating demand in an atypical year can still be met. It is calculated using the equation below.

$$Size\ CHP\ (MW) = 1.1\ \times 2\ \times \frac{Max\ CHP\ over\ every\ half - hour\ of\ the\ year}{1000}$$

Note that in this equation the need for the factor of 2 is to account for the fact that the timescale is in half-hours.

4.5. Environmental

One of the main motivations for considering heat pumps is that they are perceived to be more environmentally friendly than other forms of heating. This section will set out a methodology for determining the various environmental impacts associated with heat pumps and district heating networks. It will discuss the legislation and organisations which must be consulted with regard to the use of water by the heat pump. The impacts surrounding the construction of the district heating network will be detailed with a view to formulating a method for mitigating and eliminating such impacts. Then the issue of air quality and emissions will be addressed and the procedure for quantifying these will be developed. Addressing the core environmental principles allow for the formulation of the environmental methodology capable of further investigating the viability of a district heating network driven by a river source heat pump.

4.5.1. SEPA regulations

The principle government body in charge of regulating, improving and protecting environmental issues in Scotland is the Scottish Environmental Protection Agency (SEPA) (SEPA, 2015). This means that water issues, and in particular those pertaining to water source heat pumps, come under SEPA's jurisdiction. The Water Environment (Controlled Activities) (Scotland) Regulations 2011 covers the level of authorisation required for any projects which involve the use of natural water. These regulations are also known as CAR. Figure 27 outlines the authorising process which must be followed.

The important areas from the regulations relevant to water source heat pumps are required licences and subsistence charges. If the scheme abstracts water in excess of 2,000m^3 per day then the project requires a 'Complex License'. This involves a fee of £2,934 and an application procedure lasting four months. For the pipework and heat pump structure an 'Engineering Licence' would be required as a separate licence from the 'Complex Licence'. The fee for this would be £2,000. Subsistence charges can be avoided by ensuring that the heat pump returns the water it extracts to the same location. This should be incorporated into the design of the heat pump to avoid this extra fee and to ensure compliance of the project with SEPA.

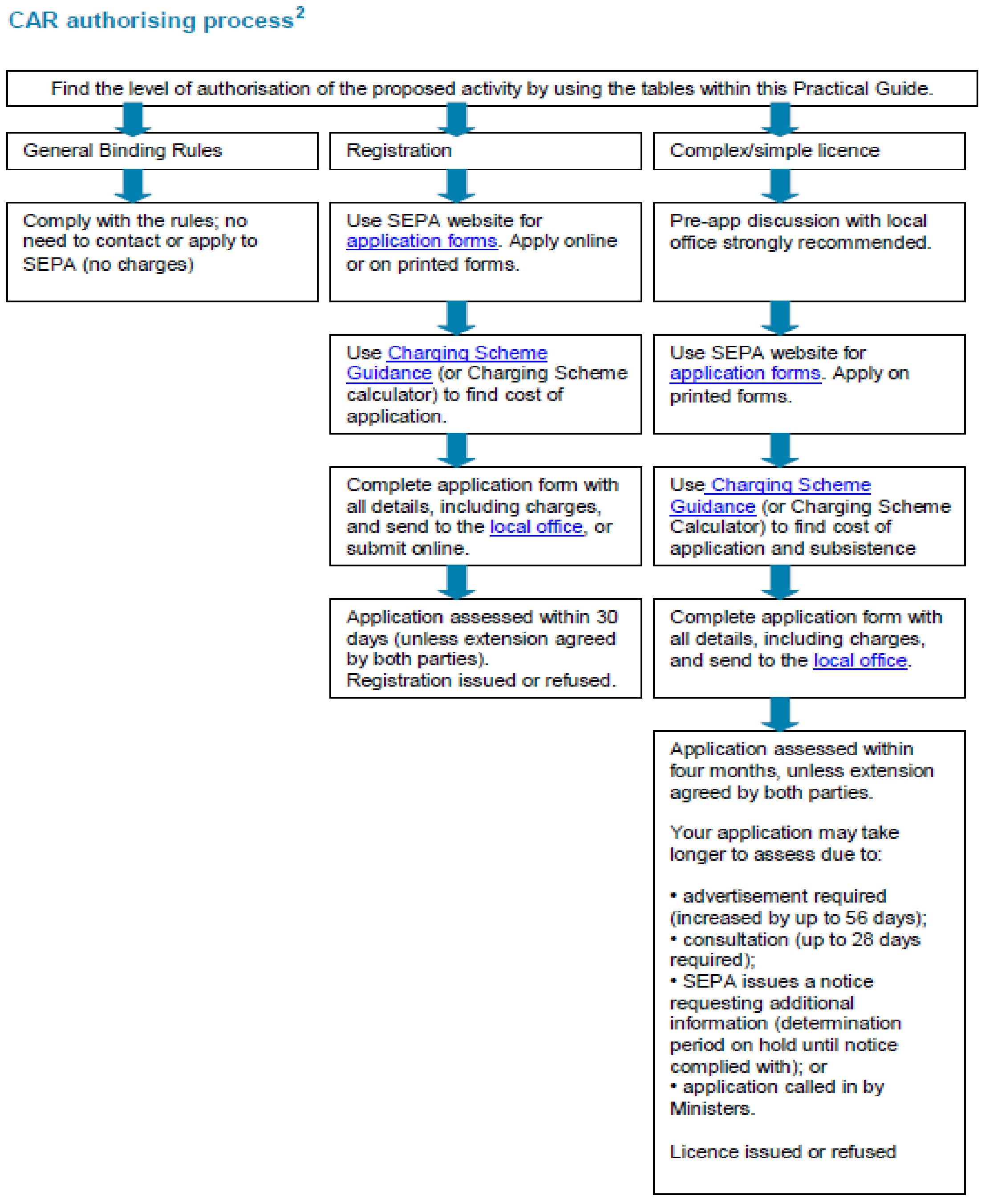

Figure 27: CAR authorisation process

4.5.2. Construction

The construction of both the heat pump and district heating network pose a large a number of potential environmental issues. The main problem comes from the expensive and far-spread pipe work which needs to be laid out to both take the heat from the heat pump to the district heat network and for the district heat network itself.

If the central district heating centre is not located at the heat pump then piping will be required to connect the two. Mapping (for example Google Maps) can be used to identify an ideal network path as well as a number of alternatives. An example network is shown in figure 28. Note that bridges are useful for piping across a river. Then the paths should be analysed from an environmental perspective considering the brief checklist provided in table 4. This can be performed on foot and ensuring photographs are taken to assess any issues.

Figure 28: Glasgow, example annotated piping network

Table 4: Environmental checklist for piping

Heat pump	District heating
Routing should use bridges to cross rivers	Possible traffic disruption if follows roads
Historical consultation	Historical consultation
Drift deposits	Disruption to public
Solid deposits	Distance from centre
Existing ground conditions	Land use

A full environmental impact assessment would be required to determine the full significance of the various potential impacts. This brief method provides a simple method for determining the obvious impacts at an early feasibility stage.

4.5.3. Emissions and air quality

The CO_2 equivalent savings are calculated by comparing the CO_2 equivalent emissions of both the energy used by a heat pump and CHP system and that of the solely CHP system to the base case of individual gas boilers. The first system will use more electricity than gas, with the heat pumps COP determining CO2 equivalent savings. The CHP only system will provide CO2 equivalent savings through the additional production of electricity. The base case will be used to determine the savings. The following equation defines how CO2 equivalent savings, in *kg/yr*, are calculated.

$$CO_2\ Savings = \frac{(E_{Base}) \times (\alpha_{gas})}{\eta_{boiler}} - Em._{emb.} - (E_{Case}) \times (\alpha_{gas}) - (E_{grid}) \times (\beta_{grid})$$

Where E_{Base} is the thermal energy produced by the gas used by the base case, in *kWh/yr*, α_{gas} is the mass of carbon dioxide equivalent emitted per *kWh* for natural gas, in *kg*, η_{boiler} is the efficiency of the individual gas boilers, $Em._{emb.}$ is the embodied emissions of the chosen case, in *kWh*, E_{Case} is the thermal energy of gas consumed in the chosen case, in *kWh/y*, E_{grid} is the net electricity imported to the grid (accounting for exports), in kWh, and β_{grid} is the mass of carbon dioxide equivalent emitted per kWh for electricity.

The embodied emissions accounts for the carbon dioxide equivalent emissions associated with the construction and materials involved with the cases. This can prove particularly difficult as it requires the energy used to build materials for devices and even then the materials used for a device are not easily obtained. Construction carbon dioxide equivalent emissions are also difficult to obtain as construction time can vary even for the same project and there is rarely any monitoring of emissions on-site. These figures should be obtained where possible.

The CO_2 equivalent emissions factors, α_{gas} and β_{grid}, can be obtained from the Department of Environment, Food & Rural Affairs (DEFRA) who provide a large variety of emission factors for greenhouse gas reporting (DEFRA, 2015). These are the figures from the 2015 update. These figures are provided so that companies can calculate and report their own emissions.

Table 5: CO_2 equivalent emission factors for gas

$\boldsymbol{\alpha_{gas}}$	$\boldsymbol{\beta_{grid}}$
0.18445 kg/kWh	0.46219 kg/kWh

It is important to note that these figures represent the carbon dioxide equivalent factor. This is the combination of all the emissions which contribute to global warming and equating them to CO_2. According the Kyoto Protocol there are 7 contributory greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Each of these has an equivalence factor to CO_2 which is treated as the base measurement for global warming impact.

The UK currently has targets to decarbonise the grid; they are committed to a greenhouse gas emission reduction of 45% by 2020 and 80% by 2050 (NationalGrid, 2015). This needs to be included in the analysis of carbon savings. It will be presumed that there will be a linear 12% reduction in the CO_2 equivalent emission factor annually. This means that by 2021 there will 47% reduction in the factor from 2015. This assumption, perhaps optimistically, expects that governmental targets will be met in the projected timeframe.

The carbon dioxide equivalent factor does include the effect of a number of global warming impact greenhouse gases. It is also useful to consider the possible reduction of emissions which effect air quality. For this section it will be assumed that the electricity consumption has no effect on air quality, as often the producers of the electricity are situated away from major cities. Nitrogen oxides and carbon monoxide are the two emission products which are useful as measures of air quality. Table 6 provides the emission factors for NO_X and CO from gas combustion.

Table 6: NOX and SOX emission factors for gas (USEPA, 1995)

NO_X	**CO**
0.000062 *kg/kWh*	0.000142 *kg/kWh*

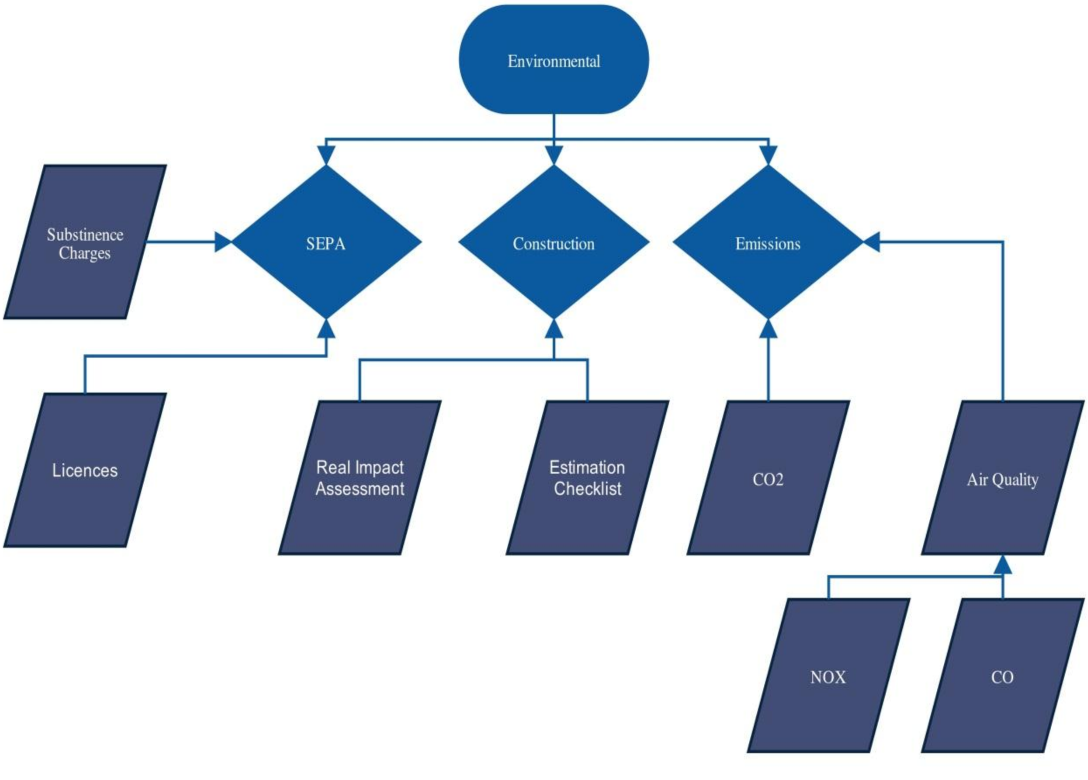

Figure 29: Environmental flow chart

4.6. Economic

The viability of any project ultimately is decided based on the economics of the project. Many sustainable projects only go ahead because of expected returns due to prospects such as incentives or reduced energy cost. Often projects will still go ahead if there is a large reduction in emissions or environmental impact as this can benefit companies in reaching overarching goals. This section will discuss the methodology involved with analysing the financial aspect of installing a district heating network driven by a river source heat pump. It will detail the eligibility and benefits of the governmental incentive scheme, the Renewable Heat Incentive. There will be discussion of the considerations involved with capital costs for both the heat pump and the district heating network, as well as potential savings (or costs) from considering operational costs. All of these considerations will be brought together to perform the economic modelling to investigate the financial viability of a project.

4.6.1. Renewable Heat Incentive (RHI)

One of the reasons that low-carbon heating technologies are becoming a viable option in the UK was the introduction of the Renewable Heat Incentive (RHI). This is an incentive which pays based on how much heat is produced. There are currently two levels of incentive; non-domestic and domestic. OFGEM outlines a few different general guidelines to decide which scheme your system would be eligible for. (OFGEM, 2015a) The following list outlines some of the factors involved.

- The renewable heating system heats one home which has an Energy Performance Certificate then it is likely domestic scheme

- Renewable heating system for commercial, public or industrial then likely non-domestic

- *“... organisations with district heating schemes where one heating system serves multiple homes.”*

The last bullet point is the most important in the context of the type of district heating scheme this thesis looks at. Most similar prospective projects should fall under the non-domestic scheme.

There are further requirements for a water source heat pump project to qualify for the RHI.

- Minimum COP of 2.9
- Minimum SPF of 2.5
- Reversible heat pumps can only measure the heating, not cooling
- Heat pumps to be sized based on design conditions
- For multiple heat pumps, the heat drawn from the water must be measured
- Electrical consumption of the heat pump must be monitored
- Can only extract heat from natural sources such as solar energy stored naturally (excluding solar collectors), heat from space heating or cooling or generally any heat from processes **other than heat generation**

The last bullet point contains a very important distinction which is underlined. It is specified that the heat which the heat pump draws upon cannot be from a heat generation source and must come from natural processes. This means that waste heat from CHP, industrial processes or power plant thermal excesses cannot be used to form part of the heat from which the heat pump draws. Care therefore must be taken that any prospective heat pump does not include waste heat from industrial processes. The COP and SPF of heat pumps could potentially be increased dramatically if this was allowed due to the increased temperature of the water. It is uncertain if this is to be reviewed at a later date with increased pressure to utilise wasted thermal heat.

"5.23. If accredited on or after 24 September 2013, heat loss through external heat distribution piping (e.g. to transport heat between buildings, or between a standalone boiler and a building) where the piping is not 'properly insulated' or where the piping is more than 10m in length and the average annual heat loss from the piping is

calculated as being 3% or more of the projected annual heat output of the plant49 50, is also not seen as serving an eligible use and as such RHI payments cannot be made in respect of the heat lost."

This is an important section from the documentation for its implications for the district heating scheme. It seems that piping losses must be kept below 3% to remain qualified for the scheme. Therefore the way that the heat is used in the district heating scheme is also important for eligibility of the RHI scheme.

The non-domestic RHI scheme continues for 20 years of the lifetime of the heat pump, with payments made on a quarterly basis. There are two tiers of payments that make up the payments. The first tier applies to the 'initial heat' which is the amount of heat generated by the heat pump if it was running at capacity for 15% of the year. Any heat generated on top of this comes under the second tier of payment. Table 7 provides the tariffs that apply for systems with an accreditation on or after the 1st of July, 2015.

Table 7: RHI Tariffs for WSHP

RHI Tariffs for Water/Ground Source Heat Pumps	
Tier 1	Tier 2
8.84 p/kWh	2.64 p/kWh

4.6.2. Capital and operational costs

One of the most important distinctions to make with regard to the economics of district heating is between retrofit and new build. New build refers to the situation where a new housing scheme or district of buildings is being planned and there are plans to install a district heating scheme. In this case the buildings can be built with designs which take into consideration of the fact the heating delivery systems are optimised to suit district heating. Piping can be laid in carefully planned layouts. This is taken further by the use of a heat pump to drive the heating network. This takes the argument back to the choice between low and high temperature networks. It is easier to construct buildings with heating delivery systems which suit low temperature district heating networks. This can help reduce the costs associated with the project.

For retrofit it is more expensive to install the heating delivery systems suited to low temperature heating networks. This means the financial analysis required for such systems generally should be specific to the existing buildings, as these buildings could have widely ranging costs for retrofit heating systems. It is easier to consider the economics of high temperature heating networks for these buildings. This is because no adjustments are needed for the heating delivery systems.

The costs involved with the cases to be examined broadly fit into three categories: capital, operational and incentives. A list of the capital costs associated with the heat pump and the district heating network are given in tables 8 and 9, and operational costs in tables 10 and 11. They are accompanied by methods for approximating the cost. Incentives are made up solely by the RHI payments described in the appropriate section.

Table 8: Heat pump: Capital costs

Component	Approximate Cost Method
Heat pump	Consider size, use case studies for comparisons
Pumping system	Analyse the required pumping depth of the river, try to minimise
Building centre	Local building heat connection
Electrical connections	Analyse the electrical consumption requirement
Landscaping	Depends on the piping work required to move the heat, river crossings need to be considered
Licences	See the section 4.5.1 SEPA regulations
Design	Costs for designing the system

Table 9: District heating network: Capital costs

Component	Approximate Cost Method
Energy centre	Consider using existing facilities, also depends on use of CHP or similar onsite thermal energy production
Piping connections	Needs to be considered building to building, mapping is required
Local building heat connection	Consider demands of building, existing facilities, and desired heating delivery system

Table 10: Heat pump: Operational costs

Component	Approximate Cost Method
Electrical costs	Demand/supply matching allows for analysis of electrical consumption
Technical maintenance	Costs with faults and upgrades, take as low percentage of capital cost
Cleaning maintenance (filtration system)	Depends on sophistication of filtration system, subject to future change in river conditions
Trained operators	Existing skills may not exist, training costs may be required

Table 11 District heating network: Operational costs

Component	Approximate Cost Method
Trained Operators	Existing skills may not exist, training costs may be required
Technical maintenance	Costs with faults and upgrades, take as low percentage of capital cost

The methodology proposed regarding the capital and operational costs is useful where data is available. These would be taken from contact with manufacturers to obtain specific costs for each of the sections. This proved difficult to achieve in this project. Particularly difficult to find was operational costs. These have been assumed to be the same as if using gas boilers because it is assumed that they are a relatively low cost. As an alternative to the methodology the capital costs are estimated based on the previous case studies discussed. These estimates are given in table 12.

Table 12: Estimations for costs

	Heat Pump	District Heating	CHP
Capital Cost	£1.25 million/MW	£2.5million	£800 k/MW

4.6.3. Financial model

The Excel spreadsheet used to perform the technical and environmental components was also used to develop a financial model. Each of the heating system configurations were examined from an economical perspective. A result obtained from the technical analysis is the total electricity and gas consumption. These were then multiplied by the cost per *kWh* of each of the respective energy sources. The addition of these two provides the annual energy cost. This process is applied to each case to obtain the energy cost of each per annum. Table 13 gives the electricity and gas prices used.

Table 13: Gas and electricity prices

Gas Price, pence per kWh	Electricity Price, pence per kWh
0.034	0.1

For the case of the CHP and WSHP the RHI payment can be subtracted from the costs. This was calculated using the two tier system outlined in the section 4.6.1 Renewable Heat Incentive (RHI). The logic used to calculate the RHI payment is given below.

$$
\begin{aligned}
&IF\ (Heat\ from\ heat\ pump\ annual) \\
&\qquad \geq (15\%\ of\ heat\ capacity\ working\ all\ year) \\
&THEN\ (Tier\ 1\ price) \times (15\%\ of\ heat\ capacity\ working\ all\ year) \\
&IFNOT\ THEN\ (heat\ from\ heat\ pump\ annual) \times (Tier\ 1\ price)
\end{aligned}
$$

$$+$$

$$
\begin{aligned}
&IF\ (heat\ from\ heat\ pump\ annual) \\
&\qquad \leq (15\%\ of\ heat\ capacity\ working\ all\ year) \\
&THEN\quad zero \\
&IFNOT\ THEN\ ((heat\ from\ heat\ pump\ annual) \\
&\qquad - (15\%\ of\ heat\ capacity\ working\ all\ year)) \times (Tier\ 2\ price)
\end{aligned}
$$

A relative saving was found by comparing the costs to the two base cases for the CHP only and CHP + WSHP cases. These savings were then used in a discounted cash flow (DCF) model(Olsson & Levin, 2015). This model is uses the concept of time value of money to provide a more realistic view of the savings possible by implementing a project. Future expected savings are discounted to account for the perspective that future cash flows are worth less than cash flows closer to the present. The following equation calculates the discounted present value (DPV), the discounted future cash flow.

$$DPV = \frac{FV}{(1+r)^t}$$

Where *FV* is the expected cash flow value in a future block of time, *r* is the discount rate, and *t* is the years in the future that the cash flow is expected to occur. This formula was used for each year and then each case was summed to calculate the DPV for a certain number of years. Generally the lifetime of a WSHP is expected to be at least 20 years, so this is the number used in the financial model. A discount factor of 4% was used. Comparing the DPV over the whole 20 years to the capital cost for each of the cases means that a payback period can be calculated. Payback periods are an essential part of the feasibility of any project so that investors can know when to expect their investments to being to bring cash flows.

Each of the cases was compared using the above financial model. This methodology, in conjunction with the technical methodology, allows for a variety of different possible heating configurations to be compared. Importantly it allows for the inspection of the feasibility of a river source heat pump from a financial perspective.

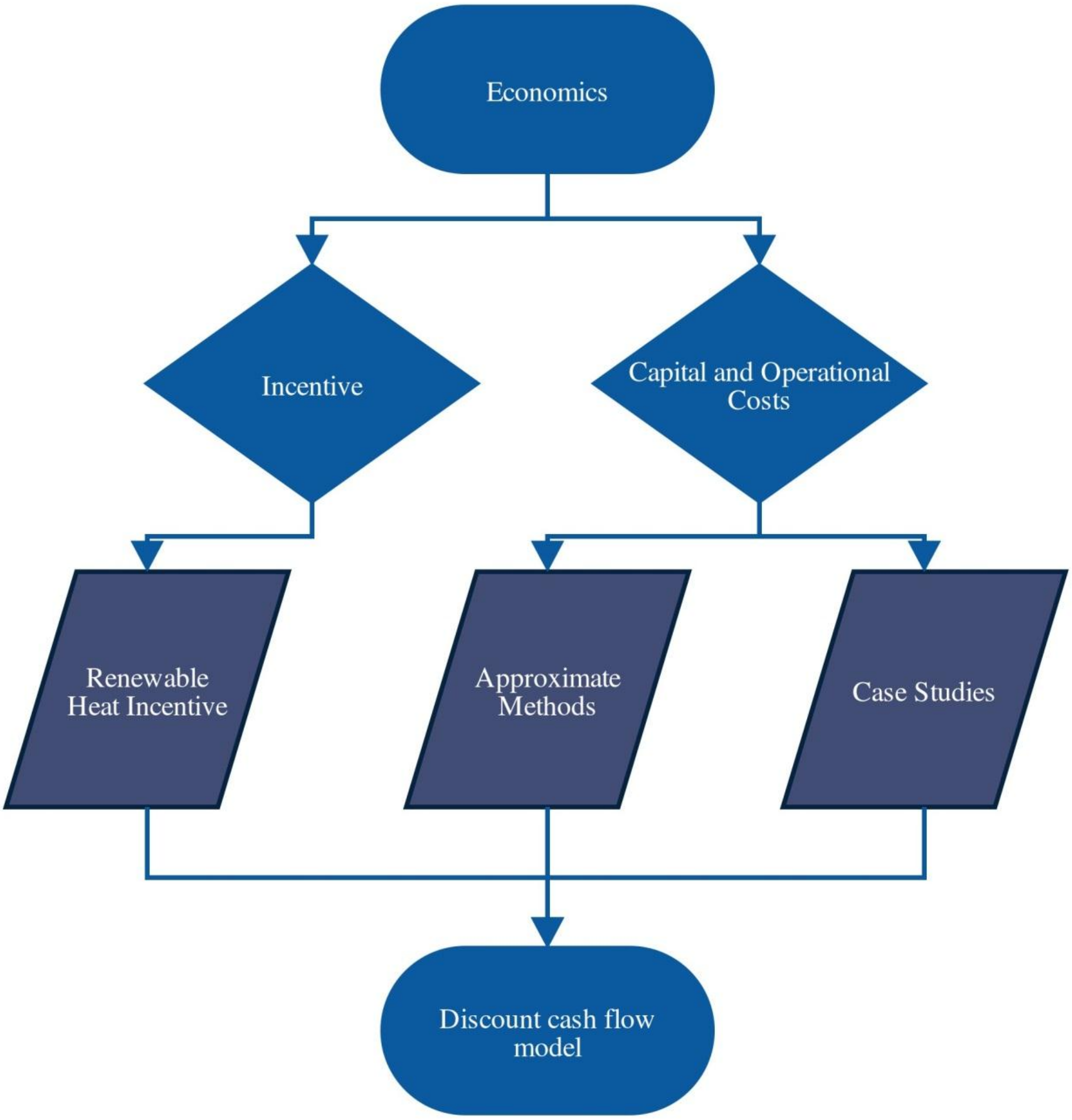

Figure 30: Economic flow chart

5. Results & Analysis

The developed methodology will now be applied to an area of Glasgow using the River Clyde as the source of heat for the heat pump. The focus is on the core areas of technical, environmental and economic. The suitability of the River Clyde will be assessed and the size of heat pump which could be used will be calculated. The Scotland Heat Map will be used to identify an area of Glasgow potentially suited for a large district heating scheme, with emphasis on exploring which size of demand fits well with the proposed heat pump. The modelling focusses on demand/supply matching for various heating system configurations and proposed sizes of district heating demand. An assessment of the environmental impacts and economic comparisons will help determine the various pros and cons of the different heating system configurations, particularly the WSHP and CHP hybrid system.

5.1. River Clyde suitability

A large dataset obtained from SEPA from 01/10/1963 to 30/09/2014 from the Clyde at Daldowie station was used to produce the flow rate exceedance curve. This is shown in graph 31. The percentage of time, over the dataset period, a large range of flow rates are exceeded is plotted against the flow rate to be exceeded. It was decided that a flow rate of 8 m^3/s was the highest suitable flow rate that could be used for the heat pump. This is because the curve begins to dip below 99% beyond this point and since the heat pump needs to provide heat for most of the year in a climate such as Scotland's, anything below 99% would have a dramatic effect on the ability of the heat pump to deliver. Since it is unfeasible to take all of the 8 m^3/s flow and also that there is little guidance from SEPA on abstraction allowances, it was assumed that for the River Clyde the maximum extraction would be 10%. This means that the heat pump can utilise a flow rate of 0.8 m^3/s.

It should be noted that the Clyde at Daldowie station is not located in the centre of Glasgow. It is closer to the outskirts of the city. Therefore there is a risk that the flow exceedance curve is unreliable. It has been assumed that the topology of the river is relatively unchanging through the city, meaning that the flow rate is also reasonably constant and so the data from Daldowie can be representative of the data in the centre.

As suggested earlier, it is important to take independent measurements at the proposed site to achieve the highest accuracy.

The River Clyde is a large, fast flowing river, and thus the high level of flow rate found for 99% of the time makes it particularly useful for a river source heat pump. Its location running through the heart of Glasgow provides ample opportunity for the use of a district heating scheme.

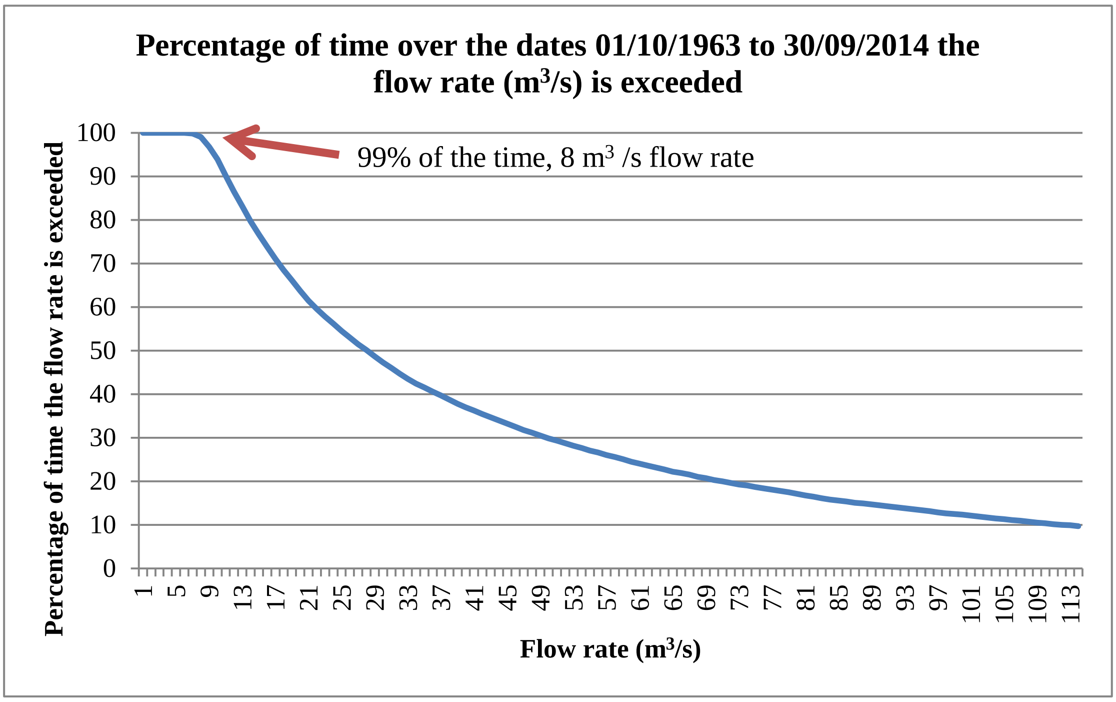

Figure 31: Flow exceedance curve for the River Clyde

It is more difficult to obtain useful data concerning the river temperature. SEPA does take water temperature measurements at some of their river stations, but this data was not available for the River Clyde. Instead the Clyde Sea temperatures were obtained to provide an insight into what the temperatures can be found on the River Clyde. Graph 32 displays the monthly average temperatures found in the Clyde Sea. The red line and the blue line denote the temperatures found at the surface layer (0-10m) and the bottom layer (40m-seabed). Given the uncertainty of assuming correlation between the Clyde Sea temperature and that of the River Clyde the lower temperature bottom layer data was used. With these temperatures, the River Clyde appears highly promising as a source for the heat pump. Since temperatures do not dip below 6°C, a ΔT of 4°C would be possible. Given the uncertainty of the data being used, a more conservative ΔT of 2°C was assumed possible. This is in line with WSHPs currently in use.

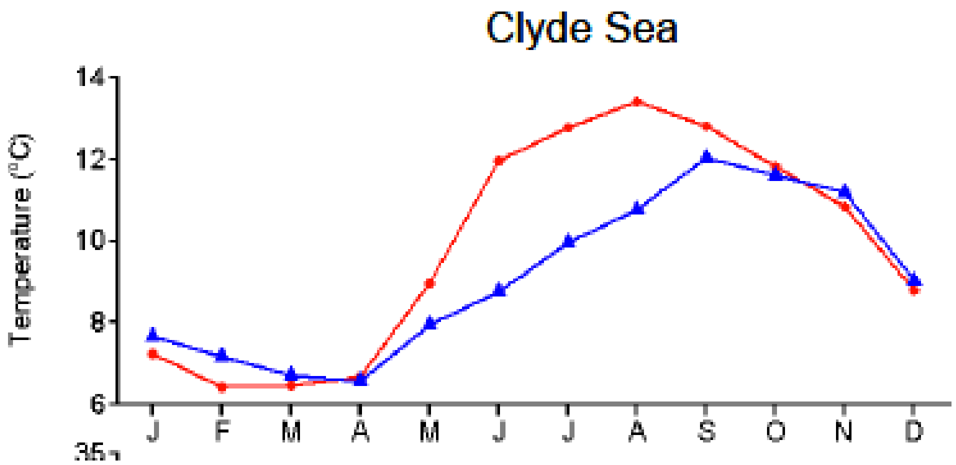

Figure 32: Monthly temperature data, Clyde Sea (ScottishGovernment, 2012)

5.2. Heat pump size

The following equation can be used to calculate the heat which can be drawn from the river and used by the heat pump.

$$Q_{in} = \dot{m}\, \rho\, C_p\, \Delta T$$

From the previous results regarding the River Clyde the flow rate is 0.8 *m³/s* and the ΔT is 2°C. The density of water is 1000 *kg/m³* and the specific heat capacity is 4200 *J/ kg* °C (M. J. Moran, Shapiro, Boettner, & Bailey, 2010).

$$Q_{in} = 0.8 \times 1000 \times 4200 \times 2 = 6720000\, W$$

Accounting for the 99% availability of the 8 m³/s flow rate introduced a factor of 0.99.

$$= 6720000 \times 0.99 = 6.65\, MW$$

Therefore the proposed heat pump size is 6.65 *MW*. This is realistic when compared to the case studies of functioning heat pumps. The heat pump system in the town of Drammen delivers 15 *MW* of heat, and that consists of three components. A 6.65 *MW* size is comparable to the 5 *MW* individual system currently operating at Drammen, suggesting that this is a feasible size. A heat pump delivering 6.65 *MW* of thermal power over a year could provide 58.3 *GWh*. In combination with another heating device, a hybrid system could provide even more heat than this. The chosen heat pump would use an open-loop design because of the size of the River Clyde.

5.3. District heating site

The Scotland heat map was used to identify a possible area of central Glasgow near the River Clyde which could benefit from district heating. Figure 33 is a screenshot of the centre of Glasgow with the heating demands overlaid. There are a number of areas with a large proportion of red squares, which signify a large heating demand.

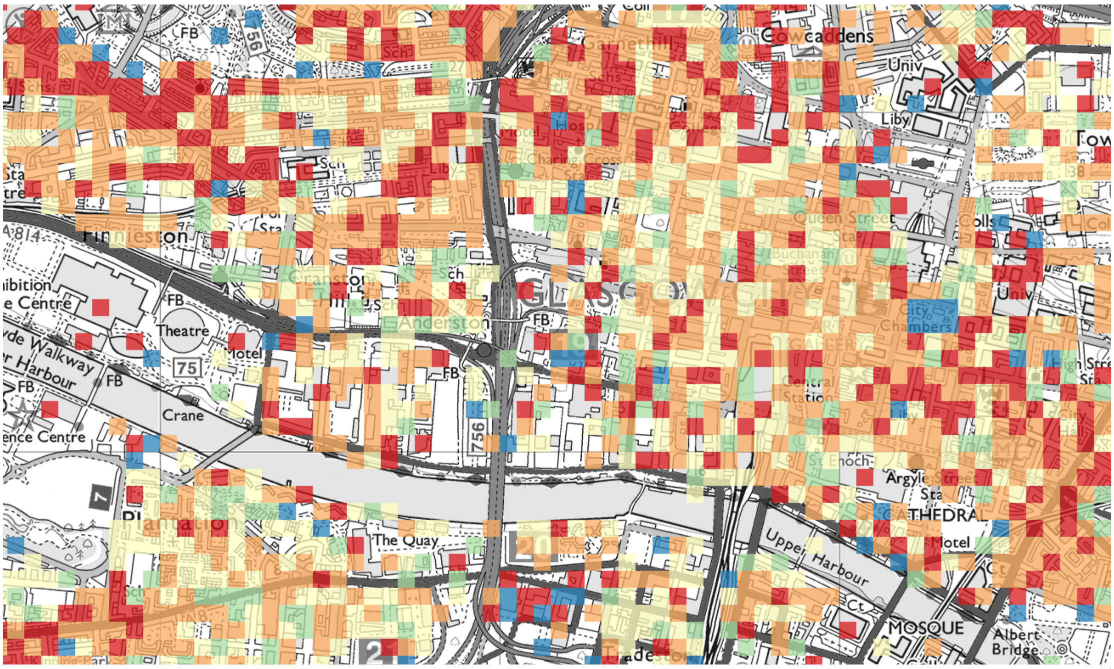

Figure 33: Central Glasgow heating demands

A number of different areas could be suited for district heating. These are close to the river meaning that potential losses from piping are minimised. Figure 34 shows the site which was chosen as a potential location for the district heating scheme. It covers a large part of the Merchant City area of Glasgow, including a shopping centre, St Enoch’s, a subway station, the courts, and City Halls. This area also has an abundance of streets connecting in an organised, grid fashion. This would be useful for planning the layout of the piping networks. There is also often ongoing construction, with old buildings being replaced by modern ones. This means that the impact of additional disruption from the construction of the scheme would be lessened. The number of buildings which will not be replaced outweighs the number that will. In terms of the distribution system of the network, it would be sensible to employ a high temperature system capable of satisfying the needs of the heating delivery systems of older buildings. The proposed area also contains a large stretch of the River Clyde. This is useful for broadening the potential locations for the heat pump, increasing the likelihood of finding a suitable site.

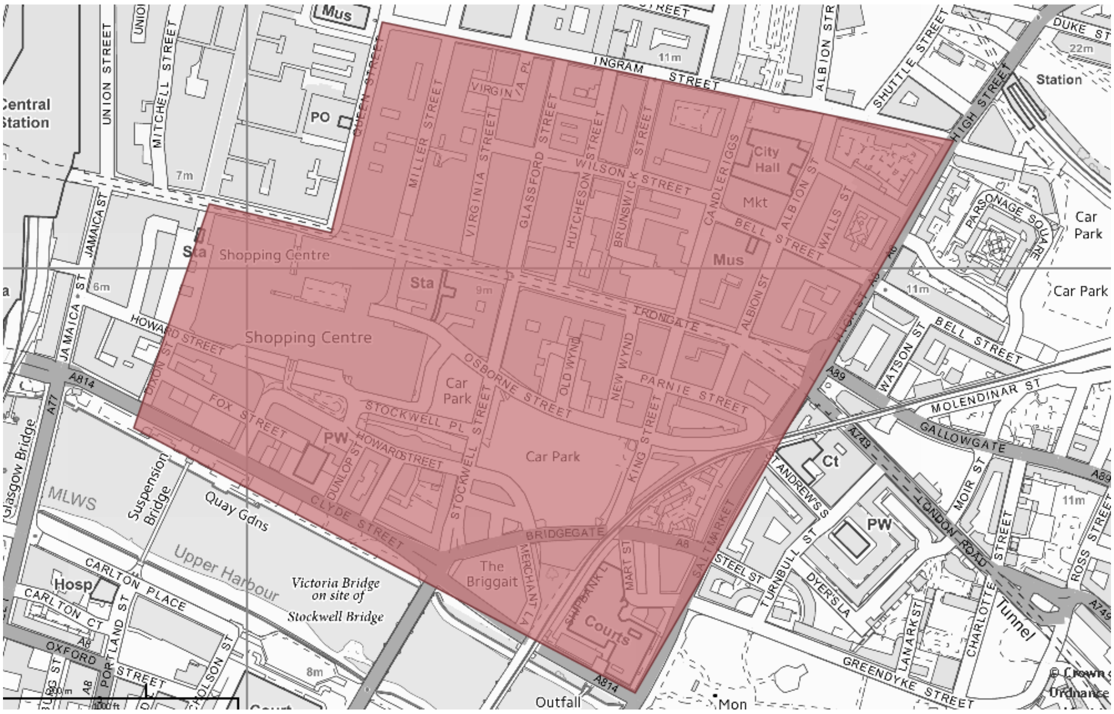

Figure 34: Proposed area for district heating

The heat map provides the annual demand of a selected area. The proposed area has an annual demand of 104 *GWh*. This is just under twice the heat pump’s maximum output of 58.3 *GWh* in a year. It is unrealistic to assume that the entire heating demand will be connected to the district heating scheme. Graph 35 shows the overlay of the social housing percentage of the proposed area. Areas of darker blue have a higher percentage of social housing. Compared to other areas of Glasgow this is relatively low. This is a weakness of choosing this area for district heating as with social housing it is easier to find an agreement to connect to the network. This means that the real heating demand of the district heating network will be significantly less than the total of the area. In the technical, environmental and economic analysis a range from 25 to 100 *GWh* annual demands was compared. This gave an indication of what annual demand will suit the proposed heat pump.

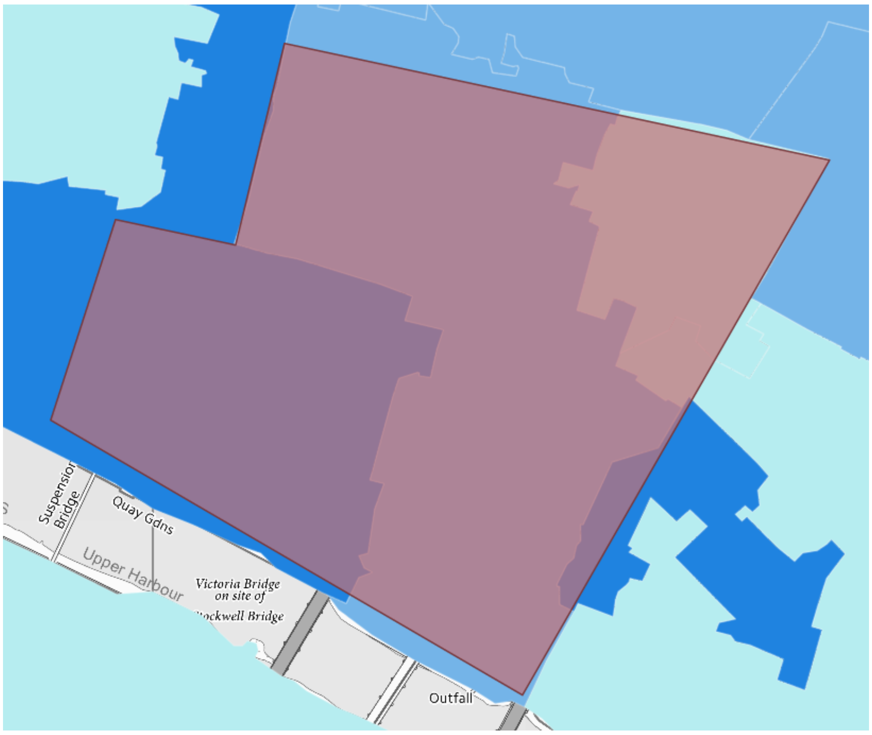

Figure 35: Social housing percentage for proposed area

The ratio of building classes is required to develop the thermal demand profile for the proposed area. This was done by inspection both through maps and through familiarity of the area. It was estimated that the ratio of residential : commercial : offices is 50 : 20 : 30. This is a rough estimate. A proper, detailed inspection of maps of the area is required to obtain a more accurate ratio. However, for the purposes of this investigation, where the demand profile will not be drastically different with a different choice of ratio, the estimated was deemed sufficiently realistic.

Figure 36 is the resulting demand profile from following the methodology. The blue line is the un-averaged demand profile and the red line is where a 36 moving average has been applied. It is apparent that the choice of moving average provides a smoother, more realistic demand profile. Daily characteristics are evident with half-hourly variations still visible and the seasonal variation is also apparent as the profile exhibits the characteristic U-shape over the year. There is a minimum in summer and a maximum in the winter.

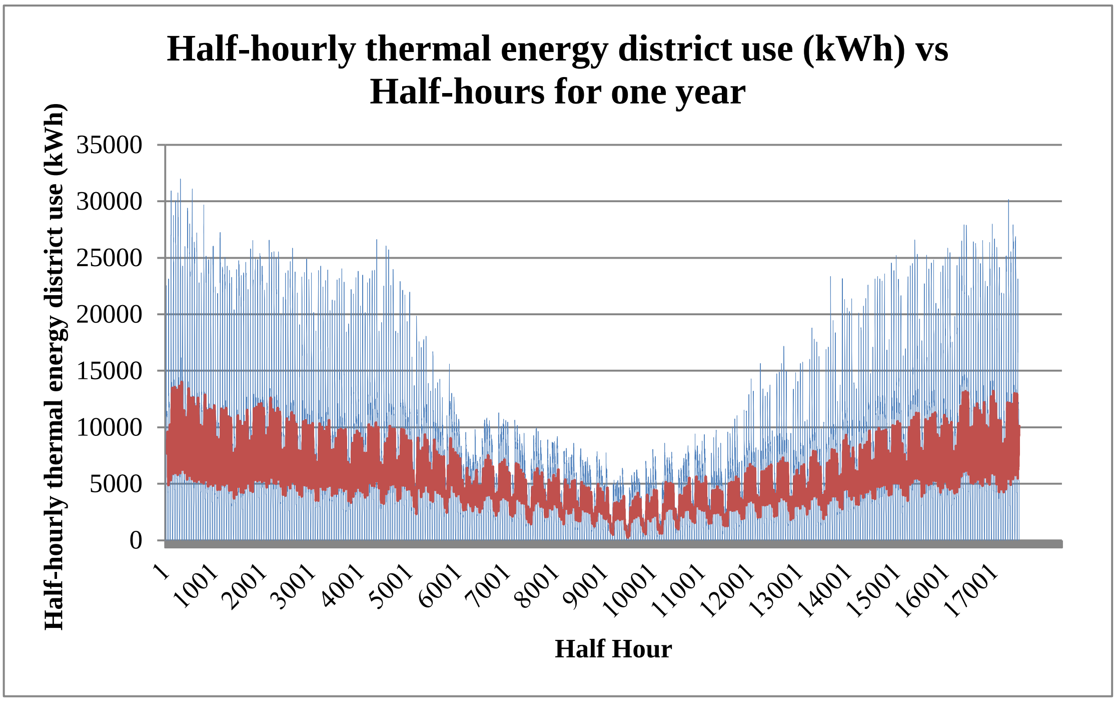

Figure 36: Thermal demand profile of proposed site

These results convey the suitability of the heat map as a tool for identifying potential areas for district heating. It does not have the data to provide an accurate profile for the demand, but by giving the annual demand it offers a basis for developing an adequate demand profile for use in investigating river source heat pumps in district heating.

5.4. Demand/Supply matching

The developed demand profile was then used in the Excel spreadsheet to perform demand/supply matching. The different heating system configurations were compared using the technical outcomes outlined in the methodology, with special importance for comparing these systems to the river source heat pump and CHP hybrid system. Emphasis was placed on analysing the performance of the configurations for different total annual demands.

An important part of the reason for the promotion of using heat pumps is to move thermal energy production away from reliance on gas and onto electricity. Heat pumps then have the advantage over conventional electrical heating with COPs in excess of 100%. Graph 37 shows the net electricity consumption of the gas and electricity case and the WSHP and CHP case against the total annual demand of the district heating scheme.

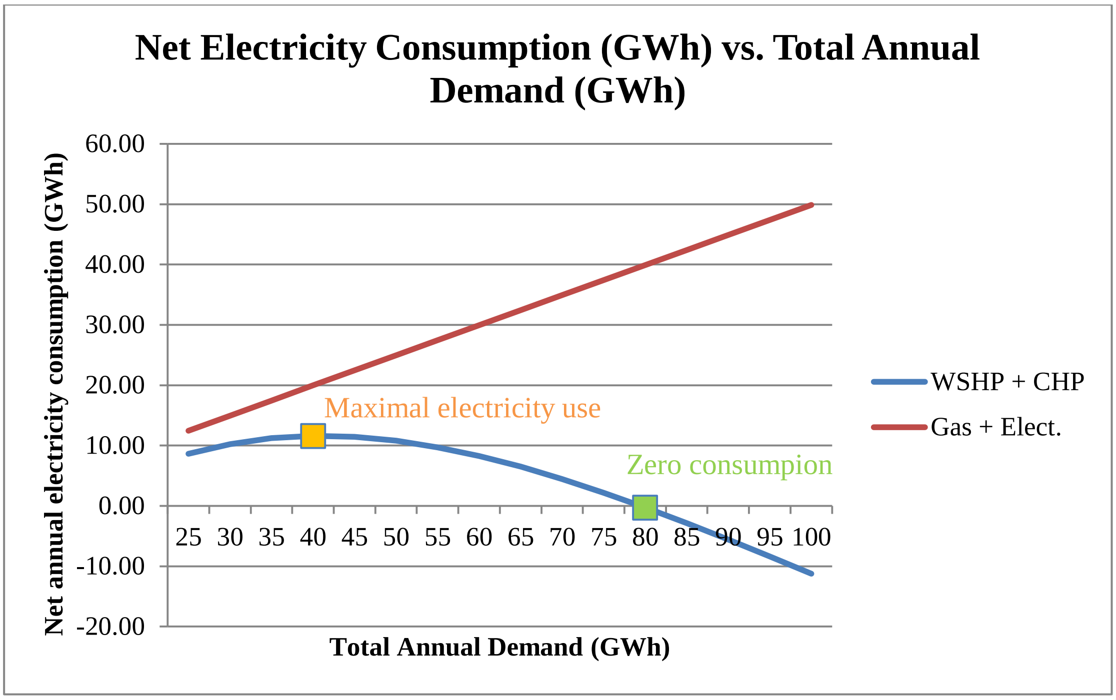

Figure 37: Electricity consumption vs. Annual demand

For the Gas and Electricity case the trend is linear, as total annual demand increases the annual electricity consumption proportionally increases. A different trend occurs with the WSHP and CHP case. For total annual demands up to 40 *GWh* the electicity consumption increases. Beyond this the trend reverses and it decreases, with an inverse linear relationship forming for total annual demands larger than 55 *GWh*.

In the model the heat pump is always the same size but the CHP varies depending on what demand the heat pump cannot cover. Therefore for low demands the heat pump is being utilised more and more, until it cannot provide any more of the heat and the CHP must be increased to compensate. This results in a larger use of CHP, and consequently a larger production of electricity. At 80 *GWh* the electricity produced becomes larger than the electricity consumed by the heat pump. It appears that the maximal use of electricity over gas is around 40 *GWh*.

It is difficult to conclude at which annual demand the heat pump's use is maximised. One of the technical outcomes, which helps achieve this, was to calculate the average capacity of the WSHP used over a year. Graph 38 shows this as a percentage against the total annual demand.

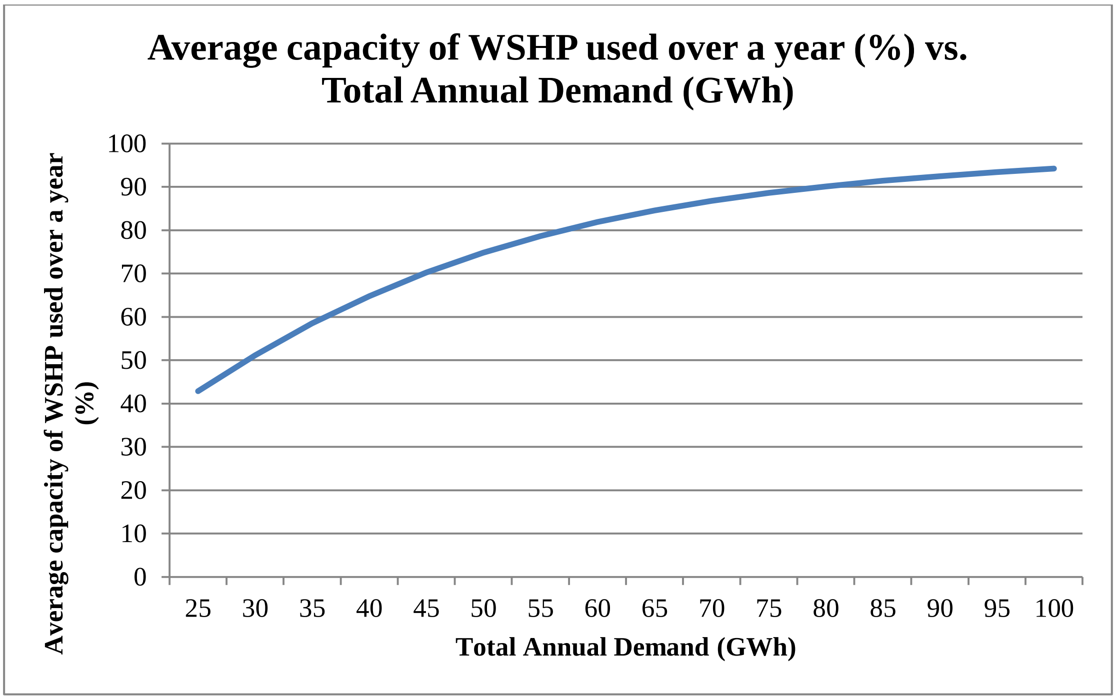

Figure 38: Percentage of capacity of WSHP used vs. Annual demand

The average capacity used increases as the total annual demand increases. This is logical because there will be more half-hours where the demand is larger when the annual demand is larger. This means the heat pump is required to produce more heat, despite the concurrent increasing size of the CHP.

It appears ideal to try and optimise the average capacity used, so this would lead to the conclusion that a higher total annual demand is desrieable. However, the size of the CHP required increases accordingly with a higher total annual demand. Graph 39 shows the capacity of CHP required against the total annual demand. The linear relationship has a steep gradient. This means an increase in the total annual demand has a large effect on the size of the CHP necessary to meet the demand. A 5 *GWh* increase in total annual demand results in an increase of 1.5 *MW* of required CHP capacity. Installing a CHP unit so large such that it dwarfs the size of the WSHP defies the reasoning for including the WSHP at all. It is important that the WSHP provides a large proportion of the annual heat demand.

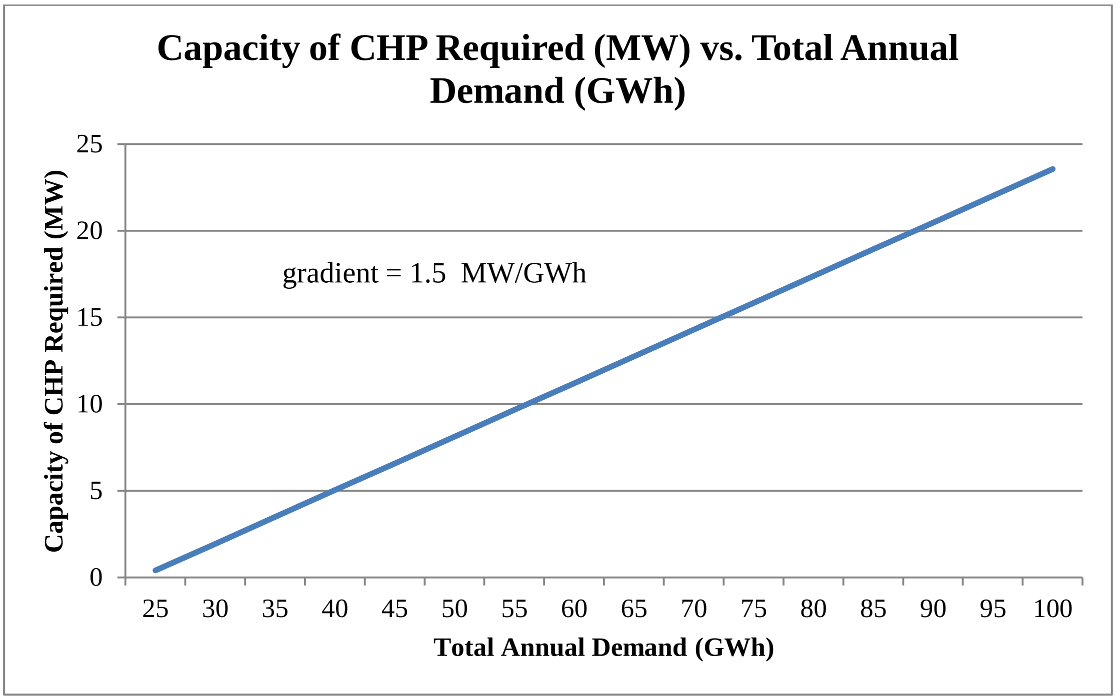

Figure 39: Capacity of CHP required vs. Annual demand

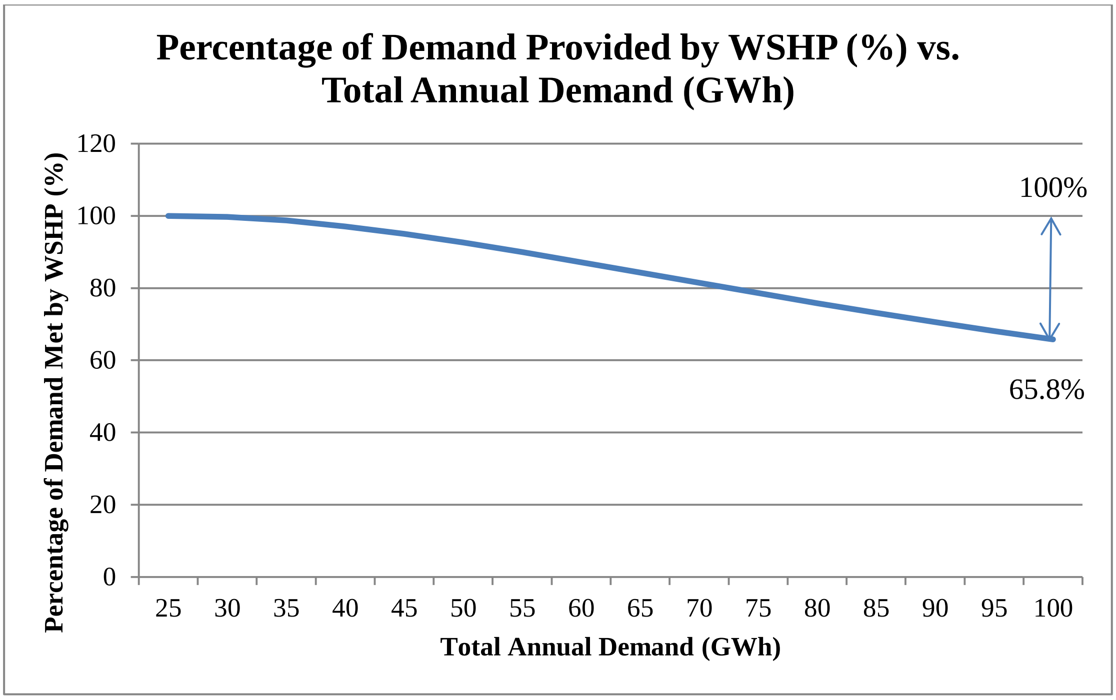

Figure 40: Percentage of demand provided by WSHP vs Annual demand

Graph 40 helps by showing the percentage of the annual demand which is met by the WSHP against the total annual demand. For a low demand of 25 *GWh* the entire annual demand can met by the heat pump with this dropping to 65.8% for a demand of 100 *GWh*.

In reality the heat pump will only be able to vary its output to a limited degree which affects the COP of performance. From this point of view it is important to choose an annual demand such that the heat pump provides a large proportion of the heat, but not all. Such a system is acting more like a real one would, with the heat pump providing the base load and the CHP meeting the fluctations.

The low temperature and high temperature distribution systems were also compared for different total annual demands. Graph 41 shows this comparison with the electricity consumption of both plotted against the total annual demand. Since the low temperature system has a higher COP it is logical that it requires smaller electricity consumption annually. This confirms the logic that low temperature systems perform better technically.

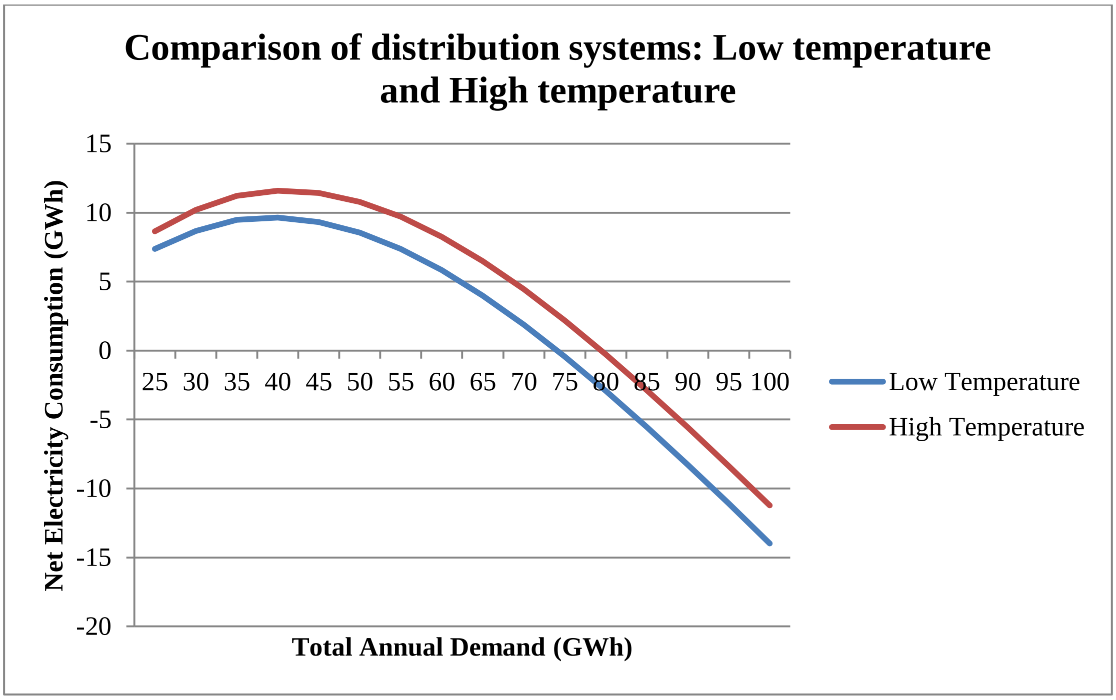

Figure 41: Distribution systems vs. Annual Demand

5.5. Environmental impact

SEPA regulations state that if the abstraction rate exceeds 2,000 m^3 per day a ‘Complex Licence’ is required. Using the 0.8 m^3/s flow rate gave a daily flow rate of 68,120 m^3/s. This is far in excess of SEPA guidelines, meaning that a ‘Complex Licence’ is required.

The environmental methodology also sets out a rough environmental impact assessment process. This was not carried out for this project, but it is possible that this could be a potential barrier. There were also no embodied emissions calculations performed for this project. This was due to insufficient data.

Graph 42 displays the CO_2 equivalent emissions versus the annual total demand. The order of the cases in terms of CO_2 emissions from lowest to highest is as follows: CHP only, CHP + WSHP, Gas Boilers and Gas + Electricity. This is because the CHP generates electricity along with heat, resulting in a reduction in the electricity imported and hence the net CO_2 emissions. All the cases have a simple linear relationship to the annual demand, with the highest gradients belonging to the highest emitters.

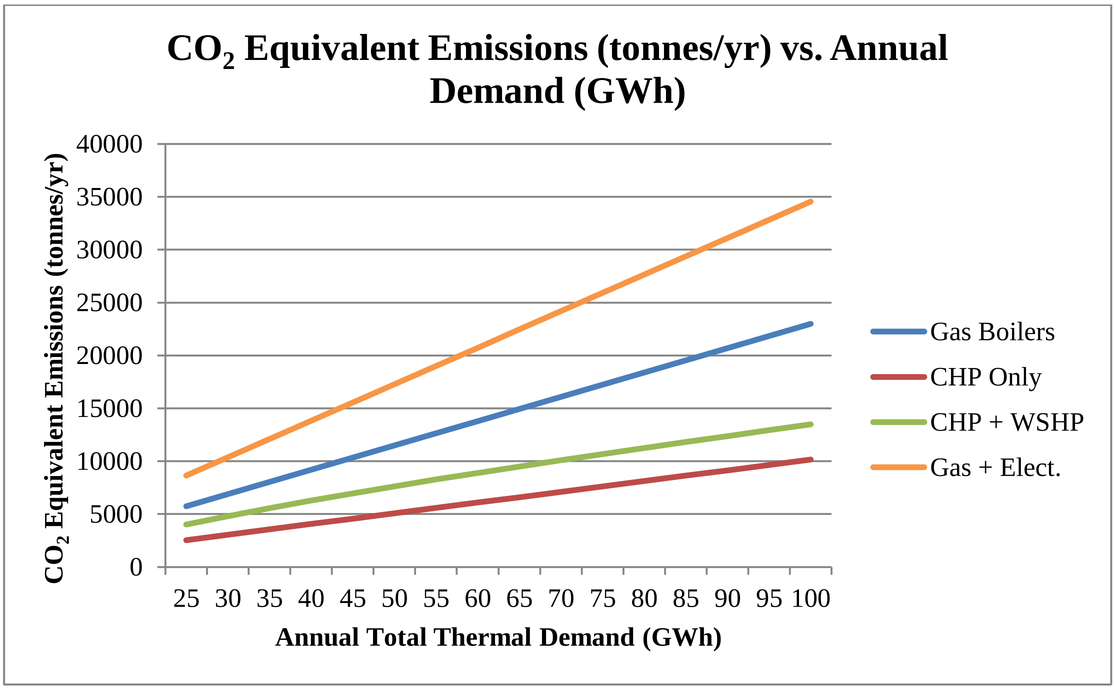

Figure 42: Comparison of cases: CO_2 emissions vs. Annual demand

The CO_2 equivalent emissions were calculated for all of the cases with an annual demand of 40 *GWh*. The previous graph used CO_2 emission factors from the current year, 2015. The predicted future trend of decarbonisation of the electricity grid will have a large impact on the environmental impacts of the various cases. This is shown in graphs 43 and 44, where the CO_2 equivalent emissions vs. year is plotted. The first uses a decarbonisation factor of 10%, which is line with current UK government targets. It is in the year 2016, in just over one year, that the CO_2 emissions from the CHP system rise above those of the CHP + WSHP system. This shows that this system is better as a long-term environmentally friendly heating system. Interestingly, the CHP system not only exceeds the CHP + WSHP system quickly, after 6 years it is the highest emitter of CO_2. This shows that while CHP is seen to be an environmentally friendly option in 2015; in the longer term it becomes environmentally worse than even gas boilers. Graph 44 uses a decarbonisation factor of 5%. Even with such a pessimistic view of the future decarbonisation of the grid it is still in less than two years that the CHP + WSHP case has less CO_2 emissions than the CHP only case. In 10 years the cases of CHP only, Gas Boilers and Gas + Electricity almost converge.

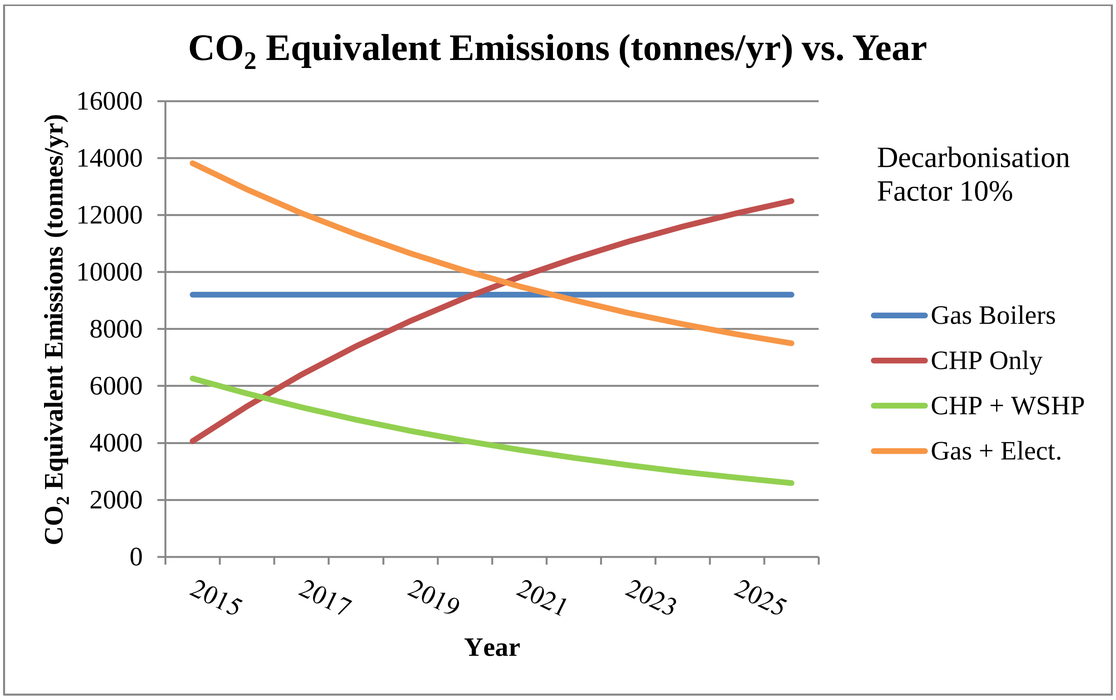

Figure 43: Projected CO_2 Emissions: Decarbonisation factor 10%

With the commitment of the UK government to the decarbonisation of the electrical grid it appears essential for heating systems to move away from gas and to electrical based systems, if they wish to reduce CO_2 emissions. WSHPs provide the best system for making the most of the electricity that is used to provide heat.

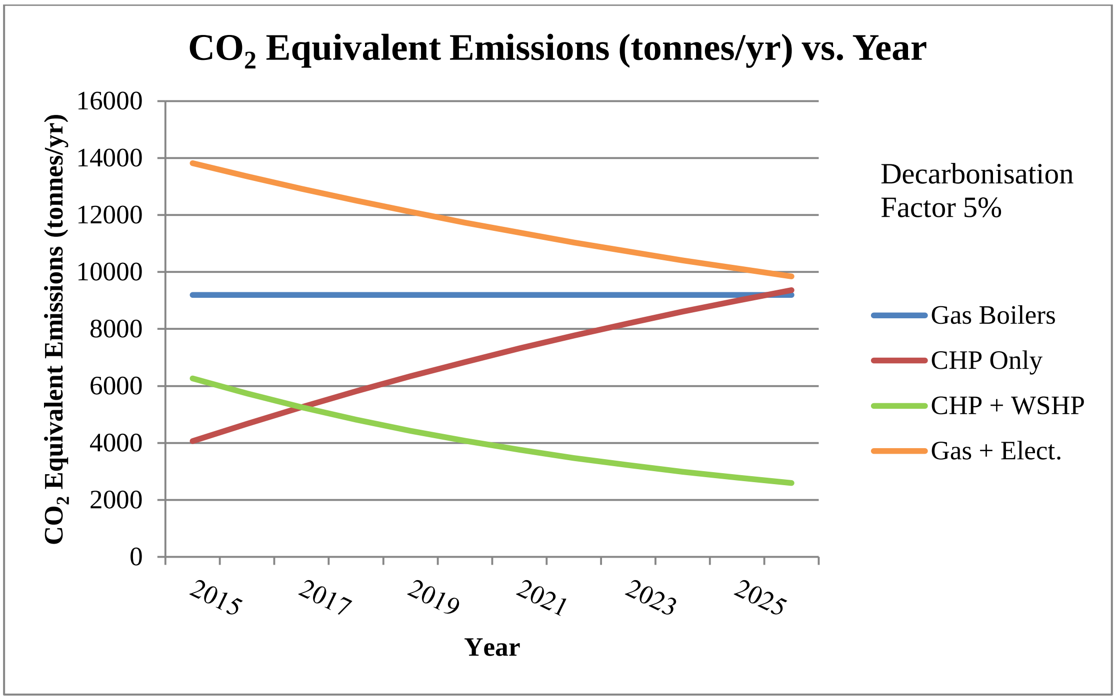

Figure 44: Projected CO_2 Emissions: Decarbonisation factor 5%

The move away from gas to electricity also helps with air quality. Graph 45 and 46 show the NO_x and CO emissions of the different cases for annual demands. They both follow the same trend with the only difference being that there is a higher factor of CO emissions. CHP is the worst offender in terms of air quality. This is because both the gas and electricity are being produced in the city. Using more electricity is better as can be seen with the Gas + Electricity and WSHP + CHP cases being the lowest offenders for air quality. The WSHP + CHP case has lower emissions than the Gas + Electricity case up to 70 *GWh*. This highlights the idea that using CHP causes worse problems than the other heating devices.

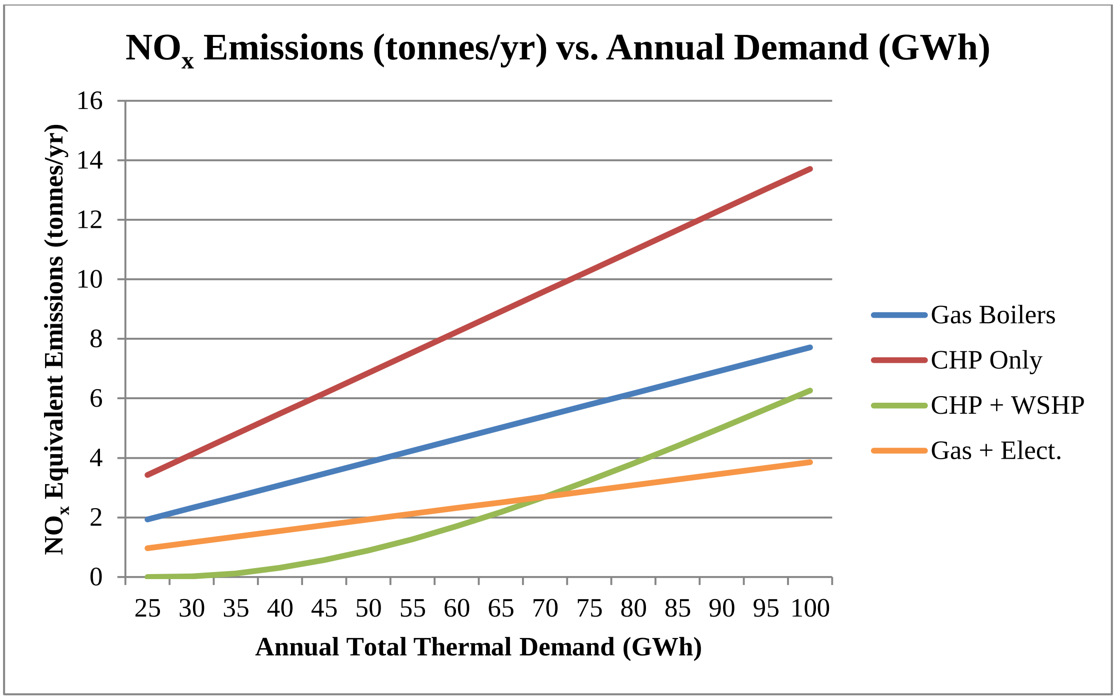

Figure 45: Air quality, NO_x emissions

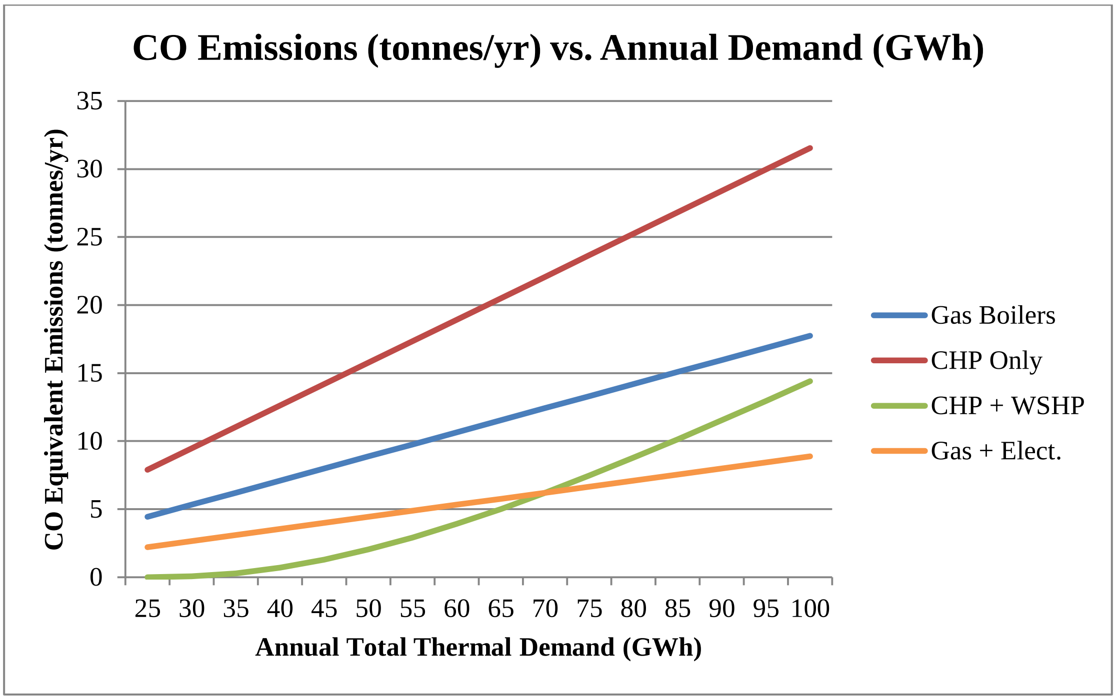

Figure 46: Air quality, CO emissions

The low temperature and high temperature distribution systems were also compared with respect to their CO_2 equivalent emissions, as shown in graph 47. The results confirm the expectation that low temperature distribution systems will have lower emissions due to the higher COP.

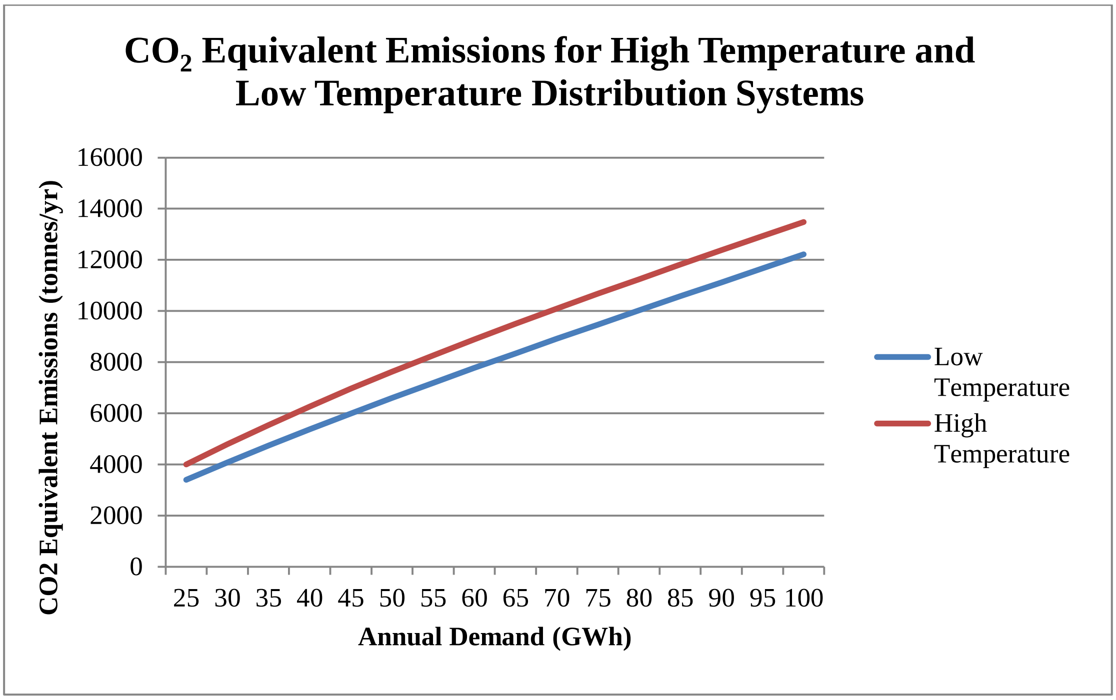

Figure 47: CO_2 emissions: Distribution systems

5.6. Economic comparisons

The RHI payments have a large impact on the economic viability of the WSHP. Graph 48 shows the difference in annual cost vs the total annual demand. With the RHI payments instead of an annual cost there is a payment for annual demands under 60 *GWh*. To illustrate the difference, for an annual demand of 40 *GWh* there is an RHI payment of £1.50 million. The viability of a WSHP is therefore heavily dependent on this payment. This raises the question of over reliance on this payment. If for some reason this government subsidy is scrapped or if it is vastly reduced, then the economics of a WSHP becomes uncertain.

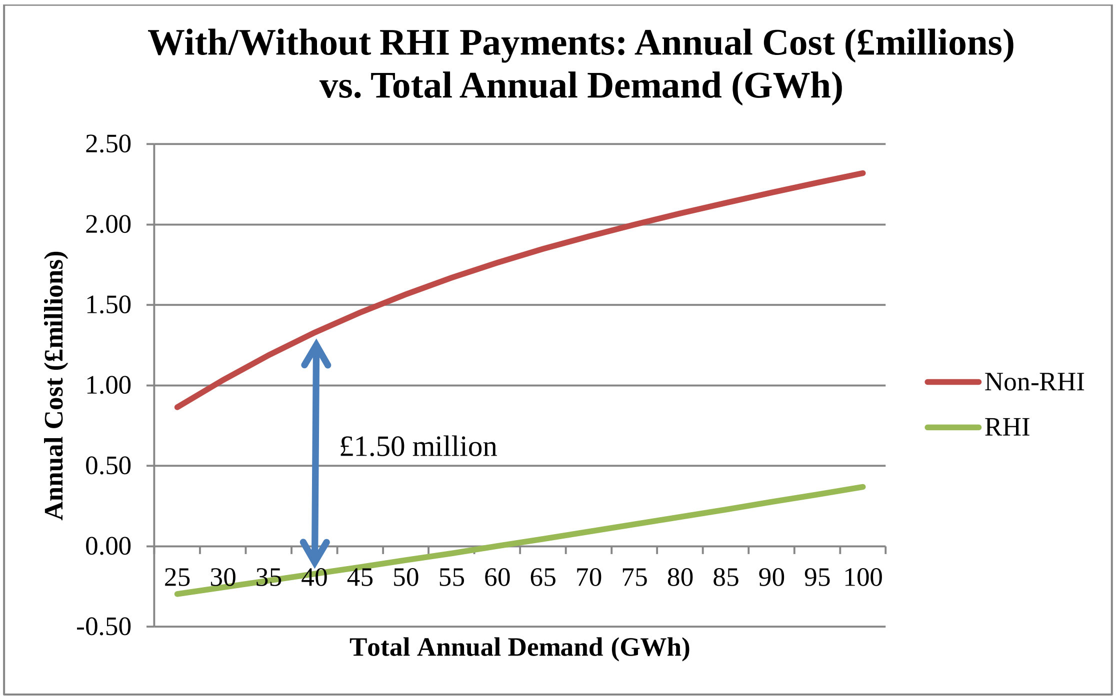

Figure 48: With and without RHI payments comparison

The annual costs of implementing the two cases, CHP + WSHP and CHP only, were compared to the annual costs of the two base cases, Gas only and Gas + Electricity, to calculate the relative annual savings. The annual savings relative to the base cases vs. the total annual demand are shown in graph 49. Greater savings are to be made upgrading from the Gas + Electricity case than the Gas only case. For higher total annual demands the savings when upgrading from Gas + Electricity increases at a larger rate than the Gas only base case. For both comparisons the CHP + WSHP case results in larger savings than the CHP only case.

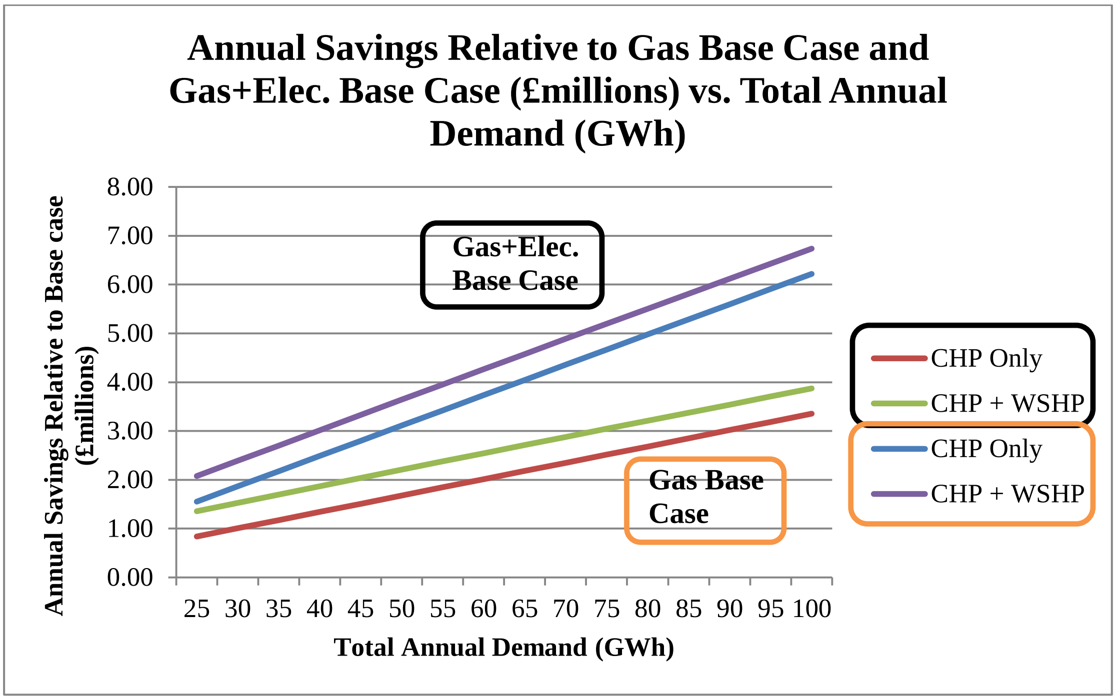

Figure 49: Annual savings of cases vs. Annual demand

The environmental results favoured a move towards electric forms of heating. Economically it is possible to obtain larger savings by moving away from electrical heating, but only in the case of conventional electrical heating. It is better to use WSHPs compared to CHP. This analysis only looks at the savings which can be made each year, later analysis will include the capital costs to present results which are better suited to investigating financial availability.

Graph 50 compares the annual costs of the low and high temperature distribution systems. The low temperature system always has an annual cost lower than that of the high temperature system. It is interesting how much of a difference there is. The low temperature system provides payments, as opposed to costs, for annual demands lower than 90 *GWh* compared to 55 *GWh* for the high temperature system. For a 40 *GWh* annual demand there is a £190,000 saving.

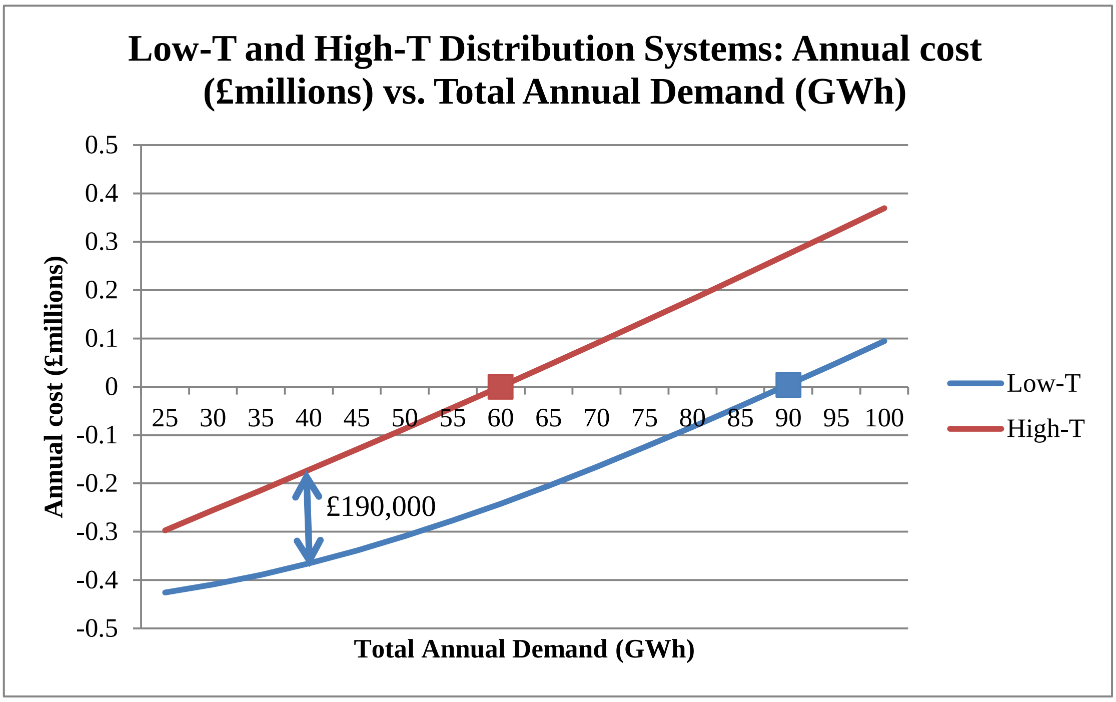

Figure 50: Distribution systems: Annual cost vs. Annual demand

This suggests that the difference paying the extra cost for a low temperature distribution system could be worthwhile. Due to difficulty in estimating the cost difference between the systems this analysis was not included, but would be an interesting avenue for future work. It does show the economic value that district heating has for new build areas. It makes sense to design homes to suit a distribution system which also suits district heating, to ensure that this form of heating delivery is optimised. This is an area worthy of further research.

The discount cash flow model was applied to each of the cases for a total annual demand of 40 *GWh*. Graph 51 shows the discounted present savings vs the year for the two cases CHP only and CHP + WSHP relative to the gas base case. The relative savings are always larger for the CHP + WSHP system than for the CHP only system. This model allows for the calculation of the number of payback years. For the CHP only case there was a payback period of 11.66 years and for the CHP + WSHP there was a payback period of 9.79 years. This is despite the CHP + WSHP having higher capital costs. Because of the higher annual savings the payback period is still smaller than that for CHP only.

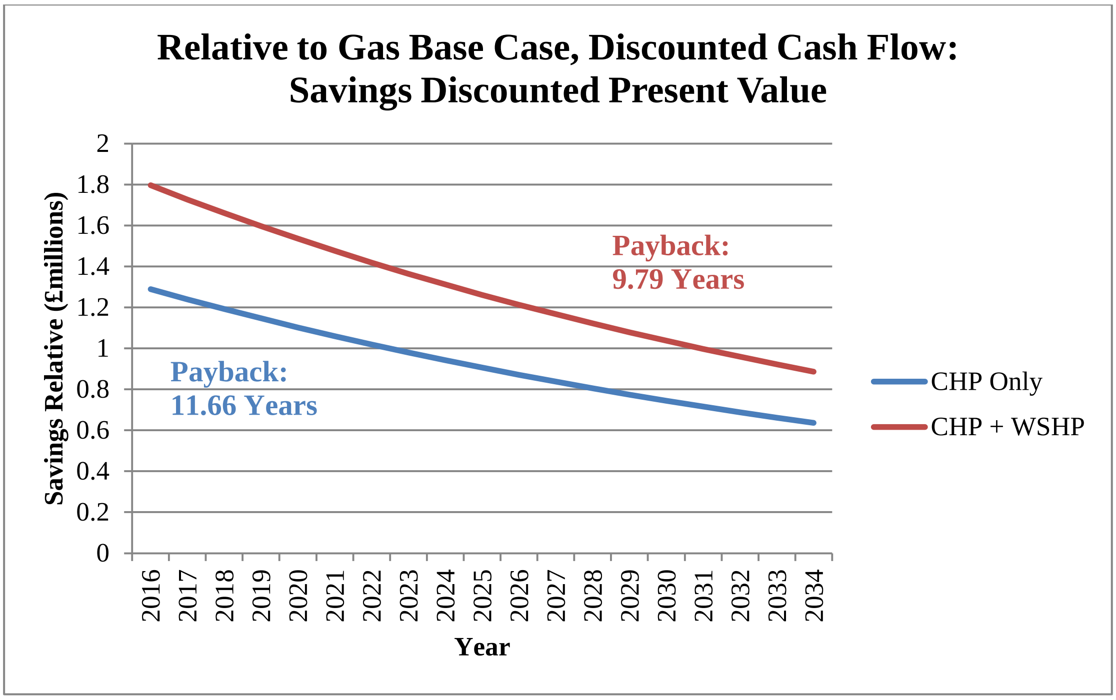

Figure 51: Discounted cash flow, Comparison to Gas

Similar calculations were performed using Gas + Electricity as the base case. The CHP + WSHP case still offer larger relative annual savings. The difference is that they are larger, with the payback period for the CHP only case now 5.46 years and for the CHP + WSHP it is 5.36 years. This emphasises the advantage of installing the CHP + WSHP case when there is conventional electrical heating. These payback periods should be considered when compared to the lifetimes of for both systems around 20 years.

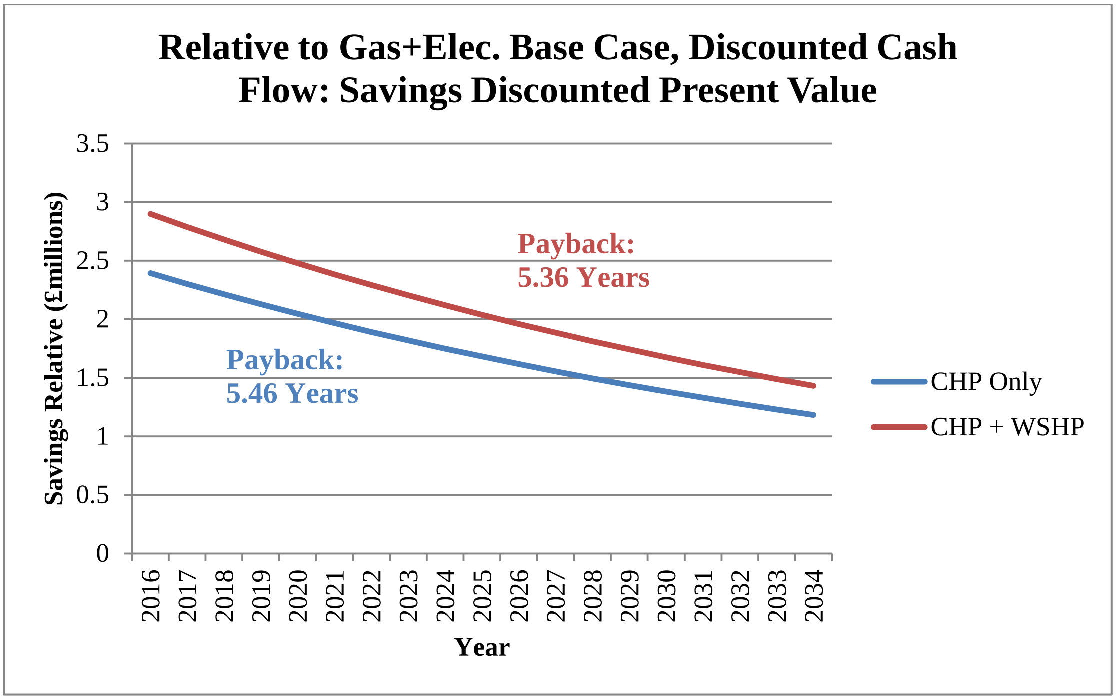

Figure 52: Discounted cash flow, Comparison to Gas + Elec.

6. Conclusions

The main aim of this thesis was to investigate the different aspects concerning large heat pumps capable of driving a district heating network, and particularly at the case of implementing one on the River Clyde in Glasgow. The success of the methodology and the results obtained from it are discussed here. The thesis ends with a section on suggestions of further work which could be done in this area.

6.1. Methodology

The methodology developed proved to be an apt tool for investigating the case of the River Clyde, Glasgow. The section concerning the properties of the river provides useful suggestions for how to best utilise a river as a heat source. The method of obtaining and analysing the flow rate data is thorough enough to be applied to most rivers in the UK. The method suggested to obtain the river temperature data is useful for when this elusive data is unavailable. There could be a more thorough description of the best practice for performing the required work to obtain the river temperatures. This applies for the flow rate too.

The heat pump sizing section of the methodology describes a variety of methods for reducing the size of the heat pump. This section could be developed to include a model for designing a heat pump, as this is what is required to properly size a heat pump. This was outside the scope of this project. The following section detailing more case studies regarding heat pumps is vital without the necessary method of heat pump design. This is so that realistic estimates of a proposed heat pump can be made. Ideally, this section would be used to validate the results of a heat pump design model. For the purposes of this thesis it was sufficient to obtain the relevant technical characteristics of a heat pump from the case studies. A COP seasonal variation model was described to account for the seasonal variation in the performance of the heat pump. It is a simply model, with simplistic assumptions. However, it proved useful as a means to include this characteristic of heat pump performance, without having the specifics of the heat pump design. Further work could be performed to more accurately model this.

The next section of the methodology described identifying a potential district heating site and a method of developing an appropriate thermal demand profile. The heat map proved to be a useful tool for identifying potential areas through high resolution data on demands and additional tools capable of showing relevant information. Once a site was selected then the method for generating the demand profile was effective. A whole thesis could be dedicated to the specifics of generating accurate demand profiles, but the developed method provided a way of providing a sufficiently realistic method to be used to test the validity of a WSHP. There could especially be improvements to the number of building classes included, as it is unrealistic to fit certain buildings into a choice of only three categories. More data could be included into the heat map such as seasonal, or even daily, variations of certain areas, or access to the types of buildings in a certain area. This sub-section ends with the description of the model used to model the effect of the choice between high and low temperature distribution system. The reality of this area of district heating is highly complex, and outside the scope of this project. The model provided a useful method of inspecting the general difference.

The demand/supply matching required the development of an Excel spreadsheet model. This model essentially compares the demand of the district heating scheme and the thermal supply of different heating configurations, four of which were chosen. The choice of configurations were useful to see how a WSHP could perform in a hybrid system, as it is unlikely a heat pump would be designed to provide all the demand. It is also unlikely that the CHP would be used as the only form of top up to the heat pump. More configurations should be analysed with particular interest in solar-assisted heat pumps. The model itself would benefit from including a form of control scheme. This will discussed further in the Further Research section.

The environmental section provided a worthwhile guide for investigating these concerns. The regulation description is thorough and provides specific details regarding relevant aspects. The construction section gives a rough environmental checklist for assessing the environmental impact. For an initial feasibility stage this is sufficient, but it would be necessary to carry out a much more specific analysis of the impacts for a later stage. These specifics are too in-depth for the scope of this thesis. The carbon emissions and air quality calculations set out provide an effective way of quantifying these particular environmental aspects. The one area which could be expanded upon is calculating the embodied emissions associated with construction. The requirement is for details regarding the components and materials used in construction of both the heat pump and the district heating.

The economic section begins with a comprehensive description of the RHI regulations relevant to the project. The capital and operational costs are then discussed, assigning an approximate cost method to the various components associated with the heat pump and district heating network. This method is cumbersome, however provides an effective way of calculating costs in the absence of real data. Even this method requires a level of data which is difficult to obtain so an alternative is provided using estimations based on previous case studies. This is adequate for investigating the economic factors. The financial model uses well sourced electricity and gas prices, and thorough calculations with the discount cash flow model.

There are limitations to the methodology which this thesis presents. However, they are often overcome by sensible estimations and alternative, albeit simpler, methods. The methods proposed are generally applicable to rivers, particularly those in Scotland. It achieves the objective of developing a generic methodology capable of investigating the viability of river source heat pumps driving a district heating network, while addressing technical, environmental and economic aspects.

6.2. Results & Analysis

The River Clyde was found to be a suitable source of heat for a heat pump capable of driving a district heating network. The analysis of the flow rate showed how the river is a fast flowing river with more than enough volume to provide for a large-scale heat pump. The river temperature data used was for the Clyde Sea and therefore very conservative measures were taken with respect to the viability of this aspect of the river. Judging by the Clyde Sea temperatures it is possibly feasible for the River Clyde to provide a higher ΔT than assumed, and therefore a higher heat input. Work should be done to take the necessary measurements to confirm this. The proposed heat pump was sized to 6.65 *MW* which compared to previous case studies is suitable for district heating.

The heating map was used to identify a prospective are for district heating on the River Clyde. A number of potential sites could have been chosen since the river runs through the centre of the city, highlighting the viability of this river. The thermal demand profile was developed, and had all the desired characteristics to represent a district heating demand.

The demand/supply matching technical analysis illuminated many of the aspects relevant to hybrid heating system configurations. It showed that heat pumps are a great method of using electricity more efficiently. The proposed heat pump did require large capacity CHP when the district heating demand was chosen to be too large. Low temperature distribution systems were confirmed as the technically best choice for heat pumps.

For the current year, 2015, the results showed that CHP only systems provide the lowest CO_2 equivalent emissions. However, when looking to the future with a decarbonised grid it is apparent that the CHP quickly falls behind the WSHP + CHP system, eventually becoming the worst offender for CO_2 emissions. Even in the pessimistic view of the future decarbonisation of the grid CHP becomes the worst offender well within its lifetime. The WSHP + CHP system has a much better environmental future. CHP is often seen as a low-carbon, environmentally friendly choice. This only holds for the present and in the future district heating networks may be left with a relatively worse CO_2 emitting heating system due to short-sightedness. For heating to become a low-carbon intensive process then there should be a move away from gas-based heating systems to electrical based heating systems. This is particularly true for heat pumps which provide a much more efficient use of the electricity than conventional electrical heating. The support for this move is strengthened by the results on air quality, where the systems featuring electrical driven heating outperform those using gas. As expected low temperature distribution systems also emit lower CO_2 emissions than high temperature distribution systems.

The RHI payments were shown to have a large impact on the economic viability of the WHSP, raising questions on the risk involved with over-reliance. Economically it was found that CHP only and WSHP + CHP invoke superior savings relative to gas only or gas and electricity. This suggested a move away from electrical heating. However, the system with the WSHP provides greater savings, suggesting that efficient use of electricity to provide heating can even beat gas. The low temperature distribution system again proved the better choice by having lower annual costs than the high distribution system. What was particularly interesting was the size of the difference. It suggests that further work should be done to consider the advantages involved with retrofitting buildings to accommodate this distribution system. The discount cash flow model showed that short payback periods, relative to the lifetimes of the systems, can be possible. The system including the WSHP has the shortest payback period, despite the highest capital cost. This conveys the savings possible by implementing, not only a district heating scheme, but one which uses a river source heat pump to provide a large proportion of the heat.

The results and analysis required to meet the objectives were successful. They showed how a district heating system driven by a river source heat pump in Glasgow on the River Clyde can be technically, environmentally and economically viable. There are issues, highlighted throughout the discussion, which may affect the conclusions being drawn in this thesis. But it appears that heat pumps and district heating can play a valuable role in the UK to push for more sustainable, low-carbon heating.

6.3. Further research

A number of areas for further research arose during the carrying out of this project and some are listed below.

Multiple WSHPs

For numerous district heating schemes in a city to be heated by WSHP the possible cumulative impacts between them needs to be considered. There will be a number of environmental issues, particularly with the river having a higher risk of freezing and overuse.

Cooling and Heating Thermal Network

Cooling is becoming a more intensive energy requirement as facilities such as datacentres become more commonplace. Thermal networks with heat pumps provide a possible avenue to provide cooling as well as heating. Heat pumps have to cool water in order to heat water in another place, meaning both can be done simultaneously. Work could be done into the integration of these into a combined thermal network.

Operational control scheme

Control of when the heat pump is used, or when it is better to use another heating system depending on the time of day or electricity price or a number of factors, could lead to higher use of the heat pump. Work should be done to develop such a scheme capable of controlling the operation to analyse potential technical, environmental and economic gains.

Thermal Storage

Storage was discussed as an option as a way to optimise the size of the heat pump. This could be incorporated into the demand/supply matching model, with a view to analysing an array of possible options.

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